S. HRG. 117–106

GLOBAL CLIMATE TRENDS FROM ENERGY-RELATED SECTORS TO CONSIDER WHERE AND HOW PROGRESS HAS BEEN MADE IN ADDRESSING CLIMATE CHANGE

HEARING

BEFORE THE

COMMITTEE ON ENERGY AND NATURAL RESOURCES UNITED STATES SENATE

ONE HUNDRED SEVENTEENTH CONGRESS

FIRST SESSION

FEBRUARY 3, 2021

Printed for the use of the
Committee on Energy and Natural Resources

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[1] Senate Resolutions 28 and 32, concerning official designations of committee membership for the 117th Congress, were passed on February 3, 2021, after this hearing took place.

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GLOBAL CLIMATE TRENDS FROM ENERGY-RELATED SECTORS TO CONSIDER WHERE AND HOW PROGRESS HAS BEEN MADE IN ADDRESSING CLIMATE CHANGE

WEDNESDAY, FEBRUARY 3, 2021

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The Committee met, pursuant to notice, at 10:11 a.m., in Room SD–G50, Dirksen Senate Office Building, Hon. Lisa Murkowski, Chairman of the Committee presiding, to consider the nomination of Governor Jennifer Granholm, to be the Secretary of Energy. Upon disposition of the nomination, the Chairman adjourned the business meeting and reconvened the Committee to take testimony on global climate trends.

The Committee met, pursuant to notice, at 10:21 a.m. in Room SD–G50, Dirksen Senate Office Building, Hon. Lisa Murkowski, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. LISA MURKOWSKI, U.S. SENATOR FROM ALASKA

The CHAIRMAN. We can move now to the hearing that is scheduled this morning, and I will turn to Senator Manchin.

OPENING STATEMENT OF HON. JOE MANCHIN III, U.S. SENATOR FROM WEST VIRGINIA

Senator MANCHIN. Thank you, Madam Chair.

So this Committee has proven itself ever ready to rise to the occasion of working together to identify and enact solutions to both present and future issues facing our country. As Chairman, I am committed to continuing these traditions and working with all of my colleagues on the issues that are important to their states and to our nation. Climate change is one of those issues—critical not only to our states and our nation, but to every country around the world.

To address climate change, we must face it head-on, on a global scale, and in every sector of our economy. No doubt, we will all have differing views on the best way to do that, but first, I believe, we must begin with a common understanding of where we stand today and what got us here. I have long said that you are entitled to your own opinions, but not your own facts. And it is in that spirit that I wanted our first hearing of this new Congress to focus on setting a baseline of global climate facts from which the Committee can build on as we advance climate solutions.

In 2019, a few of my colleagues and I visited the Arctic, where we met with several leaders, and in each country we visited, we saw the impact of climate change firsthand and heard from those leaders that it was a matter of survival, not of partisan politics. I will ad-lib here: when we had been in Ottawa, the United States was the only country of all the Arctic nations that basically used climate as a political divide. They all came to a conclusion. John, we were all there. It was a great day that we had with our Chairman, our former Chairman, almost.

[Laughter.]

Maybe.

This Committee has shown the ability to rise above that, as evidenced by the recent enactment of the Energy Act—our all-of-the-above energy innovation package with provisions sponsored by almost 70 senators last year. It is abundantly clear that the dwelling on partisan rhetoric shuts down debate, collaboration, and progress. And as we look for ways to heal the division in our own country, I believe that one way for us to overcome our differences of opinion is by first grounding ourselves in the facts, which will serve as a guide going forward.

Before hearing from our panel today, there is one fact that I would like to serve as our starting point, and that is that climate change is real and largely linked to human activity. Scientists around the world, including in our national laboratories, are researching many aspects of climate change, and the scientific record is convincing and growing. This year——

[Coughing.]

Excuse me. Oh boy, I just got tested.

This year, the Intergovernmental Panel on Climate Change——

Senator BARRASSO. Was it positive or negative?

[Laughter.]

Senator MANCHIN. That was a good one, John.

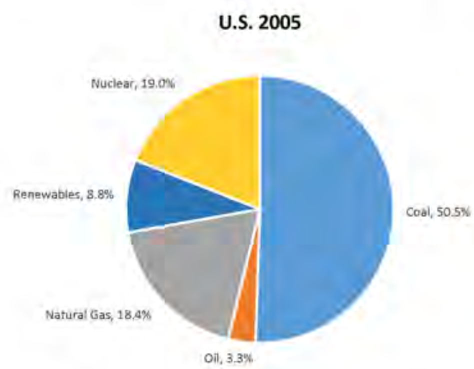
[Laughter.]

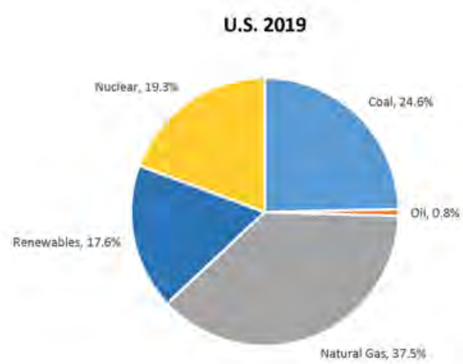
This year, the Intergovernmental Panel on Climate Change will release its sixth comprehensive report on global climate change, and I look forward to learning the new findings.

We also have an immense amount of energy data on our fingertips, thanks to the incredible work of the U.S. Energy Information Administration and international organizations like the International Energy Agency (IEA). A snapshot of that data shows that in the past 10 to 15 years, the United States has seen major transition in energy markets. We will be leaving these two panels up here for you all to view.

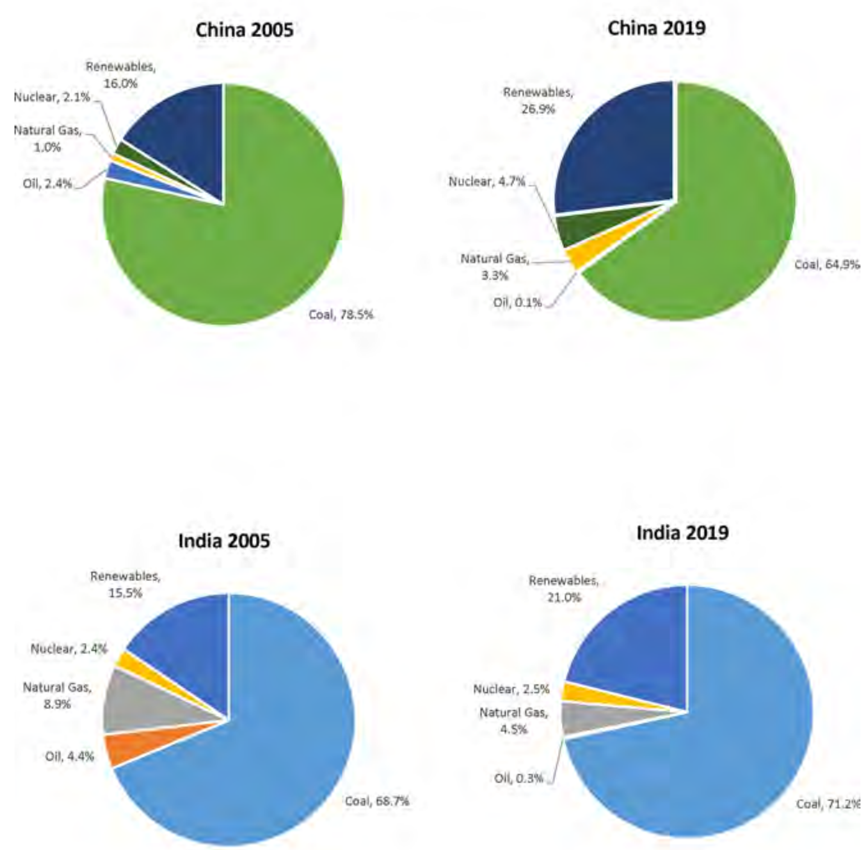
[The two panels mentioned follow:]

U.S. Electricity Generation Mix 2005 vs. 2019 (IEA)





China and India Electricity Generation Mix 2005 vs. 2019 (IEA)



Senator MANCHIN. The cost of natural gas has been cut in half from 2010 to 2020 and the cost of wind has fallen by 70 percent and the cost of solar has fallen by 90 percent. When paired with increasing energy efficiency, this has led to a rapidly changing electric power grid system. While it is much less carbon intensive, retirements of coal-powered plants have devastated communities across my home State of West Virginia along with many other traditional energy-producing states represented on this Committee.

That raises two points that we must recognize about fossil fuels. In the domestic context, the energy transition has increased hardships in the areas of the United States that have powered our nation for decades by mining its coal, producing its fuel, and generating its electricity. As our energy mix has changed, concern about the impacts on these traditional energy communities has and will remain front-of-mind for many of our members. I will continue to work hard to ensure that those communities are given new opportunities to thrive, including as a member of the new IEA Global Commission, focused on examining the impacts of a clean energy transition on individuals and communities. I am honored to join this effort and confident our discussion today will provide a strong foundation for discussions ahead as we work to address climate change and leave no one behind.

We must also recognize that although fossil fuel consumption is dropping in the U.S. power grid, the global transition in fossil fuel use should make us all recognize that fossil fuels are not going away anytime soon, particularly in countries that are seeking to expand access to electricity and energy in order to address poverty. In both the domestic and international arenas, however, the fact is that we have tackled these challenges before and we can overcome them again by focusing on the technological innovations needed to do so. Following the Clean Air Act amendments of 1990, electric utilities across the United States developed and adopted equipment that aided their compliance with the new laws to reduce or eliminate SO_X and NO_X and particulate matter. By outlining the facts about our pollution and developing the technologies needed to manage it, utilities were able to adapt and improve public health and maintain jobs, all at a lower cost than what was initially projected. This provides one principle for our Committee's work going forward: the power of innovation combined with keeping all of our options on the table will help us create high-quality jobs, reach our environmental goals, and do so cost-effectively.

I also think it applies in the global arena, as we look to lead the world on tackling the climate challenge. We must remember that the rest of the world is not necessarily ready to follow the same path as we do. By pursuing an all-of-the-above energy policy and a broad array of emissions-reducing technologies, we can simultaneously build our technology export opportunities and diplomatic relationships with those countries who choose to utilize their own fossil resources.

Today's panel includes experts that bring domestic as well as global perspectives and includes Dr. Birol, the Executive Director of the International Energy Agency; Dr. Richard Newell, the President and CEO of Resources for the Future; Dr. Angel Hsu, an Assistant Professor at the University of North Carolina; Dr. Scott

Tinker, Director of the Bureau of Economic Geology at the University of Texas; and Mr. Mark Mills, a Senior Fellow at the Manhattan Institute. I would like to welcome all of you to the Committee for this important retrospective discussion that will set the scene for forward-looking solutions. I look forward to hearing this discussion and about the trends and current state of play in global and domestic energy markets, technologies, policies, and emission reductions. Of course, the raw data and percentages are just the tip of the iceberg. Below the surface, the changes we have seen were being driven by innovation, policy, markets, and incentives. This discussion will serve an important role in setting a baseline of common facts and a historical perspective for this Committee from which we identify the common challenges and opportunities and move quickly to address them.

With that, I am going to turn it over to Senator Barrasso for his opening statement.

Senator Barrasso.

OPENING STATEMENT OF HON. JOHN BARRASSO, U.S. SENATOR FROM WYOMING

Senator BARRASSO. Thanks, Senator Manchin, and you know, in December of last year, Congress passed historic, bipartisan climate innovation legislation that I worked on closely in the Environment and Public Works Committee with Senator Carper. This was the most significant greenhouse gas reduction bill to be signed into law in well over a decade. Importantly, it won't raise costs for American families. So I look forward to working with you, Senator Manchin, on energy and environmental innovation in this same bipartisan spirit.

Today's hearing is intended to set the baseline of knowledge about contributions to global emissions. It is a very worthwhile goal. We are holding this hearing at a very critical moment. Over the past two weeks, the Biden Administration has rolled out a series of indefensible and ineffective climate policies that will sacrifice—that is the term used by the nominee to be Secretary of Energy—to sacrifice tens of thousands of American jobs. This hearing can provide an important reality check. I think we have to stop fooling ourselves into thinking that eliminating U.S. fossil fuel production is going to solve the problem, because it won't. It will just make America less competitive and less energy secure.

The energy industry has been a critical engine of economic recovery in the past. After the Great Recession, while the rest of the economy was still struggling, the oil and gas industry was investing and adding jobs at a brisk pace. Because of these investments, the U.S. has some of the lowest energy prices, cost to consumers, in the world. Now President Biden wants to kill energy jobs and drive up energy prices. Undermining America's energy security will not solve climate change. It is unrealistic to expect that China, India, and Russia and many other large emitters will stop using fossil fuels. It is just unrealistic. They know the importance of affordable energy to their own economies. Eliminating U.S. fossil fuels is not going to change any of that.

This data from the International Energy Agency has shown that the U.S. has become a significantly smaller source of carbon dioxide emissions worldwide. U.S. emissions now account for just 14 percent of the global total. That is down from 25 percent just 20 years ago. Over that same period of time, the share of total emissions from China jumped from 13 percent of the world's carbon emissions all the way up to nearly 30 percent—from 13 to 30 percent of the world's carbon emissions due to China. And it is not just China. Emerging economies like India, Brazil, South Africa, and others are all increasing energy use as they develop and grow in population. The International Energy Agency expects that by the year 2030, energy use in these and other developing countries will jump by almost 20 percent. With almost a billion people still lacking access to electricity around the world, addressing climate change is not a priority for developing countries, especially if it hampers their economic development. They do not consider it a priority in their efforts for economic development.

Affordable, reliable, and scalable energy are the keys to reducing energy poverty, to improving human welfare, and to powering economic growth. These trends mean we have to focus on practical solutions. At its most fundamental level, reducing greenhouse gas emissions is a technology challenge. Instead of raising the cost of traditional energy sources, we should work to lower the cost of alternate technologies, like carbon capture and advanced nuclear reactors. Until that happens, traditional fuels are going to continue to capture the lion's share of global energy demand.

An approach based on innovation plays to our strength in America. American innovation is the key to reducing global emissions and our goal should be to encourage and support that process and that progress.

Thank you, Mr. Chairman.

Senator MANCHIN. Thank you, Senator.

Now we are going to turn to our witnesses. And our first witness will be Dr. Birol. Doctor, thank you so much.

STATEMENT OF DR. FATIH BIROL, EXECUTIVE DIRECTOR, INTERNATIONAL ENERGY AGENCY

Dr. BIROL. Thank you very much, Senator Manchin. Senator Manchin, Senator Barrasso, still the Chairman, Senator Murkowski, members of the Committee, dear fellow witnesses, greetings to all of you from Paris, from International Energy Agency Headquarters.

So before starting my words, may I congratulate Governor Granholm for getting the approval of the Committee and, if confirmed, I am looking forward to working with Ms. Granholm as the next Secretary of Energy of the United States.

And also, many thanks to Senator Manchin for agreeing to be a member of our Global Commission on People-Centered Clean Energy Transitions. Thank you very much, sir, for joining global leaders focusing on this issue.

It's an honor for me to be here as the Head of the IEA, to be in front of you. I had the pleasure to testify several times and I can tell you, every time I learn a lot from you and I understand it's a special group that work on a bipartisan basis and reach several good results, the last one being the Energy Act of 2020, for which I thank you and I congratulate you.

Now, you have my full testimony in front of you, so I just want to focus on three points from the global picture. First, current state of play, international climate change. Our climate change is essentially an energy challenge. Why? Very simple—about 80 percent—in fact, more than 80 percent of the emissions causing climate change come from the production and use of energy. And methane comes out of that. If you look at the major emitters, I'll give you four of them, four major ones. China is, by far, the largest emitter since 15 years, China is the largest emitter, responsible about 30 percent of global emissions. But China is also, by far, the leader of solar energy. The solar energy in China is equal to all the other countries put together. India emissions are about seven percent. But on a per-capita basis, it is about the lowest in the world. The European Union—also about seven percent, and I should mention to you that the latest EU stimulus package will spend billions on new clean energy technologies. The United States—USA's international world emission reductions over the recent years and today, U.S. emissions are half of that of China, but on a per-capita basis, still very, very high. So this is the picture of where we are.

The second point I want to mention is the technologies we maybe enact to reach our climate course. We have wonderful technologies which are already ready for the markets—solar, wind, onshore wind, offshore wind, hydropower, geothermal, nuclear power—they are ready for the markets, but they alone are not enough, by far not enough to reach our climate course. Innovation, as Senator Barrasso mentioned, is the key word here and the innovation in the carbon capture and storage industry. Hydrogen and advanced nuclear will be critical to reach our climate course. We have some which are ready. They are not enough. We need innovation, other clean air technologies being made part of our markets.

Third point: clean air energy transitions will have broad repercussions and there are some challenges. I want to highlight only two for you, maybe we can discuss at length in the next minutes to come. The first one is the challenges coming from the critical minerals. Under ambitious climate policies, the energy sector will become a major force in drive and demand for copper, lithium, nickel, and cobalt and we see it still develop vulnerability of our global system in the next years to come. It is the reason IEA is preparing a major study to look at the global tensions that can arise from this challenge.

The last point I want to mention, another broader implication, is how the governments will be able to proceed clean energy transition without having major impact on the communities, on the workers. So smart, well-designed policies will be critical in order to help everybody on board. So these are two major implications while we proceed with clean energy transitions around the world.

Once again, Mr. Chairman, thank you very much for inviting the International Energy Agency. I am looking forward to your questions and the comments of my colleagues. Thank you.

[The prepared statement of Dr. Birol follows:]

Written Testimony
Hearing of the U.S. Senate Energy and Natural Resources Committee
Global Climate Trends and Progress in Addressing Climate Change

Dr Fatih Birol
Executive Director
International Energy Agency

3 February 2021

Senator Manchin, Senator Barrasso and distinguished Members of the Committee, thank you for the opportunity to appear before you today and to present the International Energy Agency's (IEA's) latest data and analysis on global climate trends and progress in addressing climate change.

Senator Manchin, it is an honor to be here, and I look forward to continuing to do everything we can at the IEA to help you and all of your colleagues. I have always greatly benefited from your partnership and insights, and I know that this Committee is in incredibly good hands.

Congratulations also to Senator Barrasso. Wyoming is such an energy powerhouse in so many ways, and I look forward to helping you in your work and priorities going forward as well.

I would also be remiss if I did not thank Senator Murkowski for her years of skillfully leading this critical Committee. I have very much enjoyed testifying in front of Chairman Murkowski and Senator Manchin over recent years, and all of us at the IEA have benefited – and I know will continue to benefit from – your global energy leadership. Let me thank you, in particular, Senator Murkowski for being such an invaluable member of our Global Commission on Energy Efficiency.

I am not an expert on the U.S. government, but I know from having first testified in front of this Committee in 2007 that this is a special group and one that has worked on a bipartisan basis to achieve real results for the American people and for the world. Congratulations, in particular, to all Senators and staff responsible for the historic Energy Act of 2020, which will materially advance so many of the key technologies that we will be talking about today.

I am particularly pleased that you have decided to use this first non-nomination hearing to establish a baseline on global climate trends and progress. As many have said before, everyone is entitled to their own opinion but not to their own facts. As a data-driven organization, we at the IEA could not agree more. Put simply, we need a robust understanding of what is happening today if we are to build a better tomorrow.

A brief overview of the IEA

Since the founding of the IEA almost 50 years ago, the United States has been a crucial pillar for the Agency. U.S. leadership and support has come from across the government, including the Senate, the House of Representatives, the White House, the Department of State, the Department of Energy and the National Labs. I would like to particularly express my excitement to work with the new Secretary of Energy, Jennifer Granholm – should she be confirmed. The IEA stands ready to help her and her new team – and all parts of the U.S. Executive Branch – in any way we can.

Since the IEA's founding in 1974, we have evolved, expanding to become the world's leading authority on global energy issues, providing data, analysis and advice to governments and industry across the full energy spectrum. Today, the IEA has 30 Member countries and partnership with key Association countries, including the world's largest emerging economies Brazil, China, India, Indonesia and South Africa. Our IEA family reflects the global nature of energy, accounting for almost 75% of the world's energy consumption.

Energy and Climate are Inextricably Linked

When looking at global climate trends – the focus of this hearing – one has to focus on energy. Currently, over 80% of global CO_2 emissions come from energy production and use – everything from electricity to industry, from heating homes to moving people and product.

The energy sector also contributes around one third of the methane emissions that arise from human activity. The IEA has long focused on this issue, especially on the leaks from oil and gas operations, which are largest part of energy sector emissions and also the most cost-effective to abate.

Early action to bring down these methane emissions will be critical for avoiding the worst effects of climate change, alongside ambitious action to reduce CO_2. Industry around the world needs to act, visibly and quickly, but there is also a strong role for policies to incentivize this action, push for transparency and improvements in performance, and support innovation in getting results.

Turning to IEA data on CO_2 – the primary greenhouse gas – prior to the Covid-19 crisis the energy sector was responsible for around 35 billion tonnes (Gt) of CO_2 emissions each year. The vast majority of these emissions come from the combustion of fossil fuels: around 45% from coal, 35% from oil, and just over 20% from natural gas.

Breaking these combustion emissions down by sector, electricity generation accounted for around 40% of the global total, followed by emissions from transport (around 25%) and industry (20%). The residential and services sectors, as well as activities such as oil and gas extraction and refining, make up the remainder.

In our estimation, energy-related CO_2 emissions came down by around 7% in 2020, and energy-related methane leaks by a similar amount. However, since these reductions were almost entirely linked to the effects of the pandemic, there is a major risk that these emissions will rebound as economies recover, just as happened after the 2008/9 Financial Crisis.

That is why the IEA continues to put such a strong emphasis on the importance of a sustainable recovery, including our groundbreaking analysis with the IMF last year laying out actionable recommendations, the IEA Sustainable Recovery Plan.

Key Global Trends – Emissions

Let us now look at how global emissions breakdown by country. The largest emitting country in the world is China, with almost 10 Gt of emissions (around 30% of the global total), which is roughly twice the amount from the United States (14% of the total). The United States in turn emits around twice as much as the European Union (8%). Indian emissions (7%) are slightly lower than the European Union, although on a per capita basis Indian emissions are currently among the lowest in the world.

Energy use in developing economies has been driven by building the infrastructure that supports the modern lifestyle that we generally take for granted: the number of people without electricity in Africa is twice the US population. The number of people in India who have basic access to electricity but own neither a refrigerator, a washing machine nor an air conditioner is four times the US population.

Between 2000 and 2019, global emissions grew by around 10 Gt. During this period, emissions in advanced economies fell by more than 10%, with emissions in the United States falling by more than any other country. Meanwhile, emissions in emerging and developing economies more than doubled, mainly due to rising emissions from China.

This divergence in regional trends is also visible if we look to the future. According to our latest IEA *World Energy Outlook*, published last October, today's policies are enough only to secure a flattening of global emissions out to 2040, a trajectory far from what will be needed to avoid severe impacts from climate change.

Within this picture, advanced economy emissions fall by around 30% from where they were in 2019, but these are offset by a 15% rise in projected emissions from the rest of the world. While China's emissions per capita are already above the global average, per capita emissions in most emerging and developing economies remain well below those in advanced economies.

The Transformation of Electricity

There has been a lot of progress on clean energy transitions in recent years, most notably in power generation. As of 2020, coal makes up around 35% of global electricity generation, with renewables just under 30%. In the IEA's view, we are set for a landmark shift before 2025 as the share of renewables overtakes that of coal.

The future is clearly moving towards clean electricity supplies, in particular solar. Thanks to policy and technology progress, as well as low-cost financing, solar PV is now consistently cheaper than new coal- or gas-fired power plants in most countries, and solar projects now offer some of the lowest-cost electricity ever seen. As we put it in our World Energy Outlook, solar is the new king of electricity.

Wind power – onshore and increasingly offshore – is a similar success story, which is something I do not have to tell given the states that many of the Members of this Committee are from. For instance, in Senator Heinrich's state of New Mexico, Senator King's state of Maine and Senator Hoeven's state of North Dakota, wind power now accounts for 20-30% of all electricity generated, thanks to rapid increases in deployment in recent years.

Today, around 10% of total electricity generation is nuclear, and lifetime extensions for existing plants as well as new technologies like Small Modular Reactors can ensure the continued support from nuclear power to a low-carbon transition. Senator Barrasso, I know this technology is a particular focus for you, as well as for many other members of this Committee. Small Modular Reactors can support the rising share of variable renewables, with shorter lead times and lower investment requirements than large-scale nuclear plants.

A Strong Focus on Grids, Electricity Security, and Critical Minerals

As the technologies used to produce electricity change, the rest of the system cannot stand still. Robust and smart electricity grids, demand-side responses, and a variety of storage technologies will be essential to provide the flexibility and reliability that we will need. Working with governments, regulators and industry to ensure high levels of electricity security is a key priority for the International Energy Agency, including with the creation of a new Renewable Integration and Secure Electricity Unit at the IEA.

Electricity grids are the backbone of today's power systems and become even more important in clean energy transitions as they help to integrate rising shares of wind and solar PV. Adequate investment is vital to expand this infrastructure and to make it smarter and more resilient, including against cybersecurity threats.

The rapid deployment of clean energy technologies also brings important new resource and security issues into focus, especially the reliable supplies of critical minerals and metals that are vital to energy transitions. Under more ambitious climate scenarios, the energy sector will become a major force in driving demand growth for copper, lithium, nickel, cobalt and rare earth elements.

This is a key focus for many of our IEA Members countries – from Europe to Australia, from Japan to Canada as well as for several other countries beyond our membership. Accordingly, we are undertaking a major new global analysis that will be released in April 2021 to examine how demand for critical minerals will evolve and explain the implications for security of supply as well as responsible and sustainable developments of the resources.

The Importance of Innovation

Low-carbon sources of electricity will play a vital role in bringing down emissions in other parts of the energy sector, as electricity expands its role in transport and industry. But clean electricity alone cannot deliver a comprehensive solution to climate change on its own.

We will need many more such technology success stories for a global clean energy transition, especially in view of the ambitious net-zero emissions goals that many governments and industries have set for themselves. The European Union, Japan, the UK and many other major world economies are aiming to reach net-zero emissions by 2050. China, the world's biggest emitter, is aiming to be carbon neutral before 2060. And U.S. President Joe Biden announced the nation's return to the Paris Agreement and is putting the fight against climate change at the centre of his administration's goals.

All of these announcements need to be backed up by equally ambitious actions to reach net-zero emissions as soon as possible and prevent global warming from surging past 1.5 degrees. Political, industrial and technology leaders must be laser-focused on innovation because, for the moment, we do not have all the technologies we need to get to net zero, especially in parts of the transport and industry sectors.

Analysis in our latest Energy Technology Perspectives report shows that almost half of the emissions reductions needed to reach net zero by 2050 will need to come from technologies that have not reached the market today. This means that we will not be able to get there by 2050 without giant leaps in innovation in a range of other clean technologies — some of which are still in the lab.

This is especially urgent in sectors like steel, cement, chemicals, shipping and aviation, where emissions are the hardest to reduce and cost-effective solutions are lagging behind. Addressing these emissions will require strong innovation efforts to bring forward technologies that can enhance electrification of end uses, like advanced battery chemistries, and technologies for the production and use of clean hydrogen, a very versatile energy carrier, and other sustainable fuels.

Avoiding Emissions from Existing Infrastructure

Solving climate change cannot be just a question of building clean from now on. It is also a question of cleaning up what we already have. Coal-fired power plants can operate for 50 years and longer. Iron and steel or cement plants have typical lifetimes of 40 years. And many of those in operation today, especially in many parts of Asia, are still very young.

Even without building any new infrastructure, the energy infrastructure that we currently have in place today alone will lead to a global warming of 1.65 °C if it continues operating as it does today for the full extent of its expected lifetimes.

Fortunately, there are ways to deal with these emissions. Carbon Capture Utilisation and Storage (CCUS) is a key opportunity to ensure that those power and industrial facilities that are still young today and have not yet recovered their upfront investment can contribute to a clean energy transition.

We have seen a lot of momentum on CCUS recently: plans for more than 30 new integrated CCUS facilities have been announced since 2017. The vast majority are in the United States and Europe, but projects are also planned in Australia, China, Korea, the Middle East and New Zealand.

The United States has been a longstanding leader on CCUS. I applaud many of you on this Committee, in particular, for your leadership on the 45Q tax credit that has supported U.S. investment activity in CCUS. I can also tell you that many other countries around the world are eager to learn from your example.

U.S. Leadership in a Crucial Decade for Energy and Climate

We are at a hugely consequential moment for the energy sector and for the urgent global response to climate change. Looking at all the numbers and analysis we have at our disposal at the IEA, let me leave you with three top recommendations as you go about your work during this critical year of 2021:

1) **Invest in a Sustainable Recovery and People-Centric Transitions** – there is a unique strategic opportunity for the United States to ensure that its economy comes out of today's crisis stronger while also bringing it closer a clean energy future. This an area where jobs, competitiveness, energy and climate priorities align. In addition to our work on sustainable recoveries, the IEA last week launched a new global commission on 'Our Inclusive Energy Future', headed by the Danish Prime Minister, along with Ministers from countries ranging from Mexico to Indonesia, from

Canada to Spain and beyond, to consider the social and economic impacts of the shift to cleaner energy technologies, including how to maximize benefits and mitigate negative effects for citizens.

2) **Harness the power of U.S. innovation to energy transitions** – the immense national scientific expertise across the country, exemplified by the U.S. National Laboratories, can play a critically important role in filling the technology gaps of energy transitions. The United States has been at the forefront of many of the technological leaps of the modern era, such as on solar PV, electric cars and advanced nuclear. With strong and bipartisan support for clean energy innovation, it has a huge opportunity to do so again.

3) **The importance of U.S. global leadership on energy and climate –** The U.S. can set the global agenda like no other country in the world. In galvanizing support for rapid clean energy transitions, it can innovate to provide real-world solutions to energy challenges across the developing world, mobilize public and private finance for sustainable energy, and ensure that we have the tools not only to meet today's energy challenge but the foresight to tackle those of tomorrow.

Conclusion

Achieving global net zero emissions in the ambitious time period that the latest science tells us we need to in order to avoid the worst consequences of climate change will require dramatic and accelerated progress across a wide range of technologies, including renewables, efficiency, CCUS, hydrogen and nuclear, among others.

It will require action across all sectors, not just electricity, making the most of those technologies that we have already, and making sure that we innovate to develop those that we still need. It will also require assembling a broad range of skills, resources and stakeholders.

With its boundless human ingenuity, rich resources and track record of successful innovation and commercialization of new technologies, the United States is extremely well placed to lead the world along with other countries in the development and deployment of energy technologies that can help ensure a secure, affordable and sustainable supply of energy for decades to come.

Senator Manchin, Senator Barrasso and distinguished Members of the Committee, thank you again for the opportunity to appear before you today. Thank you again Senator Murkowski for the close collaboration over the past years. And thank you above all for your continued strong partnership and support for the IEA.

Senator MANCHIN. Thank you, Dr. Birol.

And next we have Dr. Newell for his opening statement.

Dr. Newell.

STATEMENT OF DR. RICHARD G. NEWELL, PRESIDENT AND CEO, RESOURCES FOR THE FUTURE

Dr. NEWELL. Senator Murkowski, Senator Manchin, Senator Barrasso, distinguished members of the Committee, thank you for the opportunity to provide my testimony today. My name is Richard Newell. I'm the President and CEO of Resources for the Future, an independent, non-profit research institution that has informed energy and climate policy for decades. RFF's mission is to improve environmental energy and natural resource decisions through impartial economic research and policy engagement. The views I express today are my own and may differ from those of other RFF experts.

I've had the opportunity to testify before this Committee previously as the Administrator of the U.S. Energy Information Administration. I therefore appreciate the importance of decisions informed by the best data, science, and analysis available. It's my pleasure to be with you here again to speak today about global climate, energy, and emissions trends, particularly from a U.S. perspective.

The climate is unquestionably changing and human activity is the primary driver. Since the industrial revolution, humans have released increasing amounts of greenhouse gases to the atmosphere, leading to higher average global temperatures, melting ice caps, sea level rise, and other impacts. The consequences are stark. The average global temperature has already risen by one degree Celsius. And regions like Alaska have confronted increases twice that amount. The U.S. is the second largest emitter of greenhouse gases after China, and we remain the largest contributor to cumulative historic greenhouse gas emissions. Eighty-three to 85 percent of U.S. emissions come from the production and use of energy, particularly from fossil fuel production. Our mission's trajectory hinges on economic growth, improvements in energy efficiency, and shifts to low or zero carbon energy sources. These shifts are driven, in turn, by three major forces: energy market conditions, technological innovation, and public policy.

U.S. greenhouse gas emissions have decreased/declined since 2005, primarily due to declining coal-based electricity generation and increasing power from natural gas and renewable power sources. Wind and solar have experienced cost declines of over 70 percent since 2009 and have benefited from tax credits and other policies. Natural gas power has benefited from low prices due to shale gas innovation. There have also been substantial advances in technologies that can complement intermittent renewables to provide reliable power, such as energy storage, advanced nuclear, advanced geothermal systems, and natural gas with carbon capture.

The transportation sector is now the largest source of U.S. greenhouse gas emissions, although transport emissions have fallen by about five percent since 2005, principally due to increased fuel economy of vehicles. The cost and range of electric passenger vehicles have improved considerably, but aviation, shipping, and long-haul trucking are more difficult to electrify. U.S. emissions from industrial sources such as steel, cement, and petrochemical production, have shifted only modestly since 2005. Industrial processes that require very high temperatures or have process-related emissions require a distinct set of solutions, possibly carbon capture and storage, hydrogen or advanced nuclear technologies. Outside of energy—agriculture, forestry, and other land use emission sources present distinct issues and they also present opportunities for carbon removal through biomass, carbon sequestration in forests, grasslands, and soils. Direct air capture of carbon is also now possible through technological means.

Because the energy system is so widespread and complex, reducing emissions will require a broad and inclusive approach to incorporating new technologies. We can't know in advance which technologies will become most competitive. So expanding our solution set makes ambitious strategies more feasible.

I'll conclude with three key observations. First, the concentration of greenhouse gases in the atmosphere is increasing rapidly, causing our climate to change. Fossil fuel use is the leading cause, and the U.S. is a major contributor. Second, a wide array of technological options is both necessary and available to reduce emissions across a diverse energy landscape. And finally, given cost reductions in advances in clean energy and other emission reduction technologies, ambitious reductions are now more achievable at substantially lower cost. The success of emissions reduction strategies will depend on how well they meet the needs of diverse sectors, incentivize consumers and producers to choose low emission options, and spur technological innovation. Research shows that incentive-based policies, coupled with targeted innovation support, are the most effective means to allowing private sector incentives with society's emission reduction goals. Innovation flourishes when accelerating demand for new technology is coupled with robust support for research and development.

Senators, I want to thank you again for this opportunity to appear before you. I'll now conclude my remarks and look forward to your questions.

[The prepared statement of Dr. Newell follows:]

RESOURCES *for the* FUTURE

Hearing on

Establishing a Baseline of Global Climate Facts: Understanding the Scale and Sources of Contributions

Written Testimony of Dr. Richard G. Newell
President and CEO, Resources for the Future

Prepared for the US Senate Committee on Energy and Natural Resources
February 3, 2021

Introduction

Senator Manchin, Senator Barrasso, and distinguished members of the Committee:

Thank you for the opportunity to provide testimony to the Energy & Natural Resources Committee as part of the Committee's establishment of a baseline of global climate facts to understand the scale and sources of contribution toward global climate trends from energy-related sectors—and to consider where and how progress has been made in addressing climate change.

My name is Richard Newell, and I am President and CEO of Resources for the Future (RFF), an independent nonprofit research institution in Washington, DC. RFF's mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. The institution, which will mark its 70th anniversary next year, is committed to being the most widely trusted source of research insights and policy solutions leading to a healthy environment and a thriving economy.

Our work on topics such as emissions trading, regulatory design, and measurement of benefits and costs has been used to inform the policy conversation around climate for decades, and we understand the tradeoffs any new policy will face. Today, we focus on two strategic areas: we help decisionmakers to design smart emissions reduction strategies; and we help decisionmakers to confront climate risks and build resilience. While RFF researchers are encouraged to offer their expertise to inform policy decisions, the views expressed here are my own and may differ from those of other RFF experts, its officers, or its directors. RFF does not take positions on specific legislative proposals.

From 2009 to 2011, I served as the Administrator of the Energy Information Administration, or EIA, at the US Department of Energy. In that capacity, I had the opportunity to testify before this Committee, and it is my pleasure to be with you again this morning, to speak about global climate, emissions, and energy trends from a US perspective.

I bring to you the perspective of someone who recognizes the importance of global climate data informed by the latest and most reliable science. I have provided expertise to many of the institutions trusted to collect global energy and climate data, analyze it, and produce the reports and data repositories we rely on both nationally and globally—institutions like the National Academy of Sciences (NAS), the Intergovernmental Panel on Climate Change (IPCC), and the International Energy Forum. I am also a non-industry member of the National Petroleum Council (NPC) and appreciate the changes in energy markets around the world that have taken place over the past decade.

Global Warming and Greenhouse Gas Emissions

The IPCC and other international scientific bodies tell us clearly that the climate is, unquestionably, changing, and that human activity is the primary driver of this change.[1] Since the Industrial Revolution, as populations and economies have expanded, global energy consumption has grown rapidly,[2] and humans have released increasing amounts of greenhouse gases into the atmosphere.[3] We see the results of higher greenhouse gas concentrations in higher average global temperatures, which in turn have resulted in melting ice caps, sea level rise, and other noticeable impacts.[4] As long as net contributions to the atmosphere remain above zero, greenhouse gas concentrations will continue to rise, and temperatures will continue to increase. The consequences of our actions to date are stark: the average global temperature has already risen by 1°C (nearly 2°F), and some regions, such as Alaska,[5] have had to confront temperature increases more than twice that amount.[6]

Sources and Trends in US Greenhouse Gas Emissions

The United States is currently the second largest emitter of greenhouse gases, having been surpassed by China in 2005.[7] Yet the United States remains the largest contributor to cumulative historic emissions.[8] Greenhouse gas emissions are pervasive throughout the economy, extending across sectors from power, transport, and industry to buildings and agriculture. For the United States in particular, 83 to 85 percent of greenhouse gas emissions consistently come from the production and use of energy, particularly coal, oil, and natural gas.[9] About 95 percent of these energy-related emissions is from carbon dioxide primarily associated with fuel combustion, and the remaining 5 percent is mostly due to methane releases to the atmosphere.[10]

Overall energy use is driven principally by population and economic growth, moderated by declines in the energy intensity of the economy. While the US economy grew in real terms by 28 percent[11] from 2005 through the end of 2019, energy consumption was essentially flat, due both to improvements in energy efficiency and

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[1] "This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects...are extremely likely to have been the dominant cause of the observed warming since the mid-20th century." (p. 4) https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf

[2] https://www.rff.org/geo/

[3] "Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever." (p. 5) https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf

[4] "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen."(p. 2) https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf

[5] https://uaf-iarc.org/wp-content/uploads/2019/08/Alaskas-Changing-Environment_2019_WEB.pdf

[6] https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

[7] https://www.climatewatchdata.org/ghg-emissions?end_year=2017&start_year=1990

[8] https://ourworldindata.org/contributed-most-global-co2

[9] https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf (Table ES-4, p. ES 19-20)

[10] https://www.epa.gov/sites/production/files/2020-04/documents/us-ghg-inventory-2020-main-text.pdf (Table 2-4, p. 2-11)

[11] https://fred.stlouisfed.org/series/GDPC1#0

an increasing share of services in overall economy activity.[12] Emissions depend, in turn, on how these energy needs are met, with about 80 percent of US and global energy needs currently being met by fossil fuels.[13]

How quickly emissions grow or decline, therefore, hinges on population and economic growth, improvements in energy efficiency, and switching from more carbon-intensive fuels, like coal, to lower-carbon fuels, like natural gas, and zero-carbon energy sources, like nuclear and renewable power.[14] In addition, there is increased interest in technologies that can remove carbon dioxide from the atmosphere through natural carbon sinks, direct air capture, or bioenergy with carbon capture and storage (BECCS). These shifts among energy sources are driven in turn by three major forces: energy market conditions, technology innovation, and public policy.

Trends by Sector

US greenhouse gas emissions peaked around 2005 to 2007, and have declined during most years since then, resulting in 2019 emissions that were 11 to 12 percent below 2005 emissions.[15]

Power Sector: The vast majority of the decline in emissions has come from carbon dioxide emissions reductions associated with declining coal-based electric power production, due to a substitution toward increased power generation from natural gas and renewables.[16] Wind and solar have benefitted from cost reductions of about 70 percent and 90 percent respectively since 2009,[17] as well as financial support in the form of tax credits and state-level policies. Natural gas power has benefitted from low natural gas prices due to innovation in techniques for shale gas production. There have also been substantial advances in technologies that can complement intermittent renewables (such as wind and solar) to provide regular, dispatchable power. These include energy storage, advanced nuclear and geothermal systems, natural gas with carbon capture, decarbonized hydrogen,[18] and energy demand-side and grid management made smarter through advances in information technology.[19] RFF researchers are studying the design of state and federal policies that affect the US power sector, such as clean energy standards,[20] carbon pricing[21], and electricity market design and regulation.[22]

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[12] https://www.eia.gov/totalenergy/data/annual/ (Table 1.1)

[13] https://www.eia.gov/totalenergy/data/annual/

[14] While there are supply-chain emissions associated with renewable energy sources, the National Renewable Energy Laboratory (NREL) has found that "life cycle greenhouse gas (GHG) emissions from technologies powered by renewable resources are generally less than from those powered by fossil fuel-based resources. The central tendencies of all renewable technologies are between 400 and 1,000 g CO_2eq/kWh lower than their fossil-fueled counterparts without carbon capture and sequestration (CCS)." https://www.nrel.gov/analysis/life-cycle-assessment.html

[15] https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

[16] https://www.eia.gov/outlooks/steo/

[17] https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/

[18] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/

[19] https://www.rff.org/advanced-energy-technologies/

[20] https://www.rff.org/topics/carbon-pricing/clean-energy-standards/

[21] https://www.rff.org/publications/explainers/carbon-pricing-201-pricing-carbon-electricity-sector/

[22] https://www.rff.org/publications/explainers/us-electricity-markets-101/

Transportation Sector: Transportation sector emissions have fallen less dramatically than in the power sector, declining by roughly 5 percent since 2005, due primarily to enhanced vehicle efficiency.[23] As a result of this comparatively slower decline, the transportation sector surpassed the power sector in 2017 as the largest source of greenhouse gas emissions in the United States. The cost and range of electric vehicles (EVs) has improved considerably over the past decade, and EVs are capturing a rapidly increasing share of new model offerings and purchases. However, certain transportation emission sources, such as aviation, shipping, and long-haul trucking are currently more difficult to electrify, creating opportunities for the widespread deployment of new technologies such as low-emission liquid fuels, hydrogen, or other options. RFF researchers are examining efforts to reduce emissions due to transportation at the federal, regional, and state levels, including fuel economy standards,[24] policies to encourage adoption of electric vehicles,[25] the Transportation Climate Initiative,[26] Zero-Emissions Vehicle programs,[27] and more.

Industrial Sector: Emissions from industrial sources such as steel, cement, and petrochemical production have shifted only modestly over the past 15 years, and largely as a function of economic conditions. Industrial processes that require very high temperatures or come with process-related emissions require a distinct set of solutions—possibly carbon capture and storage, decarbonized hydrogen,[28] certain advanced nuclear technologies, direct air capture of carbon,[29] or other as-yet-undiscovered alternatives.[30] In collaboration with other experts around the world, RFF researchers are studying strategies for decarbonizing the industrial sector,[31] including clean energy standards[32] and public procurement programs for more environmentally friendly materials and products.[33]

Agriculture, Forestry, and Land Use: Outside of the energy sector, agriculture, forestry, and other land-use emission sources present a distinct group of challenges; they also present an array of opportunities for carbon removal through biomass carbon sequestration in forests, grasslands, and soils.[34] According to the 2018 National Climate Assessment, approximately 22 percent of contiguous US land is in use as cultivated cropland and pastures,[35] and in 2018, agriculture accounted for nearly 10 percent of US greenhouse gas emissions. US land

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[23] https://cfpub.epa.gov/ghgdata/inventoryexplorer/#transportation/allgas/source/all

[24] https://www.rff.org/topics/transportation/cafe-standards-and-fuel-efficiency/

[25] https://www.rff.org/publications/reports/potential-role-and-impact-evs-us-decarbonization-strategies/

[26] See https://www.rff.org/publications/reports/pursuing-multiple-goals-transportation-policy-lessons-integrated-model/ and https://www.rff.org/publications/issue-briefs/managing-investment-revenues-and-costs-transportation-climate-initiative-region/

[27] https://www.rff.org/publications/working-papers/californias-evolving-zero-emission-vehicle-program/

[28] https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors/

[29] A recent RFF study, "Benefits of Energy Technology Innovation Part 2: Economy-Wide Direct Air Capture Modeling Results," examines the potential benefits of cost reductions of direct air capture technology: https://www.rff.org/publications/working-papers/benefits-energy-technology-innovation-economy-wide-direct-air-capture/; an RFF Live event explored the potential of this technology for climate mitigation: https://www.rff.org/events/advanced-energy-technologies-series/future-direct-air-capture/

[30] https://www.rff.org/advanced-energy-technologies/

[31] https://www.sciencedirect.com/science/article/pii/S0306261920303603?via%3Dihub

[32] https://www.rff.org/news/press-releases/new-study-clean-energy-standard-can-cut-industrial-emissions/

[33] https://www.rff.org/publications/reports/green-public-procurement-natural-gas-cement-and-steel/

[34] https://media.rff.org/documents/RFF-Bck-LULUCF.pdf

[35] https://nca2018.globalchange.gov/chapter/5/

areas serve as both an emissions source and sink, but on net have acted for many years as a carbon sink, absorbing more CO_2 from the atmosphere than they emit.[36] RFF researchers are studying strategies involving land-based carbon sources and sinks, including the potential roles of tree planting[37] and forest bioenergy.[38]

Technological Inclusivity

Because of the diversity and complexity of the American energy system, reducing emissions will require a broad and inclusive approach to incorporating new technologies.[39] Since we cannot know in advance which technologies will become most competitive in the years ahead, expanding our solution set makes more ambitious and comprehensive strategies more feasible and cost-effective. As we've seen in recent years from innovations across many energy sources, the energy sector is vibrant, and holds enormous potential for innovation.

To harness this potential, economic research has demonstrated that broad, incentive-based policies can be the most effective tool to align the private sector's incentives with society's goals of reducing harmful pollution. For example, an incentive-based approach implemented in the 1990s to reducing the sulfur dioxide emissions that cause acid rain achieved its environmental goals well below the expected costs.[40] Research from Resources for the Future found that harnessing the market by allowing firms flexibility in where, when, and how emissions were reduced saved businesses $250 million per year and reduced public health damages by more than $2 billion in 2002.[41]

Effects of COVID-19 Pandemic

In 2020, the energy world—like so many other parts of our lives—was turned upside down. The effects of the COVID-19 pandemic and the associated economic disruption led to a reduction in emissions of about 10 percent during 2020.[42,43] As a result, US greenhouse gas emissions currently stand about 21 percent lower than they were in 2005.[44] As the economy recovers, many of these reductions may be short-lived. However, a variety of effects could be sustained for years, if not decades, to come. These include the retirement of some coal-fired power plants, downward revisions to future oil demand, and new pressures from the private sector for companies to reduce their greenhouse gas footprints. Other changes, such as a potential reluctance to return to public transportation, could increase emissions.[45] The direction of our energy system and its associated greenhouse gas emissions will depend on how future market, technological and policy decisions unfold, and there are many indications that we are at an important inflection point.

[36] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[37] https://www.rff.org/publications/issue-briefs/tree-planting-climate-policy/

[38] https://www.rff.org/publications/explainers/forest-bioenergy-101/

[39] https://www.resourcesmag.org/common-resources/technology-inclusive-climate-strategy-open-race-many-winners/

[40] https://www.jstor.org/stable/2647033

[41] https://media.rff.org/archive/files/sharepoint/WorkImages/Download/RFF-DP-15-25.pdf

[42] https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf

[43] https://www.rff.org/geo/

[44] https://rhg.com/research/preliminary-us-emissions-2020/#:~:text=Based%20on%20preliminary%202020%20data,tons%20of%20CO2%2Dequivalent

[45] https://www.iea.org/reports/world-energy-outlook-2020

Conclusion

Senators, in closing, I would like to emphasize three key observations:

- First, the concentration of greenhouse gases in the atmosphere is increasing rapidly, trapping heat to the planet and causing our climate to change. We know that the use of fossil fuels—coal, oil, and natural gas—is the leading cause, and that the US is a major contributor of these emissions.
- Second, because the energy system is ubiquitous and complex, and is not the only sector relevant to the climate problem, a broad, technologically-inclusive approach to reducing emissions will provide us with the widest set of options to address this challenge.
- And finally, the cost reductions and technological advances in clean energy and other emissions reduction technologies mean that ambitious reductions are now achievable at substantially lower cost.

These observations lead me to conclude that the effectiveness and efficiency of private and public emissions reduction strategies will depend on how well they meet the needs of different economic sectors, incentivize consumers and producers to choose lower-emission options, and spur innovation across a wide range of technologies that can help to decarbonize our economy. We now have a wealth of experience with state, federal, international, and corporate policies and programs, enabling the design of smart emissions reduction strategies, both economy-wide and for specific sectors.

Senators, I thank you again for this opportunity to appear before you and all of the members of the Committee today on this panel. I will now conclude my remarks, and I look forward to taking your questions.

Senator MANCHIN. Thank you, Dr. Newell.
And next we have Dr. Hsu.

STATEMENT OF DR. ANGEL HSU, ASSISTANT PROFESSOR, UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL, DATA-DRIVEN ENVIRONMENTAL POLICY LAB

Dr. HSU. Thank you, Senators Manchin and Barrasso and members of the Committee on Energy and Natural Resources, for inviting me here to testify today. It is an absolute honor to be here and share my knowledge on these issues. I am a contributing and lead author to several global climate assessments and Director of the Data-Driven Environmental Policy Lab at the University of North Carolina—Chapel Hill. Much of my research has focused on China and its contributions to global climate and energy policy. Maintaining primarily a global perspective, I would like to address four points. One, where we stand today on global climate change. Two, where our existing policies stand in limiting global temperature rise. Three, China's role in combating climate change. And lastly, the potential for some national actors and the business community to fill climate policy shortfalls.

First, I'm starting with the current status of the global climate. The latest climate science literature describes a narrowing window for meaningful climate action to restrict global temperature rise to 1.5 degrees Celsius. As Dr. Newell just said, temperatures have already risen by about 1.1 degree Celsius. Emissions increased on average around one percent each year over the last decade, with 2019 seeing a record-high emissions level predominantly driven by global fossil fuel consumption. Despite the devastating impacts of COVID–19, however, it has been the single largest, short-term influencer of greenhouse gas emissions. In 2020, carbon dioxide emissions reductions due to COVID–19 related shutdowns are estimated to be between seven and nine percent. This precipitous drop in emissions has provided now an opportunity for countries like the U.S. to consider post-COVID–19 recovery plans with climate change and energy policy considerations. There is a strong economic case for the transition away from fossil fuels to renewable energy. Costs have continuously declined for renewable energy and demand has remained robust compared to fossil fuels. For example, in 2020, over 70 percent of utility-scaled power that was added to the U.S. generation capacity was in the form of renewable energy.

Second, in terms of the current policy status, the science is clear that we need to get to zero emissions by 2050 to contain global temperature rise to 1.5 degrees Celsius. Ideally, global emissions should have already peaked in 2020. One analogy that has been used to describe the challenge is that we need emissions now to fall off a cliff. If the road had begun steadily decreasing emissions around ten years ago, we would only need to have been reducing emissions by two percent per year. Now global emissions need to decrease by seven percent per year until dropping to zero. The reality is that the ambition of national government climate policy efforts are woefully inadequate to stay within our remaining carbon budget. At our current emissions rate, we will deplete the entire remaining carbon budget within the next ten years. While the data show that countries' track record for addressing climate change has not been adequate, around 127 countries recently have pledged to decarbonize, including China, the world's largest emitter of greenhouse gas emissions. China's President, Xi Jinping, announced last September at the U.N. General Assembly that it would commit to become carbon neutral by 2060. This carbon neutrality pledge is significant. If successful, it could cool the planet by about 0.2 to 0.3 degrees Celsius by 2100 on its own.

But to meet this carbon neutrality goal, China will need to eliminate coal as part of its energy mix, which in 2018 generated 65 percent of its electricity. They have a plan to phase it out by 2050 and generate 90 percent of all electricity from non-fossil sources, including renewables and nuclear energy. To do this will require a 16-fold increase in solar energy, a ninefold growth in wind power, a sixfold increase in nuclear and a doubling of hydroelectricity. China will also need to grow renewable energy investments to around 15 trillion U.S. dollars in the next 30 years. It currently already tops global clean energy investments at around 100 billion U.S. dollars each year, more than the U.S. and EU combined, and it is a leading manufacturer of wind, solar, and electric vehicle technology. The U.S. and the world can have confidence that China will meet this carbon neutrality target. The country's past record demonstrates that it has met or has come extremely close to meeting every single energy and environmental target the country has set. It is already on track to overachieve its 2020 and 2030 carbon intensity goals and independent satellite data confirm that China has achieved significant reductions in air pollution already.

Despite the importance of Chinese climate commitments and other existing agreements however, this still won't get us all the way to net zero. Our research demonstrates that nearly 6,000 cities, states, and regions and over 1,500 companies' existing climate efforts will lower greenhouse gas emissions by 1.2 to 2 gigatons of carbon dioxide equivalent in 2030. This is additional reduction and it amounts to roughly four percent of the world's total annual greenhouse gas emissions, as much as Japan and Canada emit in a single year. In the U.S., these commitments could provide at least half of the reductions needed to meet its Paris pledge. As of October 2020, more than 1,500 businesses, 826 cities, and 103 regional governments, including 24 U.S. states, have already made net zero commitments.

To end, how national governments design post-COVID–19 economic recovery strategies will largely determine how much global emissions rebound to pre-COVID–19 levels. Global competition and cooperation on clean energy, building on continued progress from some national business actors, is one vehicle toward our decarbonization goals. Thank you very much and I look forward to further discussion and your questions.

[The prepared statement of Dr. Hsu follows:]

Testimony of Prof. Angel Hsu
University of North Carolina-Chapel Hill
Data-Driven Environmental Policy Lab

U.S. Senate Committee on Energy and Natural Resources

Hearing on "Examining Global Climate Trends and Progress in addressing Climate Change"
February 3, 2021

Thank you, Senators Manchin and Barrasso, and members of the Committee on Energy and Natural Resources, for inviting me here to testify today on global climate trends and the progress we've made in addressing climate change. I am a contributing and lead author to several global climate assessments, including the Intergovernmental Panel on Climate Change's Sixth Assessment Report and the United Nations Environment Programme's Emissions Gap Report. I also direct a research group, the Data-Driven Environmental Policy Lab or Data-Driven Lab for short, based at the University of North Carolina-Chapel Hill. Much of my research has focused on China and its contributions to global climate change and energy policy. It is an honor to be here today to share with the committee my knowledge of global trends and progress in addressing climate change.

The global climate's status is dire, and the world has a small window remaining to make the drastic cuts necessary to avoid the most dangerous impacts of climate change. Current national government policies are inadequate to produce the drastic reductions that science dictates are needed to secure a safe and prosperous climate future. We can see, however, that many countries have begun to acknowledge their role in contributing to global climate change. More than 120 governments have made pledges to decarbonize around the middle of this century or sooner.[1] There is also a large, understudied potential for bottom-up climate actions from cities, state and regional governments, and businesses to build on national efforts and create additional greenhouse gas emission reductions.

Maintaining primarily a global perspective, my comments are divided in four parts:

- A stock-taking of the global climate - what are current greenhouse gas emissions levels and trends and what global climate change impacts can we already observe? I will address global trends from the perspective of energy and industrial-related emissions, while acknowledging that

[1] ECIU. (2021). *Net Zero Tracker*. Energy & Climate Intelligence Unit. https://eciu.net/netzerotracker

land-use based emissions from agriculture and forestry comprise 23 percent of global greenhouse gas emissions.[2]

- Second, reviewing current policies and initiatives and their implications for meeting the global goals of containing temperature rise within 2 degrees Celsius or the 2015 Paris Agreement's 1.5 degree target, the threshold that scientists have established as a global tipping point beyond which the world will experience the most catastrophic climate change impacts.[3]
- I will focus in particular on China's efforts to combat climate change and the country's latest pledge to decarbonize by 2060 or earlier. In the last two decades, China has implemented a growing suite of climate and energy policies and recently unveiled plans to decarbonize its economy - the world's second largest - showing what is possible even in the world's largest emitter of greenhouse gases, and also suggesting opportunities for trans-Pacific collaborations and productive competition.
- Lastly, recognizing insufficient progress towards decarbonization, subnational governments and business actors have in recent years stepped up to fill in the climate initiative shortfalls. Whether the contributions from these actors will be sufficient to make up for limited progress elsewhere remains an unanswered question.

1. What is the global climate's current status?

The latest climate science literature describes in stark detail a narrowing window for meaningful climate action. The Intergovernmental Panel on Climate Change (IPCC) reported in September 2018 on the importance of restricting global temperature rise to 1.5 degrees Celsius above pre-industrial levels, and yet, as of 2020, temperatures have already risen by about 1.2 degrees Celsius.[4] The IPCC reports that exceeding this 1.5 degrees Celsius benchmark would result in increasingly dire environmental impacts sea level rise, extreme heat, ecosystems and species loss, and reductions to crop and fishery yields.[5]

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[2] IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.
[3] *ibid.*
[4] World Meteorological Institute (WMO; 2020). Press release: 2020 was one of the three warmest years on record. Available: https://public.wmo.int/en/media/press-release/2020-was-one-of-three-warmest-years-record
[5] Levin, K. (2018, October 7,). Half a degree and a world apart: The difference in climate impacts between 1.5°C and 2°C of warming. Retrieved from https://www.wri.org/blog/2018/10/half-degree-and-world-apart-

Climbing temperatures have caused the loss of more than 28 trillion tonnes of ice between 1994 and 2017[6], triggered oceanic thermal expansion and accelerated sea level rise.[7] Changing precipitation patterns have exacerbated flooding and drought, destroyed agricultural livelihoods and have made some areas of the globe completely uninhabitable.[8]

Despite the glaring importance of aggressive emissions reduction, efforts to combat global climate change have had mixed results. Tracking global greenhouse gas emissions trends, between 2010 and 2019, carbon dioxide (CO_2) emissions increased at an average yearly rate of 0.9 percent,[9] despite a relative flattening of global CO_2 emissions from 2014-2016[10] and 2018-2019. The year 2019, however, saw record high greenhouse emissions levels of 52.4 gigatonnes CO_2e, with 65% of all GHG emissions (including land use change) coming from fossil carbon sources. The global energy system is the primary driver of these greenhouse gas emissions trends. The world's energy mix is today composed primarily of fossil carbon sources, with coal, oil, and natural gas comprising around 64% of global electricity generation in 2018.[11]

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difference-climate-impacts-between-15-c-and-2-c-warming; Schleussner, C., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., . . . Hare, W. (2016). Science and policy characteristics of the paris agreement temperature goal. Nature Climate Change, 6(9), 827.

[6] Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., Tepes, P., Gilbert, L., & Nienow, P. (2021). Review article: Earth's ice imbalance. *The Cryosphere*, *15*(1), 233–246. https://doi.org/10.5194/tc-15-233-2021

[7] Weeman, K., & Lynch, P. (n.d.). *New study finds sea level rise accelerating*. Climate Change: Vital Signs of the Planet. https://climate.nasa.gov/news/2680/new-study-finds-sea-level-rise-accelerating

[8] Schwartz, J. (2018, -12-17T21:53:54.768Z). More floods and more droughts: Climate change delivers both. The New York Times Retrieved from https://www.nytimes.com/2018/12/12/climate/climate-change-floods-droughts.html; BAMS. (2018). Explaining extreme events of 2017 from a climate perspective. Retrieved from https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/; U.S. Global Change Research Program. (2018). Fourth national climate assessment. volume II: Impacts, risks, and adaptation in the United States. Retrieved from https://nca2018.globalchange.gov; Missirian, A., & Schlenker, W. (2017). Asylum applications respond to temperature fluctuations. Science, 358(6370), 1610-1614; Kumari Rigaud, K., de Sherbinin, A., Jones, B., Bergmann, J., Clement, V., Ober, K., . . . Midgley, A. (2018). Groundswell: Preparing for internal climate migration. Retrieved from http://www.worldbank.org/en/news/infographic/2018/03/19/groundswell---preparing-for-internal-climate-migration

[9] See https://www.globalcarbonproject.org/carbonbudget/ and Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., & Sitch, S. (2020). Global carbon budget 2020. *Earth System Science Data*, *12*(4), 3269–3340.

[10] IEA. (2020). *CO2 Emissions from Fuel Combustion: Overview* [Statistics Report]. IEA. CO2 Emissions from Fuel Combustion: Overview

[11] IEA. (2020). *Electricity statistics*. IEA. https://www.iea.org/subscribe-to-data-services/electricity-statistics

The single largest short-term influencer of greenhouse gas emissions levels in the most recent decade, however, is the COVID-19 pandemic. CO_2 emissions reductions due to COVID-19-related shutdowns are estimated to be between 7 and 9 percent - larger than previous record dips from other global events like World War II or other economic downturns.[12] The largest share of emissions reductions stem from reduced surface and air transport associated with the COVID-19 pandemic, although emissions growth had begun to show signs of slowing prior to the pandemic in 2019.[13] The precipitous drop in global greenhouse gas emissions has provided an opportunity for countries to consider post-COVID 19 recovery plans with climate change and energy policy considerations.

There is a strong economic case for the transition away from fossil fuels to renewable energy. Costs have continuously declined for renewable energy products, such that by 2019, 56 percent of all new utility-scale renewable generation capacity supplied electricity demand at a lower cost than the cheapest new fossil-fuel options available.[14] This includes two-fifths of utility-scale solar PV operating at a more affordable rate than the cheapest fossil fuel option in 2019, despite solar PV being 7.6 times more expensive than fossil fuel options just ten years ago. Renewables demand under COVID-19 has remained robust compared to demand for fossil fuels, and the share of renewables in the electricity mix increased through 2020 for many large economies, including the U.S.[15] In 2020 over 70 percent of utility-scale power that was added to the U.S.'s generation capacity was in the form of renewable energy.[16] Globally, renewable energy sources in the electricity mix have grown aggressively, with over 27 percent of global electricity generation supplied by renewables, up from 19 percent in 2010. The share of global electricity demand filled by solar photovoltaics and wind technologies have grown fivefold since 2009 and together supplied around 8.7 percent of total global generation. These global trends suggest that countries are wizened to the multiple benefits of decarbonization, in terms of economic cost savings, energy security, public health, and climate resiliency.

2. **How are current policy efforts addressing global climate change?**

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[12] Liu, Z., Ciais, P., Deng, Z., Lei, R., Davis, S. J., Feng, S., ... & Schellnhuber, H. J. (2020). Near-real-time monitoring of global CO 2 emissions reveals the effects of the COVID-19 pandemic. Nature communications, 11(1), 1-12.
[13] See ICOS. (2020). *Data supplement to the Global Carbon Budget 2020*. https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2020
[14] IRENA. (2020). *Renewable Power Generation Costs in 2019*. IRENA. https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019
[15] IEA. (2020). *Global Energy Review 2020*. IEA. https://www.iea.org/reports/global-energy-review-2020
[16] U.S. Energy Information Agency. (2021). Renewables account for most new U.S. electricity generating capacity in 2021. Available: https://www.eia.gov/todayinenergy/detail.php?id=46416

The science is clear - we need to get to zero emissions or net-negative by 2050 for a 66 percent chance of containing global temperature rise within 2 or 1.5 degrees C, respectively. To meet this charge, the IPCC states that global emissions must be halved by 2030 from 2017 levels and then fall to net zero by 2050.[17]

Ideally, global emissions would have already peaked in 2020 to allow for emissions to steadily decline and reach half by 2030 and then to zero by 2050. An analogy that has been used to illustrate the enormity of the climate challenge is equating needed emissions reductions to falling off a cliff. If the world had begun steadily decreasing emissions around 10 years ago, we would only need to have been reducing emissions by 2 percent a year. Since we didn't achieve those reductions, global emissions now need to fall off of a cliff - decreasing more than an average of 7 percent a year until dropping to zero to keep 1.5 degrees C within reach.[18] Because the long-term temperature impacts of climate-warming emissions are cumulative, what this means is that the world now has an even greater challenge to reduce emissions at a faster rate than what was previously estimated. In the words of UN Emissions Gap Report scientists, we now have "four times the work or one-third the time" to contain dangerous global temperature rise.[19]

The reality is that the current pace of reduction and the ambition of national government climate policy efforts are woefully inadequate to stay within our remaining carbon budget, which at the start of 2018 was only 420 gigatonnes of carbon dioxide.[20] At our current rate of emissions, we would deplete this entire remaining budget within the next 10 years.[21] The 2020 UN Emissions Gap Report identifies a 29-32 gigatonne CO_2-equivalent gap between current policies and projected emissions levels in 2030 that would allow us to keep the 1.5 degrees Celsius goal within reach.[22] This "emissions gap" has widened four times since 2010,[23] and has remained virtually stagnant for the last several years, prior to the COVID-19 pandemic. Translated into global temperature rise, scientists estimate that the world is on track to warm more than 3 degrees C by the end of the century.[24] The Climate Action Tracker assesses current national

[17] IPCC. (2018). *Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments—IPCC*. https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/
[18] Höhne, N., Elzen, M. den, Rogelj, J., Metz, B., Fransen, T., Kuramochi, T., Olhoff, A., Alcamo, J., Winkler, H., Fu, S., Schaeffer, M., Schaeffer, R., Peters, G. P., Maxwell, S., & Dubash, N. K. (2020). Emissions: World has four times the work or one-third of the time. *Nature*, *579*(7797), 25–28. https://doi.org/10.1038/d41586-020-00571-x
[19] *ibid.*
[20] IPCC. (2018).
[21] Hausfather, Z. (2018, April 9). *How much 'carbon budget' is left to limit global warming to 1.5C?* Carbon Brief. https://www.carbonbrief.org/analysis-how-much-carbon-budget-is-left-to-limit-global-warming-to-1-5c
[22] UNEP. (2020). *The emissions gap report 2020*. https://www.unep.org/emissions-gap-report-2020
[23] Höhne, et al. (2020).
[24] UNEP. (2020)

policies are so insufficient that without additional and more ambitious effort, there is a 97 percent probability that the world will exceed 2 degrees C temperature rise.

3. China's plans to decarbonize by 2060

While the data show that countries' track record for addressing climate change has not been adequate, around 127 countries totaling more than 68 percent of the global economy have pledged to decarbonize, including the world's largest emitter of greenhouse gas emissions - China.[25] China's President Xi Jinping announced at the September 2020 United Nations General Assembly meeting that it would commit to become carbon neutral by 2060.[26] Responsible for 28 percent of global greenhouse gas emissions,[27] China joined a number of major economies, including France and the United Kingdom, which have codified their 2050 net-zero targets into legislation, Japan, the Republic of Korea, Canada, South Africa, among others.[28] This carbon neutrality pledge is significant for several reasons. China historically has only made climate-related commitments bilaterally or in multilateral fora, such as the United Nations Framework Convention on Climate Change (UNFCCC). The bilateral climate agreement between the U.S. and China is largely hailed as being critical for securing the Paris Agreement, breaking years of impasse on climate action between the two largest climate emitters.[29] Instead, China unilaterally made its carbon neutral pledge, outside of a specific climate or energy forum, and without any qualifiers or statements of conditionality. If successful, China's achievement of its carbon neutrality goal could cool the planet by 0.2-0.3 degrees Celsius by 2100 on its own.[30]

It will be challenging for China to achieve this goal. The country will need to eliminate coal as part of its energy mix, which in 2018 comprised around 62 percent of its total primary energy supply and generates 65 percent of electricity.[31] The world's largest producer and consumer of coal, China also tops the world

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[25] ECIU. (2021). *Net Zero Tracker*. Energy & Climate Intelligence Unit. https://eciu.net/netzerotracker
[26] Ministry of Foreign Affairs, People's Republic of China. (2020). "Statement by H.E. Xi Jinping President of the People's Republic of China at the General Debate of the 75th Session of the United Nations General Assembly." Available: https://www.fmprc.gov.cn/mfa_eng/zxxx_662805/t1817098.shtml.
[27] Global Carbon Project (2020).
[28] ECIU. (2021). *Net Zero Tracker*. Energy & Climate Intelligence Unit. https://eciu.net/netzerotracker
[29] Stern, T. (2020). "Can the United States and China Reboot their Climate Cooperation?" Brookings, Sept. 14. Available: https://www.brookings.edu/articles/can-the-united-states-and-china-reboot-their-climate-cooperation/.
[30] Climate Action Tracker. (2021). *China Country Summary*. https://climateactiontracker.org/countries/china/
[31] International Energy Agency. (2020). China. Available: https://www.iea.org/countries/china.

in terms of global installed coal-fired electricity power.[32] Oil and natural gas are also prominent in China's energy supply, comprising 27 percent as of 2018.[33] They have a plan to completely phase out coal by 2050 and generate 90 percent of all electricity from non-fossil sources, including renewables and energy.[34] To do this will require a 16-fold increase in solar energy, a nine-fold growth in wind power, and increasing nuclear power by six times and doubling hydroelectricity.[35] Achieving these goals will also require China to push their original timeline for achieving their climate and energy goals earlier and more aggressively. According to Tsinghua University, one of the country's leading academic institutions charged with developing China's 2060 carbon neutrality roadmap, China will need to ramp the ambition of its original 2015 Paris pledge, such as shifting its goal for making renewables 20 percent of its energy mix five years earlier to 2025 as well as potentially increasing this target to 25 percent.[36] In 2020 national governments were called upon to increase the ambition of their 2015 Paris contributions. Although China at the time of writing has not yet submitted its "enhanced ambition" nationally-determined contribution, the top leadership has signaled its intent to do so to align with its new carbon neutrality goals.[37]

To meet these ambitious clean energy targets, China will need to grow their investments in renewable energy to around $15 trillion USD between 2020 and 2050 - a number that is more than China's entire 2018 GDP.[38] Two decades ago, China's clean energy sector was virtually non-existent, but today China top's global clean energy investments with an average total around $100 billion USD each year - double the United States and more than the United States and European Union combined.[39] These investments to develop a national innovation system with clean energy at the center have paid off - China is a leading manufacturer of wind, solar, and electric vehicle technology. China now leads the world in these technologies: five of the 10 largest wind turbine manufacturers and nine of the world's top 10 solar panel manufacturers are Chinese-owned or operated.[40] More than two-thirds of the world's solar panels and half

[32] Global Energy Monitor. (2020). Global Coal Plant Tracker. Available: https://endcoal.org/global-coal-plant-tracker/
[33] International Energy Agency. (2020). China. Available: https://www.iea.org/countries/china.
[34] Myllyvirta, L. (2020). Influential academics reveal how China can achieve its carbon neutrality goal. Carbon Brief. 14 October. Available: https://www.carbonbrief.org/influential-academics-reveal-how-china-can-achieve-its-carbon-neutrality-goal
[35] Mallapaty, S. (2020). How China could be carbon neutral by mid-century. *Nature*.
[36] *ibid.*
[37] Gabbattis, J. (2021). Analysis: Which countries met the UN's 2020 deadline to raise 'climate ambition'? Carbon Brief. Available: https://www.carbonbrief.org/analysis-which-countries-met-the-uns-2020-deadline-to-raise-climate-ambition
[38] Bloomberg News. (2020). China seeks big money's help in reaching its carbon neutral goal. Available: https://www.bloomberg.com/news/articles/2020-10-27/china-seeks-big-money-s-help-reaching-its-carbon-neutral-goal; Myllyvirta (2020).
[39] REN-21. (2020). https://www.ren21.net/gsr-2020/chapters/chapter_05/chapter_05/
[40] *ibid.*

of global wind turbines are produced in China.[41] China is also responsible for around 37 percent of passenger electric vehicles and 99 percent of the e-buses sold globally since 2011.[42] They have installed this technology at home at breakneck speed - doubling wind capacity every year from 2005 and 2009 and now having the highest installed capacity of solar PV in the world - being the first country to surpass a total of 100 GW installed in 2017.[43]

The U.S. and the world can have confidence that China will meet its carbon neutrality target. The country's past record demonstrates that it has met or has come extremely close to meeting every single energy and environmental target made. China is on track to overachieve its 2020 and 2030 carbon intensity reduction targets, with some suggesting that emissions may peak between 2021 to 2025 - much earlier than its "2030 or as soon as possible" Paris pledge.[44] Aside from the economic opportunities for its clean energy industry, China's climate actions have also been driven largely by domestic concerns over air pollution, which is estimated to have caused around 1.8 million deaths or 17 percent of all deaths in 2019 in China. Substantial investments in air pollution control have also paid dividends in climate co-benefits.[45] Independent, satellite analyses of China's air pollution reductions confirm these achievements.[46]

4. A groundswell of subnational and business climate action supports global climate efforts

While national climate policy efforts have stagnated in recent years, a groundswell of city, region, and company actors are stepping up to fill the emissions gap. Climate policy scholars increasingly view city, regional, and business actors' engagement in global climate change governance as critical to meeting national and international climate goals. Scaled-up participation from all levels of government and sectors formed a key "pillar" of the Paris Agreement.[47] Currently, more than 10,000 subnational actors, 4,000

[41] *ibid.*
[42] Bloomberg New Energy Finance. (2018).Cumulative Global EV Sales Hit 4 Million. Available: https://about.bnef.com/blog/cumulative-global-ev-sales-hit-4-million/
[43] Yan, J. and Myllyvirta, L. (2017). China has already surpassed its 2020 solar target. Greenpeace. Available: https://unearthed.greenpeace.org/2017/08/25/china-raises-solar-power-target/
[44] Climate Action Tracker. (2020). China. Available: https://climateactiontracker.org/countries/china/; Wang, H., Lu, X., Deng, Y., Sun, Y., Nielsen, C. P., Liu, Y., ... & McElroy, M. B. (2019). China's CO 2 peak before 2030 implied from characteristics and growth of cities. Nature Sustainability, 2(8), 748-754
[45] Institute for Health Metrics and Evaluation. (2021). Global Burden of Disease. Available: https://vizhub.healthdata.org/gbd-compare/.
[46] Ma, Z., Liu, R., Liu, Y., & Bi, J. (2019). Effects of air pollution control policies on PM 2.5 pollution improvement in China from 2005 to 2017: A satellite-based perspective. *Atmospheric Chemistry and Physics*, *19*(10), 6861-6877.
[47] Hale, T. (2016). "All hands on deck": The paris agreement and nonstate climate action. Global Environmental Politics, 16(3), 12-22.

businesses, 1,000 investors, among others have pledged some action on climate change.[48] These entities pledge individual commitments or join voluntary initiatives, like C40 Cities for Climate Change Leadership and the Science-Based Target Initiatives, which often commit actors to specific targets and help connect cities, companies, and other actors to share knowledge, build capacity, disclose carbon emissions information, and pursue other goals. Rather than a simple hub and spoke model of nation-state centric governance, with the UNFCCC at the center, global climate governance is increasingly described as a diverse ecosystem of actors, with multiple nodes interacting simultaneously.

Our research demonstrates that nearly 6,000 cities, states and regions, and over 1,500 companies could lower greenhouse gas emissions by 1.2 to 2.0 gigatons of carbon dioxide equivalent/year ($GtCO_2e$/year) in 2030, compared to what would be achieved merely through national policies that are currently underway.[49] This *additional* reduction amounts to roughly four percent of the world's total annual greenhouse gas emissions, or about as much as carbon Japan and Canada emit in a year. In the United States, city, region, and company commitments could provide at least half of the emissions reductions needed to meet its Paris pledge.[50] But these pledges are just the start - many subnational and corporate actors have also committed to decarbonize. As of October 2020, 826 cities and 103 regional governments, including 24 U.S. states, had made net-zero commitments, whether economy-wide or focused on a specific sector (i.e., electricity or buildings).[51] The population living in these cities and regions equals around 880 million people or around 11 percent of the global population. Around 1,565 companies representing 12.5 trillion USD have also joined in pledging a net-zero target.[52]

Summary

The challenge ahead of the world in terms of the speed and pace required to reduce emissions is pressing. How national governments design post-COVID 19 economic recovery strategies, in addition to individual behavior responses, will largely determine how much global emissions rebound to pre-COVID-19

[48] UNFCCC. (2020). Global Climate Action Portal. Available: https://climateaction.unfccc.int; Hsu, A., Yeo, Z.Y., Rauber, R., Sun, J., Kim, Y., Raghavan, S., Chin, N., Namdeo, V., and Weinfurter, A. (2020). ClimActor, a harmonized dataset of 10,000+ city and region transnational climate network participation. Nature Scientific Data.
[49] Kuramochi, T., M. Roelfsema, A. Hsu, S. Lui, A. Weinfurter, S.Chan, T. Hale, A. Clapper, A. Chang & N. Höhne (2020): Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions, Climate Policy, DOI: 10.1080/14693062.2020.1740150.
[50] Kuromochi et al. (2020)
[51] NewClimate Institute & Data-Driven EnviroLab (2020). Navigating the nuances of net-zero targets. Research report prepared by the team of: Thomas Day, Silke Mooldijk and Takeshi Kuramochi (NewClimate Institute) and Angel Hsu, Elwin Lim, Zhi Yi Yeo, Amy Weinfurter, Yin Xi Tan, Ian French, Vasu Namdeo, Odele Tan, Sowmya Raghavan, and Ajay Nair (Data-Driven EnviroLab).
[52] *Ibid.*

levels.[53] The global pandemic has provided a narrow window for governments to reset their approach to addressing climate change. The realities of precipitously declining prices for renewable energy options and a demand for renewables that has remained relatively unaffected by the global pandemic provides the space for renewable energy expansion to continue to contribute to emissions reductions and energy security in tandem. Friendly competition in the renewable energy sector between major global powers can be an effective vehicle towards decarbonization of the global economy and sustained progress towards emissions reduction targets, and continued progress from subnational and business actors in reducing supply chain emissions and switching to greener energy sources will help to fill in the gaps. The urgency for humanity to get to zero emissions by mid-century remains if we are to stave off climate change's most pernicious effects, and even then the impacts will be felt all across the world.

[53] Le Quéré, C., Jackson, R. B., Jones, M. W., Smith, A. J. P., Abernethy, S., Andrew, R. M., De-Gol, A. J., Willis, D. R., Shan, Y., Canadell, J. G., Friedlingstein, P., Creutzig, F., & Peters, G. P. (2020). Temporary reduction in daily global CO 2 emissions during the COVID-19 forced confinement. *Nature Climate Change*, *10*(7), 647–653. https://doi.org/10.1038/s41558-020-0797-x

Senator MANCHIN. Thank you, Dr. Hsu.
Now let's hear from Dr. Tinker.

STATEMENT OF DR. SCOTT W. TINKER, DIRECTOR, BUREAU OF ECONOMIC GEOLOGY, THE UNIVERSITY OF TEXAS AT AUSTIN

Dr. TINKER. Senators, distinguished members, fellow panelists, it's an honor to be here today with you. Senator Murkowski, thanks for your leadership. Senators Manchin and Barrasso, I look forward to working with you.

We all share a common desire to provide affordable, reliable energy in order to grow healthy economies and lift the world from poverty, while also minimizing environmental impacts, including climate, land, water, air. There may be a perception of division, but I think it's a false divide. Let's not let that division triumph. I had planned to mention a bit about my background and highlight key facts about global poverty, population, energy, and the economy, but that's all in my written testimony and that can be made available to anyone listening in.

Instead, I'd like to tell you a story. The films we have made the past decade on global energy, the environment, and poverty are nonpartisan and introduce critical thinking on these important issues. They are used by educators all over the world for students of all ages. As such, I am asked by teachers and faculty, globally, if I could please visit in person or Zoom in with their students for a short discussion. It would mean so much to the kids, they say. I try to do as many of these each month as I can.

Just before COVID, I was visiting an environmental class of about 50 lower division university students—an "ask me anything" format. And near the end, one student said, and I quote, "Why does any of this matter? We're all gone in 15 years anyway?" "What do you mean," I asked? "Humans. We're gone because of climate change." Trust me, I am rarely speechless. I asked the class how many felt that way. Fifty percent raised their hands. I was stunned. I asked why they felt this and if they could describe what would actually wipe out all of humanity in 15 years.

They couldn't describe how anyone would actually die. They just said they were being taught that climate change is an existential threat and learning that from their leaders. To them, that meant humans will no longer exist. I was deeply disturbed by this on many levels, for many weeks. Where was the critical thinking?

The non-partisan, non-profit Switch Energy Alliance that I formed many years ago makes critical thinking films on energy and the environment. We have worked with AP environmental science high school teachers across the country the past few years to develop a truly objective curriculum on energy for classes across the U.S. It didn't take long to discover how bias is introduced. Here's an example of two essay questions from an AP test: What are the environmental benefits of offshore wind? What are the environmental impacts of tar sands? The questions can only result in the student seeing benefits of one option and impacts of the other. When in fact, we all know, and we've heard—there are pros and cons to both. This happens at the highest levels.

Just this morning, E&E reported that a new National Academies report offers a comprehensive roadmap for achieving a carbon-free economy by mid-century and concludes that it is, quote, “on the edge of feasibility.” Of course, if the question posed to the National Academies committee was, “How do we reach a carbon-free economy?” By definition, the report will attempt to spell that out. Critical thinking would ask, “How do we reach a carbon-free economy without damaging the land, water, and local air in the process?” In other words, how do we avoid robbing from nature Peter to pay climate Paul?

I trust we all believe that humans will be here in 15 years and hopefully well beyond that. As such, each of us carries a remarkable burden. We do not want students around the world to feel duped someday when they realize that “clean” didn’t really mean “clean.” To be sure, coal, oil, and natural gas to a lesser degree, impact the environment. Let’s continue to clean them up, especially the emissions, but all forms of energy impact the environment.

As a geoscientist, I’m not against mining. I know that low-density sources of energy, such as solar, wind, biofuels, and batteries will require an unprecedented scale of mined, sometimes toxic, resources from the earth that must be disposed of when they wear out and they get disposed in the land and the ocean. Although levelized cost of electricity and energy have fallen, the cost of full-scale redundant backup makes it more expensive to the consumer. Ask California and Germany. It’s not clean or renewable or cheaper, it’s just different. So let’s converge on a plan that provides equitable energy access globally and addresses not only emissions, but all environmental impacts. The plan should focus on some key CO_2 solutions: Reduce actual CO_2 emissions into our single global atmosphere; protect the rest of the environment; be affordable, dispatchable and scalable; be deployed or deployable in the next two decades; protect U.S. security and the U.S. economy; and lift the world from energy and economic poverty.

Fortunately, solutions exist. Options you have heard from other witnesses here are remarkably consistent. Switching from coal to natural gas, especially in Asia—if Asia doesn’t act, it won’t matter. Preserve the nuclear fleet in the U.S. and support nuclear globally, especially small modular reactors, and streamline deep borehole disposal. Accelerate efficiency across all U.S. and global sectors. Natural gas, nuclear, and efficiency, in partnership with solar and wind, CCUS, hydro, geothermal, hydrogen, and others provide dispatchable, reliable, affordable energy today and it preserves industry and grows higher-wage jobs. The U.S. can lead through investment in technology, federal and state incentives, and efforts to find scalable, affordable, timely solutions. Although tempting, we have to resist the well-intended efforts to restrict market opportunities and optionality, which often result in unintended consequences.

Thank you for the opportunity to speak with you today.

[The prepared statement of Dr. Tinker follows:]

Hearing of

U.S. Senate Energy and Natural Resources Committee

Global Climate Trends and Progress in Addressing Climate Change

Invited Testimony

Dr. Scott W. Tinker

February 3, 2021

Oral Testimony

Senators, Distinguished Members and Fellow Panelists, it is an honor to be here today.

Senator Murkowski thank you for your leadership. Senators Manchin and Barrasso, congratulations. I look forward to working with you.

We all share a common desire to provide affordable and reliable energy in order to grow healthy economies and lift the world from poverty, while also minimizing environmental impacts, including climate, land, water, and air.

There may be a perception of division, but I think it is a false divide. Let's not let division triumph.

I had planned to mention a bit about my background, and highlight key facts about global poverty, population, energy and the economy today. But others have covered that pretty well, and it is in my written testimony, which can be made available to anyone listening in.

Instead, I'd like to tell you a story.

The films we have made the past decade on global energy, the environment and poverty are non-partisan and introduce critical thinking about these important issues. They are used by educators all over the world for students of all ages.

As such, I am asked by teachers and faculty globally if I could please visit in person or "ZOOM in" with their students for a short discussion. It would mean so much to the kids, they say. I try to do as many of these each month as I can.

Just before COVID I was visiting an environmental class of about 50 lower division students at a major university. An "ask me anything" format. Near the end, one student said, and I quote:

> "Why does any of this matter, were all gone in 15 years anyway?"
>
> "What do you mean?" I asked.
>
> "Humans. We're gone because of climate change in 15 years."

Trust me, I am rarely speechless.

I asked the class how many felt that way. 50% raised their hands. I was stunned.

I asked why the felt this and if they could describe what would actually wipe out all of humanity in 15 years.

They couldn't describe how anyone would *actually* die, they just said they were being taught that climate change is an *existential* threat, and also hearing that from their leaders. To them, that meant that humans will no longer *exist*.

I was deeply disturbed by this on many levels, for many weeks. Where was the critical thinking?

The non-partisan, non-profit Switch Energy Alliance that I formed many years ago makes critically thinking films on energy and the environment. We have worked with AP Environmental Science (APES) High School teachers across the country the past few years to develop truly objective curriculum on energy. Switch Classroom is are now in thousands of classrooms across the U.S. and the world.

When looking at the existing APES curriculum, it didn't take long to discover how bias is introduced. Here is an example of two essay questions from an AP test.

1) What are the environmental *benefits* of offshore wind?
2) What are the environmental *impacts* of tar sands?

These questions can only result in the student discussing benefits of one option, and impacts of the other. When in fact, as we all know, there are pros and cons to both.

This happens at the highest levels, too.

Just this morning E&E Reported that a new National Academies report offers a comprehensive road map for achieving a carbon-free economy by midcentury and concludes that it is "on the edge of feasibility."

Of course, if the question posed to the National Academies committee was, "How do we reach a carbon-free economy?" by definition the report will attempt to spell that out.

Critical thinking would instead ask, "How do we reach a carbon-free economy, without damaging the land, water, and local air in the process?" In other words, how do we *avoid robbing from nature Peter to pay climate Paul.*

I trust we all believe that humans will be here in 15 years, and hopefully well beyond that. As such, each of us carries a remarkable burden to be factually complete.

To be sure, coal and oil, and to a lesser degree natural gas, impact the environment. Let's continue to clean them up, especially the emissions. But critical thinking teaches us *all forms of energy* impact the environment.

As a geoscientist, I am not against mining! If you don't grow it, you mine it. But I know that low-density sources of energy such as solar, wind, biofuels and batteries will require an *unprecedented* scale of mined, sometimes toxic, resources from the earth. These materials must be disposed, or recycled and then disposed, in landfills or the ocean, when they wear out. Repeated mining, manufacturing, and disposal is not clean or renewable.

We do not want students around the world to feel *duped* some day when they realize that "clean" did not really mean "clean."

We must not only be *completely factual*; but *factually complete* in our work and in our communications. For example, although it is *completely factual* that the levelized cost of energy (LCOE) for solar and wind have fallen below the cost of coal, *factual completeness* tells us that LCOE is the cost are at the plant, not the cost to the consumer. LCOE does not include the high cost of redundant backup for intermittent solar and wind. The actual cost, including full-scale redundant backup, makes it more expensive to the consumer. Ask California and Germany.

Solar, wind and batteries have a role to play, but they are not clean, renewable, or cheaper.

Let's converge on a plan that provides equitable energy access globally, and addresses not only emissions, but all environmental impacts.

That plan should focus on CO_2 solutions and do several things.

- Provide energy access to lift the world from energy and economic poverty
- Reduce *actual CO_2 emissions* into our *single* global atmosphere
- Protect the rest of the environment
- Be affordable, dispatchable, and scalable
- Be deployed, or deployable, in the next two decades
- Protect U.S. security and the U.S. economy

Fortunately, solutions exist. Options you have heard from other witnesses today are remarkably consistent and include:

- Switching from *Coal* to *Natural Gas*, especially in Asia. *If Asia doesn't act, it won't matter*.
- Preserve the *Nuclear* fleet in the US and support nuclear globally, especially SMRs, and streamline deep borehole disposal
- Accelerate *Efficiency* across all U.S. and global sectors

Natural gas, nuclear, and efficiency, in partnership and supplemented by solar and wind, CCUS, hydro, geothermal, hydrogen and others can provide dispatchable, reliable, affordable energy today, and preserve industry and grows higher-wage jobs.

The U.S. can lead through investment in technology, federal and state incentives, and efforts to find scalable, affordable, timely solutions. And although tempting, we must resist well-intended efforts to restrict market optionality--with vehicles, energy production and delivery systems, and more--which often result in unintended consequences.

Thank you for the opportunity to speak with you today.

Written Testimony Follows

Written Testimony

I worked in the energy industry for 17 years before coming to the University of Texas 21 years ago. I direct a 250-person research organization that studies global earth resources, environmental impacts, and economic implications.

I formed the non-partisan Switch Energy Alliance and produce documentary films about energy, the environment, and poverty that are used by educators globally.

I have travelled to 65 countries and interacted with governments, industry, academics, and the public. I have witnessed extreme poverty and extreme wealth.

In the supplemental material, I have made twenty energy statements, each with a key graphic and reference source. I have tried to be completely factual, and factually complete.

A few highlights from those statements are followed by a brief discussing on carbon dioxide solutions.

- Global population is ~ 7.7 billion and increasing. *We are not evenly distributed.*
- The world is becoming urban. *Dense cities need dense energy.*
- About half of the global population lives on less than $2000 a year. The U.S. individual poverty level is $12,700.
- A successful energy transition must address global energy poverty. *Energy won't end poverty, but you can't end poverty without energy.*
- Asia represents 55% of global population and since 1965 energy demand grew nearly 14X. *Providing affordable energy, while also reducing emissions, must happen in Asia.*
- Asia represents 75% of the world's coal electricity generation.
- The coal/gas ratio in China is 20X that is the U.S.
- China continues to build coal power plants at a rapid rate. *Coal is an Asian story.*
- Solar and wind were the fastest-growing sources of global electricity since 2005 in terms of *rate*, yet provided <25% of the *growth* in global electricity demand. *Scale matters.*
- Natural gas was the fastest-growing source of global electricity *generation* since 1985.
- China controls global lithium, cobalt, and many other mined resources required for panels, turbines, and batteries, bringing into question energy security and human rights.
- Solar and wind are intermittent and require backup, which adds considerably to levelized cost (LCOE) to the consumer.
- To electrify half of today's global vehicle fleet would require over 3 trillion new batteries every 15 years or so. *Mining, manufacturing, and disposing batteries is not "green."*
- Coal, oil, nuclear, natural gas, and hydrogen are much denser than biomass, hydro, wind, geothermal, and solar. *Energy density matters for environmental impact and cost.*
- *All forms of energy* require significant resources from the earth, which are *non-renewable*.

Given this context, proposed CO_2 solutions must do several things.

- Provide energy access to lift the world from energy and economic poverty
- Reduce *actual CO_2 emissions* into our *single* global atmosphere
- Protect the rest of the environment
- Be affordable, dispatchable, and scalable
- Be deployed, or deployable, in the next two decades
- Protect U.S. security and the U.S. economy

Viable options, in relative order of impact, include

- Fuel switching from Coal to Natural Gas, especially in Asia. U.S. natural gas development and LNG transport are needed to provide natural gas to Asia
- Preserve the U.S. Nuclear fleet while streamlining deep borehole disposal and permitting for new smaller modular reactors
- Support dispatchable Nuclear in India and China, and modular reactors in emerging economies
- Accelerate efficiency across all U.S. sectors
- Support distributed Solar and Wind and in certain settings, dispatchable Solar and Wind
- Create a world-leading Carbon Capture Utilization and Storage hub in the offshore Gulf of Mexico, and pursue other CCUS options onshore
- Support Hydro and Geothermal, where resources are viable
- Build out Hydrogen capability and infrastructure in the U.S., leveraging existing pipeline infrastructure and rights of way

In summary, natural gas, nuclear, and efficiency, in partnership with optimized solar and wind are proven to reduce CO_2, with a lower overall environmental footprint; are dispatchable, reliable, affordable, and ready today; and preserve industry and grow higher-wage American and global jobs. Importantly, *carbon neutral is not always nature neutral.*

For transport, improved ICE efficiency; natural gas and fuel cells; and EVs and PHEVs especially in cities will all reduce CO_2. Batteries at scale will have an unprecedented mining and landfill disposal impact on the environment, and charging them in Asia is done mostly with coal. Battery recycling technologies must be developed and scaled.

The U.S. can lead through investment in technology, federal and state incentives, and efforts to find scalable, affordable, timely solutions.

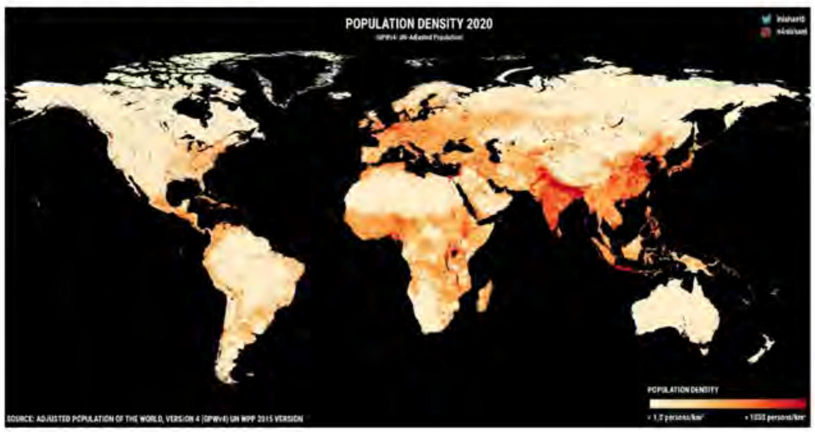
Policy makers should resist well-intended efforts to restrict market optionality, which often result in unintended consequences.

Energy Statements Follow

Energy Statements

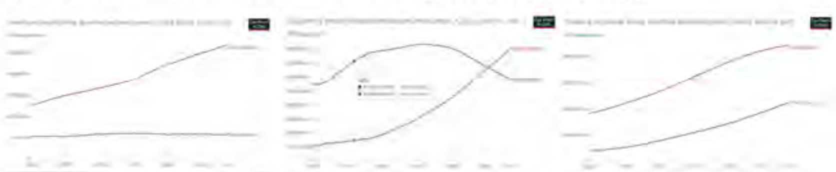
I believe the statements that follow to be both factually correct, and as complete as I can make them, given limited space and what I understand today. Time and progress always provide improved clarity. There are links to key sources in the text, and data sources are shown on each graph.

Statement 1. Global population is ~ 7.7 billion and increasing. Population is not evenly distributed. Cities in high income regions such as the U.S. and Europe show up as dense red dots on a global map. In middle to lower income regions such as India, SE Asia, and sub-Saharan Africa, population is very dense, but spread across urban and rural.



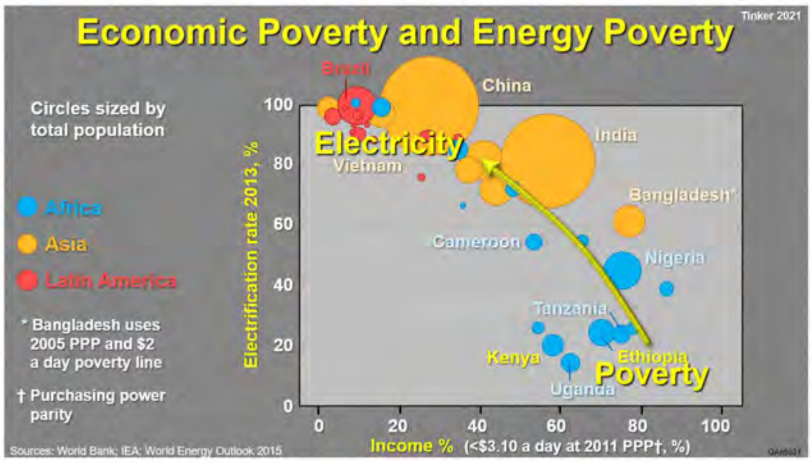
https://ourworldindata.org/urbanization

Statement 2. Across most high-income countries, more than 80% of the population live in urban areas. In many low to lower-middle income countries, the majority still live in rural areas. The urban migration is illustrated very well by the U.S., China, and India. The U.S. was wealthy in 1960. With population growth the urban (red) migration continued with rural (blue) remaining flat. China was poor in 1960. With industrialization, the urban (red) population has grown rapidly while the rural population plateaued and fell below urban. India remains poor. With extreme population growth, rural (red) population is still almost double urban (blue). ***Dense cities require dense energy.***

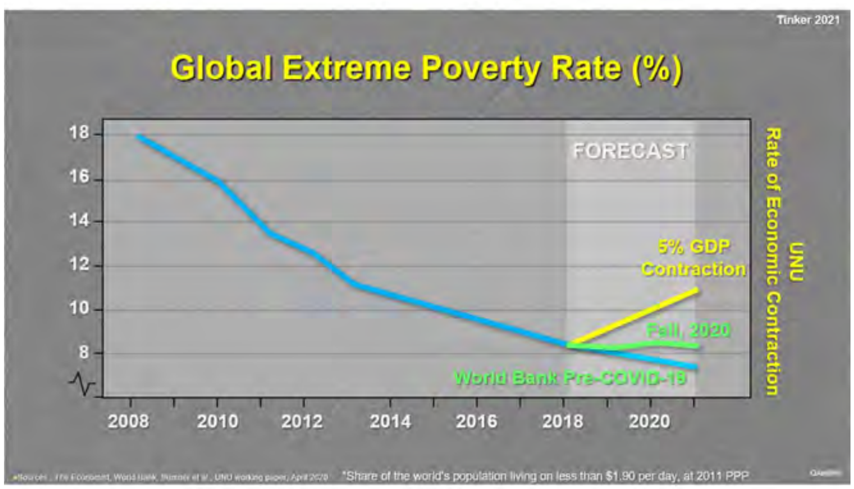


https://ourworldindata.org/urbanization

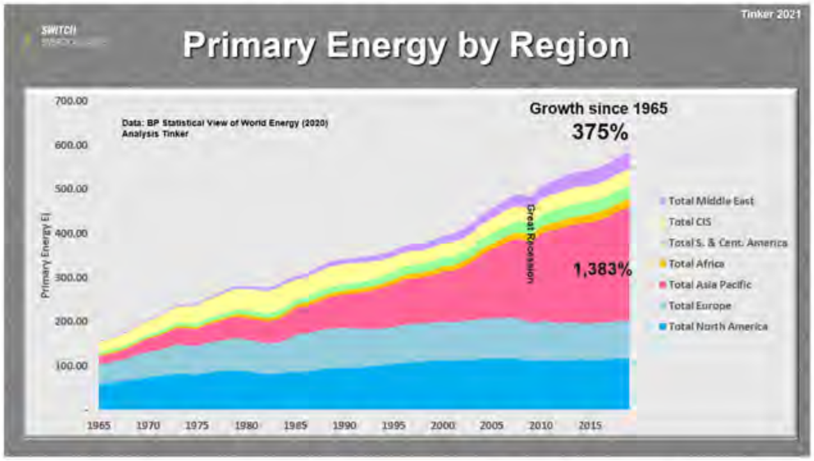
Statement 3. Affordable, reliable, and scalable energy underpins modern economies. Lack of energy, so called energy poverty, is tied directly to economic poverty. As I have written, this creates a paradox. ***Energy won't end poverty, but you can't end poverty without energy***.



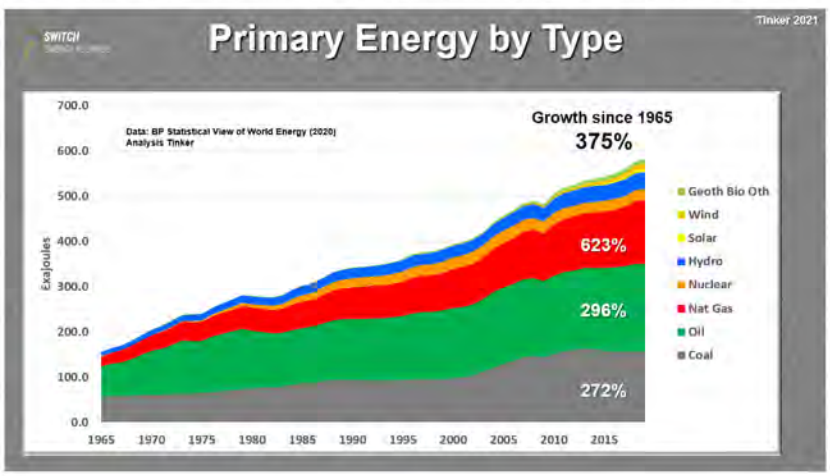
Statement 4. About half of the global population lives on less than $2000 a year. The U.S. poverty level for an individual in 2020 was $12,760, which is over 6X the income of half of the world's population today. The negative economic impacts from COVID-19 will have a detrimental impact on global poverty. Any successful energy transition must address global energy poverty.



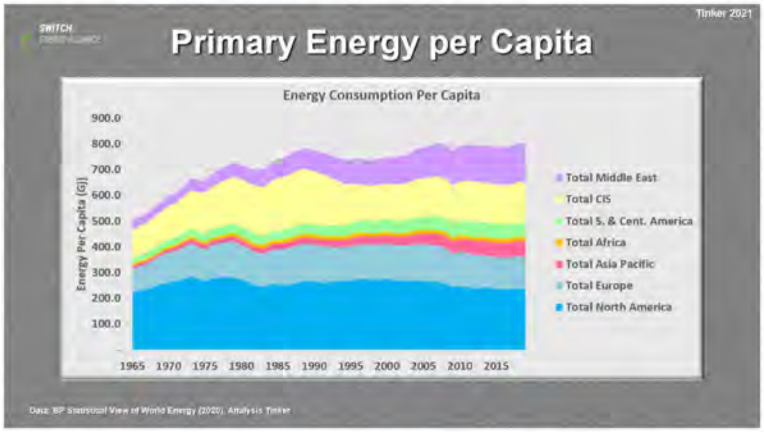
Statement 5. Global energy demand has increased 375% since 1965. That growth was led initially by the U.S. and Europe, but eclipsed quickly, and overwhelmingly, by the Asia Pacific with nearly 1400% growth. The rest of the world is just getting started in terms of energy demand.



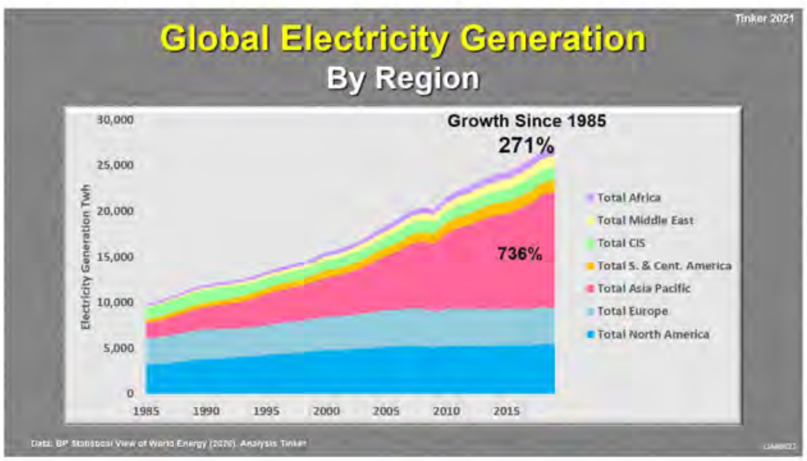
Statement 6. The global energy mix has been decarbonizing since 1965, when it was dominated by coal (carbon) mostly for power generation, and oil (complex carbon-hydrogen chains) mostly for transportation. Today the energy mix includes significant natural gas (CH_4: mostly hydrogen) and in lesser amounts nuclear, hydro, and emerging solar, wind, biofuels, and geothermal. In 1965 fossil fuels were 94% of the energy mix. In 2019 they are 84%, with natural gas growing over 600% since 1965.



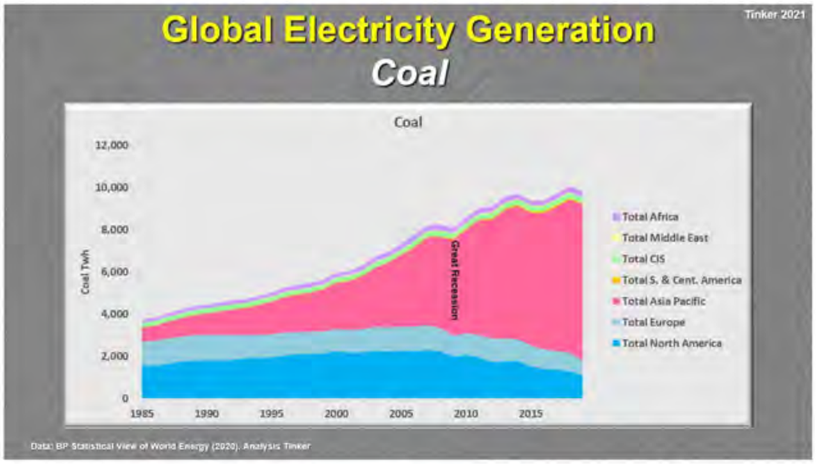
Statement 7. North America, Russia, the Middle East, and Europe consume more energy on a per capita basis. This is no surprise, as modern economies require energy. Decreases in per capita consumption continue, owing to energy efficiency. Asia Pacific, South and Central America, and Africa consume significantly less energy on a per capita basis. This is changing, as their economies begin to grow. Approximately 78% of the global population (~ 6 billion people) live in Asia Pacific, South and Central America, and Africa today. Providing them modern energy is a major challenge.



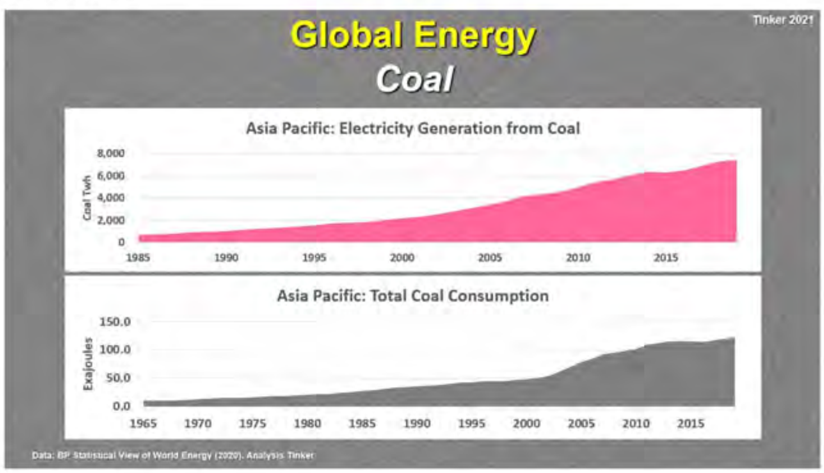
Statement 8. A similar story emerges when looking at just the power sector, with the Asia Pacific, comprising 4.6 billion people (55% of global population and growing) dominating electricity generation, having grown over 700% in demand since 1985. The data are generation in Terawatt hours (Twh), not installed capacity, which masks generation capacity factors for different energy sources.



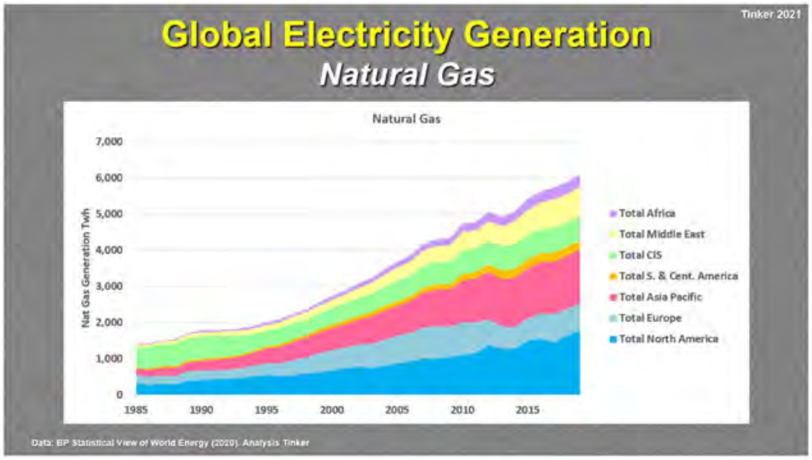
Statement 9. Asia represents 75% of the world's coal generation for electricity. Of the approximate 13,000 Twh of total electricity generated in Asia, 58% comes from coal. In other words, charging electric vehicles in Asia is done with 58% coal. Coal is used for many other things, in addition to electricity.



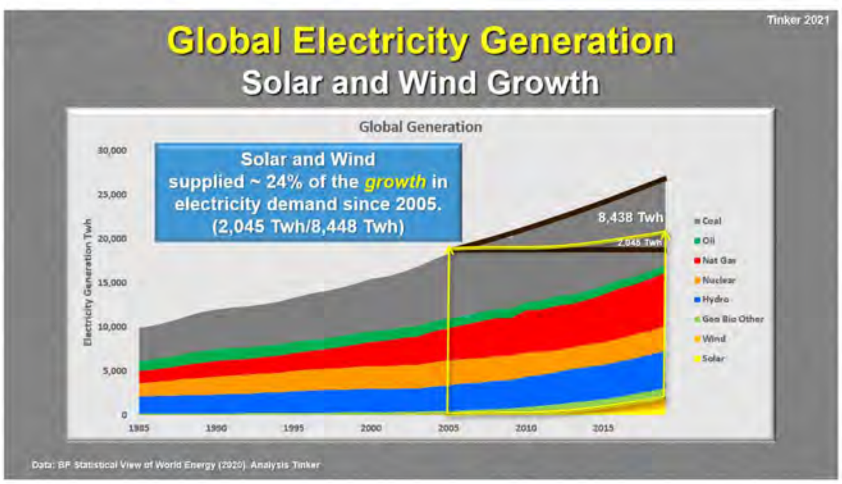
Statement 10. Coal consumption in Asia for *power generation* continues to increase, as does *overall* coal consumption in Asia. Although pledges have been made by China to go "carbon neutral" by 2060, they, and other countries in Asia, continue to build coal power plants at a rapid rate. These plants will operate for 60 to 80 years.



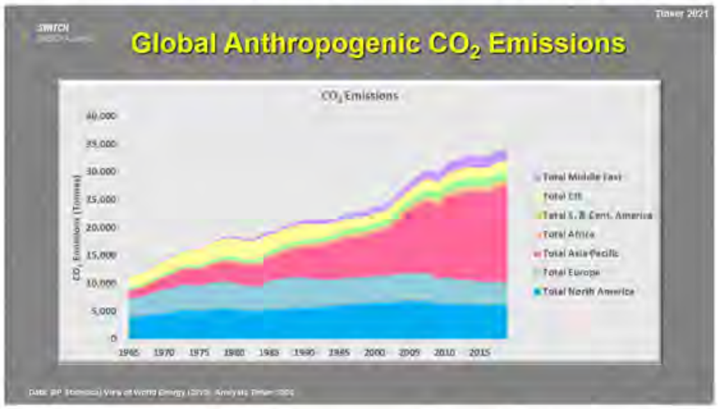
Statement 11. Natural gas (CH_4, mostly hydrogen) is increasing as a fuel for electricity generation in every geopolitical sector. The global natural gas/coal ratio in electricity generation has grown from 38% in 1965 to 62% in 2019, and continues to increase.



Statement 12. Solar and wind are the fastest-growing sources of electricity in terms of rate. However, in actual Twh of generation, solar and wind supplied only 8.0% of global electricity, and 3.3% of total global energy in 2019. After 15 years of growth, solar and wind represent only ***24% of the growth*** in demand for electricity from 2005 to 2019.



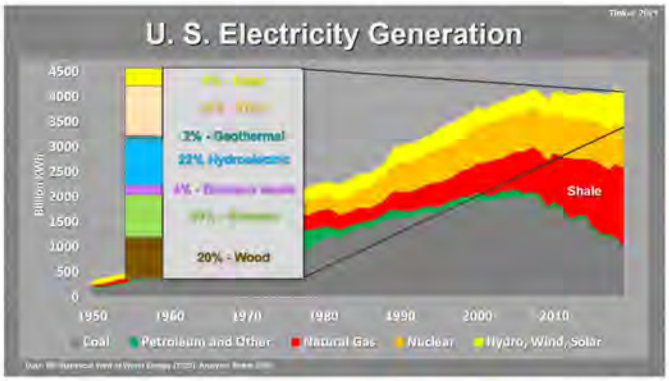
Statement 13. Anthropogenic sources of CO_2 come from several sectors including, in relative order of amount, electricity generation, agriculture and land use, transportation, manufacturing, and heating and cooling. Global CO_2 emissions track Primary Energy consumption by region, with the U.S. and Europe decreasing, Asia growing tremendously (>50% of global), and the rest of the world just getting started.



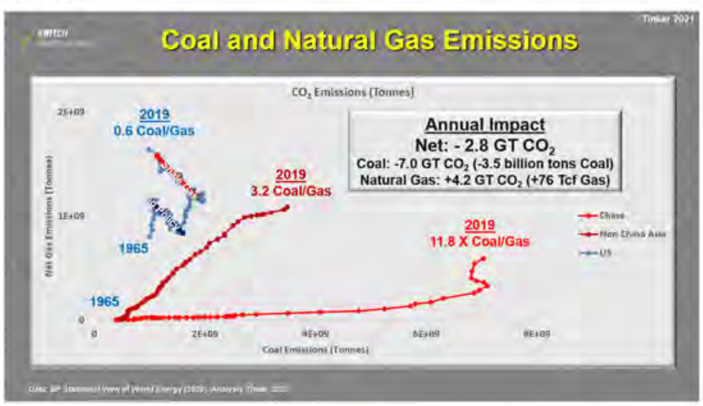
Statement 14. There has been much work done on strategies to reduce global CO_2 emissions starting in 2005 with the thoughtful "wedge" approach out of Princeton. To address climate change, an approach must address **scale** (billions of tons per year) and **cost** (trillions of dollars) and **time frame** (a decade or two). In electricity, the surface power density of energy options is very important. An objective look suggests that although solar and wind, and the batteries to make them reliable, have a role to play, they have power densities so low that a tremendous amount of **non-renewable** "stuff" to make the panels, turbines and batteries is required to capture and store the wind and the sun. This "stuff" would require an unprecedented scale of global mining and manufacturing, and later landfill disposal when the panels, turbines, and batteries wear out. ***Robbing from nature Peter to pay climate Paul.*** By contrast, nuclear with zero emissions or fuel switching from coal to natural gas each provide dispatchable electricity and address the challenge of scale, cost, and time frame. Hydro (largest source of renewable energy today) and geothermal are both dispatchable, and although very low power density, still have roles to play.

Energy source	Median PD [W/m²]
Natural gas	482.10
Nuclear power	240.81
Petroleum	194.61
Coal	135.10
Solar power	6.63
Geothermal	2.24
Wind power	1.84
Hydropower	0.14
Biomass	0.08

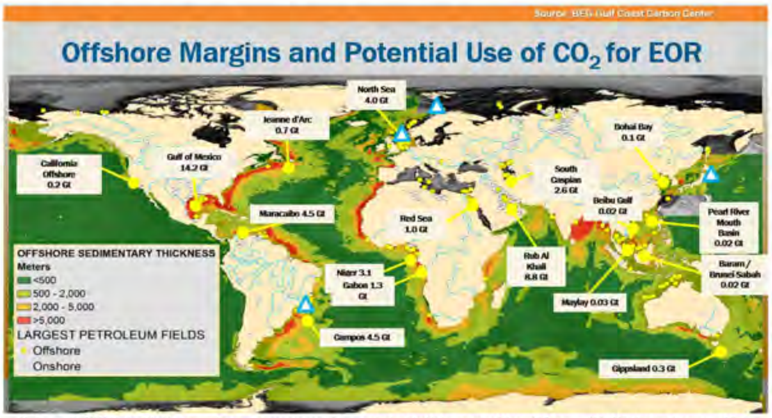
Statement 15. In terms of fuel switching, U.S. CO_2 emissions from the power sector have decreased substantially. In fact, the U.S. met the proposed 2015 Clean Power Plan target emissions reductions for 2030 a decade early in 2020, without the Clean Power Plan. CO_2 reduction was driven by affordable and abundant natural gas from hydraulically fractured ("fracked") shales replacing coal in power generation, and to a lesser degree, growth of wind and solar, efficiency gains, and exporting manufacturing overseas, mostly to Asia. ***Exporting manufacturing does not reduce emissions into the single global atmosphere.***



Statement 16. Asia is developing its economy on coal just like the U.S. and Europe did. Asia consumes 11X more coal annually than the U.S. (122 Ej vs. 11 Ej). In terms of global CO_2 emissions 15%, 29%, and 22% come from the U.S., China, and non-China Asia, respectively. The coal/gas ratio in the U.S. is 0.6X (decreasing); in China is 11.8X; and in non-China Asia is 3.2X (increasing). If Asia were to transition to a coal/gas ratio like the U.S., it would reduce Asian coal consumption by 2.8 Gt/yr. (billion tonnes/yr.), increase natural gas by 76 Tcf/yr., and result in a net reduction in CO_2 emissions of 2.8 GT/yr. A substantial "wedge."

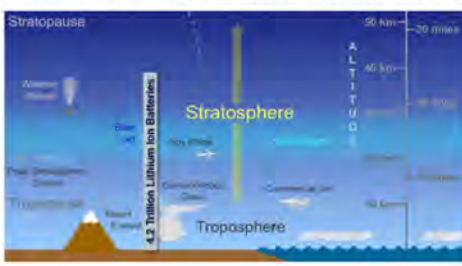


Statement 17. Carbon Capture, Utilization, and Storage (CCUS) represents a potential wedge. Work the past two decades indicates that, in the right setting, safe CCUS at scale is technically feasible. CCUS will require government incentives (e.g., Section 45Q tax credit) to make the economics work for those who own the pore space, those who develop the infrastructure, and those who pay others to honor their pledges. The Bureau of Economic Geology is a leader in CCUS. Under DOE Secretary Moniz, we pursued understanding of offshore CCUS, which is the most likely way to achieve scale, cost, and timeframe.

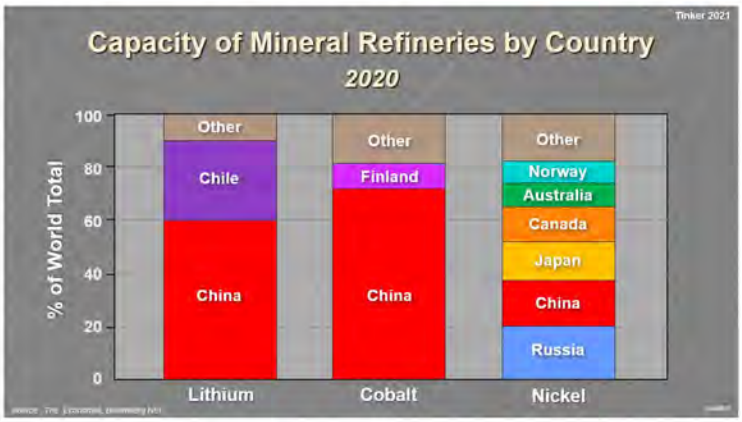


EOR Source: ISO/TC265 Carbon Dioxide Capture, Transportation and Geological Storage – Carbon Dioxide Storage using Enhanced Oil Recovery (CO_2-EOR): Cyphers, Kopema, and Godec

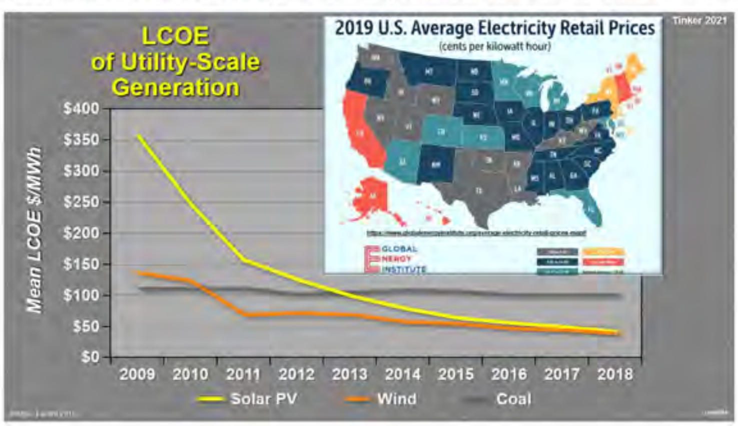
Statement 18. In terms of transportation, air, rail, ship, and vehicle, all present emissions challenges. For vehicles, internal combustion engines (ICE), electric vehicles (EV), and fuel cells (FC), all have advantages and disadvantages when it comes to reducing CO_2 emissions without further damaging other parts of the environment. In terms of EVs, the mining and later landfill disposal required to power enough vehicles to impact CO_2 reductions is unprecedented. To electrify half of today's vehicle fleet of 1.2 billion with the equivalent number of batteries in a single Tesla S (7100; see below) would require over 4 trillion new batteries every 15-20 years as the batteries wear out. Four trillion Tesla S batteries would build a U.S. football field-sized solid battery tower 25 miles into the stratosphere. Global EV sales increased 46% from 2019 to 2020. Much of the growth happened in China and Korea, where sales rose by 135% and 60% respectively. Depending on the source of electricity (i.e., not coal in Asia), EVs can reduce emissions. But, ***mining, manufacturing, and disposing batteries is not "green."***



Statement 19. China now controls much of the world's mineral refining capacity and mining resources related to batteries and solar panels, which presents a national security risk with increased vehicle electrification. Mining practices in parts of the world violate human rights. To manufacture and deploy enough solar panels, wind turbines, and batteries to replace dispatchable coal, natural gas, and nuclear will require tremendous land use and mining of non-renewable lithium, cobalt, copper, other metals, rare earth elements, polysilicon, etc. It will also require landfill disposal of massive and toxic materials.



Statement 20. The levelized cost of electricity (LCOE) for solar and wind are now below coal, and in places natural gas. Unfortunately, LCOE is incomplete because it represents the cost of electricity at the generation source, not the actual cost to the consumer. To be reliable, intermittent solar and wind require almost 100 % redundant and expensive backup from natural gas plants or batteries, which ***makes them more expensive to the consumer***. This is partly why people in California, the N.E. U.S., and Germany pay more for electricity. The higher cost is regressive and inequitable to low-income people.



End of Written Testimony

Senator MANCHIN. Thank you, Dr. Tinker.

And finally, we have Mr. Mills. Thank you for being here, Mr. Mills.

STATEMENT OF MARK P. MILLS, SENIOR FELLOW, MANHATTAN INSTITUTE

Mr. MILLS. Thank you, incoming Chairman Manchin, very much for——

Senator MANCHIN. We'll get this worked out pretty soon.

[Laughter.]

Mr. MILLS. And thank you, outgoing Chairman Murkowski. I was tempted to make an allusion to Bill Murray in the movie we all know and love. But thank you for inviting me, it's an honor and a pleasure, and Senator Barrasso and members of the Committee.

Since the purpose of this hearing is to establish a baseline on the state of affairs regarding carbon dioxide emissions associated with energy, permit me to note three basic realities and each of them have implications for the subject at hand. These are realities, in fact, that help explain why, as the Committee's Joint Staff Memorandum notes, that global carbon dioxide emissions continued to increase prior to the pandemic lockdowns, despite massive investments in non-hydro carbon energy production both in Europe and the United States and China.

First, it's indisputable—and it's a good thing that the world will use far more wind turbines and solar machines and electric cars in the future. The reason for that, aside from obvious policies encouraging all three, is anchored in the fact that those technologies are all profoundly better than they were a decade or two ago, and given the magnitude of future global energy needs to bring people out of poverty, more options are always better.

Second, it's equally indisputable that all energy machines are, necessarily, built and operated using materials that must first be extracted from the earth. Replacing hydrocarbons with the wind, solar and battery-powered machines—the principal vectors in most countries on these discussions—doing that constitutes a major shift in both the nature and the quantities of these energy materials. It's a switch from using mainly liquids and gases to using solids, and it's a switch that, on average, results in a tenfold increase in the quantity of materials mined and processed per unit of energy delivered to society.

And third, the United States is today, and will be for the foreseeable future, a net importer of either wind, solar, or battery machines, or key components for those machines or, in fact, for most of the critical energy minerals and materials needed to build them.

Now, these realities have implications in the accounting of carbon dioxide emissions. They also have economic, and of course, geopolitical, environmental, and even human rights implications. I know, briefly, that the U.S. is essentially, as the Committee knows, self-sufficient today in net hydrocarbon use. It's an importer, though, of alternative energy materials and machines. This means that replacing the former, which supply 80 percent of America's energy, with the latter, would replace a very large share of the domestic GDP with imports.

So given the way the world is, not as we wish it would be, increasing domestic use of wind, solar, and batteries results in a de facto export of carbon dioxide emissions. That's because mining and processing of energy minerals and the fabrication of energy machines is inherently energy-intensive, and most of that energy used takes place offshore. By calculating the magnitude of that, one could call it offshoring of emissions, it's actually complex. There are some analyses that have, for example, looked at the impact of processing battery materials or fabricating battery components in China, which, in fact, this Committee may know is a major, if not the dominant, share of such industries.

With China's grid that's two-thirds coal-fired, that processing and fabrication leads to supply-chain carbon dioxide emissions that constitute a significant share and can even be the entire share of any emissions that are eliminated by replacing a combustion engine with an electric vehicle in many parts of the United States. In fact, in more broadly looking at global mining, its oil use for heavy machinery, of course, rivals the total oil use of global aviation—of course, before the Great Lockdowns. Meanwhile, the path contemplated in the Paris Accord will lead to the greatest acceleration in demand for mining that the world has ever seen.

This all points to the need for a realistic supply-chain emissions analyses, accounting of the carbon dioxide of where it really comes from and de facto export of carbon dioxide emissions, something that's lacking in the current carbon accounting, but also points, frankly, to an opportunity for the United States to revitalize our domestic mining and mineral processing industries, something I note that China has been focused on for years.

I'd like to conclude by noting that there's some irony in the fact that the world that's coming full-circle to revisit the importance of mining. It's humanity's oldest industrial activity, in fact. Way back in 1934, speaking of baselines, the great American philosopher and technology historian, Lewis Mumford, who was born in Queens, by the way, observed in a seminal book about technology and civilization that the industrialization of mining was a major and, in fact, in his view it was the primary vector, the primary driver in the creation of modern capital markets, in the organization of labor, and in our understanding of our relationship with the environment. Given green energy plans, I expect we'll be revisiting those lessons in the coming decades.

I thank you for the opportunity to testify.

[The prepared statement of Mr. Mills follows:]

Testimony of
Mark P. Mills, Senior Fellow, Manhattan Institute
Before
U.S. Senate Committee on Energy and Natural Resources
On
Establishing a Baseline of Global Climate Facts: Understanding the Scale and Source of Contributions

February 3, 2021
Dirksen Senate Office Building, Washington D.C.

Good morning. Thank you for the opportunity to testify before this Committee. I'm a Senior Fellow at the Manhattan Institute where I focus on science, technology, and energy issues. I am also a Faculty Fellow at the McCormick School of Engineering at Northwestern University where the focus is on future manufacturing technologies. And, for the record, I'm a strategic partner in a venture fund focused on software startups in energy.

Since the purpose of this hearing is to establish a baseline on the state of affairs regarding carbon dioxide emissions associated with supplying energy to society, permit me to note three basic realities, each with implications for the subject at hand. These are realities that help explain why, as this Committee's join staff memorandum notes, in the pre-pandemic trends, "the United Nations Environment Program has found that greenhouse gas emissions continued to increase" despite massive European and U.S. investments in non-hydrocarbon energy production.

First, it is indisputable, and it's a good thing, that the world will use more wind and solar machines, and more electric cars. The reason for that, aside from policies encouraging all three, is anchored in the fact those technologies are all profoundly better than they were a decade or two ago and, given the magnitude of future global energy needs, more options are always better.

Second, it is equally indisputable that all energy machines are, necessarily, built and operated using materials that must be first extracted from the earth. Replacing hydrocarbons with wind, solar and battery-powered machines constitutes a significant shift in both the nature and quantities of those "energy materials." It is a switch from using mainly liquids and gases to using solids. And it's a switch that, on average, results in a ten-fold increase in the quantity of materials mined and processed per unit of energy delivered.

Third, the United States is today, and will be for the foreseeable future, a net importer of, either wind, solar and battery machines, or key components for them, or for most of the critical "energy minerals" needed to build them.

All these realities have implications for the baseline accounting of carbon dioxide emissions trends. These realities also have economic, geopolitical, environmental and even human rights implications. While the U.S. is essentially self-sufficient today in net hydrocarbon use, it is an importer of alternative energy materials and machines. This means that replacing the former, which supply 80 percent of America's energy, with the latter would replace a large share of the GDP with imports.

And, given the world as it is, not as we'd wish it, increasing domestic use of wind, solar and batteries results in a *de facto* export of carbon dioxide emissions. That's because mining and processing of energy minerals, and the fabrication of energy machines, is inherently energy-intensive – and most of that energy use takes place offshore. Calculating the magnitude of that offshoring of emissions is complex. Some analyses have, for example, examined the processing of battery materials, or fabrication of battery components in China, where a major if not dominant share of such industries now resides. With China's 60 percent coal-fired grid, this leads to supply-chain carbon dioxide emissions that are a significant share, even the entire share, of emissions eliminated by replacing a combustion engine in many parts of America.

In general, it's worth noting that the aggregate use of oil by heavy machinery in global mining rivals oil use in global aviation, the latter of course before the Great Lockdowns. And it's as challenging to replace oil in mining as it is in aviation. Meanwhile, the energy path contemplated with the Paris Accord will lead to the greatest acceleration in demand for mining that the world has ever seen.

All this points to the need for realistic supply-chain emissions analyses, something largely lacking in the current global carbon accounting. It also points to an opportunity for the United States to revitalize our domestic mining and mineral processing industries, something that China has been focused on for years.

There is some irony in the fact that the world is coming full circle to revisit the importance of mining. It's humanity's oldest industrial activity. In fact, way back in 1934, speaking of baselines, the great American philosopher and technology historian, Lewis Mumford, observed in his seminal book on technology and civilization that the industrialization of mining was a major, indeed in his view, a primary driver in the creation of modern capital markets, the organization of labor, and our understanding of our relationship with the environment.

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EXPANDED TESTIMONY

The Material Cost of "Clean Tech"

The materials extracted from the earth to fabricate everything, including wind turbines, solar panels, and batteries (to store grid electricity or power electric vehicles) are typically out of sight, located at remote quarries, mine sites, and mineral-processing facilities around the world. Those locations matter in terms of geopolitics and supply-chain risks, as well as in general environmental terms, including accounting for carbon dioxide emissions. The scale of the material demands for "clean tech" machines is, for many, surprising.

For example, replacing the energy output from a single 100-MW natural gas-fired turbine, itself about the size of a residential house (producing enough electricity for 75,000 homes), requires at least 20 wind turbines, each one about the size of the Washington Monument, occupying some 10 square miles of land.[1] Building those wind machines consumes enormous quantities of conventional materials, such as concrete, steel, and fiberglass, along with less common materials, including "rare earth" elements such as dysprosium. A World Bank study noted what every mining engineer knows: "[T]echnologies assumed to populate the clean energy shift … are in fact significantly more material intensive in their composition than current traditional fossil-fuel-based energy supply systems."[2]

As it happens, all forms of renewable energy require roughly comparable quantities of materials in order to build machines that capture nature's flows: sun, wind, and water. Wind farms come close to matching

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[1] Landon Stevens, "The Footprint of Energy: Land Use of U.S. Electricity Production," Strata, June 2017. This calculation understates land usage; at least double the number of wind turbines, plus storage, would be needed to replace the continuous availability of electricity from conventional generation.

[2] Daniele La Porta et al., *The Growing Role of Minerals and Metals for a Low Carbon Future* (Washington, DC: World Bank Group, 2017), p. xii.

hydro dams in material consumption, and solar farms outstrip both. In all three cases, the largest share of the tonnage is found in the use of conventional materials like concrete, steel, and glass. Compared with a natural gas power plant, all three require at least 10 times as many total tons mined, moved, and converted into machines to deliver the same quantity of energy.[3]

For example, building a *single* 100-MW wind farm—never mind thousands of them—requires some 30,000 tons of iron ore and 50,000 tons of concrete, as well as 900 tons of nonrecyclable plastics for the huge blades.[4] With solar hardware, the tonnage in cement, steel, and glass is 150% greater than for wind, for the same energy output.[5]

If episodic sources of energy (wind and solar) are to be used to supply power 24/7, even greater quantities of materials will be required. One needs to build additional machines, roughly two to three times as many, in order to produce and store energy when the sun and wind are available, for use at times when they are not. Then there are the additional materials required to build electricity storage. For context, a utility-scale storage system sufficient for the above-noted 100-MW wind farm would entail using at least 10,000 tons of Tesla-class batteries.

The handling and processing of such large quantities of materials entails its own energy costs as well as associated environmental implications. But first, the critical supply-chain issue is not so much the increase in the use of common (though energy-intensive) materials such as concrete and glass. The core challenges for the supply chain and the environment reside with the need for radical increases in the quantities of a wide variety of minerals.

The world currently mines about 7,000 tons per year of neodymium for example, one of numerous key elements used in fabricating the electrical systems for wind turbines. Current clean-energy scenarios imagined by the World Bank (and many others) will require a 1,000%–4,000% increase in neodymium supply in the coming several decades.[6] While there are differing underlying assumptions used in various analyses of mineral requirements for green energy, all reach the same range of conclusions. For example, the mining of indium, used in fabricating electricity-generating solar semiconductors, will need to increase as much as 8,000%. The mining of cobalt for batteries will need to grow 300%–800%.[7] Lithium production, used for electric cars (never mind the grid), will need to rise more than 2,000%.[8] The Institute for Sustainable Futures at the University of Technology Sydney last year analyzed 14 metals essential to building clean-tech machines, concluding that the supply of elements such as nickel, dysprosium, and tellurium will need to increase 200%–600%.[9]

The implications of such remarkable increases in the demand for energy minerals have not been entirely ignored, at least in Europe. A Dutch government–sponsored study concluded that the Netherlands' green ambitions alone would consume a major share of global minerals. "Exponential growth in [global]

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[3] U.S. Department of Energy (DOE), "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities," September 2015, p. 390.

[4] Vaclav Smil, "To Get Wind Power You Need Oil," *IEEE Spectrum*, Feb. 29, 2016.

[5] U.S. Department of Energy (DOE), "Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities," September 2015.

[6] La Porta et al., *The Growing Role of Minerals and Metals*.

[7] Matt Bohlsen, "Cobalt Miners News for the Month of November 2019," Seeking Alpha, Nov. 26, 2019; John Petersen, "The Cobalt Cliff Will Crush Tesla's Business and May Restore Some Sanity to the EV Industry," Seeking Alpha, Sept. 29, 2019.

[8] Jamie Smyth, "BHP Positions Itself at Centre of Electric-Car Battery Market," *Financial Times*, Aug. 9, 2017.

[9] Elsa Dominish, Sven Teske, and Nick Florin, "Responsible Minerals Sourcing for Renewable Energy," Institute for Sustainable Futures, University of Technology Sydney, 2019.

renewable energy production capacity," the study noted, "is not possible with present-day technologies and annual metal production."[10]

Behind the Scenes: Ore Grades and "Overburden"

The scale of these material demands understates the total tonnage of the earth that is necessarily moved and processed, all of which requires the use of energy-consuming machines and processes. Forecasts of future mineral demands focus on counting the quantity of refined, pure elements needed—but not the overall amount of the earth that must be dug up, moved, and processed.

For every ton of a purified element, a far greater tonnage of ore must be physically moved and processed. That is a reality for all elements, expressed by geologists as an ore grade: the percentage of the rock that contains the sought-after element. While ore grades vary widely, copper ores typically contain only about a half-percent, by weight, of the element itself; thus, roughly 200 tons of ore are dug up, moved, crushed, and processed to get to one ton of copper. For rare earths, some 20 to 160 tons of ore are mined per ton of element.[11] For cobalt, roughly 1,500 tons of ore are mined to get to one ton of the element.

In the calculus of economic and environmental costs, one must also include this so-called overburden—the tons of rocks and dirt that are first removed to get access to often deeply buried mineral-bearing ore. While overburden ratios also vary widely, it is common to see three to seven tons of earth moved to get access to one ton of ore.[12]

For a snapshot of what all this points to regarding the total materials footprint of the green energy path, consider the supply chain for a single electric car battery, which in final form weighs about 1,000 pounds.[13] Providing the refined minerals needed to fabricate a single EV battery requires the mining, moving, and processing of more than 500,000 pounds of materials somewhere on the planet.[14] That's 20 times more than the 25,000 pounds of petroleum that an internal combustion engine uses over the life of a car.

The core issue here for a green energy future is not whether there are enough elements in the earth's crust to meet demand; there are. Most elements are quite abundant, and nearly all are far more common than gold. Obtaining sufficient quantities of nature's elements, at a price that markets can tolerate, is fundamentally determined by technology and access to the land where they are buried. The latter is mainly about government permissions.

However, as the World Bank cautions, the materials implications of a "clean tech" future creates "a new suite of challenges for the sustainable development of minerals and resources."[15] Some minerals are difficult to obtain for technical reasons inherent in the geophysics. It is in the underlying physics of extraction and physical chemistry of refinement that we find the realities of unsustainable green energy at the scales that many propose.

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[10] Pieter van Exter et al., "Metal Demand for Renewable Electricity Generation in the Netherlands: Navigating a Complex Supply Chain," Metabolic, Universiteit Leiden, and Copper8, 2018.

[11] Laura Talens Peiró and Gara Villalba Méndez, "Material and Energy Requirement for Rare Earth Production," *Journal of the Minerals, Metals & Materials Society (JOM)* 65, no. 10 (August 2013): 1327–40.

[12] McArthur River Mine (Glencore), "Overburden," 2020.

[13] A Tesla 85-kWh battery pack weighs 1,200 lbs.; Neil Brooks, "Tesla Battery Weight Overview—All Models," enrg.io, Jan. 20, 2020.

[14] There is, over the life span of a conventional car, 50,000 pounds of cumulative gasoline consumption (counting upstream coproduction of associated liquids).

[15] La Porta et al., *The Growing Role of Minerals and Metals*.

Sources of Minerals: Conflicts and Dependencies

The critical, and even vital, roles of specific minerals have long been a concern of some analysts and various government commissions over the years. One can trace a straight line from an electric car to Inner Mongolia's massive Bayan Obo mines (for rare earths), and to mines in the Democratic Republic of Congo (for cobalt in batteries). Both of those regions represent the world's largest supply of rare earths and cobalt, respectively.[16]

Politically troubled Chile has the world's greatest lithium resources, although stable Australia is the world's biggest supplier. Elsewhere in the battery supply chain, Chinese cobalt refiners have quietly gained control over more than 90% of the battery industry's cobalt refining, without which the raw cobalt ore is useless.[17]

The Institute for Sustainable Futures in Sydney, Australia, cautions that a global gold rush for green minerals to meet ambitious plans could take miners into "some remote wilderness areas [that] have maintained high biodiversity because they haven't yet been disturbed."[18] And then there are the widely reportedly cases of abuse and child labor in mines in the Congo, where 70% of the world's raw cobalt originates.[19]

Late in 2019, Apple, Google, Tesla, Dell, and Microsoft found themselves accused in a lawsuit filed in a U.S. federal court of exploiting child labor in the Congo.[20] Similar connections can be made to labor abuses associated with copper, nickel, or niobium mines around the world.[21] While there is nothing new about such real or alleged abuses, what is new is the rapid growth and enormous prospective demand for tech's minerals and green energy minerals. The Dodd-Frank Act of 2010 includes reporting requirements on trade in "conflict minerals." A recent Government Accountability Office (GAO) report notes that more than a thousand companies filed conflict minerals disclosures with the Securities and Exchange Commission, per Dodd-Frank.[22]

Automakers building electric cars have joined smartphone makers in such pledges for "ethical sourcing" of minerals.[23] Car batteries are, however, create the biggest demand for "conflict" cobalt.[24] Companies can make pledges; but unfortunately, the facts suggest that there is little correlation between such pledges and the frequency of (claimed) abuses in foreign mines.[25] In addition to moral questions about exporting the environmental and labor challenges of mineral extraction, the strategic challenges of supply chains are a top security concern as well.

Strategic Dependencies: Old Security Worries Reanimated

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[16] Hong-Rui Fan et al., "The Giant Bayan Obo REE-Nb-Fe Deposit, China: Controversy and Ore Genesis," *Geoscience Frontiers* 7, no. 3 (May 2016): 335–44; DOI and USGS, "Mineral Commodity Summaries 2020."

[17] John Petersen, "The Cobalt Cliff Could Eradicate Non-Chinese EV Manufacturing Before 2030," Seeking Alpha, July 3, 2019.

[18] Ashley Stumvoll, "Are There Potential Downsides of Going to 100% Renewable Energy?" *Pacific Standard*, June 20, 2019.

[19] Douglas Broom, "The Dirty Secret of Electric Vehicles," World Economic Forum, Mar. 27, 2019.

[20] Jennifer Smith, "Apple, Google, Tesla, Microsoft and Dell Are Accused of Exploiting Child Labor in the Democratic Republic of Congo by African Families Whose Kids Have Been 'Maimed or Killed' Mining Cobalt to Be Used in Lithium Batteries," *Daily Mail*, Dec. 16, 2019.

[21] Kate Hodal, " 'Most Renewable Energy Companies' Linked with Claims of Abuses in Mines," *The Guardian*, Sept. 5, 2019

[22] GAO, "Conflict Minerals: 2018 Company Reports on Mineral Sources Were Similar in Number and Content to Those Filed in the Prior 2 Years," September 2019.

[23] Andreas Cremer, "Automakers Pledge Ethical Minerals Sourcing for Electric Cars," Reuters, Nov. 29, 2017.

[24] Vivienne Walt and Sebastian Meyer, "Blood, Sweat, and Batteries," *Fortune*, Aug. 23, 2018.

[25] Hodal, "Most Renewable Energy Companies."

Supply-chain worries about critical minerals during World War I prompted Congress to establish, in 1922, the Army and Navy Munitions Board to plan for supply procurement, listing 42 strategic and critical materials. This was followed by the Strategic Materials Act of 1939. By World War II, some 15 critical materials had been stockpiled, six of which were released and used during that war. The 1939 act has been revised twice, in 1965 and 1979, and amended in 1993 to specify that the purpose of that act was for national defense only.[26]

As recently as 1990, the U.S. was the world's number-one producer of minerals. It is in seventh place today.[27] More relevant, as the United States Geological Survey (USGS) notes, are strategic dependencies on specific critical minerals. In 1954, the U.S. was 100% dependent on imports for eight minerals.[28] Today, the U.S. is 100% reliant on imports for 17 minerals and depends on imports for over 50% of 28 widely used minerals. China is a significant source for half of those 28 minerals.[29]

The Department of Defense and the Department of Energy (DOE) have issued reports on critical mineral dependencies many times over the decades. In 2010, DOE issued the Critical Materials Strategy; in 2013, DOE formed the Critical Materials Institute, the same year the National Science Foundation launched a critical-materials initiative.[30] In 2018, USGS identified a list of 35 minerals as critical to security of the nation.[31]

But decades of warnings about rising mineral dependencies have yielded no significant changes in domestic policies. The reality is that depending on imports for small quantities of minerals used in vital military technologies can be reasonably addressed by building domestic stockpiles, a solution as ancient as mining itself. However, today's massive domestic and global push for clean-tech energy cannot be addressed with small stockpiles. The options are to accept more strategic dependency, or to increase domestic mining.[32] And both those options have unaccounted for implications for total fuel-cycle carbon dioxide emissions.

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[26] National Research Council, *Managing Materials for a Twenty-First Century Military.*

[27] National Mining Association (NMA), "U.S. Mines to Markets," 2014.

[28] USGS, "Risk and Reliance: The U.S. Economy and Mineral Resources," Apr. 12, 2017.

[29] DOI and USGS, "Mineral Commodity Summaries 2020."

[30] GAO, "Strengthened Federal Approach Needed to Help Identify and Mitigate Supply Risks for Critical Raw Materials," September 2016.

[31] USGS, "Interior Releases 2018's Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy," May 18, 2018.

[32] Dave Keating, "Europe Waking Up to Raw Materials 'Criticality'," EURACTIV.com, Dec. 11, 2019.

Senator MANCHIN. Thank you, Mr. Mills.

And now we will turn to our Chairwoman for her questions. She was just regrouping there and she is ready.

The CHAIRMAN. I am absolutely ready. I was getting ready to go over to HELP and then come back but you have given me an opportunity.

Senator MANCHIN. You are going to start right out, ma'am.

The CHAIRMAN. I am going to start right out.

Senator MANCHIN. You are still officially our Chairperson.

The CHAIRMAN. I do have to comment, Mr. Mills, your last statement there included the recognition or the reality that we are switching our vulnerability, if you will, from liquid state to soon, solid state. That is something that I think we need to be thinking about, and it is something that this Committee has focused on. Senator Manchin and I had our Critical Minerals bill that we included in the Energy Act, but we know we need to be doing more in that regard, and what you have highlighted here, I think, is very important. And you, Dr. Birol, in your comments mentioned much the same.

And again, I want to extend my thanks and my appreciation to Dr. Birol. You and your leadership, the opportunity that I have had to serve as a member of the Global Commission on Energy Efficiency, some of the best practices that we have been able to work through and talk about, I just so appreciate your leadership there.

I guess I would direct this question to both Dr. Birol and you, Mr. Mills. We have seen recent executive actions, Senator Barrasso mentioned them earlier when we were taking up the confirmation of Jennifer Granholm for Secretary of Energy, but these actions potentially jeopardize the very future development and production of U.S. fossil fuel resources. As we know, U.S. LNG markets, our exports are particularly important for markets in Asia. So the question to you both is, if future U.S. oil and gas exports are no longer available within the broader global market, this reduction in supply is going to be met elsewhere. And so, to you perhaps, Dr. Birol, what countries benefit the most from U.S. oil and gas exports and where will future supplies then come from if the U.S. cuts its exports?

And then, following that, Mr. Mills, if you can speak to what a reduction in U.S. oil and gas production really means for the development of the global markets. I appreciate your views on this.

Dr. Birol.

Dr. BIROL. Thank you very much. Thank you very much, Senator Murkowski, once again and thank you very much for your leadership in addressing one of the critical issues of clean energy, mainly energy efficiency best practices for households, for industry, for the transportation sector, with other leaders around the world.

Now, if the United States' production is set to decline, and if there's still strong demand for oil around the world, the gap will be met mainly by the cheap cost Middle East countries. Having said that, when we look at the current oil demand numbers, as it is out of COVID, they went down substantially, and we do not expect that the demand will go there where it was before COVID in the next three or four years to come, just on that issue and there is a huge amount of spare capacity in the markets now which the markets can make use of.

In terms of LNG, the flexible nature of U.S. LNG contributed a lot around the world and brought the price of gas down since the last few years and interestingly enough, the main purchaser of U.S. LNG today, by far, is China. From an emissions point of view, U.S. LNG, if it replaces coal in Asia, it can lead to significant emission declines, both in terms of CO_2 emissions, but also for air pollution.

Having said that, the methane emissions are very important here and it is very important to note that several customers around the world will soon look at the methane footprint of their gas exporters and therefore, it is perhaps an important task for the current Administration to take note of.

Thank you.

The CHAIRMAN. I appreciate that.

Mr. Mills.

Mr. MILLS. Thank you, Senator Murkowski.

I would say first that the IEA has been remarkably honest—and I don't mean this as any surprise or shock—at outlining the realities of where the world's energy markets are going in the near term, both with respect to the demand for critical energy minerals, but also with respect to where oil and gas demand are trending given the nature of the world. So it's my go-to for—we'll call it honest analyses at the global level.

Your question about what will happen to the U.S. and world development is, I think, a particularly appropriate one, as we know the demand for oil is not—and all the forecasts show—it's not going to decline, it's going to roughly where it was. Who produces that oil and who's going to produce the natural gas, we know—I would add to the OPEC nations—Russia is the other principal beneficiary and some other African nations, but principally it's Russia and OPEC. The world divides simplistically into oil and gas, transportation and electric power, roughly speaking. And the United States' role in the transportation markets and the cost for people to get around in cars, we can distill our impact in a very simple way. We, in America, were essentially responsible for the collapse of world oil prices to the benefit of world consumers who drive and fly. There will be about a billion cars added to the world's roads over the coming couple decades. Even if all the existing cars become electric, which is going to be extraordinarily difficult, there will still be an enormous demand for oil—markets, consumers, will want that oil to be cheap. We drove the price down.

We can continue to drive the price down. It's essential to swing producers. That's what's happened. The United States became, in the last decade, to the total shock of the world, the swing producer. It's to the detriment of U.S. oil companies, by the way, because it means you're a price taker, you're not a market maker. Every time prices go up, as we all know, it's like Mardi Gras again in the oil fields and they start drilling and prices collapse.

Natural gas is the go-to source of electricity for the world, not—the coal is still growing, as you all know, but natural gas is the go-to and there, as well, the U.S. shale fields directly caused the collapse in global gas prices. Just the anticipation of the U.S. entering global markets caused prices to collapse. Gazprom began negotiating and renegotiating new prices with Europe. The world benefited. The world's electric consumers benefited from American shale fields.

Lastly, I'll note, in terms of development, the United States—and this sounds a little bit bombastic because, but I'm a Canadian as well as an American—the American oil and gas industry is the technologically most sophisticated in the world. It has path-breaking capabilities, not just to produce marginal oil and gas more inexpensively, but more efficiently—which in the fuel cycle for carbon dioxide emissions matters–and more environmentally sensibly. So we are the pioneers on that. If we push that oil production and gas production to parts the world which are not as cautious and not as good at it as us, the oil and gas will be produced there. It will be less efficient and less clean and probably more expensive, which I think is a net bad for the world.

The CHAIRMAN. Mr. Chairman, thank you and Ranking Member Barrasso. I think both gentlemen have well pushed me beyond my time, but I think their responses and the reality of the role that the United States has played in a very dramatic way, very quickly, in terms of being that player in production, in what we have been able to do with our allies, is nothing short of extraordinary and I would certainly hate to see us go backward with that very significant and dominant role.

Thank you.

Senator MANCHIN. Thank you, Madam Chairman.

And with that, Senator Heinrich has another conflicting committee meeting and I want him to take my time right now.

Senator HEINRICH. Thank you to the former and current Chairmen.

Dr. Newell, the Ranking Member brought up the concern that embracing renewable power sources could lead to an unaffordable energy supply. Could you sort of walk us through the major sources of electric power generation today and how they stack up based on levelized cost of energy (LCOE)? In other words, what sources are most expensive today and what are the cheapest and what does that say about where we are going?

Dr. NEWELL. Thank you, Senator.

So there's been dramatic change over the last ten years or so in what's called the levelized cost of electricity production, which takes the upfront capital cost of building a new plant and also takes account of the fuel cost that you would use to operate a gas or a coal-fired plant and it puts those two things together and expresses it in, you know, dollars or cents per kilowatt-hour. So what we've seen is, as I mentioned in my testimony, a very, very substantial drop in the cost of both wind and solar power since 2009. Solar power has come down in its levelized cost by about 90 percent and wind, which had been thought of as actually a relatively mature renewable technology, has actually come down by about 70 percent.

What that has done is that it has really flipped on its head the relative stacking of where new capacity additions are coming from and whereas it was true in the past that natural gas was actually a favored, low-cost provider of electricity, that has changed substantially. What we've seen over the last decade is that renewables, both wind and solar are competing with natural gas for new capacity additions. The U.S. Energy Information Administration, which is where I look for constant tracking of this levelized cost of electricity, is coming out with its Annual Energy Outlook today. It hasn't been released yet, but in a preview of that the EIA kind of reconfirmed what it has shown over, you know, many years now, which is that renewable energy, in terms of new capacity additions for electric power, is taking increasing market share. And that looking forward, renewable power will actually be the majority of new capacity additions. That's without any future changes in policy.

If you look at the other sources of electric power, natural gas tends to be there next—natural gas combined cycle. And then, coal and nuclear power, in terms of new capacity additions, are relatively more expensive now compared to both natural gas and renewables.

Senator HEINRICH. Obviously, we have seen a lot of stranded coal assets over the last few years. If the current trend continues with respect to the decline that we have seen historically in solar prices, as well as in wind generation prices, is there a risk that assets, gas assets in particular, that were financed with the idea to be 30-year assets, if they should be financed more on a 15-year or shorter timeframe—what is the risk of natural gas generation assets becoming stranded assets in the coming years?

Dr. NEWELL. Yes, so the issue of what I would refer to as climate financial risk is an increasingly important conversation both in the investment community, of course, to you know, power producers and energy producers as well. So this is why it's important, I think, to lay out in advance what our future policies will be. Investment unfolds over time. These aren't sudden shocks to the system. As you alluded to, you know, new investments are made. They do last, you know, a significant period of time. They can last, you know, one, two, three, decades.

But policy also evolves. And energy transitions also evolve over the course of years and decades. So I don't expect these to be sudden shifts. Whether or not there are stranded assets, that will depend upon if there, again, if there are sudden shifts and that investors can't anticipate what kind of cost recovery they'll get on their investments.

Senator HEINRICH. Dr. Birol, in its World Energy Outlook (WEO) analyses, IEA historically, fairly consistently, underprojected both growth trends and the cost reductions for renewable energy. While analyses, I realize, are based on different policy cases, IEA analyses historically predicted a linear path, but the shifts that we have seen, consistently actually since the 1970s on, have clearly been exponential paths, not linear paths. And I think this potentially points to the need for a reassessment of the scenarios or assumptions that are used.

I know that IEA has made some changes to the WEO over the past couple of years, particularly in 2020, but I was hoping you could speak to those adjustments. What adjustments has IEA made in modeling or assumptions to improve projections of renewable energy in the future?

Dr. BIROL. Thank you very much, Senator Heinrich.

I am very happy that you asked me this question again. So last time you had the same question. I want to repeat my answer, if I may. What we do is, Mr. Senator, we look at the projections if the governments do not change their policies, what kind of world we are facing, which we call our reference scenario or stated policy scenario. And here, with the policies governments are putting in place, we have seen a strong penetration of solar, but the level of the solar penetration was not high enough, not as much as we would like to see it to reach our climate progress. But in addition to that scenario, you might have missed that scenario——

Senator HEINRICH. Sure.

Dr. BIROL [continuing]. Which we call the sustainable development scenario. We have seen a huge increase of solar power. Indeed, only a few months ago I had the liberty to call solar the new king of global electricity markets. The reason I said so is that one, in the year 2020 of all the power plants installed in the world, 50 percent were solar. The other 50 percent—all the other technologies put together, namely coal, plus oil, plus gas, plus nuclear, plus wind, hydro, 50 percent—solar 50 percent. The main reason here is the governments are changing their policies, providing incentives to solar power and, as of today, as we have suggested in our sustainable development scenario, solar power is the cheapest source of electricity generation in many parts of the world.

Just for you to note, Mr. Senator, on the 18th of May this year, the International Energy Agency will come out with the world's first roadmap to "Net Zero by 2050"—what the energy sector would actually look like if the governments around the world take policies in order to reach net zero emissions by 2050, which I expect that solar power will get the lion's share of the electricity generation, even much higher than what we said before, which is, I believe, good news for everybody.

Senator HEINRICH. Thank you.

Senator MANCHIN. Thank you, Dr. Birol. Thank you, Senator.

Senator Barrasso.

Senator BARRASSO. Senator Manchin, in terms of time constraints, if you would like to go next, that would be just fine with me and I am happy to stay. I know you have a conflict a little later.

Senator MANCHIN. I appreciate it so much, Senator. And I will, and then I will turn the Chair over to you.

This is to Dr. Hsu. I want all of you to think about this right now: the Paris Accord and the U.S. entering back into the Paris Accord. My understanding of the Paris Accord is there are different timetables for different participants. And now, with things changing since that started to where we are today, think about where we are and if we should all be on a level playing field. But my question is going to be, can the United States, can China, can all those in the Paris Accord meet the net zero carbon reduction by 2050?

And I will start with Dr. Hsu because of her deep interest and deep involvement in the China energy market.

Dr. Hsu.

Dr. HSU. Thanks so much, Senator Manchin, for that excellent question.

So as you know, the Paris Agreement is formulated on this bottom-up process. And so, instead of the old Kyoto model, which is what we had in 1992, where there were these targets, these timetables that were agreed upon by all parties, the Paris Agreement decided to allow the countries themselves to determine what timetables and targets to meet for their nationally determined contributions, or their NDCs. And so, the science dictates or provides this broad picture of where we need to go as a world in order to hit these targets of containing global temperature rise, within 1.5 degrees Celsius, but the countries themselves can then determine what types of target years and commitments on climate change mitigation, adaptation, financing, what those look like. So——

Senator MANCHIN. Don't you think—if I may interrupt, I am so sorry—with your knowledge that you have, especially with China being one of the greatest emitters, but all of us, if we are on a trajectory to hit that and China says they can, can the United States make it? Can China make it? And what should we be able to do to make enforcement for the other ones? If they are going to say we belong to the Paris Accord, but they are not going to attain any achievements whatsoever in meeting the net zero carbon by 2050, how can we enforce that?

Dr. HSU. So that's a really good point, and I think one of the major criticisms of the Paris Agreement is the fact that it's not legally binding. And so, because of that, then it's largely up to country governments themselves to implement laws and legislations to actually implement those particular policies to meet their goals.

I think for China, one area and one reason why I have a lot of optimism—and we can see based on their track record that they will meet their Paris Agreement targets—is the fact that they have adopted their Paris Agreement goals within their five-year plans. And so, it's actually codified into binding laws at the very top level and then implemented at the local provinces. And so, I think we can have really a reasonable assurance that China will actually meet their goals because it's part of their law. And then the 14th five-year plan, which will be released in the coming weeks, is also expected to incorporate many of these energy and climate targets for the Paris Agreement to help them achieve their goals. And then also, we should be expecting an enhanced-ambition Paris pledge, an NDC that will also reflect the fact that they now have this longer-term 2060 carbon neutrality target.

But then, even still, you're absolutely right that when you look at the climate models and the scenarios, all of these Paris pledges that countries have made, do not add up to get us to net zero by 2050.

Senator MANCHIN. Right.

Dr. HSU. In fact, it's leading to about a 3.6 median degree Celsius warming world by 2100. And currently, we have about a 97 percent probability that we're going to already overshoot to two degrees Celsius. So, absolutely, the targets and the pledges that are put forth in the Paris Agreement are completely inadequate.

So that said, I think that's why it's important, and why China's net zero commitment, and exactly as Dr. Birol mentioned, many governments are making these net zero pledges and——

Senator MANCHIN. The bottom line with China is they are keeping their own records. Do we know, do we have insight, are we seeing factual information and making sure that we are getting the correct information? And if I may, you might answer real quick on that because I want to ask if anybody else has a comment on this.

Dr. HSU. Yeah, I mean, I think that's also a major question that was an obvious sticking point in the 2009 Copenhagen negotiations—

Senator MANCHIN. Yes.

Dr. HSU [continuing]. Where the U.S. really pressed China to open up its climate change and energy data and to have transparency on regiment reporting and verification in order to move forward on international climate agreements. I think one of the points that I want to emphasize is that we don't need to rely, necessarily, on official Chinese statistics and data to have assurance that they are meeting their climate goals.

Senator MANCHIN. Okay.

Dr. HSU. For me, as a scientist, I use a lot of satellite remote sensing data, from U.S. satellites and also from the EU, for example.

Senator MANCHIN. Wonderful.

Dr. HSU. And we can see, we can observe from space and use that data to see that China actually has been really effective in reducing, primarily, air pollution and other fossil fuel related——

Senator MANCHIN. Thank you, Dr. Hsu. I am so sorry, but I have to see if any other of our witnesses have anything to comment on the Paris Accord, how we hold people accountable.

Dr. TINKER. Senator, this is Scott Tinker from the——

Senator MANCHIN. Hey, Dr. Tinker, go ahead, please.

Dr. TINKER. Thank you.

Yes, I think it's really important here, and I'll try to be very brief, to look at pledges and then look at results. And so, if you look at the Paris Accord, the U.S. response to that with the Clean Power Plan, we did not implement it, that was proposed. We were proposing to reduce by 32 percent our emissions in the power sector by 2030. We set a self-imposed base year, 2005, which was prior to 2007 in the United States for our highest emissions.

We met that goal, that 32 percent reduction by 2030—non-COVID-related—in 2020, ten years earlier. So the U.S. reduced 700 million tons of emissions and continues to—How? Replacing coal with natural gas, renewables, solar, and wind. With state portfolio standards and other things and efficiency, but also exporting manufacturing, which doesn't count into the single global atmosphere. That's kind of a shell game.

And so, how do you really do this? How do you actually reduce CO_2 emissions? The United States has actually affected change faster than any other country who has pledged. Now, how do we continue to do that globally, I think you're asking. It's a very viable question and part of that comes from—something can be completely factual, but not factually complete. And I think that's what's happening with LCOE. Yes, solar and wind are the fastest growing sources in capacity and rate, but they're just getting started and everything grows exponentially early.

In fact, solar and wind, since 2005, globally—and this comes from the IEA's own data, which are fantastic, by the way—have provided less than 25 percent of the growth in global electricity demand—so the other 75 percent of that growth is satisfied somewhere else.

Natural gas is the fastest growing source of global electricity since 1985 by a lot, and there are reasons for that. But I think as we really converge on the scalability of these global solutions, we have to look at what actually reduces at scale emissions with everything that is being done now and there are many great opportunities to do that, but we want to be factually complete, not just completely factual.

Senator MANCHIN. Thank you so much. My time is expired and if you all want to think about that, if I get a second round, I will have you all comment at that time. I am so sorry, but thank you.

And with that, Senator Barrasso.

Senator BARRASSO. Thank you so much, Senator Manchin.

Mr. Mills, many environmentalists insist that industrialized countries reduce their greenhouse gas emissions principally, if not exclusively, through the use of solar, wind, and electric battery technologies. They often fight, you know, coal, natural gas, nuclear power, hydropower projects. Can you discuss the costs to the environment if these industrialized countries attempt to reduce their emissions principally through just solar, wind, and electric battery technologies?

Mr. MILLS. Senator, I think that's one of the key issues that is the proverbial elephant in the room and the IEA and Dr. Birol have mentioned this, others have mentioned it. The work that I've done is looking at research that comes, in fact, from the U.N. Environment Program from the IEA, from the World Bank, from academic and research institutes, primarily in Europe, which asks that question—what is the impact on the environment broadly, not just carbon dioxide emissions?

I spoke about carbon dioxide emissions because of a simple fact that since most of the world's battery materials are processed in China, and as we've heard earlier, from where two-thirds of the grid there is coal-fired, that means that the energy to make battery materials emits carbon dioxide. And just, as a calibration point, making a battery and the materials for it that can store the amount of energy equal to a barrel of oil requires consuming about 100 barrels of oil equivalent of energy. So that consumption of energy just to build the battery, which doesn't produce energy, but stores it, has carbon dioxide emissions.

But more importantly, to your point, it's not just that. It has water use implications, land use implications, and toxic mineral management implications because of the processes involved. In fact, the World Bank issued a report just two years ago, very concerned about what they called a gold rush for energy minerals in fragile parts of the world where it's easier to open up mines than in the European and North American continents, specifically because of the need for a whole host of materials, not just the rare earths that are famously or infamously talked about. Rare earths, as you know, are not rare, they have rare properties which are useful, but we don't mine them anymore, significantly, but it's also nickel and cobalt, very basic materials—the call on copper, which is one of the biggest minerals mined in the world—biggest in terms of quantities. Copper use doubles per car compared, for electric car, compared to a non-electric car for obvious reasons. It has more electrical equipment in it. Nickel use goes up because of battery's use of nickel.

So the demand for nickel alone, which is not a rare material, goes up literally exponentially in the true exponential sense. It's going to have to come from somewhere. It'll have environmental impacts. I think we will probably not mine it here. I don't see any evidence that the United States is embracing the opening of new mines in a timeframe that will be meaningful. So it will come from Russia's Norilsk mine in the Arctic, which I'll just note and end on this point for the record, is where you could say that the world's first oil spill in service of electric cars happened already last year. There was a massive oil spill at the Siberian—Russian-Siberian nickel mine. The amount of oil spilled into the Arctic was almost equal to the amount of oil spilled from the Exxon Valdez, which was much more infamous and well known. It was the oil stored at the mine site to operate mine equipment and it caused a lot of angst, and properly so, in the environmental community of Russia.

Senator BARRASSO. So let me ask you this then, Mr. Mills.

Last week, President Biden signed an Executive Order prohibiting new oil, gas, and coal leasing and permitting on federal lands and waters. Is there any reason to believe that that Executive Order by President Biden is going to reduce the amount of oil and gas that the world will consume?

Mr. MILLS. I could make that answer an easy and short one—no.

Senator BARRASSO. No.

Mr. MILLS. There's no reason to believe that will happen. The world's consumption of oil, recovering particularly from the Great Lockdowns, is going to increase not decrease.

Senator BARRASSO. So is it fair to characterize President Biden's Executive Order as completely ineffective as a means to address climate change?

Mr. MILLS. It, as a practical means, is utterly ineffective. It will not reduce the consumption of oil or the emissions of carbon dioxide from the combustion of petroleum.

Senator BARRASSO. So then, is it fair to expect that President Biden's Executive Order is going to outsource American oil and gas production, the tens of thousands of American jobs that come with it, to foreign countries including OPEC members and Russia?

Mr. MILLS. The short answer is yes, but it also, by increasing the use of batteries here to offset the oil, if it were to be so mandated, we will also export jobs and economic development for that to those nations that make those minerals and materials, as I have outlined.

Senator BARRASSO. Thank you.

One question for Dr. Tinker. U.S. carbon dioxide emissions have been steadily declining since 2007 and the International Energy Agency's most recent forecast expects U.S. emissions to decline by another 17 percent by 2030. Other industrialized countries are also expected to reduce their emissions by 2030. However, emissions in countries which have been defined as developing countries—and we can get into the issue of whether that is a good definition or not—they are expected to increase over the next ten years. In some regions of the world they have increased: 30 percent in Southeast Asia, 27 percent in India, 14 percent in Africa.

Is it accurate, Dr. Tinker, to say that all of the future growth in global emissions is going to come from these so-called developing countries?

Dr. TINKER. It is, but there's a reason for that. I think the United States and Western Europe—we built our fundamental economies on coal and oil for transportation and power generation. We've come to a level of wealth now that we're transitioning—decarbonizing coal and natural gas, oil and beyond. And so, the emerging and developing world, as they grow are also using coal as a reliable fuel. I don't fault that at all. It is lifting their economies from global poverty and creating the products that we all consume so we keep our emissions there to keep the stuff we want cheap.

And so, how do we accelerate? How do China and Southeast Asia and nations that will follow, particularly India? India is just getting started. They passed the United States in coal consumption now, but are way behind China. And a number of people say, how did that happen? How can you accelerate into some other baseload dispatchable electricity stores in these countries? And that's really the great challenge before us, I think an opportunity for the United States to help lead, in many ways, this effort.

So, yes, that's where the emissions are coming from. The goal is then to accelerate through that as you balance the energy and the economy and the environmental impacts as well, and it's doable, but not if we're not able to support technologically and economically and in leadership in the United States, for that to happen.

Senator BARRASSO. So if we want to help these developing countries reduce their emissions, would you agree that the United States should really develop technologies to lower emissions that we can then export these technologies so they would be used in these other locations around the world?

Dr. TINKER. Technologies and energies. I have visited China many, many, many times throughout the last couple of decades and done work there, looking at their shale opportunities and natural gas, and other—they have natural gas resources but it's not at the level we—those exist in Russia, has already been mentioned—et cetera. LNG could bring some of that natural gas in as options in addition to the nuclear developing, the hydro and the solar and the wind. So it's resources as well as technologies. The United States needs an environmentally adept way to develop oil and gas. Oil and gas isn't clean—nobody ever said it was, nothing is, no form of energy is, but we are leading in that.

And so, how do you accelerate and bring those technologies to the world such that they can skip the steps we went through to get to the high-density drilling, the high-volume extractions and the very small surface pads, minimizing use of the water and other kinds of things that need to happen for the extraction of fluids—and by the way, those are much more extreme than mining.

Senator BARRASSO. Thank you.

Dr. TINKER. Absolutely.

Senator BARRASSO [presiding]. Thank you, Dr. Tinker, we are having a little bit of a technical problem with the feedback. With that, let me turn to Senator Hirono.

Senator HIRONO. This is for Dr. Birol. In your testimony, you highlight the need for ambitious actions and note that almost half of the emission reductions needed to reach net zero by 2050 will need to come from technologies that have not reached the market today. And you note the importance of American leadership. As you know, American leadership on clean energy is a priority for President Biden. What kind of ambitious incentives or mandates do you think the U.S. needs to put in place within the next year or two to remain a leader in emission reductions and clean energy technologies?

Dr. BIROL. Thank you. Thank you very much, Senator Hirono.

This is an extremely important fact. In fact, Senator Manchin asked the Paris question, and this very much leads to the Paris question, how to reach the emission reductions, to reach emission reductions in 2050 to net zero emissions. So we need three things here. One, to make the most out of the existing clean energy technologies. What are those? Renewables, efficiency, nuclear power, these are the key ones, but these are as you said, Senator Hirono, these are not enough to make the emissions come to net zero by 2050.

Senator HIRONO. Right.

Dr. BIROL. As our analyses show, half of these emission reductions need to come from technologies which are not in the market yet.

Senator HIRONO. Yes.

Dr. BIROL. Therefore, the key word is innovation. What are those? For me, a critical one—perhaps the most critical one—is carbon capture, utilization and storage. This is an extremely important one, looking at the current energy infrastructure we have around the world. Second, advanced nuclear power. Third, hydrogen. Fourth, the batteries, advanced batteries. And when I look over the history of the United States, innovation is in the DNA of the U.S. energy industry. In fact, U.S. industry in general, and I will look at the Internet, I look at the chips, the United States was at the forefront, so my expectation is the United States, not only at home, but internationally shows the leadership to push these clean energy technologies, which are not in place yet, but very important for the future. You have at the DOE wonderful laboratories across the country and they can play a particular role here in my view.

Senator HIRONO. Yes.

Dr. Birol, the question was, you know, what kind of mandates or incentives should we put in place, because I know we are doing things to aid battery development, for example, but are there ways that we can incentivize the commitment to moving into those innovative areas that you are talking about? But let me just ask one more thing though. You talk about using existing technologies and one action that we can take today using technologies that are already on the market is to lower methane emissions from oil and gas wells. And in January 2012, an IEA report noted that reducing methane emissions from oil and gas operations is among the most cost-effective and impactful actions that governments can take to achieve global climate goals. However, the report notes that while reducing methane emissions may be cost-effective, many companies are not voluntarily doing so.

There was, at one time, a federal methane regulation on the books to require companies to detect and reduce methane leaks. The Trump Administration repealed it last year. So how important do you think it is for the U.S. to resume regulating methane emissions, that being a very cost-effective way that we could use existing technology for the oil and gas industry? Should we reassert that regulatory requirement?

Dr. BIROL. Thank you very much, Senator.

First of all, coming back to your first question, incentives for the clean energy technologies, which aren't in the market yet, it can be many ways. For example, this Committee, your Committee has for the CCUS, the 45Q tax credits was an excellent move in the right direction. And also, the economy recovery packages which will be coming soon, I hope they will provide incentives for the clean energy technologies plus the research and development budget for these technologies can be increased and some mandates can be deployed in order to give a strong push to clean energy technologies which aren't in the market yet.

Now methane—thank you very much for referring to our report. Methane is a powerful greenhouse gas and especially is so, and when we look at the world, we said for the CO_2 emissions, China is the number one country, but for methane, the United States is the number one country in terms of methane emissions, followed closely by Russia. And methane emissions reduction is not rocket science. You need to have the right regulations in place in order to minimize the venting and flaring, and methane is—all of it has a price—is a price of natural gas. What you need for this is to put in the right policies and mandatory framework. And I know that many companies are already making some efforts, but it's a major issue for the United States and many other countries, including Russia and other Middle East countries to address this issue.

Our analyses show that a big chunk of the methane emission reductions are, as you mentioned, cost-effective and in effect, some of them are in the negative cost.

Senator HIRONO. Thank you very much.

Thank you, Mr. Chairman.

Senator BARRASSO. Thank you, Senator Hirono.

Now we have Senator Cassidy.

Senator CASSIDY. Thank you, Mr. Chairman and Mr. Ranking Member.

Dr. Mills, there was a great exchange you had with Dr. Barrasso, but I just wanted to make it clear when we potentially don't deliver our oil and gas, we will shift production of the oil and gas to other countries with lower environmental standards, which is to say, per unit of oil or gas produced there would be more greenhouse gases emitted into the atmosphere. Is that a fair statement?

Mr. MILLS. The efficiency from a carbon dioxide perspective is typically lower in the other—all the other provinces. But the issue I was referring to was other environmental features—water use, well water contamination, spillage, labor practices. The whole panoply of environmental issues about which we are, in America in particular, very cautious. Many nations aren't as cautious as we are. But your question about the carbon dioxide efficiency of primary energy extraction, as I said in my testimony, is actually rather complex. The issue is not that there isn't some energy used to produce energy, minerals, including oil, but who produces it because the world will use more oil in the future than it is in the present—for the near foreseeable future, a decade or two at least. If we don't produce it, your point is absolutely correct, others will, and it's not complicated to figure out who they are.

Senator CASSIDY. Yes, I see that.

And you point out Russia, and we have seen with methane emissions increase from Russia and so, presumably, if they took over gas production you would continue to see that increased methane from Russia. Granted, I think Senator Hirono points out wisely that we need to decrease ours, but I have more faith in us making that commitment than I do in Russia.

Mr. Newell, in your response to Senator Heinrich, you spoke about the levelized cost of electricity, but it is fair to say that that levelized cost of electricity for wind does not include the backup plans needed to address the intermittency of the wind and the baseload that would be required to run concomitantly. Is that true?

Dr. NEWELL. Senator, yes. You know, one of the——

Senator CASSIDY. I have another question. I have limited time—

Dr. NEWELL. Yeah, one of the inadequacies of the concept of levelized cost is that it doesn't directly address intermittency of different resources. And so, that you may——

Senator CASSIDY. Let me ask another question because I have limited time. What I don't know, does the price that is quoted for wind, is that a net of the federal subsidy that goes for the production tax credit or whatever is used? So, you know, it's not the true production cost, it is a production cost minus the subsidy. Is that correct?

Dr. NEWELL. That's not correct, Senator.

So the costs that I cited do not include the subsidies. If you include federal tax incentives or state-level renewable portfolio support, that would further reduce the cost. They've come down in real costs aside from tax credits and other support policies.

Senator CASSIDY. Thank you very much.

Dr. Birol, I always enjoy your testimony. I enjoy all of your testimonies. You mentioned the reliable supplies of critical minerals and metals vital to energy transitions. I don't know this answer, but I have read that there is actually not enough cobalt in the world to completely go to an all-electric vehicle standard. Is that true or am I misunderstanding that?

Dr. BIROL. Thank you very much, Senator.

As I said a few minutes ago, we are looking at the impact of the ambitious climate policies on the availability of critical minerals in the next 10, 20 years or so. We are going to release this report in April. If you wish, I will be very happy to report to your Committee what the results are, what our intentions are, but currently it is not a major issue. But with the increasing demand, there may be clashes of supply and demand, number one. Second, there may be implications on the prices. And third, this can also lead, in some cases, to some energy security implications.

But these are not issues that cannot be addressed, they can be addressed through different trading partners, I mean, reliable trading partners, putting in—stand ups and finding substitutes to those critical minerals. But as I said, we will come out with our report in April to show where the stress points are—what are the implications for the governments who are pushing clean energy transitions for their economies and for their energy security.

Senator CASSIDY. I look forward to that report. Thank you and I yield back.

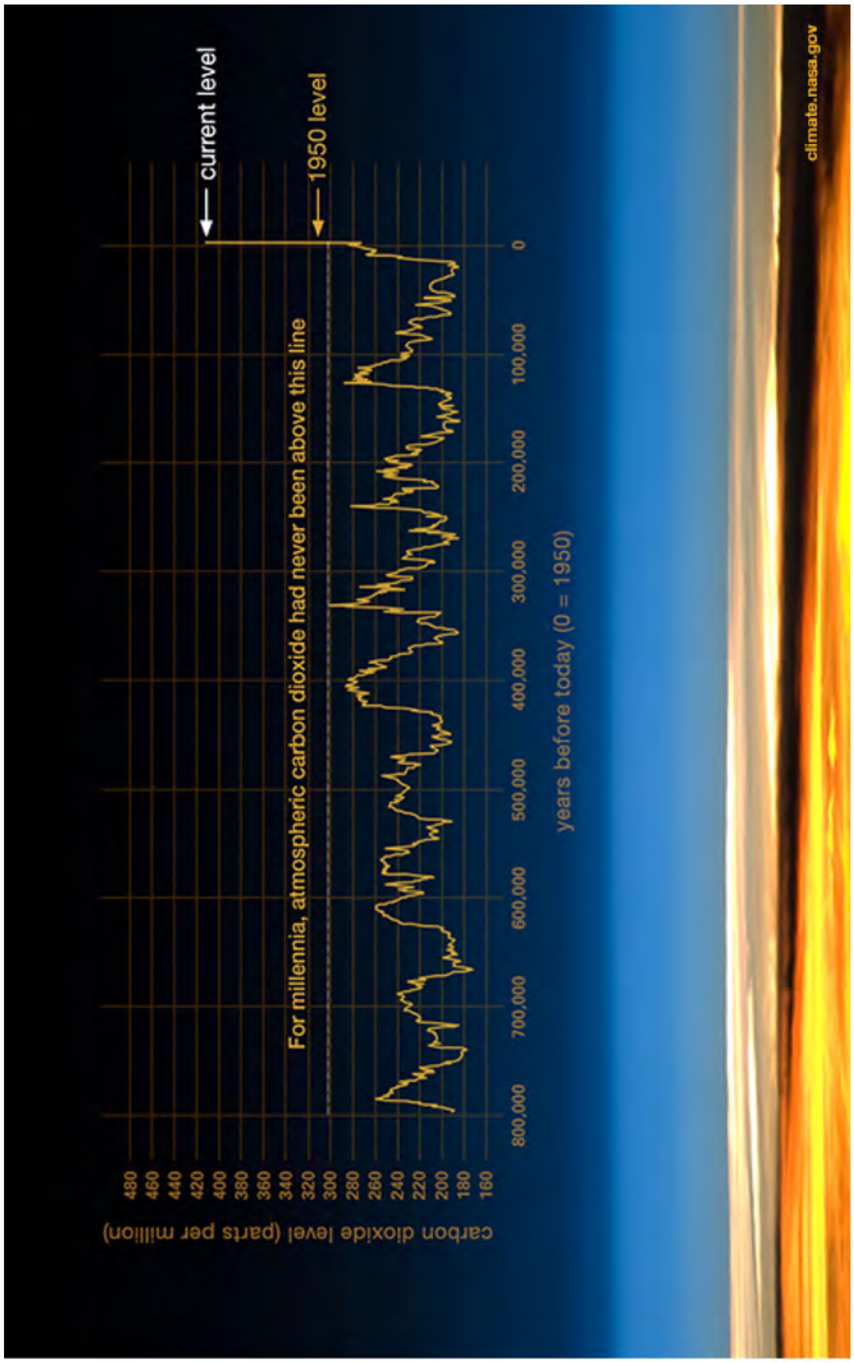
Senator BARRASSO. Thank you.

Senator MANCHIN [presiding]. Thank you, Senator.

And now we have Senator King.

Senator KING. Mr. Chairman, we have been talking a lot today about the cost of transition to a new, lower carbon economy. I have a couple of slides, several slides, I would like to share that put this into perspective of the costs of not making this transition. If the tech people can put up the first slide for me.

[Chart number 1 is displayed.]

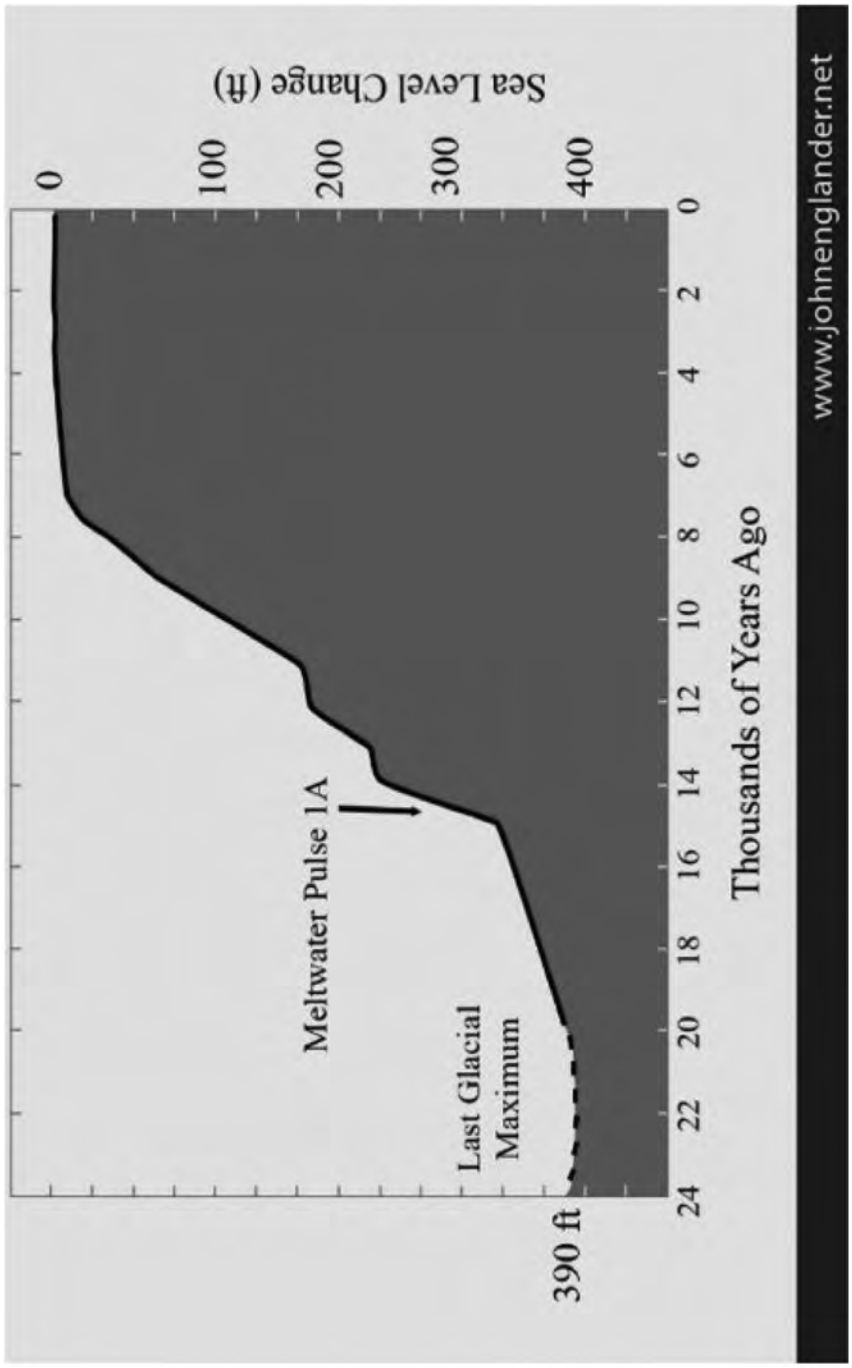


current level
1950 level
For millennia, atmospheric carbon dioxide had never been above this line
carbon dioxide level (parts per million)
480 460 440 420 400 380 360 340 320 300 280 260 240 220 200 180 160
800,000 700,000 600,000 500,000 400,000 300,000 200,000 100,000 0
years before today (0 = 1950)
climate.nasa.gov

Senator KING. This is several hundred thousand years of CO_2 in the atmosphere. Many people talk about natural variations, and as you can see from this chart, there are natural variations, but if you look at the far-right side of the chart, we are way outside of those natural variations, we are well above now 400 parts per million of CO_2. This is a vivid demonstration of the fact that we are in uncharted territory. In fact, it is not really uncharted. Three million years ago was the last time we had 400 parts per million. And by the way, the oceans were about 60 feet higher.

Speaking of the oceans, if you can put up chart number two.

[Chart number 2 is displayed.]



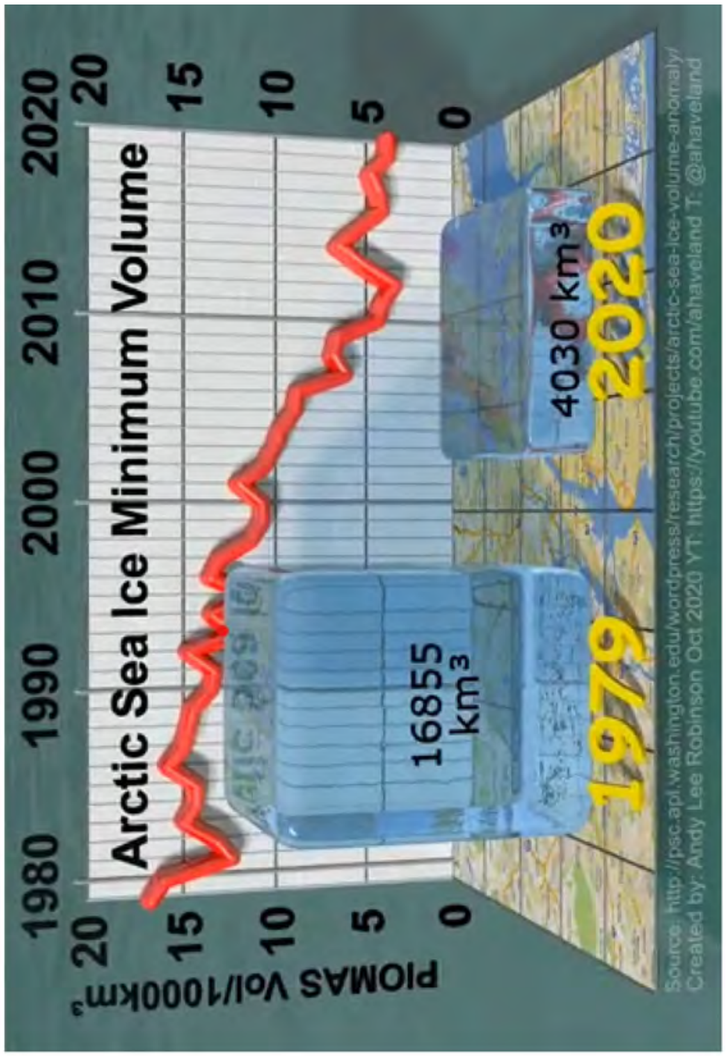
Sea Level Change (ft)
0
100
200
300
400
390 ft
Last Glacial Maximum
Meltwater Pulse 1A
0
2
4
6
8
10
12
14
16
18
20
22
24
Thousands of Years Ago
www.johnenglander.net

Senator KING. This is a really fascinating piece of data. This is 24,000 years of history. And the low point on the left is the height of the Ice Age. It was when a huge amount of water was locked up in the glaciers. And what you see is the increasing depth of the ocean. It is about 390 feet of difference between 24,000 years ago and today. There are two important things I want to point out on this chart. You will see in the middle there is a very steep incline of increasing water depth, called Meltwater Pulse 1A. The reason that is significant is that during that period, the ocean level rose a foot a decade and many scientists believe that we are in a similar moment right now. The point I am trying to make is this is not science fiction. This has happened in the past.

And the other interesting thing about this chart is if you go over to the right where you see it sort of levels off at the top, that is the current sea level. It is about the last 8,000 years. Eight thousand years happens to be recorded human history. In other words, the oceans have been where they are and we all think of them as being constant. The point of this chart is that in fairly recent times, 25,000 years, they have not been constant at all. The Chesapeake Bay, 15,000 years ago, was a nice river valley of the Susquehanna River. It was mostly dry land. So the whole East Coast would move about 180 miles east, 15,000, 20,000 years ago during the Ice Age.

Here is the third chart, which talks about the practical effects of what we are looking at.

[Chart number 3 is displayed.]


Arctic Sea Ice Minimum Volume
PIOMAS Vol/1000km³
1980 1990 2000 2010 2020
0 5 10 15 20
16855 km³
4030 km³
1979
2020
Source: http://psc.apl.washington.edu/wordpress/research/projects/arctic-sea-ice-volume-anomaly/
Created by: Andy Lee Robinson Oct 2020 YT: https://youtube.com/ahaveland T: @ahaveland

Senator KING. This is ice concentration in the Arctic. It has reduced by 75 percent in the last 40 years. The point I am making is we are talking a lot today about the cost of transition. We also have to talk about the cost of not transitioning and the dramatic impacts that we are facing. You want to rebuild Miami or New Orleans or New York, Washington, DC, any coastal communities? If we are talking about six to eight feet of sea level rise in the next century, that is a catastrophe, both a human catastrophe and an economic catastrophe.

We are talking about baseline in this hearing and I wanted to talk about the fact that we are in a very, very dangerous time and facing, what I think, could be catastrophic changes, if not within our lifetime, certainly within the lifetime of our children and grandchildren.

A couple of questions:

Dr. Hsu, Senator Barrasso mentioned this, given the magnitude of this problem and the fact that it is an international problem and that there are developing countries that don't have the technological and industry base that we have, wouldn't a good adjunct to the Paris Climate Agreement be technology sharing? This should be an international moonshot, if you will, to develop the technologies both for efficiency and for carbon-free production.

Dr. Hsu, is that something we should be working on, bearing in mind, I have already used a lot of my time, but give me a couple of sentences on that, please?

Dr. HSU. Yes, I absolutely agree with you. Thank you for the question. But I also think it's not just about technology sharing and cooperation, but it's also about competition. We can also compete, as the U.S., in promoting clean technologies abroad and accessing markets that are now growing in their demand for clean technology because of their decarbonization goals and their targets on the Paris Agreement.

So I think that permits even more opportunity for green competition as well, and not just technology sharing.

Senator KING. Great.

Mr. Mills, I want to understand your testimony. You are talking about the costs of building batteries, for example. And I understand there are environmental costs. There is no free lunch in energy. I learned that a long time ago. However, are you saying that the emissions that go into the manufacturing of a single car battery would be equal to the emissions saved by that car battery in an electric car over, say, 150,000 miles of a ten-year life? Is that—I don't think you are saying that, but I just want to be sure.

Mr. MILLS. Senator, thanks for the question. I am saying that. In fact, there are very robust studies on this. I was not speaking to the economic costs, because the baseline I believe we were talking about was emissions. I was pointing out that the emissions associated with the energy consumed to fabricate batteries to make and process the key minerals and materials are significant that the data show and numerous academic—these are not, you know, studies promoted by advocates of either forms of energy. The analyses of what is involved in the fuel cycle to make the battery and battery materials, the range of energy cost—energy cost, not dollar cost—to fabricate barrels-of-oil equivalent of energy storage consumes 100 to 300 barrels of oil of energy to fabricate that quantity of batteries. So that——

Senator KING. But my question is how many barrels of oil would be offset by that battery over a ten-year life?

Mr. MILLS. That's a very fair question. It does, it offsets over its life, oil. It depends on where the cars exist. In the world that exists today, batteries that are fabricated with those, the way we now do it, result in emissions that are only partly offset depending on where they're driven. One of the European studies finds that if you drive the Tesla in Norway, for example, half of the emissions savings that you have by not burning oil are wiped out by making the electric car. If you drive the vehicle in most of Germany, two-thirds of all the emission savings are wiped out and if you drive it in Poland, obviously, they have an electric grid that's coal-fired, then you have a net increase in emissions.

So, yes, I was saying exactly that. That's what needs to be a part of the accounting.

Senator KING. Well, I would appreciate if you could supply those studies for the record for the Committee. I would be very interested in following up.

Mr. MILLS. Yes, sir.

Senator KING. One final comment, not a question. I know my time is up. I want to associate myself with Senator Hirono. The low-hanging fruit of climate change prevention is methane, and most of the methane comes from unregulated oil and gas drilling, whether it is in Russia or here. I think that is an area where we need to lead, but we also could be talking to Russia about some kind of methane treaty, if you will, because it is cost-effective. We ought to be doing it and it is, by far, the easiest, shortest, and most cost-effective way to deal with climate change.

So, thank you. Thank you, Mr. Chairman.

Senator MANCHIN. Thank you, Senator.

Next, we have Senator Daines.

Senator DAINES. Thanks, Mr. Chairman.

Since President Biden took office just two weeks ago, we have seen attack after attack on made-in-America energy and union jobs, and we know how devastating this will be to Montana's economy, Montana families, and the reliability of the electric grid. Just look at what California went through last summer as it relates to what happens when you take radical shifts to the left, and the lack of reliability that comes from those shifts. These actions could actually move us away from our climate ambitions. Today, the United States leads the world in reducing energy-related carbon emissions. We are number one. We have achieved this through innovation, not regulation. However, a recent report found that President Biden's ban on federal energy leasing will lead to a 5.5 percent increase in carbon emissions in the power sector by 2030.

The cancellation of the Keystone XL pipeline, which has undergone extensive environmental reviews and would have achieved net zero emissions by 2023, will force major quantities of crude oil onto the rails, which now will emit up to three million tons of carbon dioxide annually into the atmosphere. Let me say that again. The cancellation of the Keystone XL pipeline could lead to an increase of three million tons of carbon dioxide emissions per year. By the way, any ban on fracking is also expected to drastically increase emissions. I am a chemical engineer by degree. I like to look at the numbers. The science tells us that these radical moves to the left are actually going to increase CO_2, not decrease CO_2.

Mr. Mills, have technological breakthroughs like horizontal drilling and hydraulic fracturing lowered our emissions and do you believe that heavy-handed regulatory approaches, like the executive actions seen over the past two weeks, actually move us away from emission reduction goals?

Mr. MILLS. Well, thank you, Senator, for the question.

Chemical engineering is one of the disciplines I respect enormously as a physicist. I chose physics because chemistry was hard.

[Laughter.]

So the answer is yes, of course. The hydraulic fracturing in the United States is so productive and so economically responsive—it's fast, which is non-trivial in capital markets—that it drove world prices of gas down, drove down domestic prices, and as most analysts know, the principal reason for the reduction in coal use in America is because gas got so cheap. So it is a profound impact globally. There is certainly a path to tremendous improvements yet in those markets, in terms of economic and resource efficiency.

Senator DAINES. Thank you very much.

Just last week during a press briefing, one of President Biden's top aides, Gina McCarthy, stated, and I quote, "Climate change is the most significant public health challenge of our time."

Let me just state the obvious. We are in the midst of a global pandemic. So I would have to say this is certainly not the case. It was also not the case before the pandemic hit. The greatest indicator of health status is poverty and access to reliable, affordable electricity, which usually provides clean water. That is intrinsically linked to human welfare. The policies initiated over the past two weeks, which are being pushed by the left, only compromise energy access and jobs, which will now exacerbate the health and economic crisis that we are in now. They will lead to higher energy costs, higher gas prices for Americans at a time when families are struggling to make ends meet and keep food on the table.

As shown by the U.S. reduction in emissions, it is possible to grow our economy and specifically, our energy sector, while meeting our environmental goals. In fact, in 2019, energy-related emissions fell by 2.6 percent in the U.S. Meanwhile, China increased their emissions by nearly twice as much.

Dr. Birol, can you speak to how U.S. carbon emission reductions compare to countries like China and India?

Dr. BIROL. Thank you, Mr. Senator.

You are right, in fact, in the last decade or so, U.S. emissions declined significantly, mainly as a result of natural gas replacing coal, but also from a big push for renewables—solar and wind. These were two main reasons. And today, U.S. emissions are half of that of China, globally. China is about 30 percent of the global emissions, United States, 14. Having said that, if you look at it—because people look at emissions from different angles, the U.S. per capita emissions is one of the highest in the world, much higher than China.

And I would like to say that I liked very much Mr. King's grasp of what would happen if we don't act. In addition to those, the implications on climate change, I can tell you that if the U.S. does not act, push to create an age of transitions, U.S. industry, U.S. technology may be well beyond the curve. Others are moving. It's not only a policy, but also market-driven transitions. Therefore, the U.S. has been always the leader of innovation, new technologies, and I believe why the U.S. preserve this important, strong force in the global energy markets, pushing innovation would be also an economic idea in addition to playing an important role responsibly as a leader of the international economy.

Senator DAINES. Thank you, Dr. Birol.

I am out of time, but let me just say this. In Montana, we have the nation's largest reserve of recoverable coal and large-scale coal plants. We are uniquely positioned in Montana, speaking of innovation, to be a leader in carbon capture research and development. Thirty-five percent of carbon emissions reductions have already been achieved in these high-efficiency, low-emissions coal plants. So I am all about innovation. We have some great ways we could do that in Montana.

Mr. Chairman, thank you.

Senator MANCHIN. Thank you, Senator.

And now we have Senator Cortez Masto.

Senator CORTEZ MASTO. Thank you, Mr. Chairman. Thank you for this conversation. This has been a fantastic conversation. And as always, I always learn something from my good friend, the Senator from Maine, Senator King. I have always enjoyed listening to his questions. But he nailed it for me, and this is why I think it is so important to have this discussion.

I have been hearing the discussion here about the cost of transition versus the cost of not transitioning, but we have not talked about the benefits of transitioning. Here has been my concern all along as I have sat in for the last four years of the Senate is, I have watched China take advantage economically over the United States and other countries and they are still pursuing that, they are investing billions of dollars. This is an area we now, as the United States, when it comes to clean technology, have the ability to lead if we actually invest in the research, the development, and the deployment, because whoever can lead in this clean technology, whatever country has the best technology, is going to have a better economic advantage moving forward and we are transitioning, no matter what anybody says.

I am going to stop preaching, but let me just say this. I am going to ask both Dr. Hsu and Dr. Birol—you know, part of the conversation that I think is important for the Paris Agreement is not whether there is enforcement, not whether we can ensure their carbon reduction, it is the fact that we are trying to achieve a goal here and incentivizing all of our states, all of our private sector, all of our government to work together to go down the path toward this clean energy and develop this new technology because this will create jobs, this will give us an economic advantage, and other countries will want to understand it as well or possibly be able to engage in that.

Is that correct? What are the benefits for us entering into the Paris Agreement? And Dr. Hsu, let me ask you.

Dr. HSU. It's a great question and thank you so much, Senator, for asking it.

You're absolutely right. If we look at China two decades ago, it basically didn't even have a clean energy sector to really speak of and then because of that massive amount of investment, they were able to, basically, eat all other country's lunch when it comes to producing solar, wind turbines, for example. I think I stated in my testimony that two-thirds of all wind turbines are coming from China, half of all solar panels are produced in China. So there's a huge market out there for these technologies.

Some estimates that I've seen predict that by 2030, there's going to be a $23 trillion market for climate-smart investments, and so this will just continue to grow as countries, exactly as you said, work to meet the goals of the Paris Agreement. So, yes, I think absolutely by sticking to these old fossil fuel based industries that our economy has relied on to achieve the emissions reductions in the past decade, I think, it's short-sighted. I think the world is moving in the direction of decarbonization and if the U.S. doesn't act quickly and decisively enough, they're going to miss an opportunity.

Thank you.

Senator CORTEZ MASTO. Yes, and with that said, I do understand. Listen, China is trying to decarbonize by 2060, but we also know China is continuing to invest in fossil fuels from emerging countries, right? So we know that the emerging countries right now are challenged and they are going to be transitioning, but right now, they are looking for the lowest cost. So it does make sense for us to work to figure out how we develop this technology for carbon capture, utilization, and storage and how we address the methane gas because it is not going to go away anytime soon, nor should we look to put people out of work, right? We want to transition to the jobs. We want to transition to the technology, the jobs of the future and transition those skills along the way. Everybody should be employed.

With that said, let me ask Dr. Birol. For purposes of the Paris Agreement, you talked a little bit about the benefits of it—renewables, efficiency, nuclear power, advanced nuclear power—and you talked a little bit about incentives that the United States can engage in, including tax credits, as well as research, development, and deployment. What else should we be doing to ensure that we are incentivizing across the states in this space to develop the technology that is necessary for this clean energy?

Dr. BIROL. I think, if I may, Madam Senator, combining this question with your wonderful comments about the competition is very important here between the countries to develop the clean energy technologies. One lesson for the United States from history, we all agree today that the solar is one of the cheapest sources of electricity generation, and it was the United States which put—between 1975 and 2000—U.S. Federal Government subsidies, about $3 billion in order to bring the cost of solar down, from 1975 to 2000. And afterwards, if I may say so, dropped the ball and today, when we look at the picture, only one percent of the solar PV module shipments come from the United States and seven out of ten solar PV is coming from Asia.

So I think we need to learn from this example. What kind of incentives? It can be tax incentives, it can be subsidies, mandates and some, in my view, some standards are needed. You talk about the methane. Methane—to capture methane is really an easy business. It is for the many companies—they just don't need to be greedy. They just need to put additional technical improvements reducing venting and flaring, which will happen only if there are regulations there. In my view, strict regulation on methane is a part of the incentives, if I may say so.

Finally, Madam Senator, even if there was no climate change concern, I still believe that the United States would still push the advanced technologies to be a leader in the global economy because—and today if American manufacturers are changing their strategies—and pushing the electric vehicles, it is not only to save the planet, but it is also putting their businesses, their strategies on the right track to make money for themselves and for their shareholders.

Senator CORTEZ MASTO. Thank you.

And Mr. Chairman, thank you. I know my time is up, but let me just say this. This is our moonshot. This is it. In this century, this is what we have to tackle. And I come from a mining state. I am very proud of the mining that we have. We have the ability to create new jobs around the critical minerals that are going to be necessary for this clean energy, from the extraction to the production, all the way to the end product. And we should be doing that. We should be engaging on how we continue to develop these new technologies from out of the ground to the finished product, because that is good for our economy, it is good for jobs, and it gives us that competitive advantage that I would like to see the United States lead with.

So thank you.

Senator MANCHIN. Thank you, Senator.

Senator Hoeven.

Has Senator Hoeven been able to get back? If not, we will go for a quick second round—anybody that might have—I have one to finish up on.

Dr. TINKER. Mr. Chairman, this is Scott Tinker. Is my microphone working yet?

Senator MANCHIN. It is now, yes.

Dr. TINKER. Okay, I apologize. I'm not sure what happened there. I've got a lot to share on each of these topics.

Senator MANCHIN. Okay, Scott. Well, we will get back to you.

Anybody that did not have a chance to respond to my first question, if you recall, on the Paris Accord? Where we are going, different times, different elements, different people, many different countries meeting different timetables and hitting the net zero by 2050.

Yes sir, Doctor.

Dr. NEWELL. Yes, Senator. One of the things to recognize is that the concept of net zero and why has that gotten so much salience and the reason is that when carbon dioxide emissions are put into the climate system, they stay there for a thousand years, right?

They don't go away. And so, the concept of net zero is that if we want to stabilize the climate and stop temperature from rising, we need to get to net zero emissions to stabilize the stock of greenhouse gases in the atmosphere. So, that's the—it's a very simple concept and it's, you know, it's gotten increased policy salience.

Now the United States, and this has come up before, the United States—we contribute about 15 percent of global greenhouse gas emissions. It means 85 percent is coming from other countries. And so, how do we prevent the impacts on the United States, in our own self-interest, from climate change? How do we prevent additional sea level rise and temperature change? We need to do that both for our own actions and, very importantly, by encouraging actions by other countries, because 85 percent of the impacts we're feeling are actually coming from other countries.

So how do we do that? We have to engage in international agreements, like the Paris Agreement. And I think in order for us to expect other countries to react in kind, we need to lead by example. So that's what I would say, Senator. And finally, in terms of, you know, particular net zero goals, in order to stabilize the climate, I would think we need to get to net zero as quickly as possible. Exactly when that is, is going to depend on how technologies unfold, how policies unfold, how market conditions change. I guess I'd finally——

Senator MANCHIN. There is nothing enforcement about the Paris Accord. That is the problem. There is nothing enforcing it whatsoever.

Dr. NEWELL. Yes, the Paris Accord is based, as was described earlier, on bottom-up commitments by countries.

Senator MANCHIN. Okay.

Dr. Tinker, I don't think you have commented on this. Am I right?

Dr. TINKER. I haven't——

Senator MANCHIN. I know Dr. Hsu has. Dr. Tinker, please.

Dr. TINKER [continuing]. Or maybe I did but you didn't hear me.

Senator MANCHIN. Yes, we have you. We have you, Doctor.

Dr. TINKER. Thank you. I probably was talking to myself, but thank you.

You know, I think it's really important on the Accord optionality—so replacing CO_2 dense emissions with less dense—and you have to think about those that are intermittent and those that are baseload as well. So replacing coal and natural gas has had a huge effect in the United States. Capturing the CO_2 from that natural gas would have even more of an effect and then, supplementing that with other things.

I think the levelized cost conversation, which didn't come through, we'd have to be complete on that. Again, when you have to back up materials, back up intermittent energy with something and it's 100 percent backup, plus or minus, in batteries or redundant plants. That raises the cost. It really—Dr. Birol knows this very well—that the levelized cost does not represent the cost to the consumer. It doesn't. That's why California and the Northeast U.S. and Germany pay so much more for electricity today, the consumer does. It's regressive.

And it's not—it's just physics and economics. You have to back intermittent energy up if you want steady electricity. So we have to look at the complete cost of electricity. Density matters—a lot of stuff. I definitely respect and am very close with the state geologist in Nevada. And mining—it is important. We have to think candidly about how much mining we will enable here if we're going to manufacture stuff here—where does it come from? I've put solar in, in Columbia in our film, "Switch On", a film on energy poverty. And it takes stuff from all over the world to do that, to bring it to it, to manufacture it and deploy it, the production chains for this are phenomenal.

So how are we going to accomplish that globally to truly reduce emissions in a real world where others are making most of our stuff now in this country? It's such a practical question.

Senator MANCHIN. Doctor, I hate to cut you short. I have two others.

Dr. TINKER. Okay. Sure.

Senator MANCHIN. If you don't mind.

Dr. TINKER. You bet.

Senator MANCHIN. We will get back.

So I am going to go to Mr. Mills and then we are going to finish up with Dr. Birol real quick. I am sorry to indulge, but we want to get these out.

Mr. Mills.

Mr. MILLS. Thank you, Senator. I'll take you at your word and answer the question about what do I think about the probability of reaching that goal by 2050. If I were betting, and I'll take the public bet, we won't reach the goal.

Senator MANCHIN. The United States or all?

Mr. MILLS. Neither the United States or the world. And I say that not because it's aspirational, or should or shouldn't—aside from that entirely. The inertia in these systems, the world, is so great and the magnitude of the resources that we have to put to work is so large, that it would require efforts that are equivalent to a World War II type of mobilization, not just for a few years, but for decades.

The physical resource requirements, and I look forward to the IEA study on this, I suspect it will look like other World Bank and IMF studies, are astonishing. I just don't think the world is prepared to mine that much material, move that much material, and spend that much capital. So I would bet against it happening. So that would argue that we have to start thinking seriously, as some organizations do, about resilience and adaptation to whatever happens to the climate in the coming decades.

Senator MANCHIN. Thank you.

And Dr. Birol.

Dr. BIROL. Thank you very much, Mr. Manchin.

So I would like to bet either way. We are going to, as I said, making a study on the 18th of May, we are publishing, to see what needs to be done to reach net zero by 2050, and I can tell you that it requires Herculean efforts to reach that major transformation of the energy sector around the world, and one key word here—there are many, many challenges—but one important challenge, in my view, is there is a need for intelligent collaboration among the countries around the world. This is the biggest challenge. And if we don't come together, it will be very difficult to reach this target.

And here, yet finally, one opportunity. Many countries around the world, including the United States, are putting in place economic recovery packages. Once-in-a-generation in scale, trillions of dollars, and many governments are putting incentives in for clean energy technologies. This can well create an unprecedented momentum for the clean energy technologies and try to give a strong support to reach those targets. But once again, it requires Herculean efforts to reach those targets, which, I believe, from the pictures of Mr. King, is compulsative for all of us to reach.

Thank you.

Senator MANCHIN. Thank you, Dr. Birol.

We have Senator Hoeven and then Senator Barrasso will finish up the second round.

Senator Hoeven.

Senator HOEVEN. Thank you, Mr. Chairman, I appreciate it very much.

Dr. Birol, when you appeared before us earlier you talked about the importance of, in terms of fossil fuels, coal-fired electric plants providing a substantial amount of energy throughout the world and that is going to continue to be the case, and then emphasized that carbon capture and storage, you called, not just one of the most important technologies, but the most important technology that exists because of its ability to marry the benefits of good, normal stewardship and continued, dependable energy production. So I guess my first question is, do you stand by that statement? Is CCUS indispensable in terms of making sure we have dependable, low-cost energy and meeting our objectives in terms of the production of CO_2 emissions?

Dr. BIROL. Even more than before, Mr. Senator. It is getting more and more important, more and more critical, CCUS in power generation, industry and elsewhere. The problem is not energy. The problem is emissions. Energy is good. Emissions are bad.

Senator HOEVEN. Right, but isn't the demand for fossil fuels, coal-fired electric production, going to continue, particularly in a lot of countries outside the United States? And so, isn't cracking the code in terms of making CCUS commercially viable, which we can do here with our technology, isn't that vitally important, not just for us, but really for the world?

Dr. BIROL. Very much so. I think it will be not only important for the new power plants to be clean, but also for the existing power plants today. One-third of all the emissions in the world come from coal-fired power plants around the world. And if the United States was a leader of carbon capture, utilization and storage technologies, and it can well be a very important product for exported technology around the world. And this, this is what I would expect from the United States.

Senator HOEVEN. So we are trying to make that happen. Thank you for your comments and I agree with you and we are working hard to make that happen. We worked hard to get 45Q in place. So my question is, what kind of enhancements—and we are working on funding from the Department of Energy, loan guarantees—what else can we do, should we do, to make this happen? How do we help make this happen in the United States, lead the way forward, deploy it commercially, advance the technology and really lead the world here? What kind of things can we do to help make that happen?

Dr. BIROL. When I look at the numbers, 45Q seems to be working. We have seen several new projects coming online. Maybe an extension of 45Q and maybe providing additional incentives for the, especially for the industry sector—cement, iron, steel and others—who have to push the CCUS technologies and, as such, bringing the cost down. Today, the issue is not whether or not technology works, the issue is the cost of the technology. We just need to bring the costs down.

As we have seen in the solar, learning by doing, we brought the cost down and with CCUS may well have the same pattern if there was leadership there.

Senator HOEVEN. So those would be the keys—enhancement of 45Q, help through Department of Energy and other sources too, for the front-end cost to put this technology on the plants, and then loan guarantees to help those companies actually finance their costs to not only advance the technology, but to put it into place and operate on a commercially viable basis. Those, you think, would be the keys—make this happen instead of just talk about it, then we have to work with our Department of Energy and our companies to do those things, you would say?

Dr. BIROL. Yes, definitely, especially now the focus needs to be in the industry sector as well—iron, steel, cement and other special chemical industry—and we are going to, we are, I believe, working with the Department of Energy in order to provide them some assistance.

Senator HOEVEN. And you think that could have a huge impact for our country and that we could really lead the world forward—correct?

Dr. BIROL. Definitely. And the United States can be the leader of this technology around the world, and as such, not only benefits the U.S. economy, but in terms of reducing the emissions, keeping the energy in the United States, but also exporting this technology around the world.

Senator HOEVEN. And a lot of great jobs, right?

Dr. BIROL. Yes, exactly. CCUS is a job-creating machine.

Dr. TINKER. Senator Hoeven.

Senator HOEVEN. Thank you very much, Doctor and thank you, Mr. Chairman——

Dr. TINKER. Senator Hoeven, just briefly.

Senator HOEVEN. Yes, sir.

Dr. TINKER. Technology matters with CCUS as well. So the ability to put fluids in at rate and in the volumes, and there again, the United States has a remarkable advantage—the Gulf of Mexico, where infrastructure exists and sites to capture, and then being owned by the Federal Government and the states in the offshore—is a remarkable site for large-scale CCUS. It could be world-leading in setting up a hub for capture, transmission, disposal, and monitoring and verifying its storage—50 gigatons of potential storage there. So we have a remarkable opportunity to lead that, but the geology does matter.

Senator HOEVEN. Thank you, Dr. Tinker, I appreciate that very much. And again, thank you, Mr. Chairman.

Senator MANCHIN. Senator Barrasso.

Senator BARRASSO. Thank you, Mr. Chairman.

Dr. Tinker, China is the world's largest emitter of carbon dioxide, and it accounts for about 30 percent of global emissions. So while Chinese emissions have been rising for decades, U.S. emissions, as we've talked previously, have been steadily declining since back in 2007 and are expected to decline another 17 percent by 2030. So in 2015, China said they are going to cap their emissions by 2030, so 2015 all the way up to 2030. Is it fair to say that China's pledge is really just business as usual for them?

Dr. TINKER. Well, it's interesting. Yes, in some senses, but business as usual is really transition as usual. Nothing is static. So the transition in fuels is very real. China is transitioning. It's growing its economy on coal but will transition away from that. So it is business as usual in that transition. Accelerating through that transition is really the great opportunity the United States can lead, Senator, as we go forward here—is really helping to move through the emissions that Dr. Birol said so well, it's the emissions. And it's also the water, air, and land impacts. It's the environment that we're talking about, the whole environment.

So business as usual is an interesting term, but nothing is business as usual.

Senator BARRASSO. Then, since you mentioned Dr. Birol—Dr. Birol, let me ask you this. The IEA's 2019 Energy Policy Review for the United States recommends that, it says, "As the United States is poised for further production growth over the coming decade, facilitating the buildout of supporting infrastructure will be a key factor to maximize the benefits of shale, both at home and abroad." So, on balance, would you agree that the construction of natural gas pipelines, LNG export terminals here in the United States is a good thing for the United States, for the world, and for the environment?

Dr. BIROL. Yes, U.S. LNG, especially where it is exported to Asia, as I said a few minutes ago, as of these last two months, the biggest buyer of U.S. LNG is China, by the way, and other Asian countries. When it replaces coal it reduces the emissions. But once again, it is important that the methane emissions in the United States need to be addressed and minimized, otherwise soon there may be some challenges to find the customers as they may look at the methane footprint of U.S. LNG. But in general, it can help to reduce the emissions from coal and also help to reduce the air pollution in the cities in Asia.

Senator BARRASSO. Let me ask you, since the IEA was, I understand, created to ensure the security of energy supplies, particularly oil, the United States is now the world's largest producer of crude oil and natural gas. On balance, has the emergence of the United States as the top oil and gas producer increased the stability and security of global energy markets?

Dr. BIROL. Definitely, yes.

Senator BARRASSO. Thank you.

Thank you, Mr. Chairman.

Senator MANCHIN. And with that, I want to thank all the witnesses. You all have been wonderful. I appreciate the time you have spent to come here in person, but also those on the web. I appreciate very much you sharing with us your expertise and we are going to be calling on you much, much more during this Congress.

With that, members have until the close of business tomorrow to submit additional questions for the record.

The Committee stands adjourned.

[Whereupon, at 12:30 p.m., the hearing was adjourned.]

APPENDIX MATERIAL SUBMITTED

U.S. Senate Committee on Energy and Natural Resources
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Questions from Chairman Joe Manchin III

Question 1: One of the undercurrents in the changing energy mix has been shifts within the financing markets, including commitments made in the private sector by Fortune 500 companies, sovereign wealth funds and private equity groups, and utilities in response to customer preferences.

a. What lessons learned, either globally or domestically, can we take from the last few year of these trends – both the pitfalls to watch out for and the opportunities within these drivers?

In recent years, there has been a broad push by investors and policy makers to align decision-making in the financial sector with improving sustainability in the real economy. This is focusing corporate attention on climate related risks and has proceeded in parallel with a move by financial institutions to identify and evaluate the financial risks associated with energy transitions. In addition, a number of initiatives to classify sustainable investments have emerged. While these trends are affecting corporate governance and strategies, and have increased the flow of funds into sustainable finance, they have not yet provided a tangible boost to real investment in clean energy. For example, since 2014, overall sustainable debt issuance has grown over tenfold, but actual capital expenditures in clean energy projects, for example in renewables and efficiency improvements, have remained relatively stable over the same period.

Successful energy transitions will require a large increase in investment in a wide range of efficient and clean energy technologies, across the entire energy economy. This is clearly a huge investment opportunity, and the resilience demonstrated by sustainable debt and ESG strategies so far in the downturn may offer relative value to investors even in an era of lower returns. Further policy efforts to expand sustainable finance frameworks may spark continued investor interest in clean energy.

However, the availability of additional funds from the capital markets nonetheless represents an uncertainty for the prospects of financing energy transitions. There is no guarantee that energy-related asset classes will be able to attract sufficient capital to support investment relative to other sectors in the economy, particularly in fuel supply sectors, which are affected by a mix of climate-related concerns and weak fundamentals, and in clean energy assets, which often lack the scale and liquidity to meet institutional investor criteria. The risk and return requirements of investors still depend on the thrust and clarity of policy signals from governments, as well as on the speed and success of measures in recovery packages to stimulate growth.

b. Where have the foreign investments made by other countries, including China, made the most notable recent impacts in energy markets?

Foreign investments have an important impact in markets with underdeveloped financial markets and domestic companies with restricted balance sheets. Overall foreign direct investment flows, across all sectors, fell sharply in 2020 as a result of the Covid-19 pandemic, by more than 40% according to UNCTAD, and further weakness is expected in 2021. However, this decline was far from uniform across different economies. Africa provides a range of examples: foreign investment in Nigeria fell quite sharply, largely due to the impact of lower oil prices, but remained quite stable in Mozambique due to continued spending on a major new gas project. Senegal saw

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higher inflows of foreign direct investment in 2020, supported by rising investments in energy. India also increased foreign direct investment in 2020, with infrastructure and energy playing an important part.

The availability and diversity of different sources of finance varies according to the strength and clarity of domestic energy policies and investment frameworks. In many countries in sub-Saharan Africa, weak frameworks to underpin investment by independent power producers and persistent cross-cutting risks around currency and political stability means that power systems are dependent on high degrees of international public finance, which are unable to mobilize growing levels of long-term private capital. By contrast, some markets in Latin America that have put in place clear frameworks for the procurement of renewables around competitive auctions, combined with good macroeconomic management, have attracted increased foreign direct investment by large international private companies. This has helped to improve the affordability of renewables deployment, for example, as well as cultivate a domestic market for financing by local banks.

Question 2: The U.S. power sector has reduced its carbon emissions by nearly 30% over the past 20 years. The changes in the U.S. have stemmed from innovation and policy at the federal and state levels, but there are likely other forces shaping trends in other countries.

a. In the global context, where do you see emerging trends in the transportation, industrial, or buildings sectors where the U.S. may become more competitive.

Electrification and hydrogen are two of the major global trends in the context of clean energy transitions that span across transport, industry and buildings, in which the US has a potential competitive edge.

On electrification, the transition to electric mobility is the most visible trend. The IEA estimates that 2020 electric car sales reached a new record of 3 million cars, around 4% of global car sales. Sales growth over 2019 in the US was moderate (4% year-on-year) but strong in Europe (135%) and China (12%), on the back of strong government support. As battery technologies continue to improve and costs decline, prospects for electrification are becoming brighter for heavy-duty vehicles also. The US is at the cutting edge of battery technology and therefore strategically positioned to expand its presence in global value chains for electric mobility.

Electrification efforts, however, span beyond transport. Energy services in buildings (space and water heating, cooking and space cooling) are becoming increasingly electric, and the digitalization of such services allows for improved household energy management. The US has an extensive network of companies and expertise in developing and providing such digital solutions.

Expanding the production and use of hydrogen is another key trend that is gaining global traction. Producing hydrogen from water through electrolysis or from fossil fuels with CCUS are promising low-carbon pathways. The US is well-placed to expand its operational and manufacturing capacity in both cases. Electrolysers share the same scientific principles as well as some materials and manufacturing processes with batteries, a technology in which the US is a technology leader. The US also has vast experience in operating CCUS.

The US could additionally seek to expand domestic hydrogen demand in key sectors, with a view to global markets. The production of steel solely based on hydrogen is currently piloted in Sweden, with the first

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commercial plant scheduled to enter into operation as soon as 2026. In the US, the share of steel production through direct reduced iron (DRI), i.e. the route that is the basis for hydrogen-based steel production, is among the highest in the world. The US is also active on deploying fuel cell electric vehicles, although China's fleet, in particular of fuel cell electric buses and commercial vehicles, is growing rapidly. The US has a robust fuel cell manufacturing network that is well-placed to deliver to new national and international market segments.

Question 3: One of the problems we face is ensuring that energy and emissions data is easily available, detailed, and verifiable. Unlike the U.S. and other developed economies, the capacity to obtain and verify data may be low, and potentially subject to political interference. Recent articles reported that China has announced 72GW of new wind capacity in 2020, more than the rest of the world combined.

a. Is this an example of data that lacks verification, or is this a fact of China's ambition on clean energy?

The National Energy Administration of China officially announced renewable electricity capacity additions on 30 January 2021 (http://www.nea.gov.cn/2021-01/30/c_139708580.htm). Accordingly, China installed 71.7 GW of new wind capacity in 2020 (68.6 GW onshore and 3.1 GW offshore).

b. While China is increasing its build-out of renewable energy, what is the trend on fossil energy in the past decade?

See combined answer below.

c. Is China still adding new fossil capacity to their power and industrial sectors?

Over the past decade (2010 through 2019), China completed 48 GW of new coal-fired power capacity each year on average, compared with 30 GW per year in the rest of the world. In 2020, China had half of the global coal-fired power capacity in the world. China completed 5 GW of natural gas-fired power capacity per year from 2010 through 2019.

China continues to actively build new fossil fuel-based power generation capacity. At the start of 2020, China had a large pipeline of new coal-fired power capacity, with over 200 GW either under construction or in a planning phase (S&P Global). China also had close to 50 GW of natural gas-fired power capacity either under construction or in a planning phase.

China's output of crude steel, mostly based on coal, has risen by 5.1% per year on average between 2010 and 2019 (compared with 3.0% globally) (World Steel). Cement production over the same period has risen by 2.6% (2.5% globally) (USGS) with fossil fuels providing the bulk of the heat in this sector.

Despite this large increase in industrial output, final consumption of fossil fuels in China's industry sector has declined by 1.4% on average between 2010 and 2018, although higher rates of electricity usage in industry (5.8% during this period) are supported by the large fossil fuel expansion in the power sector described above (IEA World Energy Balances).

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Question 4: Carbon management technologies like carbon capture, utilization, and sequestration have an important role to play in mitigating global emissions, but despite 13 commercial-scale carbon capture facilities in the U.S., we are still shy of large-scale deployment of these technologies.

a. What specific steps are now needed to commercialize CCUS technologies in the U.S. and other countries?

See combined answer below.

b. Where do you see the greatest market opportunities if the U.S. becomes a leader in exporting these technologies?

CCUS technologies will need to play an important role in addressing climate change, supporting emissions reductions in key heavy industries and underpinning approaches to carbon removal through Direct Air Capture (DAC) and bioenergy with CCS (BECCS). CCUS can also enable industrial or fossil energy-producing regions to contribute to energy transitions, including through retrofitting of existing facilities and creating new opportunities to use fossil resources to produce low-carbon hydrogen. Many CCUS technologies have been demonstrated at scale: the main challenge for large-scale deployment is a lack of economic drivers for investment in many regions of the world.

The US is the global leader in CCUS development and deployment and today is one of very few countries to have a targeted incentive for CCUS investment, with the 45Q tax credit. Alongside complementary measures, such as the California Low Carbon Fuel Standard, 45Q is spurring a new wave of CCUS investment plans.

Further commercialization of CCUS in the US could be achieved by considering a) increasing the value of the 45Q tax credit for higher-cost but critical applications of CCUS, including cement production or DAC; b) introducing a direct-pay option for 45Q to support up-front capital costs for projects; and c) direct support or low-cost financing for shared CO2 transport and storage infrastructure to enable CCUS deployment across a range of sectors and applications.

The IEA has identified important global momentum for CCUS; in many emerging economies, existing assets in power generation and heavy industries have only recently been built. The US could capitalize on its global CCUS leadership and innovation strengths with potential to export capture technologies including DAC, technologies for CO2 use (for example, in building materials or synthetic fuels) as well as technologies and know-how for CO2 storage (including monitoring technologies) and CO2 enhanced oil recovery (CO2-EOR).

Question 5: As we look to tackle climate change and transition to a cleaner energy future, we cannot abandon the communities in traditional energy states like West Virginia. This challenge is not unique to the United States. China has an extensive coal sector for power generation and industry, which may pose similar problems as the Chinese leadership considers its own energy transition.

a. Are there lessons learned from other countries about how to ensure no communities and workers get left behind during energy transitions?

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It is vital that workers and communities affected by clean energy transitions be supported and protected. Many countries and regions have implemented programmes to provide financial support, retraining and business development services, and good examples exist in Spain, Canada and a number of US states. Spain's Just Transitions Strategy, for example, requires "just transition agreements" between the government, unions and businesses in all regions affected by climate transitions. These agreements will support comprehensive strategies to offset negative impacts and finance green projects. Canada created and funded recommendations from a Task Force on Just Transition for Canadian Coal Power Workers and Communities.

Governments can learn from previous experience and best practice policies, which are now being examined by the Global Commission on People-Centred Clean Energy Transitions. The IEA is delighted that Chairman Manchin is among the global thought leaders and ministers that have agreed to join the Global Commission, which will make key recommendations later in 2021.

Questions from Senator John Barrasso, M.D.

Question 1: The IEA's "Energy Policy Review the United States 2019" recommends that the U.S.:

> *Evaluate the allocation of decision-making authority for the permitting and siting of natural gas pipeline projects in order to identify possible ways to shorten lead times and reduce uncertainty for investors.*

a. Does IEA have any specific recommendations on how to reallocate decision-making authority for the permitting and siting of natural gas pipeline projects in the U.S.?

See combined answer below.

b. Please explain why expediting the permitting and siting of natural gas pipeline projects in the U.S. is so important.

Future production growth and exports of natural gas depend on a complementary buildout of gas pipelines. While private companies decide on whether to develop new energy infrastructure, the government plays an instrumental role in permitting. Energy infrastructure projects often require approvals from various federal, state and local authorities. Though the government has made efforts to streamline federal licensing for energy infrastructure, there remain cases of midstream infrastructure struggling to keep pace with shale production growth due to permitting setbacks, local opposition, and court challenges. Timely siting of gas pipelines can also benefit efforts to reduce associated gas flaring rates from oil production.

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Early and cooperative engagement among relevant stakeholders, notably federal, state and local governments, as well as local communities, can help mitigate concers. Some countries have also legislated timelines for infrastructure permits, though this should be balanced against the need for thorough impact assessments.

Question 2: In your testimony, you mentioned the need to reduce methane emissions from oil and gas systems. How important is streamlining the buildout of natural gas gathering lines so that producers can gain access to markets for their gas instead of flaring it?

The technologies that can be used to prevent and reduce methane leaks are well-known by companies and governments. The challenge is to incentivize the deployment of these abatement technologies via voluntary or regulatory means. In some cases, investment in abatement technologies is economic, as the gas saved pays for the installation of better equipment, development of new routes to market, or the implementation of new operating procedures. However in other cases, deploying methane abatement measures may not pay for itself, or there may be barriers that prevent companies from taking action that would otherwise be cost-effective. As a result policy and regulatory interventions may serve to incentivize companies to take steps to reduce their emissions.

In the case of associated gas, of an estimated 935 billion cubic metres (bcm) of gas that was extracted in association with oil worldwide in 2019, we find that only around 75% ended up being used on-site by the operator, or re-injected into the well, or marketed to consumers. Of the remaining 25%, we estimate that around 55 bcm was released as methane to the atmosphere, and the remaining 150 bcm flared. One reason often put forward for flaring is that the oil extraction occurs far from existing gas infrastructure; however, geo-spatial analysis shows that the majority of gas flaring worldwide in 2019 took place at sites that were less than 20 km from existing natural gas pipelines. Whichever approach is taken to address this problem, reductions in flaring and venting of associated gas need to go hand-in-hand to ensure effective management of emissions.

Question 3: Under the Paris Agreement, China has pledged to cut its energy-related emissions intensity by 60 to 65 percent between 2005 and 2030. According to the data in IEA's "CO2 Emissions from Fuel Combustion" database, in the previous 25 years –1980 to 2005 – China cut its emissions intensity by 62 percent.

a. Is it fair to say that, according to IEA's data, China has agreed to cut its emissions intensity from 2005 to 2030 at essentially the same rate as it did from 1980 to 2005?

See combined answer below.

b. Why doesn't this amount to business as usual for China?

From 1980-2005, China reduced carbon intensity of its economy (in PPP terms) by close to 60%. China has committed to reduce its carbon intensity by 60-65% in the 2005-2030 period, with the IEA World Energy Outlook projecting 65% reductions by 2030 in China in the Stated Policies Scenario.

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While this commitment is only a modest increase on historic improvement rates, reaching the target does require a step up from business as usual in policy-making, in two ways:

- Historic improvements in emissions intensity were aided by structural shifts in the economy. China moved away from high energy-use segments to those that have lower energy use and higher value added. Structural shifts in China during the next decade will be slower, meaning that emissions intensity improvements will rely more on targeted decarbonisation activities.
- Many of the low-cost emissions abatement opportunities have been exhausted to date in China, including the retirement and replacement of inefficient industrial and power plant capacity. In the coming decade, China will need to accelerate action to deliver the same pace of improvements, including the deployment of more renewable energy capacity.

China appears on track to meet or surpass the current target in their nationally determined contribution (NDC) under the Paris Agreement. However, in order to reach China's recently announced target for net-zero emissions by 2060, action would need to be accelerated, broadly in line with the IEA's Sustainable Development Scenario (IEA World Energy Outlook 2020). This scenario provides a comprehensive view of what increased ambition might look like if China's net-zero target were reflected in a revised NDC.

Question 4: In the IEA's World Energy Outlook (WEO) forecasts, we noticed that the reference "Stated Policies" scenario and the "Sustainable Development" scenario have exactly the same gross domestic product (GDP) figures. It seems that GDP is an input to the Sustainable Development scenario, whereas GDP should be an output of the Sustainable Development scenario. As a result, policymakers cannot see the economic impacts of meeting different emission and sustainability objectives, which limits the usefulness of WEO forecasts. Will IEA consider changing this practice and model economic impacts in future WEO forecasts so it is more valuable to policymakers?

It is correct that the Stated Policies and Sustainable Development scenarios have similar assumptions about the rates of economic growth. This is designed to be valuable to policymakers as it allows decision makers to see clearly the potential impact of policies that influence the energy system and consumer behavior. However, we recognize that there is significant uncertainty over the future rate of economic growth. For this reason, we have also looked at scenarios with different levels of GDP growth, notably the Delayed Recovery Scenario in the World Energy Outlook 2020, in which the economic impacts of the Covid-19 pandemic are more prolonged. This also has the effect of reducing emissions compared with the Stated Policies Scenario, however, these emissions reductions come primarily from reduced economic activity, rather than from accelerated structural changes in the energy sector. The Delayed Recovery Scenario underlines that low economic growth is not an effective low-emissions strategy; the reductions in emissions are far from sufficient to achieve climate objectives and come at a significant social and economic cost.

Question 5: Do you agree that high energy costs are regressive and inequitable to lower-income people?

High energy costs can disproportionately impact lower-income households for several reasons:

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- Costs to provide basic levels of comfort and services represent a higher share of their disposable income. This could make basic energy services unaffordable for a larger number of households, who may forgo other basic services to cover energy costs.
- Lower-income individuals also tend to be less energy efficient, facing barriers such as poor building integrity, higher upfront costs to replace appliances and vehicles with efficient versions, and split incentives between renters and owners.
- Energy pricing is often regressive to begin with, by spreading system costs evenly on a volumetric basis, regardless if heavy consumers contribute to total costs more than average consumers.

While keeping energy prices low can prevent inequities from getting worse, fossil fuel consumption subsidies are not advisable, and potentially could exacerbate inequity by disproportionately benefitting higher income households. The removal of fossil fuel subsidies can have benefits to energy markets, climate change and government budgets around the world (Link).

The regressive impacts of energy costs can be better managed through enhanced retail rate design within regulated utilities, better use of efficiency standards, and energy efficiency programs that target only low-income households (Recommendations of the Global Commission for Urgent Action on Energy Efficiency, 2020).

Question 6: Based on the Intergovernmental Panel on Climate Change "Global Warming of 1.5°" report, the United Nations says that greenhouse gas emissions "would need to fall by about 45 percent from 2010 levels by 2030" for the world to be on a path to net zero emissions by 2050. As a consequence, many policymakers in the United States and elsewhere have called for cuts of this magnitude. Based on what you know today, do you expect global emissions in 2030 will be 45 percent lower than 2010 levels? If not, why?

The World Energy Outlook 2020 examined a new case in which global emissions fall by 45% from 2010 levels by 2030. This is a very ambitious level of emissions reduction, and achieving it would require a singular, unwavering focus around the world from governments, industries and consumers. A large number of unparalleled changes across all parts of the energy sector would need to be realised simultaneously, at a time when the world is trying to recover from the Covid-19 pandemic. Building on this work, and in line with a request by the COP26 Presidency, the IEA is currently working to develop a new IEA Special Report, to be released on 18 May 2021, providing the first comprehensive energy-sector pathway towards global net-zero emissions by 2050.

Questions from Senator Maria Cantwell

Question 1: Pricing Carbon

Two years ago during another hearing in this committee, almost all of the witnesses agreed by a show of hands that putting a price on carbon pollution, either indirectly or directly, is a good thing.

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- Do you believe that an economy wide price on carbon, applied upstream where fossil fuels enter the economy, is the most efficient mechanism to decrease carbon emissions at the necessary scale and speed?

See combined answer below.

- Do you believe that a predictable, market-based carbon price will incentivize the markets to reduce carbon emissions faster and more efficiently than could be achieved through direct regulation of emissions within specific industry sectors?

A clear and consistent CO_2 price would be a very efficient approach to encourage companies, industries and consumers to reduce emissions through everyday decisions and operations. It could also be usefully applied to other greenhouse gas emissions – such as methane emissions that can occur in oil and gas operations – to ensure that these also fall in line with climate objectives.

A clear and consistent CO_2 price can also provide an important signal for investment decisions, particularly for technologies that are ready for commercial deployment. It would be important to ensure that the price does not unfairly impact small businesses and lower-income citizens by recycling any revenue that is generated by the price.

However, a CO_2 price alone is unlikely to deliver efficient levels of technology innovation in line with affordable and secure clean energy transitions. Of the wide range of clean energy technologies needed, some are still at an early stage of development, or exist only as prototypes (IEA Clean Energy Innovation, 2020). Governments have a particularly central and wide-ranging role to play in this space. In addition to the provision of funds for R&D, they set overall national objectives and priorities and play a vital role in determining market expectations. They also have unique responsibilities for ensuring the flow of knowledge, investing in enabling infrastructure and facilitating major demonstration projects, all critical steps to bring new technologies to market.

__Question 2__: CCUS and Nuclear

I strongly support efforts to boost innovation to help bring new forms of energy to the market, but unclear whether carbon capture utilization and storage (CCUS) technologies and nuclear technologies will ever be cost competitive with existing electricity generation sources without an economy wide price signal that accurately reflects the cost of carbon emissions.

Do you think predictable carbon pricing is important to making CCUS technologies and advanced nuclear technologies economical and getting the private sector investments we need to ramp up these solutions?

See combined answer below.

- Do you think a predictable price on carbon is more likely to spur energy markets to invest in technologies like CCUS and advanced nuclear than additional funding for more intangible policies like additional R&D?

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See combined answer below.

- Do you think predictable carbon pricing can help keep existing American nuclear reactors open that otherwise will shutdown?

Carbon pricing is an important strategy for achieving economy-wide emissions reductions and guiding long-term investment decisions in clean energy technologies. It can improve the competitiveness of technologies such as CCUS and advanced nuclear in the power sector, but alone may not encourage private sector investment in these technologies at the scale and in the timeframe needed to support both energy security and emissions reduction goals (see discussion in previous question).

Funding for R&D will remain important for both CCUS and advanced nuclear technologies, including to support future cost reductions, but would likely need to be complemented by targeted measures for deployment to encourage private investment. This is in much the same way that mandates and feed-in tariffs have supported investment in renewable technology options for many years.

For nuclear reactors in operation today, many face challenging market conditions. For those reactors operating in competitive markets, wholesale electricity prices and revenues have been depressed in 2020 due to a combination of reduced electricity demand tied to Covid-19 measures, very low natural gas prices and higher output from renewables.

Many American nuclear reactors in operation today face challenging market conditions. For those reactors operating in competitive markets, wholesale electricity prices and revenues have been depressed in 2020 due to a combination of reduced electricity demand tied to Covid-19 measures, very low natural gas prices and higher output from renewables.

In many instances, in the United States and beyond, the contribution of nuclear reactors to low-carbon electricity supply is undervalued. Over the past 50 years, nuclear power has helped avoid an estimated 23 billion tonnes of CO_2 emissions (IEA Nuclear Power in a Clean Energy System, 2019), which was largely uncompensated. Current electricity market designs also tend to undervalue nuclear power's contributions to power system stability and electricity security.

Predictable and significant carbon pricing would improve the financial prospects of American nuclear reactors, significantly reducing the likelihood of shutting them down before the expiration of their operating licenses, which span 60 years from the initial date of operations in most cases. With improved financials and independent safety checks, these licenses would provide for nuclear power to continue providing large volumes of low-carbon electricity into the 2030s and 2040s.

Question 3: Aligning National Policies with Business Climate Goals

The past year could be remembered as a turning point in addressing the climate crisis with major corporations committing to decarbonize their operations by ever more aggressive timeframes as the private sector realizes that taking action to decarbonize is not only good socially, but also good for business.

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- Why do you think businesses are committing to these bold greenhouse gas emission targets?

Corporations and local authorities can have a big impact in pioneering, developing and adopting cleaner forms of energy and more sustainable practices within their supply chains and jurisdictions. This can include the implementation of efficiency measures in buildings and factories they own, the build out of new technologies and infrastructure to support modal and fuel shifts in transport, the integration of digital technologies to facilitate smarter energy management and direct contracting for cleaner forms of fuels and power from local producers and utilities.

That said, clean energy transitions will depend on ramping up investment at scale, in assets that are integrated into national and international energy networks. While distributed solutions play an important role, in the IEA Sustainable Development Scenario, over 80% of low carbon power investments over the next two decades are based on utility-scale assets that depend on continuous investment in a widespread and integrated electricity grid. The attractiveness of investing in low carbon fuels, such as clean hydrogen, will depend on the ability of suppliers to tap into diverse sources of demand, enabling infrastructure and the ability to price and trade gas in competitive markets. Such investments and enabling markets depend on the presence of supportive national or regional regulations and policies.

- Do these local and corporate emissions reduction activities have an impact on global emissions?

Corporations and local authorities can have a big impact in pioneering, developing and adopting cleaner forms of energy and more sustainable practices within their supply chains and jurisdictions. This can include the implementation of efficiency measures in buildings and factories they own, the build out of new technologies and infrastructure to support modal and fuel shifts in transport, the integration of digital technologies to facilitate smarter energy management and direct contracting for cleaner forms of fuels and power from local producers and utilities.

That said, clean energy transitions will depend on ramping up investment at scale, in assets that are integrated into national and international energy networks. While distributed solutions play an important role, in the IEA Sustainable Development Scenario, over 80% of low carbon power investments over the next two decades are based on utility-scale assets that depend on continuous investment in a widespread and integrated electricity grid. The attractiveness of investing in low carbon fuels, such as clean hydrogen, will depend on the ability of suppliers to tap into diverse sources of demand, enabling infrastructure and the ability to price and trade gas in competitive markets. Such investments and enabling markets depend on the presence of supportive national or regional regulations and policies.

- Do you believe a coordinated national policy will accelerate the commitments we're already seeing at the corporate level?

Yes. Clear national policy commitments from governments are fundamental to providing investors and companies the long-term signals necessary to plan and undertake the capital intensive investments that support clean energy transitions.

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Question 4: China Winning the Clean Energy Race

There is no doubt that making the clean energy investments we need to stop carbon pollution is going to be a multi-trillion dollar global market opportunity. The question, I believe, is whether that market --and the millions of associated jobs-- will be captured by the U.S., or its foreign competitors.

China is the world's largest producer, exporter and installer of solar panels, wind turbines and electric vehicles. China is investing roughly $100 billion each year, double what the US and the EU combined invest.

- Is the U.S. losing the clean energy race to China and the rest of the world?

The U.S. and China have both emerged as leaders in clean energy, but there is considerable scope for each country to scale up ambitions, investments and innovation in the years ahead to meet long-term sustainability goals. Over the past five years, capital expenditures in clean energy (including renewables, efficiency, and newer technologies such as battery storage and CCUS) in the United States has averaged around $90 billion, around one quarter of total energy investment. In China, clean energy investments of around $170 billion have accounted for around 40% of total energy investment, boosted by growth in manufacturing capacity for key equipment such as solar panels and batteries.

Preliminary indications for 2020 point to overall resiliency of clean energy sectors compared with fossil fuels, and deployment in both countries in key areas such as wind, utility-scale battery storage and electric vehicles increasing, despite the pandemic. The U.S. has been more successful in mobilizing private finance and contributions from the capital markets, while China's development has depended more on state owned enterprises and financing from state banks. The respective public budgets for energy-related research, development and deployment activities on par in 2019, though the US continues to mobilize higher levels of early-stage private investment.

- What does China's clean energy leadership mean in terms of global greenhouse gas emissions?

Investments made by China in clean energy projects, manufacturing capacity and technology development have facilitated cost reductions in traded equipment that serves sectors, such as renewables and electric mobility, around the world. Their focus on continuing to support a range of energy technologies, such as hydrogen and CCUS, may support future cost reductions, as well as demonstrate new business models and policy approaches, in those areas. China is also reforming its overall financial system to better direct capital to sustainable energy projects and companies. That said, these clean energy investments have often come with weak profit margins (e.g. in solar PV manufacturing) and high degrees of price competition among Chinese and international companies, with the state remaining a critical actor to channeling finance and supporting development.

Another question concerns the nature of China's investments abroad and how they will evolve alongside the country's domestic clean energy ambitions. International energy finance from China Development Bank and Export-Import Bank has declined since 2016 and such institutions have tended to finance more fossil fuel than clean energy-related investments. While some of this funding has come for natural gas projects, which can in

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some countries support near-term emissions reductions in power and industry, such institutions have also continued to fund unabated coal power in emerging market and developing economies even as western commercial banks have pulled back.

- One common argument against taking action here in the U.S. is that it won't matter because the rest of the world will just keep on releasing carbon pollution – do you agree with that premise?

More than a dozen countries and the European Union, which accounted for around 10% of global CO2 emissions in 2019, have set ambitious net-zero targets in law or proposed legislation. These targets play a key role in the Sustainable Development Scenario in accelerating action on reducing emissions elsewhere around the world. They help to stimulate innovation and develop regulations and markets for low emission products and services. That said, the world is still far from putting emissions into decisive decline. Much will depend on how the world manages existing energy infrastructure in power, heavy industry and other emitting sectors, which has the potential to lock-in emissions for decades to come if used as in the past.

The future also increasingly relies on the decisions taken within emerging market and developing economies outside China, who see the fastest growing investment needs in the years ahead and where per capita energy use (and emissions) remain well below the global average. Many of these fast-growing economies will be building out their national infrastructure in the coming years, requiring energy-intensive construction materials such as cement, steel, and rising incomes will also spur demand for a range of manufactured goods and appliances. These economies represent potential dynamic markets for US companies, investors and development finance. Opening a low-carbon, inclusive model for social and economic development of these economies will be crucial for the future of global energy use and emissions.

Recognizing the critical role of such economies, the IEA will release in 2021 a Special Report on Financing Clean Energy Transitions in Emerging Market and Developing Economies.

Question 5: Need to Upgrade the Grid to Handle more Renewables

Last year we saw renewable electricity generation in the U.S. exceed coal for the first time in over 130 years and it is expected to increase again in 2021, providing 21% of U.S. electricity. As our generation modernizes, we also need to modernize the grid to not only better integrate the rising share of renewables, but also to make the grid smarter and more resilient, including against cybersecurity threats.

- What do you think are the most effective tools government can provide to make the necessary grid investments?

Grid investment needs are projected to increase by two-thirds over the next decade worldwide under stated policies, including an increase in the United States, and by more in a Sustainable Development Scenario (IEA World Energy Outlook 2020). Governments can play a role in several areas that support efficient and timely grid investment, including:

- Provide clear and stable regulations to recover efficient levels of investment in new infrastructure, upgrades and digitalization projects. For example, Order #1000 issued by the US Federal Energy

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Regulatory Commission in 2011 effectively promoted efficient transmission planning and fair allocation of costs. As a result, US grid investment has increased significantly in recent years.

- Establish and empower bodies to create and implement coordinated grid planning across the largest regions possible, based on long-term energy strategies, and with regular updates tracking progress.
- Establish processes to identify priority grid projects to resolve known or expected congestion and/or increase system reliability and efficiency.
- Develop transparent and efficient processes for the licensing and permitting of grid infrastructure, with support for projects of common interest.

- With the electric grid an essential piece of infrastructure in today's economy, what economic benefits or risks would we face if we don't invest in modernizing the grid?

Electricity is an integral part of all modern economies, supporting a range of critical services from healthcare to banking to communications and transportation. The secure supply of electricity is thus of paramount importance. A failure to invest in electric grids in a timely manner risks to undermine the reliability of electricity supply and to stifle economic prospects across all sectors. For example, there is potential for negative impacts on the cost of manufacturing, productivity of industry, quality of services and overall efficiency of business operations. In the most severe events, a lack of investment in grid infrastructure could lead to electricity shortages, brownouts and blackouts, all of which are extremely expensive for modern economies and create risks for investment in industrial sectors.

- What more do we need to be doing to make sure our grid remains resilient, economic, and reliable?

In addition to the efforts listed previously, government can encourage and incentivize the acceleration of digital upgrades of grid infrastructure and enhancing interconnections to neighboring countries to lay the groundwork for tomorrow's power systems. The digitalization of power systems is part of a broader trend across the energy landscape that presents new opportunities and challenges for modern economies (IEA Digitalisation and Energy, 2017).

Clean energy transitions will bring a major structural change to electricity systems around the world, calling for additional efforts on several fronts, including on cyber resilience and climate resilience (IEA Power Systems in Transition, 2020). The rapid growth of connected energy resources and devices brings benefits but also expands the potential cyberattack surface, while increased connectivity and automation throughout the system bring efficiency gains while also raising risks to cybersecurity. Governments around the world can enhance cyber resilience through a range of policy and regulatory approaches, ranging from highly prescriptive approaches to framework-oriented, performance-based approaches. Enhancing resilience to climate-driven disruptions is also becoming more important to electricity security, stemming from rising global temperatures, more extreme and variable precipitation patterns, rising sea levels and more extreme weather events. Beyond setting clear responsibilities and identifying risks, authorities should be ready to manage and mitigate risks, monitor progress and share experiences, respond quickly to outages or attacks and capture lessons learned.

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Questions from Senator Joe Manchin III

Question 1: One of the undercurrents in the changing energy mix has been shifts within the financing markets, including commitments made in the private sector by Fortune 500 companies, sovereign wealth funds and private equity groups, and utilities in response to customer preferences.

a. What lessons learned, either globally or domestically, can we take from the last few years of these trends – both the pitfalls to watch out for and the opportunities within these drivers?

No reply

b. Where have the foreign investments made by other countries, including China, made the most notable recent impacts in energy markets?

No reply

Question 2: As we have seen over the past several years, climate change-driven extreme weather poses a serious and growing threat to our communities and our nation's energy infrastructure.

a. To what extent has increasingly extreme weather posed a serious threat to our energy security, and what incidents stand out in the past ten years as potentially new trends?

Climate change raises atmospheric and ocean temperatures, to more powerful tropical storms and increased rainfall. In addition, higher sea levels increase flooding damages when storms do occur. Stronger storms increase the risks to the U.S. energy system along both the Gulf Coast and the East Coast. The Gulf Coast is home to the greatest concentration of domestic refineries, natural gas processing operations, and energy imports and exports. The region also has substantial oil and natural gas production facilities. Storms have repeatedly disrupted these activities, causing shutdowns that raise energy prices and have the potential to disrupt supply for U.S. consumers. Along the East Coast, more tropical storms will increasingly disrupt energy consumers through damage to the electricity grid, as well as coastal energy infrastructure such as refineries, ports, and distribution networks. Hurricanes Irene (2011) and Sandy (2012), both of which struck the East Coast, knocked out electricity for 6.7 and 8.7 million customers, respectively. Irene and Sandy forced the closure of oil refining capacity capable of processing 238,000 barrels per day and 308,000 barrels per day, respectively, and forced the closure of 25 (Irene) and 57 (Sandy) petroleum product terminals. In 2020, Hurricane Laura's impact on the Gulf Coast led to disruptions that withheld more than 14 million barrels of petroleum. Hurricanes Gustav (2008), Ike (2008), and Katrina (2005) cumulatively led to outages of greater than 20 million barrels of supplies.

Question 3: The power sector has made notable improvements in carbon intensity over the past decade and now comes in second to transportation in terms of emissions. The Department of Energy, however, has 10

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offices dedicated to various types of power generation, but only one office for each of the other major sectors of the economy, namely transportation, industry, and buildings.

a. Given the role of the DOE in research and development, and its organizational tilt toward the power sector, can you describe how other sectors undertake innovation or commercialize new technologies?

The process of innovation is not simple, and some other facts about the energy system need to be kept in mind. The size of the energy system is immense: every day the world consumes millions of barrels of oil, millions of tons of coal, and hundreds of billions of cubic feet of natural gas. The energy capital stock is also widely dispersed in the economy and is very long lasting (e.g., cars, power plants, buildings). And, at least in the United States, the energy system is mostly in the hands of the private sector, with annual investments measured in the hundreds of billions of dollars. To be useful and practicable, energy innovations must therefore scale. Energy innovations must make economic sense within the market and policy setting faced across multiple distinct sectors. And innovations will necessarily take time to unfold and have an impact at the local, national, and global levels.

So what is needed to advance the process of energy innovation? Past experience suggests that three key ingredients tend to accelerate innovation—not just in energy, but across many sectors of the economy, including: agriculture, chemicals, semiconductors and computers, the Internet, and biopharmaceuticals.

The first ingredient is substantial, sustained, and effectively managed funding for research and development that is tightly linked to the private sector. The second is robust, growing demand for new products and innovations. And the third is a vibrant, competitive private sector. Each of these three elements have tended to underpin robust innovation across many sectors, be it health, information technology, or agriculture.

While the role of fundamental research as an engine of innovation is well documented, innovation investments by private firms are insufficient given their near-term decision horizons and the challenges they face in capturing the payoffs from innovation. As a result, government support and other forms of collaboration are needed to step in and help support fundamental research. Public support tends to involve a number of different approaches including broad-based R&D tax credits; public funding for basic scientific research; and energy-focused applied research, development, and demonstration. A critical element is support for education and training to grow and maintain the human capital base that underpins the innovative process. The stability of R&D efforts is also key, given long time frames are sometimes required for innovative effort. Highly variable funding streams are disruptive to the innovative process and building and sustaining human capital.

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Despite the importance of fundamental research, however, innovation also depends crucially on a second key ingredient of success: demand. That is, what we individually demand, what industry demands, and what government policy demands from the energy fuels and technologies we buy.

Our economy can do a superb job of incentivizing the private sector to deliver the kinds of innovation we need, so long as demand is pulling the market in a direction that reflects the value of reducing emissions. Once that value is created, we know that innovators will get to work finding ways to lessen the cost of reducing emissions and meeting other energy goals. Due to externalities, government policy is needed to create a value for reducing emissions: this is essential to meeting environmental goals. The reason is that the private sector is both an engine of innovation as well as the customer. The vast majority of both R&D and relevant equipment purchase decisions takes place in the private sector by industry, businesses, and households.

Placing a value on emissions reductions, ideally in a way that gives rise to a clear and consistent price on greenhouse gas emissions, can stimulate the necessary demand. Targeted support for the deployment of advanced emerging energy technologies can also help stimulate demand for technologies that may not currently be widely cost-competitive but have the potential for becoming so through "learning by doing" in deployment. Such support includes mechanisms like tax credits, procurement, and advance purchase agreements.

In sum, energy innovation is likely to flourish in sectors where the supply of innovations supported through robust research and development is coupled with accelerating demand for new technologies that reduce emission while meeting our other needs.

b. In particular, are there sectors of the U.S. economy that have lacked funding from U.S. research agencies?

Yes. Research and development for clean energy and carbon-reducing innovation in other sectors of the economy (e.g., industrial process emissions; agriculture, forestry, and other land uses; carbon removal technologies) is underfunded. The U.S. federal government invests less than a quarter of what it invests in health innovation in energy innovation, and less than a tenth of what it invests in defense innovation. Within the energy sector, industry and fuels, buildings, and transportation are relatively underfunded compared to electric power-related technologies. Currently, areas of the economy that are relatively difficult and expensive to decarbonize warrant particular attention, including low-carbon liquid transportation fuels (especially for aviation and long-haul trucking), structural building materials requiring high heat and involving industrial process emissions (e.g., cement and steel), and carbon removal technologies. At the same time, there is a need for continued support for innovation in electric power technologies to enable deep decarbonization of the grid, including electricity storage, demand-side load balancing, advanced nuclear, carbon capture and storage, and long-distance transmission.

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Question 4: Although the U.S. EIA has a strong record of comprehensive data collection and analysis, change in the energy sector is accelerating and may increasingly uncover gaps related to factors such as additions of renewable and storage resources to the electric grid, the energy-water nexus, and the supply of critical minerals. Additionally, the Department of Energy carries out several surveys of energy use in economic sectors such as manufacturing and buildings that inform public and private sector users of that data.

a. Are there actions you would recommend to improve the energy data collection and modeling systems in the U.S. and internationally?

With respect to energy data collection, it would be valuable to undertake a comprehensive review of energy data needs to: inform robust decisionmaking in both the public and private sectors; assess those needs relative to current data collections by EIA, other government agencies, and the private sector; and identify gaps best filled by EIA, other agencies, or through public-private partnerships. EIA's principal data collection surveys and survey respondent pools were originally developed to cover the fossil fuels (i.e., coal, oil, and natural gas) and utility-scale electric power generation sources (e.g., nuclear, hydroelectric, wind, geothermal, solar). The surveys have been updated and expanded to include greater attention to alternative and distributed sources of energy (e.g., biofuels and solar power) and to cover energy demand from manufacturers and commercial and residential buildings.

Yet, the frequency and depth of data collection needs for increasingly important aspects of the energy system are in constant flux, including for energy consumption and energy-consuming equipment (in transport, buildings, and industry); alternative and distributed energy sources; electricity storage (e.g., capacity, charging, and discharging); energy equipment and component costs (e.g., for solar); allied issues such as emissions, water, critical materials (e.g., for energy storage and renewables); carbon dioxide utilization and storage; and energy infrastructure (including ash disposal sites and abandoned wells and mines). At the same time as we are experiencing significant evolution in the energy system, there is also tremendous evolution in information technology systems and in the availability of data collected by the private sector through numerous means. Taking stock of these evolving needs is warranted to ensure an energy information system that is positioned to support robust decisionmaking during a period of significant transition.

A number of resources are available to help underpin further assessment of our energy data systems, including:

- Improving the Quality and Scope of EIA Data (2011),
- Effective Tracking of Building Energy Use: Improving the Commercial Buildings and Residential Energy Consumption Surveys (2012)
- Transportation Energy Data Book (2021),
- How We Travel: A Sustainable National Program for Travel Data (2011),
- NREL energy data books,
- Annual U.S. Transmission Data Review (2018),

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- USGS Water Data for the Nation, and
- Openei.

With respect to energy modeling systems, the most important need is for EIA to establish and implement a plan for developing its modeling capability for the United States to assess strategies to achieve 100 percent clean electric power and net-zero greenhouse gas emissions economy-wide. Both are increasingly prominent policy objectives at the state, federal, and international levels and will entail substantial modeling innovations across virtually all sectors comprising the National Energy Modeling System (NEMS), which has a long history of development and evolution. There is also an increasing need for power sector-specific modeling that can complement NEMS and provide more granular assessment in space and time of reliability, storage, distributed generation, transmission grid modernization, demand response, integration with other sectors, electricity market design, and other issues related to deep decarbonization strategies that tend to require a power-flow model reflecting the physical nature of the electric power system. There have been efforts underway in the Department of Energy to improve this capability.

Questions from Senator John Barrasso, M.D.

Question 1: Based on the Intergovernmental Panel on Climate Change "Global Warming of 1.5°" report, the United Nations says that greenhouse gas emissions "would need to fall by about 45 percent from 2010 levels by 2030" for the world to be on a path to net zero emissions by 2050. As a consequence, many policymakers in the United States and elsewhere have called for cuts of this magnitude. Based on what you know today, do you expect global emissions in 2030 will be 45 percent lower than 2010 levels? If not, why?

To achieve emissions reductions of 45% relative to 2010 levels by 2030 would require enhanced public policies, increased investment and deployment of new technologies, and robust engagement with international partners. Without those actions it is extremely unlikely that emissions will decline to that degree. Although the costs of new energy technologies such as wind, solar, and energy storage have fallen dramatically in recent years, fossil fuels currently provide roughly 80% of primary energy for the U.S. and the world. Achieving the goals laid out by the IPCC is technically feasible but would require a change in policies beyond those already in place. Recent studies have laid out the opportunities to achieve these goals, but they will require robust efforts at all levels of government.

For a reference, turn to the IEA 2019 World Energy Outlook. The IEA projected the following reductions in CO_2 by 2030 relative to 2010:

- Current Policy case:
  Global: Increase 15% by 2030 relative to 2010
  U.S.: Decrease 14% by 2030 relative to 2010

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- Stated Policy case
  Global: Increase 23% by 2030 relative to 2010
  U.S.: Decrease 18% by 2030 relative to 2010
- Sustainable Development case:
  Global: Decrease by 17% by 2030 relative to 2010
  U.S.: Decrease 43% by 2030 relative to 2010

Based on these projections, 45% reductions by 2030 relative to 2010 levels are nearly achievable **for the U.S.** with policy consistent with the Sustainable Development Scenario, but global reductions would fall short. Hence more ambitious policy would be needed.

However, analogous estimates for 2040 relative to 2010 demonstrate the importance of time frames for energy system transitions:

- Current Policy case:
  Global: Increase 17% by 2040 relative to 2010
  U.S.: Decrease 26% by 2040 relative to 2010
- Stated Policy case
  Global: Increase 36% by 2040 relative to 2010
  U.S.: Decrease 17% by 2040 relative to 2010
- Sustainable Development case:
  Global: Decrease 48% by 2040 relative to 2010
  U.S.: Decrease 71% by 2040 relative to 2010

Based on these projections, global reductions of 48% by 2040 (not 2030) are achievable with policies in line with the IEA Sustainable Development Scenario.

Question 2: Do you agree that high energy costs are regressive and inequitable to lower-income people?

Low-income households and households of color currently spend a disproportionate share of their income on energy services. Rising energy costs could exacerbate this problem. However, certain policies that reduce greenhouse gas emissions can also help reduce energy poverty. In particular, research from RFF demonstrates that revenue-neutral carbon pricing policies can be progressive by returning revenues to Americans, which can more than offset higher energy costs due to the carbon price for low-income households.

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Questions from Senator Maria Cantwell

Question 1: Carbon Price

Two years ago during another hearing in this committee, almost all of the witnesses agreed by a show of hands that putting a price on carbon pollution, either indirectly or directly, is a good thing.

- Do you believe that an economy wide price on carbon, applied upstream where fossil fuels enter the economy, is the most efficient mechanism to decrease carbon emissions at the necessary scale and speed?

  Yes. Economists generally agree that an economy-wide carbon price is the most cost-effective method of emissions reductions. Research at RFF and many other institutions has consistently demonstrated the advantages of carbon pricing as a broad-based strategy for both reducing near-term emissions and providing the necessary incentives for longer-term innovation in low-carbon technologies.

- Do you believe that a predictable, market-based carbon price will incentivize the markets to reduce carbon emissions faster and more efficiently than could be achieved through direct regulation of emissions within specific industry sectors?

  Yes. Carbon pricing provides flexibility across sectors, and to each emitting firm, in a way that sector-specific polices cannot. Under carbon pricing, firms have the flexibility to decide the best way to reduce emissions, and the economy as a whole is stimulated to find the lowest cost options available for reducing emissions (across all sectors).

Question 2: CCUS and Nuclear

I strongly support efforts to boost innovation to help bring new forms of energy to the market, but unclear whether carbon capture utilization and storage (CCUS) technologies and nuclear technologies will ever be cost competitive with existing electricity generation sources without an economy wide price signal that accurately reflects the cost of carbon emissions.

- Do you think predictable carbon pricing is important to making CCUS technologies and advanced nuclear technologies economical and getting the private sector investments we need to ramp up these solutions?

  Yes. Predictable policies with clear and stable financial incentives are necessary for long-term financing of large projects. Predictable carbon prices provide clear incentives for both near-term investment in clean energy technologies, as well as longer-term innovation to lower the cost and increase the performance of these technologies in the future.

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- Do you think a predictable price on carbon is more likely to spur energy markets to invest in technologies like CCUS and advanced nuclear than additional funding for more intangible policies like additional R&D?

  Yes, both types of policies are highly desirable to accelerate clean energy innovation. Market signals sent by a predictable price on carbon will reward low (or zero) carbon technologies such as nuclear power. In addition, robust and stable public funding for research, development, and demonstration of advanced clean energy technologies is necessary to expand options, increase performance, and reduce the cost of a wide range of approaches for substantial economy-wide emissions reductions.

- Do you think predictable carbon pricing can help keep existing American nuclear reactors open that otherwise will shutdown?

  Yes. In its *Annual Energy Outlook 2020*, the EIA projected that, by 2028, a carbon price of $15 per ton would forestall the retirement of 8.3 GW to 9.2 GW of nuclear power through 2050. In addition to climate benefits, keeping those nuclear plants open would provide benefits to human health in the form of reduced local air pollution, well in excess of the costs of doing so.

Question 3: Aligning National Policies with Business Climate Goals

The past year could be remembered as a turning point in addressing the climate crisis with major corporations committing to decarbonize their operations by ever more aggressive timeframes as the private sector realizes that taking action to decarbonize is not only good socially, but also good for business.

- Why do you think businesses are committing to these bold greenhouse gas emission targets?

  Many leading businesses view themselves as having an institutional responsibility for their own emissions, others as a catalyst for achieving economy-wide adoption of responsible climate practices, and others simply view decarbonization of the economy as the direction society is heading due to the exigencies of climate change. Investors, shareholders, customers, and other corporate stakeholders are increasingly pushing for more action by corporations and have turned their attention beyond disclosure and transparency to commitments for action.

- Do these local and corporate emissions reduction activities have an impact on global emissions?

  Yes. Every individual action that reduces emissions contributes to overall global emissions reductions relative to what they otherwise would be. However, due to competitive forces between both firms and countries, systemic policy change is necessary to drive substantial and sustainable emissions reductions at a national and global level. Voluntary corporate actions and standardized financial disclosures are important to building experience, momentum, and support for economy-wide emissions reductions, but they need to be supported by mandatory emissions reduction strategies.

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- Do you believe a coordinated national policy will accelerate the commitments we're already seeing at the corporate level?

  Yes. A coordinated national policy would accelerate commitments from corporations, and it would enable them to operate successfully in a competitive environment while achieving broader societal needs for emissions reductions.

Question 4: China Winning the Clean Energy Race

There is no doubt that making the clean energy investments we need to stop carbon pollution is going to be a multi-trillion dollar global market opportunity. The question, I believe, is whether that market --and the millions of associated jobs-- will be captured by the U.S., or its foreign competitors.

China is the world's largest producer, exporter and installer of solar panels, wind turbines and electric vehicles. China is investing roughly $100 billion each year, double what the US and the EU combined invest.

- Is the U.S. losing the clean energy race to China and the rest of the world?

  No reply

- What does China's clean energy leadership mean in terms of global greenhouse gas emissions?

  No reply

- One common argument against taking action here in the U.S. is that it won't matter because the rest of the world will just keep on releasing carbon pollution – do you agree with that premise?

  No. Climate change is a global problem and requires all nations to act. Following similar announcements from the European Union, Japan, and South Korea, China announced in October 2020 its intention to reduce emissions to net zero by 2060. China has demonstrated its interest in being a world leader in clean energy and advanced manufacturing, seeing it as an economic driver of the future. By working with international partners, the United States can accelerate emissions reductions by reclaiming a leadership position on this issue, as well as taking concrete complementary steps with regard to R&D investment, technology transfer, climate finance, and other key aspects of addressing climate change. The only way to address this global commons problem and its impacts on the United States is to reduce national emissions (and take other complementary actions) and use that commitment and leadership to leverage reciprocal actions by other countries.

Question 5: Need to Upgrade the Grid to Handle more Renewables

Last year we saw renewable electricity generation in the U.S. exceed coal for the first time in over 130 years and it is expected to increase again in 2021, providing 21% of U.S. electricity. As our generation modernizes, we also need to modernize the grid to not only better integrate the rising share of renewables, but also to make the grid smarter and more resilient, including against cybersecurity threats.

- What do you think are the most effective tools government can provide to make the necessary grid investments?

  Transmission infrastructure is often built to address reliability concerns related to congestion on the grid, which is a fairly localized issue. There needs to be more focus on other reasons for grid expansion, including achieving our energy policy and greenhouse gas reduction goals and expanding regional electricity markets. To achieve the president's goal of substantially decarbonizing the grid in the next 15 years, more transmission infrastructure will be needed. Currently, those who essentially have monopolies on the transmission grid may not have strong desires to grow the grid as such expansion can reduce the possibilities for earning congestion rents. Therefore, allowing for competition in certain regions for transmission additions may be beneficial.

  Congress could clarify that FERC should focus on "beneficiary pays" models for transmission development to help spread the costs more equitably to all who benefit from new lines, instead of loading them on to projects (the "participant pays" approach). FERC has articulated the "beneficiaries should pay" principle, but it can do more to ensure it is applied in practice.

  DOE and FERC could work together to develop a national transmission plan that reflects all the goals of the federal government related to climate, clean energy, and renewables integration. Such a plan could serve as a roadmap for regional transmission planning. The focus could be on interstate transmission that needs to be prioritized, as it has been difficult to site in recent years. Congress could help to make these activities a priority for these agencies.

  FERC could create a new system for regional transmission planning that takes a regional view of benefits and does not automatically defer to the plans of investor-owned utilities (IOUs). This approach could create possibilities for competition in transmission development. FERC could exert more oversight of IOU transmission planning instead of deferring to states and IOUs.

  FERC needs to help accelerate the clean energy interconnection process for new projects. There is currently a long delay in many places, and projects are often abandoned solely due to the lack of access. In addition, FERC needs to do more to help plan transmission to facilitate interconnection with and access to markets for offshore wind power.

  Congress should clarify federal authority for transmission line siting (like national gas pipelines). Now more than ever, transmission planning is a national issue, not a local one.

  Congress could allocate more funding to DOE for research on a broader grid and on the benefits of developing a national DC grid.

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Congress could use tax credits to encourage transmission development that helps to bring renewables to market (similar to how they are used for solar and wind currently).

Congress could use an infrastructure bill to help fund transmission development in key locations of national importance or to fund loans for such projects, perhaps those that are identified as particularly crucial in the national transmission planning process referred to above.

- With the electric grid an essential piece of infrastructure in today's economy, what economic benefits or risks would we face if we don't invest in modernizing the grid?
  - Failure to invest in modernizing the grid could put both electricity decarbonization and economy-wide decarbonization goals at risk.
  - Failure to invest in transmission could raise the cost of renewables integration.
  - Failure to invest in modernizing the grid could raise the cost of electrification of transportation and other sectors by limiting access to clean electricity (or to cost-effective clean electricity).
  - Failure to invest in modernizing the grid could make the grid more vulnerable to outages due to attacks, weather, or other disrupters.
  - Failure to invest in transmission could limit access to low-cost renewables for certain customers. Limiting effective renewables integration could ultimately raise the cost of electricity to consumers.
- What more do we need to be doing to make sure our grid remains resilient, economic, and reliable?
  - DOE could allocate more funding to grid-related research to help in the development of future grid enhancements. The research should have both technical and regulatory/governance components.
  - Give serious consideration to the recommendations in the study from the National Academies, *The Future of Electric Power in the United States*.

Questions from Senator Mazie K. Hirono

Question 1: One important component of the trends in global carbon pollution emissions examined in the hearing is the damage that these emissions cause. In Hawaii we have among the most ambitious clean energy goals—to achieve 100 percent renewable power and a carbon neutral economy by 2045. Hawaii is ambitious because it has to be. Our coasts are eroding, our corals are bleaching, and our freshwater is being threatened. If the United States proceeds with the status quo and does not take bold, ambitious steps to mitigate climate change, what will that price tag be and what communities will pay that price?

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The social cost of carbon (SCC) is an estimate, in dollars, of the economic damages that would result from emitting one additional ton of carbon dioxide into the atmosphere. The SCC puts the effects of climate change into economic terms to help policymakers and other decisionmakers understand the economic impacts of decisions that would increase or decrease emissions. The SCC is currently used by the U.S. federal government, state governments, and foreign governments to account for the damages from climate change in their actions and to inform billions of dollars of policy and investment decisions.

RFF researchers are leading a team of distinguished economists and scientists to improve the science behind estimates of the social cost of carbon through a process that ensures the highest levels of scientific quality and transparency and builds the scientific foundation for future estimates. Specifically, the initiative is implementing the recommendations of the landmark National Academies of Sciences (NAS) report, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*.

Using the estimates developed by the Interagency Working Group on the Social Cost of Greenhouse Gases in 2016, and updating for inflation, results in a central estimate for the year 2020 of about $53 per ton of carbon dioxide at a 3 percent discount rate. Sensitivity cases result in $79 per ton and $15 per ton for alternative discount rates of 2.5 percent and 5 percent, respectively. These estimates and the underlying methods have been subject to multiple rounds of review by analysts, stakeholders, and the courts, and they represent the best estimates currently available for this purpose. Over the next year, RFF will complete its efforts to implement the near-term NAS recommendations, and will offer the outcomes to the recently reestablished Interagency Working Group as it implements the recent executive order related to producing revised estimates of the social cost of greenhouse gases by January 2022.

From a more local perspective, a recent report from RFF focused specifically on Florida and analyzed the projected impacts of climate change on the state by 2040. It found that climate change will result in more intense tropical storms, flooding, and human mortality. It also found that climate policies such as carbon pricing can reduce emissions while making low-income households better off.

Question 2: In your testimony, you noted that the cost reductions and technological advances in clean energy and other emissions reduction technologies mean that ambitious reductions are now achievable at substantially lower cost. The IEA stated in the 2020 World Energy Outlook that "solar projects now offer some of the lowest cost electricity ever seen." Setting aside for now the massive benefits from reducing the impacts of climate change, will consumers see lower energy bills in the future as we add more renewable sources of power?

- Compared to a situation without the substantial cost reductions that consumers have experienced, people have already seen lower electricity bills due to innovation in solar and wind power, which have benefited from cost reductions of about 70 percent and 90 percent respectively since 2009. As a result, solar and wind are now cost-competitive in many contexts compared to other power sources, even aside from their environmental benefits. In addition, several studies—including one from Princeton University and one from UC Berkeley's Center for Environmental Policy, GridLab, and Energy Innovation—

suggest that lower bills in the future are also possible. The reasons are in part that as more renewables (and other complementary resources, such as storage) are added to the grid, there can be greater learning that results in lower costs in the future. This possibility of greater learning is likely to be particularly true for storage, as its costs come down with more investment and experience. Another consideration, however, is that as the share of intermittent renewables becomes very high, the need for electricity storage, transmission, and/or backup generation grows as well, offsetting at least part of the direct cost reductions associated with the lower-cost renewable power generation. The impact on the overall system-wide cost will depend on the share of renewables, and reductions in the costs of these complementary technologies. Comparing costs across different electricity sources needs to be done with care, as renewables are intermittent and will necessitate additional investment to store energy, transmit it from the source to where the demand is, or to encourage flexibility at load sites (effectively, encouraging customers to store energy). This will require creativity and cooperation by state regulators and utilities, and customer willingness to shift electricity demand in time. Further research and analysis on the best ways to make all of these renewables-accommodating strategies work could be helpful.

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Questions from Senator Joe Manchin III

Question 1: It seems that the climate solutions we need are often made in China or in facilities it finances.

a. Given your research on China, can you describe sectors or technologies where China has outplayed the United States?

China leads the world in clean energy research and development. As mentioned in my written remarks, China's clean energy investment is number one in the world at $100 billion USD each year - double the United States and more than the United States and European Union combined.[1] These investments to develop a national innovation system with clean energy at the center have paid off - China is a leading manufacturer of wind, solar, and electric vehicle technology. China now leads the world in these technologies; five of the 10 largest wind turbine manufacturers and nine of the world's top 10 solar panel manufacturers are Chinese-owned or operated.[2] More than two-thirds of the world's solar panels and half of global wind turbines are produced in China.[3] China is also responsible for around 37 percent of passenger electric vehicles and 99 percent of the e-buses sold globally since 2011.[4] China is also leading in solar water heating technology and is the world's largest producer of hydropower.

b. Similarly, do you see opportunities for us to outcompete or even collaborate with China in emerging markets?

Both collaboration and competition with China in clean energy technology is possible. Deborah Seligsohn, Assistant Professor of Political Science at Villanova University, and I outline a path forward for U.S.-China collaboration and competition on climate change and clean energy in a white paper we wrote a few months ago.[5] We recommend that the U.S. and China can cooperate and compete through developing a "winning coalition"[6] industrial policy approach that links sector-specific climate policies with local issues; that sends direct, high-stakes, and clear signals to motivate industrial actors; that sequences policies to ensure long-term stability of decarbonization strategies. Examples of green industrial policies include aggressive policies that work towards powering all electricity through zero-emissions and renewable energy sources; setting targets for zero-emissions in the buildings and transportation sectors; and galvanizing growth in green jobs and manufacturing. Already, some U.S. cities and states have adopted these targets, including Minnesota, which has

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[1] REN-21. (2020). https://www.ren21.net/gsr-2020/chapters/chapter_05/chapter_05/
[2] *ibid.*
[3] *ibid.*
[4] Bloomberg New Energy Finance. (2018).Cumulative Global EV Sales Hit 4 Million. Available: https://about.bnef.com/blog/cumulative-global-ev-sales-hit-4-million/
[5] Hsu, A. and D. Seligsohn. (2020). Future U.S.-China Cooperation on Climate Change: Working Towards a Green New Deal. Available: https://cpb-us-w2.wpmucdn.com/web.sas.upenn.edu/dist/b/732/files/2020/10/Angel-Hsu-Deborah-Seligsohn_Future-U.S.-China-Cooperation-on-Climate-Change_Final.pdf
[6] Jonas Meckling, Nina Kelsey, Eric Biber, and John Zysman. "Winning coalitions for climate policy," Science 349, no. 6253 (2015): 1170-1171.

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proposed sourcing the state's entire electricity needs from carbon-free sources by 2030[7] and Los Angeles, which has a target to increase the number of zero-emission vehicles to 100 percent by 2050.[8]

The U.S. and China can compete with each other through nationally-focused green industrial policies, but they can also cooperate on this front as well. California has has even signed several memoranda of understanding (MOUs) directly with China, including a cleantech partnership, which commits to exchange policies on emissions trading, zero emissions vehicles, building energy efficiency, etc.[9] The U.S. and China have commonalities with respect to climate change and energy issues that lend well to cooperation. As the two largest emitters on greenhouse gas emissions, both countries must rapidly shift from fossil fuel dependencies in order to achieve decarbonization by mid-century. Both countries also need to consider "just transitions" of workers from fossil fuel industries into clean energy sectors. The U.S.'s reengagement to the Paris Climate Agreement is a first step in reestablishing global trust in the U.S.'s contribution to global climate mitigation efforts. John Kerry as the U.S. Special Envoy on Climate Change has a longstanding relationship with his Chinese counterpart, Vice Minister Xie Zhenhua, which will also help facilitate exchange and cooperation between the U.S. and China on climate change.

Question 2: One of the undercurrents in the changing energy mix has been shifts within the financing markets, including commitments made in the private sector by Fortune 500 companies, sovereign wealth funds and private equity groups, and utilities in response to customer preferences.

a. What lessons learned, either globally or domestically, can we take from the last few years of these trends – both the pitfalls to watch out for and the opportunities within these drivers?

My research has been tracking the growth in private and non-state actor climate change commitments since they were formally recognized as a key pillar of achieving global climate goals through the Paris Agreement. On the one hand, the growing momentum by these private and non-state actors is a boon for the global climate. National government policies fall woefully short of delivering the needed emission cuts for us to be on track towards the 1.5 degrees C global temperature rise goal.[10] Our research has shown that at least 450 or 20 percent of the world's largest companies according to the Fortune Global 500 and Global Forbes 2000 lists are engaged in voluntary climate action and have set their own emission reduction targets.[11] Combined with the efforts of

[7] Bjorhus, J. (2021). Legislators push to shrink Minnesota's carbon footprint to zero by 2050. Minnesota Star Tribune, Feb. 5. Available: https://www.startribune.com/legislators-push-to-shrink-minnesota-s-carbon-footprint-to-zero-by-2050/600019340/.
[8] "Sustainable City pLAn," https://plan.lamayor.org/ on Eric Garcetti, Mayor of Los Angeles, "Sustainability," https://www.lamayor.org/sustainability.
[9] Hsu, A. and D. Seligsohn. (2020). Future U.S.-China Cooperation on Climate Change: Working Towards a Green New Deal. Available: https://cpb-us-w2.wpmucdn.com/web.sas.upenn.edu/dist/b/732/files/2020/10/Angel-Hsu-Deborah-Seligsohn_Future-U.S.-China-Cooperation-on-Climate-Change_Final.pdf
[10] United Nations Environment Programme (2020). Emissions Gap Report 2020. Nairobi.
[11] NewClimate Institute, Data-Driven Lab, et al. (2020). Global Climate Action from Cities, Regions, and Businesses: 2019 edition. Available: http://datadrivenlab.org/wp-content/uploads/2019/11/Report-Global-Climate-Action-from-Cities-Regions-and-Businesses_2019.pdf

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regional and city governments, the potential for private actors to reduce global emissions beyond national governments is estimated to be around 1.0-2.0 gigatonnes of carbon dioxide per year. There is a real opportunity for national governments to work together with these actors to increase the ambition of government climate policies and to further help finance and accelerate existing efforts. Given the OECD estimates $6.9 trillion USD per year to 2030 is required in infrastructure investments to meet the Paris Agreement's 1.5 degrees C goal, it is critical for governments to engage the private sector on climate change.[12] Public investment is vastly insufficient to meet the nearly five-time annual increases in low-carbon energy and energy-efficiency[13] required.

In terms of pitfalls, there are still open questions with respect to the implementation of private sector pledges. Since many private sector pledges occur outside of a formal regulatory context, meaning that companies or financial institutions may voluntarily make a climate commitment that is beyond any regulatory requirement, such promises may be made in good faith only. There is risk of "greenwashing," whereby corporations make climate pledges nominally and fail to follow through. There is also risk of rollbacks from other actors, whereby other corporate, city or national government actors may decide to weaken their own climate efforts based on private actors' efforts.

b. Where have the foreign investments made by other countries, including China, made the most notable recent impacts in energy markets?

Since I am most familiar with China's energy investments in emerging markets and developing countries, I will focus on these areas, although China has also invested in developed country energy markets,[14] and provide an overview of where China has made an impact in foreign energy investments through its own development banks as well as through the Belt and Road Initiative (BRI).

China's two main development banks have been key players in China's investment in global energy markets through direct loans and also the BRI.[15] The Belt and Road Initiative has been a major pathway through which China's financing for energy and infrastructure projects has flowed. First announced in 2013, BRI is an international development plan that promises to invest $1 trillion (US) in energy and infrastructure projects across more than 100 countries, although there lacks a clear definition of what constitutes an official "BRI" project.[16] The Chinese Development Bank and Chinese Import-Export Bank (EXIM) have financed an estimated $246 billion USD in the global energy sector between 2000 and 2014 - more than all Western

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[12] OECD, World Bank, and UN Environment. (2018). Financing Climate Futures. Available: https://www.oecd.org/environment/cc/climate-futures/policy-highlights-financing-climate-futures.pdf.
[13] IPCC (2018), Global Warming of 1.5 degrees C, Intergovernmental Panel on Climate Change, Geneva, http://www.ipcc.ch/report/sr15/.
[14] Li, Z., Gallagher, K. P., & Mauzerall, D. L. (2020). China's global power: Estimating Chinese foreign direct investment in the electric power sector. Energy Policy, 136, 111056.
[15] Liu, C. and Urpelainen, J. (2021). Why the United States should compete with China on global clean energy finance. Brookings Institute. Available: https://www.brookings.edu/research/why-the-united-states-should-compete-with-china-on-global-clean-energy-finance/
[16] Ang, Y. (2019). Demystifying Belt and Road: The Struggle to Define China's "Project of the Century". Foreign Affairs. Available: https://www.foreignaffairs.com/articles/china/2019-05-22/demystifying-belt-and-road

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development banks combined.[17] The World Resources Institute (WRI) and Boston University researchers found that of the $143 billion that China's public banks invested in BRI countries from 2014 - 2017, three-fourths went to finance oil, gas, and petrochemical projects.[18] The power sector is one of the key energy sectors where Chinese investment flows. Coal accounts for a quarter of BRI financing, with highly polluting coal-fired plants receiving about $56.1 billion USD over the last 20 years, although the amount, as with other fossil fuel sectors such as oil, invested has fallen in the last three years.[19] Through overseas project contracting, Chinese companies have been competitive in securing bids to develop energy sector projects, many of which have been concentrated in South Asia and Southeast Asia, although there have been plans to expand to other parts of Asia and Central and Eastern Europe.[20] As of late 2020, however, China's leadership signalled its intent to no longer support additional overseas coal-fired power, with the country's head climate envoy, former Vice Minister Xie Zhenhua announcing at a European business forum that China has issued a green finance catalogue to make clear it will no longer support coal-projects.[21]

At the same time, China has been investing more than any other country in renewable energy overseas, at $32 billion in 2017, and increasing this amount over time.[22] Part of this investment is led by Chinese renewable energy companies, which are increasingly seeking opportunities in developing and low-income countries as they grow market share in global wind and solar power technology. These investments are being made in a range of geographic locations, including both developed and developing countries. Boston University's Global Energy Finance Database is one of the most comprehensive catalogues of China's overseas investments through the BRI and its two major development banks over the past decade.[23] For projects under construction or in development, wind and solar projects comprise around 12 percent, with a rise in hydropower investments to around one-third.[24] Both Europe and Latin America are the largest beneficiaries of the 12,166 MW wind power capacity China has invested overseas, both comprise 35 percent each; for solar, Latin America and North America comprise just over half of installed capacity receiving Chinese support.[25] China is also supporting 9,045 MW of nuclear capacity buildout primarily in Europe/Central Asia and South Asia. We would expect the share of overseas investments in renewable energy increases as demand abroad increases. China's

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[17] Kong, B., Gallagher, K.P., 2017. Globalizing Chinese energy finance: the role of policy banks. J. Contemp. China 26 (108), 834–851; Liu and Urpelainen (2021).

[18] L. Zhou, S. Gilbert, Y. Wang, M. Muñoz Cabre, and K.P. Gallagher. 2018. "Moving the Green Belt and Road Initiative: From Words to Actions.." Working Paper. Washington, DC: World Resources Institute. Available online at http://www.wri.org/publication/moving-the-green-belt.

[19] Boston University Global Policy Development Center. China's Global Energy Finance. Available: https://www.bu.edu/cgef/#/all/EnergySource.

[20] Ren, P., Liu C. and Zhang L (2017). China's Involvement In Coal-fired Power Projects Along The Belt And Road. Global Environmental Institute. Available: http://www.geichina.org/_upload/file/report/China's_Involvement_in_Coal-fired_Power_Projects_OBOR_EN.pdf.

[21] Mission of the People's Republic of China to the European Union. (2020). Xie Zhenhua Attends China-EU High-level Forum on Green Cooperation. Nov. 19. Available: http://www.chinamission.be/eng/mh/t1833687.htm.

[22] Jiang, K. and J. Woetzel. (2017). How China is leading the renewable energy revolution. The World Economic Forum Agenda blog. Available: https://www.weforum.org/agenda/2017/08/how-china-is-leading-the-renewable-energy-revolution.

[23] Boston University Global Policy Development Center. China's Global Energy Finance. Available: https://www.bu.edu/cgef/.

[24] Springer, C. (2020). Greening China's overseas energy projects. China Dialogue. Available: https://chinadialogue.net/en/energy/greening-chinas-overseas-energy-projects/.

[25] ibid.

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manufactured solar photovoltaic panels are more cost-competitive due to economies of scale and the country's expert supply chains, making them 20 percent more cost-effective than U.S. counterparts.[26] It is no surprise that China is responsible for more than 60 percent of global solar cell production.[27]

Question 3: One of the problems we face is ensuring that energy and emissions data is easily available, detailed, and verifiable. Unlike the U.S. and other developed economies, the capacity to obtain and verify data may be low, and potentially subject to political interference. Recent articles reported that China has announced 72GW of new wind capacity in 2020, more than the rest of the world combined.

a. Is this an example of data that lacks verification, or is this a fact of China's ambition on clean energy?

The National Energy Agency announcement that China had installed 72 GW of new wind power capacity in 2020 - more than double its previous record, as well as 49 GW of solar power, the most since 2017, is certainly impressive and surprised analysts, considering that total global wind installations in 2019 were only 60 GW.[28] Having consulted on-the-ground clean energy experts in China, my conclusion is that there are a few factors that could explain this high number. First, China exceeded predictions of its 2020 installed wind and solar capacity, which the International Energy Agency (IEA) had already predicted would be high - 32 GW of wind and 50 GW of solar.[29] A few factors could have precipitated China's reported exceedance of these numbers. China's feed-in tariff, which provides a subsidy to encourage production of wind energy, was planned to end at the end of 2020. A late-year rush, after much of economic activity was stalled due to COVID-19 in 2020, could have explained the spike in numbers from project developers seeking to lock-in the feed-in premium before it expired, resulting in 46 GW and 22 GW of solar in December alone.[30] A second explanation that could explain the spike in numbers is from analysts positing that China could have changed the definition for how installations are counted to include permitted or partially completed projects instead of only counting those that are fully commissioned and connected to the electric grid.[31] Analysts I spoke with do not think that this high increase in the numbers imply a lack of data verification and certainly believe this increase is in the realm of possibility for China, given that the pipeline of known or planned wind projects was certainly enough to reach 72 GW at the end of 2020.

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[26] Goodrich, A. C., Powell, D. M., James, T. L., Woodhouse, M., & Buonassisi, T. (2013). Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy & Environmental Science, 6(10), 2811-2821.
[27] Timperely, J. (2018). China leading on world's clean energy investment, says report. Carbon Brief. Available: https://www.carbonbrief.ochina-leading-worlds-clean-energy-investment-says-report
[28] Murtagh, D. (2021). China Blows Past Clean Energy Record With Wind Capacity Jump. Bloomberg News. Available: https://www.bloomberg.com/news/articles/2021-01-20/china-blows-past-clean-energy-record-with-extra-wind-capacity#:~:text=China%20blew%20past%20its%20previous,than%20double%20the%20previous%20record.
[29] IEA. (2020). Renewables 2020. Available: https://www.iea.org/reports/renewables-2020
[30] Deign, J. (2020). What Is Going On With China's Crazy Clean Energy Installation Figures?. Available: https://www.greentechmedia.com/articles/read/what-is-going-on-with-chinas-crazy-clean-energy-installation-figures.
[31] ibid.

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b. While China is increasing its build-out of renewable energy, what is the trend on fossil energy in the past decade?

While China's energy mix is still predominantly reliant on fossil fuels, and in particular, coal. As mentioned in my written testimony, coal in 2018 comprised around 62 percent of its total primary energy supply and 65 percent of electricity generation.[32] The world's largest producer and consumer of coal, China also tops the world in terms of global installed coal-fired electricity power.[33] Oil and natural gas are also prominent in China's energy supply, comprising 27 percent as of 2018.[34]

In terms of pace, China has set targets for increasing the percentage of non-fossil energy as part of its energy mix. In the 13th Five-Year Plan, China set a target for increasing non-fossil energy in total primary energy consumption to 15 percent by 2020 and to 20 percent by 2030. China has been successful in steadily reaching these targets. According to the International Energy Agency (IEA), coal comprises 65 percent of China's electricity mix, down from 77 percent in 2010. In terms of total primary energy, coal comprised 62 percent of supply, down from 71 percent in 2010.[35] In terms of the historical trend over the past decade, coal supply has grown by about 10.5 percent, while coal consumption has grown by 11.5 percent.[36] There is evidence, however, of carbon reduction policies starting to take effect in China - from 2015 to 2018 coal supply decreased (for the first time in recent years) by just under 1 percent according to the IEA.[37]

Oil and natural gas continue to play a supporting role to coal in the overall energy supply mix, but not in the electricity generation mix. Here, hydropower remains the second largest source of electricity generation at 17 percent, followed by wind and nuclear at 5 percent each. Since 2010, non-fossil energy (renewables and nuclear) have increased their share in the electricity generation mix from 21 to 32 percent. Therefore, the overall fossil picture in China is still one dominated by coal, but also one that is in the beginning stages of transition. Growth of both consumption and production of coal have slowed in recent years, compared to oil and gas consumption which have remained much more steady (see Figure 1 below).

[32] International Energy Agency. (2020). China. Available: https://www.iea.org/countries/china.
[33] Global Energy Monitor. (2020). Global Coal Plant Tracker. Available: https://endcoal.org/global-coal-plant-tracker/
[34] International Energy Agency. (2020). China. Available: https://www.iea.org/countries/china.
[35] IEA. (2021). *China—Countries & Regions*. IEA. Retrieved March 1, 2021, from https://www.iea.org/countries/china
[36] BP (2020)
[37] *ibid.*

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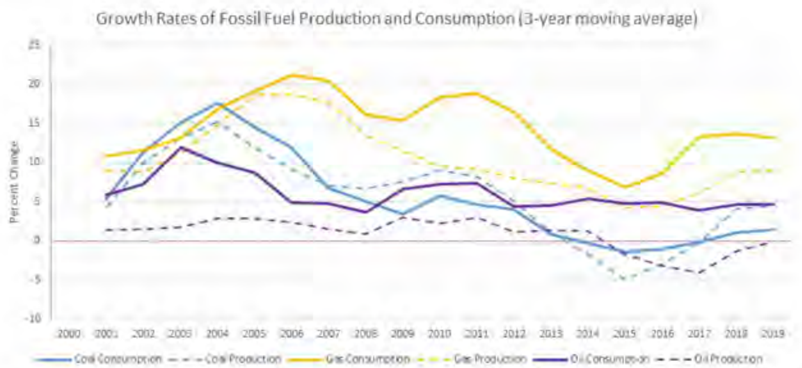

Figure 1. Three-year moving average of fossil fuel production and consumption growth rates in China. (Data source: BP Statistical Review of Energy; figure created by Brendan Mapes, Data-Driven EnviroLab).

c. Is China still adding new fossil capacity to their power and industrial sectors?

While China is leading the world in terms of clean energy investment and installed capacity for wind and solar power,[38] they are still adding new fossil capacity to their electricity generation and industrial sectors. China brought 38.4 gigawatts of new coal-fired power online in 2020,[39] which after taking decommissions into account raised net capacity by 29.8 GW. China also initiated 73.5 GW of new coal plant proposals in 2020, which was over five times the 13.9 GW initiated in the rest of the world. Despite the increase in coal-fired power capacity, the utilisation rate of the existing fleet continues to decline, signalling a persistent problem of oversupply that's been covered widely by energy reporting outlets. In 2020, coal plants in China were running just 45 percent of the time, almost 10 percent lower than the global average.[40]

While these additional fossil capacity numbers may seem incompatible with China's Paris Agreement targets and climate goals, there are a few points to consider. The coal-fired power plants the Chinese are building are

[38] REN-21. (2020). Renewables 2020: Global Status Report. (Paris: REN21 Secretariat). Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf.REN-21. (2020). Renewables 2020: Global Status Report. (Paris: REN21 Secretariat). Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf.
[39] Stanway, D. (2021, February 3). China's new coal power plant capacity in 2020 more than three times rest of world's: Study. *Reuters*. https://www.reuters.com/article/us-china-coal-idUSKBN2A308U
[40] EMBER. (2020). *Global Half-Year electricity analysis*. https://ember-climate.org/wp-content/uploads/2020/08/Report-Ember-Global-Electricity-Review-H1-2020.pdf

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more efficient than their predecessors, and more efficient than existing plants in the United States.[41] At the same time, China is shutting down and canceling outdated, inefficient and more polluting coal-fired power plants. The Global Energy Monitor reports that China has already decreased its pipeline of plants being built or planned by more than 70 percent since the end of 2015, with 134GW of planned capacity cancelled in 2019 alone.[42] A recent report by the China's Central Environmental Inspection Group (CEIP) revealed criticism of the National Energy Administration's continued approval of large coal-fired projects and indicating a crackdown on its lax enforcement, suggesting that we would expect to see more cancellations of coal-fired capacity moving forward.[43]

Xi Jinping's carbon neutrality target by 2060 will almost certainly reverse this trend, however, as projections anticipate China will need to nearly eliminate fossil fuels from its electricity mix to meet this goal.[44] China's top climate think tank - the Institute for Climate Change and Sustainable Development (ICCSD) at Tsinghua University - has put forth recommendations that coal consumption should peak between now and 2025, and that new coal power capacity should be strictly controlled.[45] Under ICCSD recommendations, between 2030 and 2050 the share of coal in the energy mix would decline by 1.8 percent per year, while non-fossil energy share would increase by percent per year.

China's upcoming adoption of its 14th Five-Year Plan (2021-2025) and subsequent sector-specific roadmaps, including one for its energy sector, will determine the degree of additional fossil capacity to be added in the short-term. In the short-term, until China peaks emissions, it is expected that the country's fossil fuel capacity in both the electricity and industrial sectors will continue to grow as stop-gap measures to meet demand. A low-carbon transition could be accelerated to meet this demand with mostly renewables, some expansions in gas-fired power capacity, as well as battery storage and pumped storage hydropower. In particular, gas-powered energy generation could see as much as a 40-50 GW increase by 2025, or 50 percent above current levels.[46] PetroChina, China's top natural gas supplier, predicts that natural gas consumption could double over the next

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[41] Hart, M., L. Bassett, and B. Johnson. (2017). Everything You Think You Know About Coal in China Is Wrong. Center for American Progress. Washington, D.C. Available: https://www.americanprogress.org/issues/green/reports/2017/05/15/432141/everything-think-know-coal-china-wrong/.
[42] Global Energy Monitor. (2019). Boom and Bust 2019. Available: https://endcoal.org/global-coal-plant-tracker/reports/boom-and-bust-2019/
[43] China Ministry of Ecology and Environment. (2021). The Sixth Central Ecological and Environmental Protection Supervision Group feedback to the National Energy Administration. Available: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202101/t20210129_819526.html; Carbon Brief. (2021). Q&A: Could an environmental inspector's criticisms accelerate China's climate policies?. Available: https://www.carbonbrief.org/qa-could-an-environmental-inspectors-criticisms-accelerate-chinas-climate-policies
[44] Myllyvirta, L. (2020, October 14). Influential academics reveal how China can achieve its 'carbon neutrality' goal. *Carbon Brief*. https://www.carbonbrief.org/influential-academics-reveal-how-china-can-achieve-its-carbon-neutrality-goal.
[45] Myllyvirta, L. (2020, October 14). Influential academics reveal how China can achieve its 'carbon neutrality' goal. *Carbon Brief*. https://www.carbonbrief.org/influential-academics-reveal-how-china-can-achieve-its-carbon-neutrality-goal
[46] Oxford IES. (2020). *Natural gas in China's power sector: Challenges and the road ahead*. Oxford Institute for Energy Studies. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/12/Insight-80-Natural-gas-in-Chinas-power-sector.pdf

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15 years.[47] Because of China's carbon neutrality commitments, the role of natural gas would likely be limited to medium-term demand gap-filling, until more commercially-viable battery storage options come online.[48]

Question 4: As we look to tackle climate change and transition to a cleaner energy future, we cannot abandon the communities in traditional energy states like West Virginia. This challenge is not unique to the United States. China has an extensive coal sector for power generation and industry, which may pose similar problems as the Chinese leadership considers its own energy transition.

a. What background can you provide on the coal sector and its employment trends in China?

Since 2016 China has been deliberately drawing down the number of employment opportunities in the coal and steel sectors to deal with oversupply and respond to environmental pollution concerns. By 2018, direct coal industry employment was estimated to be 3.2 million jobs, down from 4.9 million in 2014.[49] This drawdown has been accompanied by re-skilling and long-term safety net payments for workers who are at risk of being displaced (the total number estimated being 1.8 million coal and steel workers or around 10 percent of those employed in these sectors).[50] China has already pledged 100 billion RMB (around 14.3 billion USD) to aid workers made redundant due to central government policies to shrink both the coal and steel industries.[51]

Question 5: Although the U.S. EIA has a strong record of comprehensive data collection and analysis, change in the energy sector is accelerating and may increasingly uncover gaps related to factors such as the rapid integration of renewable generators on the grid, the build-out of electric vehicle infrastructure, the energy-water nexus and the supply of critical minerals. Globally, the energy emissions information may not be as detailed or reliable, while also increasingly subject to the new factors mentioned above.

a. Are there actions you would recommend to improve the energy data and modeling systems in the U.S. and internationally?

b. What are the prospects and opportunities for further developing independent verification measurements of energy use and emissions, such as the remote sensing observations you mentioned?

Since these two questions are related, I will address them together. There is a lot of potential for energy and climate data to improve given advances in machine learning, computational processing capabilities, and the emergence of new data sources, including satellite remote sensing data and sensors connected through the

[47] Weijun, S. (2020, October 20). PetroChina predicts massive Chinese gas demand growth. *Petroleum Economist*. https://pemedianetwork.com/petroleum-economist/articles/geopolitics/2020/petrochina-predicts-massive-chinese-gas-demand-growth
[48] Oxford IES (2020)
[49] He, G., Lin, J., Zhang, Y., Zhang, W., Larangeira, G., Zhang, C., Peng, W., Liu, M., & Yang, F. (2020). Enabling a Rapid and Just Transition away from Coal in China. *One Earth*, *3*(2), 187–194. https://doi.org/10.1016/j.oneear.2020.07.012
[50] LeVine, S. (2017, November 22). The big layoff in China. *Axios*. https://www.axios.com/the-big-layoff-in-china-1513307124-6bf18f3d-834d-430e-9a32-a42403f794ba.html
[51] He et al. (2020).

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Internet of Things (IoT). My colleagues and I wrote about the existing gaps in climate emissions monitoring and data, and the potential for new technologies to address them in an open access article in *Frontiers in Big Data*.[52] In brief, there are some recommendations that could accelerate the kinds of technological solutions we address in this article to respond to some of the challenges that are outlined above and that could be more responsive when there are new gaps that emerge:

- Investigate the potential for machine-learning and AI applications: advances in computational processing and modeling are already being used in energy and climate modeling but could be expanded to cover larger geographies and more sectors. The Climate Change AI project[53] provides an overview of AI and ML-based approaches in a range of energy-related sectors, from transport to building electricity consumption. Notably, the consortium of researchers contributing to this analysis evaluate the potential and leverage to extend AI/ML-based approaches to each sector and application. Demand and supply forecasting in the electricity sector, for example, has high potential for AI/ML to allow for real-time electricity scheduling and long-term planning.
- Open access data and data sharing: the machine-learning algorithms mentioned above, however, are only as powerful and accurate as the underlying data that is used to train them. More incentives should be provided to encourage both public and private actors to share energy and climate-related data that could be shared as a public good to develop ML/AI-based approaches that could then be replicated to other contexts and parts of the world. Engaging large tech companies would be critical to utilize existing cloud and security infrastructure to provide protected and even anonymized access to data in a way that allows for developers and researchers to develop these ML/AI models.
- Leverage new data sources: satellites with increasing higher resolution to monitoring energy-related emissions are improving and coming online every day. The Environmental Defense Fund, for example, is developing MethaneSAT, a satellite that will provide global, high-resolution data of methane emissions - a currently poorly monitored and tracked greenhouse gas with a 20x higher global warming potential than carbon dioxide. We detail in the *Frontiers in Big Data* paper how a growing ecosystem of sensors connected through the IoT provides potential to monitor in real-time energy and emissions sources, including vehicles, buildings, shipping, and others.

Questions from Senator John Barrasso, M.D.

Question 1: Global Energy Monitor and the Helsinki-based Centre for Research on Energy and Clean Air recently reported:

> *While appetite for new coal power investments is slowing throughout most of the world, it is on the rise in China. In 2020, China built over three times as much new coal power capacity as all other countries in the world combined – the equivalent of more than one large coal plant per*

[52] Hsu, A., Khoo, W., Goyal, N., and M. Wainstein. (2020). Next-generation Digital Ecosystem for Climate Data Mining and Knowledge Discovery: A Review of Digital Data Collection Technologies. in Special Issue: Innovations and Perspectives in Data Mining and Knowledge Discovery. Frontiers in Big Data.
[53] Climatechange.ai

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> *week. In addition, over 73 gigawatts (GW) of new coal power projects were initiated in China, five times as much as in all other countries, while construction permits for new coal projects also accelerated.*

Is it fair to say that coal will continue to remain the primary source of electricity generation in China for the next couple of decades?

There are several dozen projections, both by Chinese researchers and analysts as well as international groups, that speculate China's future energy trends. Prior to President Xi Jinping's Sept. 2020 carbon neutrality announcement, many of them, including BP's energy demand forecast and the China National Petroleum Corporation's, predicted coal remaining a dominant sector in the country's energy demand.[54] As mentioned in my written testimony, coal cannot remain a primary source of electricity generation in China if it plans to meet its newly announced carbon neutrality target. Chinese climate and energy modelers have already developed a new roadmap that will completely phase out coal by 2050 and generate 90 percent of all electricity from non-fossil sources, including renewables and nuclear energy. To do this will require a 16-fold increase in solar energy, a nine-fold growth in wind power, and increasing nuclear power by six times and doubling hydroelectricity.[55]

<u>Question 2</u>: You have noted that Article 8 of "Regulations of the People's Republic of China on Open Government Information" states:

> *The government information disclosed by administrative organs may not endanger state security, public security, economic security and social stability.*

In your view, can emissions and energy data from the Chinese government be trusted?

I believe the Chinese government has made great strides over the last decade to improve its emissions and energy data, both in terms of accuracy and transparency. Since 2007, China's Ministry of Environmental Protection (MEP) has required thousands of power plants to install continuous emissions monitoring systems (CEMS) on exhaust stacks and to upload these data on an hourly, pollutant-specific basis to a website available to the public.[56] In 2010 the MEP reported that 7,988 state-controlled enterprises had installed CEMs, although some studies suggest that there currently are over 10,000 CEMs that measure emissions from air and other

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[54] Meidan, M. (2019). Glimpses of China's energy future. Oxford Institute for Energy Studies, Oxford University. Available: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/09/Glimpses-of-Chinas-energy-future.pdf.

[55] Mallapaty, S. (2020). How China could be carbon neutral by mid-century. Nature; Myllyvirta, L. (2020). Influential academics reveal how China can achieve its carbon neutrality goal. Carbon Brief. 14 October. Available: https://www.carbonbrief.org/influential-academics-reveal-how-china-can-achieve-its-carbon-neutrality-goal

[56] Schreifels JJ, Fu Y, Wilson EJ (2012) Sulfur dioxide control in China: Policy evolution during the 10th and 11th five-year plans and lessons for the future. Energy Policy 48:779–789; Hsu, A. (2013). Environmental Reviews And Case Studies: limitations and challenges of provincial environmental protection bureaus in China's environmental data monitoring, reporting and verification. Environmental Practice, 15(3), 280-292.

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parameters, at power plants alone throughout the country.[57] The latest numbers indicate that 96 to 98 percent of China's total thermal capacity is now covered by CEMS, with air pollutant emissions data for sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) publicly available and accessible for analysis and independent verification.[58] International scholars have evaluated these CEMS data of regulated power plants and verified reported reductions in air pollution, primarily sulfur dioxide emissions generated from fossil fuel combustion, using both government-reported CEMS and independent satellite data, derived from U.S.-based satellites and sensors.[59] The spatial and temporal resolution for independent satellites to continuously monitor global emissions should continue to improve as national governments and private actors further invest in these systems, allowing for further independent verification of not only China's climate policy implementation but other countries as well.[60]

China has also recently released a critical report of the Central Environmental Inspection Group's (CEIP) evaluation of the National Energy Administration (NEA), China's government agency that oversees the country's energy industries.[61] The report indicated a crackdown on the NEA's lax enforcement of its interpretation and implementation of environment and climate policies. The openly critical nature of this report indicates a renewed and transparent seriousness with which the Chinese government is tightening enforcement on energy policies.

<u>Question 3</u>: China disposes very high volumes of batteries and other electronic-waste every year. Can you discuss some of the issues surrounding the waste stream from advanced and renewable energy and storage technologies in China?

In per capita terms, China generates a volume of e-waste (7.2 kg/capita) that is just below the global average (7.3 kg/capita).[62] In absolute terms, China (10.1 million tonnes), the United States (6.9 million tonnes), and

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[57] Zhu, F., H. Li, and S. Qiu. (2010). Development and application prospects of gas continuous emission monitoring systems. Environmental Monitoring Management and Technology 22(4):10–14. in Chinese.
[58] Tang, L., Xue, X., Qu, J., Mi, Z., Bo, X., Chang, X., ... & Dong, G. (2020). Air pollution emissions from Chinese power plants based on the continuous emission monitoring systems network. Scientific Data, 7(1), 1-10.
[59] Karplus, V. J., Zhang, S., & Almond, D. (2018). Quantifying coal power plant responses to tighter SO2 emissions standards in China. Proceedings of the National Academy of Sciences, 115(27), 7004-7009.
[60] Hsu, A., Khoo, W., Goyal, N., and M. Wainstein. (2020). Next-generation Digital Ecosystem for Climate Data Mining and Knowledge Discovery: A Review of Digital Data Collection Technologies, in Special Issue: Innovations and Perspectives in Data Mining and Knowledge Discovery. Frontiers in Big Data.
[61] China Ministry of Ecology and Environment. (2021). The Sixth Central Ecological and Environmental Protection Supervision Group feedback to the National Energy Administration. Available: https://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202101/t20210129_819526.html; Carbon Brief. (2021). Q&A: Could an environmental inspector's criticisms accelerate China's climate policies?. Available: https://www.carbonbrief.org/qa-could-an-environmental-inspectors-criticisms-accelerate-chinas-climate-policies
[62] Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann,P. : The Global E-waste Monitor – 2021, United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), https://globalewaste.org/map/

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India (3.2 million tonnes) were the top 3 e-waste offenders in 2020, generating 38% of the global e-waste stream.[63]

The e-waste stream in China has historically gathered significant global attention because of the high degree of informality in the e-waste processing and recycling sector, which has had the side-effect of severely degrading environmental areas around large e-waste processing centers such as Guiyu in Guangdong province. There have been increased efforts however to formalize the e-waste recycling and processing industries in China, especially since 2015.[64]

As far as batteries specifically are concerned, China does generate a significant volume of batteries and battery waste as the world's largest manufacturer of lithium ion batteries for EVs – but China also recycles by far the largest volume of batteries in the world as well. In 2019, China recycled around 69 percent of the total battery stock available for recycling globally, or around 67,000 tons of lithium-ion batteries.[65]

Part of the e-waste issue in China is also a by-product of macroeconomic realities globally. China has been a large importer of e-waste streams (among other waste) from developed countries historically, and has been imposing increasingly strong import bans on e-waste (and other waste materials) since 2018.[66] The global economics of waste processing made China a favorable end-market but the new restrictions, which have purportedly been due to environmental health and sustainability concerns for the Chinese population, have meant that higher-income nations have been forced to find new countries to export waste to for recycling, because the processing capacity often does not exist domestically, or would represent a significant increase in costs.[67]

Question 4: Do you agree that high energy costs are regressive and inequitable to lower-income people?

Yes, I agree, but shifting the costs and impacts of climate change to lower-income people is also equally, if not, more damaging and inequitable. Global economic impacts of climate change could cost as much as $7.9 trillion

[63] Forti, V., Baldé, C.P., Kuehr, R., and Garam Bel. (2020). The Global E-waste Monitor 2020. Available: http://ewastemonitor.info/wp-content/uploads/2020/12/GEM_2020_def_dec_2020-1.pdf
[64] Li, W., & Achal, V. (2020). Environmental and health impacts due to e-waste disposal in China—A review. *The Science of the Total Environment*, *737*, 139745. https://doi.org/10.1016/j.scitotenv.2020.139745
[65] www.greentechmedia.com/articles/read/how-china-is-cornering-the-lithium-ion-cell-recycling-market
[66] Fu, J., Zhang, H., Zhang, A., & Jiang, G. (2018). E-waste Recycling in China: A Challenging Field. *Environmental Science & Technology*, *52*(12), 6727–6728. https://doi.org/10.1021/acs.est.8b02329
[67] DW, D. (2019, May 4). After China's import ban, where to with the world's waste? | DW | 05.04.2019. DW.COM. https://www.dw.com/en/after-chinas-import-ban-where-to-with-the-worlds-waste/a-48213871

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USD in 2050,[68] with developing and least-developed countries bearing the brunt of these impacts.[69] Climate change has also been found to exacerbate inequality between rich and poor nations, by around 25 percent over the last half-century.[70] My group's research has shown that lower-income communities often bear the brunt of environmental and climate-related harms, including a higher burden of air pollution and urban heat.[71] These disproportionate exposures have the potential to translate to a range of socioeconomic and health disparities.[72]

Question 5: Based on the Intergovernmental Panel on Climate Change "Global Warming of 1.5°" report, the United Nations says that greenhouse gas emissions "would need to fall by about 45 percent from 2010 levels by 2030" for the world to be on a path to net zero emissions by 2050. As a consequence, many policymakers in the United States and elsewhere have called for cuts of this magnitude. Based on what you know today, do you expect global emissions in 2030 will be 45 percent lower than 2010 levels? If not, why?

Based on the latest 2020 UN Environment Emissions Gap Report, we are not on track to reach 45 percent percent reduction from 2010 emission levels by 2030.[73] There currently exists a 29 to 32 gigatonne carbon dioxide equivalent (CO2e) gap between conditional and unconditional nationally-determined contributions to the Paris Agreement, respectively.[74] These projections imply that without additional policy efforts, the world is on track to emissions levels around 59 gigatonnes CO2e in 2030.[75] This "emissions gap" implies that existing national-level climate policy efforts, as well as those pledged both unconditionally and conditionally to the Paris Agreement, are insufficient to lead the world to a 45 percent below 2010 emissions levels in 2030.

Question 6: The *Washington Free Beacon* has reported that "One-third of the polysilicon China produced in 2019, for example, came from the Xinjiang region, where more than a million Uighurs are being held in government-run camps."

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[68] Galey, P. (2019).Climate impacts 'to cost world $7.9 trillion' by 2050. Available: https://phys.org/news/2019-11-climate-impacts-world-trillion.html
[69] International Monetary Fund. 2017. Seeking Sustainable Growth: Short-Term Recovery, Long-Term Challenges. Washington, DC, October.
[70] Diffenbaugh, N. S., & Burke, M. (2019). Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences, 116(20), 9808-9813.
[71] Hsu, A., Tirthankar Chakraborty, Ryan Thomas, Diego Manya, Amy Weinfurter, Nicholas Chin, Nihit Goyal and Andrew Feierman. Measuring what matters, where it matters: A spatially explicit Urban Environment and Social Inclusion Index for the Sustainable Development Goals. Frontiers in Sustainable Cities (2020); Hsu, Angel and Sheriff, Glenn and Chakraborty, Tirthankar and Manya, Diego, Disproportionate Exposure to Urban Heat Island Across Major U.S. Cities (September 1, 2020). Available at SSRN: https://ssrn.com/abstract=3684952 or http://dx.doi.org/10.2139/ssrn.3684952.
[72] Tessum, C. W., Apte, J. S., Goodkind, A. L., Muller, N. Z., Mullins, K. A., Paolella, D. A., ... & Hill, J. D. (2019). Inequity in consumption of goods and services adds to racial–ethnic disparities in air pollution exposure. Proceedings of the National Academy of Sciences, 116(13), 6001-6006.
[73] United Nations Environment Programme (2020). Emissions Gap Report 2020. Nairobi.
[74] ibid.
[75] ibid.

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a. Is this figure accurate?

I'm unsure to which figure the Senator is referring to being accurate, but with respect to the polysilicon number, some news reports cite analysts that say that as much as 45 percent of polysilicon supply comes from Xinjiang, although I personally am unable to verify this number outside of these publicly available news sources and reports.[76]

b. What other components, which are used in solar panels, wind turbines, or electric batteries, are manufactured or processed in the Xinjiang region of China?

Questions from Senator Maria Cantwell

Question 1: Carbon Price

Two years ago during another hearing in this committee, almost all of the witnesses agreed by a show of hands that putting a price on carbon pollution, either indirectly or directly, is a good thing.

- Do you believe that an economy wide price on carbon, applied upstream where fossil fuels enter the economy, is the most efficient mechanism to decrease carbon emissions at the necessary scale and speed?

From an economic theory perspective, an economy-wide price on carbon would be an efficient way to appropriately price the social cost of carbon, including its externalities in the form of air pollution and related environmental and health impacts. In practice, carbon pricing has proven not to be the most efficient mechanism to decrease carbon emissions at the necessary scale and speed required to meet global climate goals because pricing policies have not been implemented, largely due to unfavorable politics surrounding carbon pricing policies and carbon taxes in general. According to the 2018 UN Emissions Gap Report, only 10 percent of global carbon emissions are priced appropriately to limit temperature rise to 1.5 degrees C and half of fossil-fuel based emissions are not priced at all (UNEP, 2018),[77] a shortfall that reflects governments' lack of carbon pricing adoption and a classic global market failure.

- Do you believe that a predictable, market-based carbon price will incentivize the markets to reduce carbon emissions faster and more efficiently than could be achieved through direct regulation of emissions within specific industry sectors?

A predictable, market-based carbon price would lead to more efficient carbon emission reductions than direct regulation of emissions would produce, yet these carbon price reductions would likely take longer to realize than direct regulations' could incentivize. This longer period for emissions reductions would result from

[76] Murtagh, D. (2021). Why It's So Hard for the Solar Industry to Quit Xinjiang. Available: https://www.bloomberg.com/news/articles/2021-02-10/why-it-s-so-hard-for-the-solar-industry-to-quit-xinjiang

[77] UNEP (2018). The Emissions Gap Report 2018. United Nations Environment Programme, Nairobi

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marketplace lag-times and path dependencies. A factory, for instance, may choose to pay the price of elevated emissions while this route is cheaper than the technological retrofits needed to reduce emissions. Command and control government actions, however, can use new laws and regulations to force private industry to make immediate changes no matter the cost. The most efficient way to reduce emissions, and indeed the *only* way to bring about the emissions reductions necessary to avert climate change's worst impacts, would involve both carbon pricing and direct regulation of emissions within specific industry sectors.

<u>Question 2</u>: CCUS and Nuclear

I strongly support efforts to boost innovation to help bring new forms of energy to the market, but unclear whether carbon capture utilization and storage (CCUS) technologies and nuclear technologies will ever be cost competitive with existing electricity generation sources without an economy wide price signal that accurately reflects the cost of carbon emissions.

- Do you think predictable carbon pricing is important to making CCUS technologies and advanced nuclear technologies economical and getting the private sector investments we need to ramp up these solutions?

Yes, but carbon pricing is not the only policy that is needed to make CCUS technologies and advanced nuclear economical. There also needs to be a significant ramp up of investment in research and development to make these technologies more cost competitive.

Predictable carbon pricing can be one component of a strategy for making CCUS technologies more economical. Other complementary efforts will likely be needed given the timeframe available for ramping up CCUS technologies to the point needed to limit warming below 1.5 degrees C. In 2020, the total global amount of operation CCUS technology amounted to 40 Megatonnes per annum (Mtpa), with an additional almost 40 Mtpa in advanced development stages.[78] The amount of CCUS needed to limit warming to below 1.5 degrees C depends on the intensity and level of global emissions, which will depend on the global energy mix. Several scenarios for limiting warming to below 1.5 C have been constructed as part of the IPCC process, and in general there is consensus that if emissions are reduced more slowly between 2020 and 2030, up to 1 Gigaton per annum of operational CCUS capacity would be needed by 2030.[79] There exist scenarios that do not rely on CCUS by 2030, but these rely on more than halving global emissions by 2030, for instance. This represents a possibility of a 25-fold increase in operational CCUS capacity being needed by 2030 if emissions reduction is not undertaken quickly.

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[78] Global CCS Institute. (2020). *Global Status of CCS 2020.* Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf

[79] de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama, 2018: Strengthening and Implementing the Global Response. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*

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- Do you think a predictable price on carbon is more likely to spur energy markets to invest in technologies like CCUS and advanced nuclear than additional funding for more intangible policies like additional R&D?

It is possible that a carbon price would spur this kind of investment, but would also depend on how legislation around the carbon price was designed and implemented. The short-term promise of CCUS technologies for emissions reduction lie in retro-fitting existing facilities with CCUS where available, and present a more gradual pathway for some sectors like heavy industry to be transformed, as CCUS technologies are among the cheapest or only abatement options available for some of these industries.[80] However, the large scale of CCUS technology needed to be deployed under scenarios where global emissions are not drastically reduced in the short term means that many potentially complementary development and funding pathways should likely be pursued. Policies supporting market preferences for technologies like lower-carbon cement, steel, or chemicals could also be a potential accelerator for CCUS development.[81] Given the scale of the issue, R&D in this case may still be welcome and needed for advancing CCUS tech especially as technological progress for CCUS across sectors is highly uneven. Large efficiency increases and deployability advances for CCUS for certain sectors like cement are still needed,[82] and well-targeted R&D funding will likely be helpful in these cases.

- Do you think predictable carbon pricing can help keep existing American nuclear reactors open that otherwise will shutdown?

If predictable carbon pricing is successful in producing the necessary economic urgency for emissions reduction, then it is possible that nuclear power will have a continued role to play. Deployable and flexible low-carbon power will be important for managing grid resilience relating to unexpected demand spikes or outages during the renewables transition, and nuclear power can be one source of resilient grids.[83] The IAEA has noted that while several nuclear plants in the US have closed over recent years (with additional plants slated to close by 2025), the overall share of nuclear power in electricity generation has remained relatively stable, due to increases in performance and operator experience.[84] This presents one case for nuclear plant longevity being tied potentially to increasing demand, rather than stable demand, and low-carbon power grid transition could provide one avenue for such demand hikes to occur. Whether carbon pricing is the most efficient way to achieve the impetus for transitioning to lower-carbon technologies is addressed in answers to questions above.

<u>Question 3</u>: Aligning National Policies with Business Climate Goals

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[80] Baylin-Stern, A., & Berghout, N. (2021, February 17). Is carbon capture too expensive? – Analysis. *IEA*. https://www.iea.org/commentaries/is-carbon-capture-too-expensive
[81] IEA (2019), Transforming Industry through CCUS, IEA, Paris https://www.iea.org/reports/transforming-industry-through-ccus
[82] IEA (2020), *CCUS in Clean Energy Transitions*, IEA, Paris https://www.iea.org/reports/ccus-in-clean-energy-transitions
[83] Friedmann, S. J., Ochu, E. R., & Brown, J. D. (2020). *Capturing Investment: Policy Design to Finance CCUS Projects in the US Power Sector* (p. 60). Columbia Center on Global Energy Policy. https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/CCUS-Finance_CGEP-Report_040220.pdf
[84] IAEA. (2020). *United States of America 2020* [Country Nuclear Power Profile]. IAEA. https://cnpp.iaea.org/countryprofiles/UnitedStatesofAmerica/UnitedStatesofAmerica.htm

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The past year could be remembered as a turning point in addressing the climate crisis with major corporations committing to decarbonize their operations by ever more aggressive timeframes as the private sector realizes that taking action to decarbonize is not only good socially, but also good for business.

- Why do you think businesses are committing to these bold greenhouse gas emission targets?

In my experience, companies are committing to ambitious greenhouse gas emission targets for a range of reasons, outside of regulatory requirements. Companies are increasingly becoming aware of climate change and their own contribution to the problem, as well as the risks posed by a warming climate, including increased droughts and floods, weather extremes, sea-level rise, hurricanes and extreme weather patterns, changes in growing seasons.[85] They see potential cost savings with energy efficiency and climate-related actions, as well as opportunities to demonstrate leadership and promote corporate social responsibility by developing climate strategies. Shareholders are increasingly demanding companies to take climate action by disclosing climate-related information and setting emission reduction targets.[86] Companies' own employees, including a high-profile case of Amazon workers staging a walk-out and protest for the company to take climate responsibility, are also demanding corporate climate action.[87] Our October 2020 study documented more than 1,565 companies have made some type of commitment to decarbonize, whether their full emissions footprint or within a specific scope or sector (i.e., electricity).[88] This number continues to grow as the UN Framework Convention on Climate Change's Race to Zero Campaign and other initiatives like the Business Ambition for 1.5 Coalition are actively recruiting businesses to pledge net-zero commitments.

- Do these local and corporate emissions reduction activities have an impact on global emissions?

Yes, as mentioned in my written testimony, my research group along with a consortium of global researchers at the New Climate Institute, PBL Netherlands Environmental Assessment Agency, the German Development Institute, and Oxford University, have quantified the global potential for city, region, and business actors to contribute additional climate mitigation beyond current national government policies in the order of 1.0 to 2.0 gigatonnes of carbon dioxide equivalent/year in 2030.[89] While this study assessed the potential based on these actors' largely voluntary commitments to reduce greenhouse gas emissions, my research group has also found that these actors are delivering on their promises. In a study of more than 1,000 European cities that participate

[85] NOAA. https://www.noaa.gov/education/resource-collections/climate/climate-change-impacts. NASA. (2021). Vital Signs: Climate Change Effects. Available: https://climate.nasa.gov/effects/.
[86] Matsuo, T. and S. LaMonaca. (2020).Shareholders Keep Up the Pressure on Corporate Climate Action. Available: https://rmi.org/shareholders-keep-up-the-pressure-on-corporate-climate-action/
[87] Paul, K. (2020). Hundreds of workers defy Amazon rules to protest company's climate failures. Available: https://www.theguardian.com/technology/2020/jan/27/amazon-workers-climate-protest.
[88] NewClimate Institute & Data-Driven EnviroLab (2020). Navigating the nuances of net-zero targets. Research report prepared by the team of: Thomas Day, Silke Mooldijk and Takeshi Kuramochi (NewClimate Institute) and Angel Hsu, Elwin Lim, Zhi Yi Yeo, Amy Weinfurter, Yin Xi Tan, Ian French, Vasu Namdeo, Odele Tan, Sowmya Raghavan, and Ajay Nair (Data-Driven EnviroLab).
[89] Kuramochi, T., Roelfsema, M., Hsu, A., Lui, S., Weinfurter, A., Chan, S., ... & Höhne, N. (2020). Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions. *Climate Policy*, *20*(3), 275-291; NewClimate Institute, Data-Driven Lab, PBL, German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE), Blavatnik School of Government, University of Oxford. 2019 edition.

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in a voluntary climate action network, the European Covenant of Mayors for Climate and Energy,[90] and adopt emission reduction goals that are more ambitious than the European Union's own target, 60 percent were measured on track to achieve or exceed their 2020 emission reduction target.[91] This is the largest-scale evidence that subnational and non-state actors are implementing and achieving voluntary climate goals.

- Do you believe a coordinated national policy will accelerate the commitments we're already seeing at the corporate level?

Yes, we make this conclusion in our analysis of corporate and subnational commitments - these efforts are absolutely not a replacement for coordinated national policy. National policy sets long-term, overall goals and can provide incentives and regulatory frameworks to facilitate and even catalyze more and more ambitious corporate and subnational climate actions.

<u>Question 4</u>: China Winning the Clean Energy Race

There is no doubt that making the clean energy investments we need to stop carbon pollution is going to be a multi-trillion dollar global market opportunity. The question, I believe, is whether that market --and the millions of associated jobs-- will be captured by the U.S., or its foreign competitors.

China is the world's largest producer, exporter and installer of solar panels, wind turbines and electric vehicles. China is investing roughly $100 billion each year, double what the US and the EU combined invest.

- Is the U.S. losing the clean energy race to China and the rest of the world?

Yes, considering available data on clean energy investment and production, it is fair to say that the U.S. is behind China in terms of the "clean energy race." See my above responses.

- What does China's clean energy leadership mean in terms of global greenhouse gas emissions?

There are multiple ways to answer this question. First, since China is the world's largest emitter of greenhouse gas emissions, representing around 28 percent of the global total,[92] its decision to decarbonize by 2060 is significant since this pledge alone would eliminate more than a quarter of global emissions. The Climate Action Tracker estimates that this commitment alone could lead to between 0.2 to 0.3 degrees C cooling in 2100.[93] A second way to answer this question would be in terms of China's contributions to global clean energy technology, which would influence the greenhouse gas emissions of many other countries outside of China. As mentioned above, China is a leader in clean energy technology investment globally, more than any other

[90] EU Covenant of Mayors for Climate and Energy. Available: https://www.covenantofmayors.eu/
[91] Hsu, A., Tan, J., Ng, Y.M., Vanda, R. and N. Goyal. (2020). Performance determinants show European cities are delivering on climate mitigation. Nature Climate Change.
[92] World Resources Institute. (2021). Climate Analysis Indicators Tool (CAIT). Available: cait.wri.org
[93] Climate Action Tracker. (2020). China going carbon neutral before 2060 would lower warming projections by around 0.2 to 0.3 degrees C. Available:
https://climateactiontracker.org/press/china-carbon-neutral-before-2060-would-lower-warming-projections-by-around-2-to-3-tenths-of-a-degree/

country.[94] These investments in clean energy technology beyond China's borders, could aid countries in reducing reliance on fossil fuels or eliminating them from electricity production or transport. The emissions impact of this clean energy technology adoption in other countries would be significant, although is still uncertain. China's overseas investment in the energy and infrastructure sectors are still primarily in fossil fuel rather than clean energy, leading to approximately 314 million tons of CO_2 emissions per year,[95] the equivalent of roughly Viet Nam's CO_2 emissions in 2017.[96]

- One common argument against taking action here in the U.S. is that it won't matter because the rest of the world will just keep on releasing carbon pollution – do you agree with that premise?

Countries are rapidly developing plans and working to decarbonize their economies for a multitude of reasons. First, it makes economic sense, since renewables are now more affordable than fossil-based energy, as I mentioned in my written testimony. Considering the social cost of continued fossil fuel use, including a range of health and environmental externalities from air pollution, the larger economic impact makes the economic case for renewables even stronger. Second, there are significant economic opportunities associated with climate-smart investments, which are anticipated to be in the order of $23 trillion USD by 2030 in emerging markets as these countries work to meet their Paris Agreement goals.[97] As of December 2020, 127 national governments, representing 63 percent of global emissions, have committed to net-zero emission targets by mid-century.[98] This number is likely to increase as countries are being asked to submit enhanced ambition Nationally Determined Contributions to the Paris Agreement as part of the treaty's five-year ratchet mechanism.[99]

Question from Senator Mazie K. Hirono

<u>Question</u>: One important component of the trends in global carbon pollution emissions examined in the hearing is the damage that these emissions cause. In Hawaii we have among the most ambitious clean energy goals—to achieve 100 percent renewable power and a carbon neutral economy by 2045. Hawaii is ambitious because it has to be. Our coasts are eroding, our corals are bleaching, and our freshwater is being threatened. If the United States proceeds with the status quo and does not take bold, ambitious steps to mitigate climate change, what will that price tag be and what communities will pay that price?

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[94] Joel Jaeger, Paul Joffe, and Ranping Song(2017). "China Is Leaving the U.S. Behind on Clean Energy Investment." World Resources Institute. Available: http://www.wri.org/blog/2017/01/china-leaving-us-behind-clean-energy-investment/

[95] Ma, Xinyue. "Understanding China's Global Power." Global Development Policy Center (2020).

[96] World Resources Institute. (2021). Climate Analysis Indicators Tool (CAIT). Available: cait.wri.org.

[97] International Finance Corporation. (2016). Climate Investment Opportunities in Emerging Markets An IFC Analysis. Available: https://www.ifc.org/wps/wcm/connect/59260145-ec2e-40de-97e6-3aa78b82b3c9/3503-IFC-Climate_Investment_Opportunity-Report-Dec-FINAL.pdf?MOD=AJPERES&CVID=lBLd6Xq.

[98] Climate Action Tracker. (2020). Paris turning point: net zero targets would bring warming to 2.1°C/. Available: https://climateactiontracker.org/press/global-update-paris-agreement-turning-point/

[99] Gabbatiss, J. (2021). Analysis: Which countries met the UN's 2020 deadline to raise 'climate ambition'?. Available: https://www.carbonbrief.org/analysis-which-countries-met-the-uns-2020-deadline-to-raise-climate-ambition

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The damages to human welfare wrought by unchecked climate change is perhaps the least certain function of even the most rigorous integrated assessment models. No one can say with any degree of certainty just how much communities will pay in loss of life, land, resources and livelihoods if the U.S. does not lead the world to take bold action to mitigate climate change, yet the best estimates show that the U.S. would stand to lose at least 7% and as much as 14% of its annual GDP this century.[100] For perspective, 14 percent of the 2019 U.S. GDP is approximately $3 trillion. The enormous uncertainty in projecting climate damages means that the actual losses could be much greater than these, and the fact that climate change impacts are likely to increase non-linearly in frequency and severity means that the damages could be exponentially greater than the science predicts. Some areas will pay a higher price than others, as coastal communities and areas already affected by flooding, erosion, and water stress likely see the greatest losses the soonest. Yet no community will be spared the steep and mounting costs brought about by unchecked climate change.

[100] Kahn, M. E., Mohaddes, K., Ng, R. N., Pesaran, M. H., Raissi, M., & Yang, J. C. (2019). *Long-term macroeconomic effects of climate change: A cross-country analysis* (No. w26167). National Bureau of Economic Research.

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Questions from Senator John Barrasso, M.D.

Question 1: When we talk about energy transitions, how important is energy density to the reliability and economics of competing technologies, and what are the implications for renewable technologies?

Tinker: Energy density is a very important concept when considering energy options. Although energy density is not tied one-to-one to reliability, economics, or environmental impacts—including CO_2—there are some general and important relationships.

Summary. In general, for comparing electricity, we talk about Surface Power Density (W/m^2). For those sources of energy that are *reliable* (always on, dispatchable, baseload, such as hydro, geothermal, coal, oil, natural gas, and nuclear) the lower the surface power density, the more land/nature it takes to produce an equivalent amount of energy. High surface power density sources like nuclear and natural gas require much less land/nature than low density sources. Further, *low-density* sources that are also *intermittent* (not always on, dispatchable, or baseload) like solar and wind, require some form of redundant backup (like batteries, or natural gas load following plants) to make them reliable. This backup not only requires land, but is also expensive. In terms of economics, that is partly why levelized cost of energy/electricity (LCOE), which was discussed during the hearing, *does not properly compare various sources* because it does not include the cost of backup. When backup is added, wind and solar become more expensive to the consumer.

A bit more. In physics, energy density is the amount of energy per unit volume. Specific energy is energy per unit mass. In terms of comparing electricity sources we talk about surface power density, which is energy per unit area (W/m^2). This describes the amount of power obtained per unit of Earth surface area, including all supporting "stuff" (infrastructure, manufacturing, mining of fuel, and decommissioning). For the best reference on this, see the book *Power Density* by Vaclav Smil. Although solar and wind, and the batteries to make them reliable, have a role to play, they have power densities so low that a tremendous amount of ***non-renewable*** "stuff" to make the panels, turbines and batteries is required to capture and store the wind and the sun. This "stuff" will require an unprecedented scale of global mining and manufacturing, and later landfill disposal when the panels, turbines, and batteries wear out. I call this ***Robbing from nature Peter to pay climate Paul.*** By contrast, nuclear with zero emissions, or fuel switching from coal to natural gas, both provide dispatchable electricity and address the challenges of scale, cost, and time frame.

Energy source	Median PD [W/m^2]
Natural gas	482.10
Nuclear power	240.81
Petroleum	194.61
Coal	135.10
Solar power	6.63
Geothermal	2.24
Wind power	1.84
Hydropower	0.14
Biomass	0.08

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Question 2: You testified that it is important to be "factually complete, not just completely factual." Much has been made of the fact that some renewable technologies have a lower "levelized cost of electricity" (LCOE) than coal or natural gas, and that these technologies are near or at parity. Is LCOE the proper metric by which to compare these technologies? What are some other considerations?

Tinker: Before answering this question, I'll point out a couple of examples (in addition to LCOE) from the Hearing of completely factual, but not factually complete.

- China's leadership in developing solar, wind, and EV ***capacity*** is completely factual. But to extend that to China soon reducing its CO_2 emissions, well, as Paul Harvey used to say, "now for the rest of the story…" A factually complete account tells us China is also leading in coal and new nuclear, and will soon overtake Japan as the world's top buyer of LNG, etc. As will be discussed in a later question, China's emissions are not soon decreasing.
- Comparing growth in installed capacity of various electricity sources is completely factual. But differentiating between installed capacity and actual generation brings us closer to a factually complete statement. All sources of electricity have different capacity factors, which measure actual output/maximum possible output. The higher the capacity factor, typically the more efficient the power plant. Nuclear has the highest; hydro, natural gas, and coal have the next highest; and wind and solar have the lowest. This is just the reality of intermittency due to night, clouds, and non-windy times. For example, 100 GW of new solar capacity will generate less than half of 100 GW of new coal capacity. For this reason, I prefer looking at actual generation when comparing various sources, which tends to incorporate capacity factors.
- The graphs shown by Senator King regarding CO_2 emissions and sea-level rise were completely factual, and I appreciate the Senator diving into the science. A factually complete account would mention the natural drivers of glacial–interglacial cycles. The shape of Earth's orbit and the tilt and wobble of Earth's axis brings us predictably closer to and farther from the Sun, which was worked out by hand by Serbian physicist Milankovitch while under house arrest in WWI. These cycles last about 100,000 years and Earth has experienced dozens such "ice ages" in the last few million years. In the longer glacial component of each cycle, continental ice some thousand feet thick typically covers Canada and comes down to Wisconsin, Michigan, and New York, locking up sea water and drawing down global oceans significantly, as the Senator showed. When the Earth begins to warm, the large volume of ice melts and sea levels rise quickly (centimeters/yr.). When much of the ice has melted, sea level rises much slower (a few mm/yr.) as we have seen for the past 8000 years. A factually complete account tells us humans have been adapting to this slow sea-level rise since the Stone Age. Importantly, the ***rate*** of rise, which matters when considering human impacts on the climate, has not yet changed much. NOAA maintains about 100 sea-level monitors on all U.S. coasts and several islands, and to my knowledge not a single monitor shows that the *rate* of sea-level rise has accelerated. One probabilistic approach suggests rate of global rise may have increased in the last decade or two, but that has been debated. This is very interesting, as sea level rise (natural and human forced) is considered one of the greater risks of climate change.

Now to the question. LCOE is not the proper way to compare retail costs of electricity (cost to the consumer). For a deeper discussion, see Gulen. As discussed in another question, *low-density* sources that are also *intermittent* (not always on, dispatchable, or baseload) like solar and wind, require some form of redundant backup (like batteries, or natural gas load following plants) to make them reliable. This backup not only requires land and infrastructure, it is also expensive. In terms of economics, this is why LCOE

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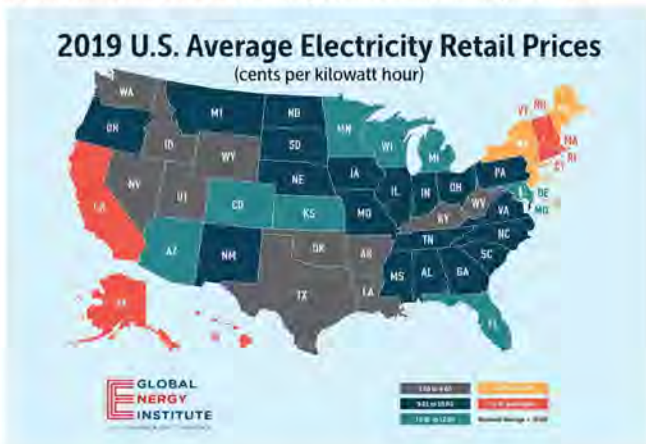
(levelized cost of energy/electricity), which was discussed during the hearing, *does not properly compare various sources* because it does not include the cost of backup required for intermittent energy. When this significant cost is added, intermittent wind and solar can make electricity twice as expensive to the consumer. A comparison of retail electricity prices in the U.S. by state shows this. Such higher electricity prices are a regressive cost and inequitable to lower income families. The same is seen in Europe, where the electricity prices in solar- and/or wind-heavy economies like Germany, Denmark, and Spain ($0.25–0.30/kwh) are more than double those in coal-heavy countries like Poland ($0.13/kwh).



Question 3: You recently wrote that: The panels, turbines and batteries wear out after 10 to 20 years, and the metals, chemicals and toxic materials required to make them must be constantly mined, manufactured, and disposed of in landfills. Coupled with some carbon dioxide emissions associated with those processes, solar and wind are neither renewable nor clean.

Please expand on this statement.

Tinker: All forms of energy require mining or drilling of non-renewable Earth materials to extract or capture the energy. From high energy density forms like coal, oil, natural gas, uranium, and thorium, to low energy density energy forms like sunlight (panels), solar heat (mirrors), geothermal heat (drilling), the motion of wind (turbines), gravity from water (dams), etc. Low-density, intermittent sources of energy require more Earth materials to capture an equivalent amount of energy than high-density, reliable energy. In other words, to manufacture and deploy enough solar panels, wind turbines, and batteries to replace dispatchable coal, natural gas, and nuclear will require tremendous land use and mining of ***non-renewable*** lithium, cobalt, copper, other metals, rare Earth elements, polysilicon, etc. It will also require landfill disposal of massive and toxic materials.

Rather than "clean" or "green" we should use words that actually mean something, like "lower emissions," "lower particulates," "reduced use of land," "reduced water impact," etc. When we do this, we see that some forms of energy have lower CO_2 emissions at the collection source (like wind turbines and solar panels) but have higher impacts on mining and landfill disposal when all of the stuff required to collect them wear out. These are the kinds of trade-offs that must be discussed and weighed thoughtfully to make valid decisions.

In terms of transportation, air, rail, ship, and vehicle all present emissions challenges. For vehicles, internal combustion engines (ICE), electric vehicles (EV) and fuel cells (FC) all have advantages and disadvantages when it comes to reducing CO_2 emissions without further damaging other parts of the environment. In terms of EVs, the mining and later landfill disposal required to power enough vehicles to impact CO_2 reductions is unprecedented. To electrify half of today's vehicle fleet of 1.2 billion with the equivalent number of batteries in a single Tesla S (7100; see below) would require over 4 trillion new batteries every 15–20 years as the batteries wear out. Four trillion Tesla S batteries would build a U.S. football field-sized solid battery tower 25 miles into the stratosphere. Global EV sales increased 46% year over year from 2019 to 2020. Much of the growth happened in China and Korea, where sales rose by 135% and 60% respectively. Depending on the source of electricity (i.e., not coal in Asia), EVs can reduce emissions. But, ***mining, manufacturing, and disposing batteries is not "green."***

As an aside, China now controls much of the world's mineral refining capacity and mining resources related to batteries and solar panels, which presents a significant national security risk when considering increased vehicle electrification. Further, mining practices in parts of the world violate human rights.

Question 4: Do you agree that high energy costs are regressive and inequitable to lower-income people?

Tinker: Yes.

Question 5: Based on the Intergovernmental Panel on Climate Change "Global Warming of 1.5°" report, the United Nations says that greenhouse gas emissions "would need to fall by about 45 percent from 2010 levels by 2030" for the world to be on a path to net zero emissions by 2050. As a consequence, many policymakers in the United States and elsewhere have called for cuts of this magnitude. Based on what you know today, do you expect global emissions in 2030 will be 45 percent lower than 2010 levels? If not, why?

Tinker: This question requires a significant discussion using global data. I give such lectures all over the world. Barring that, I will try to be brief. No, I do not think emissions will be 45 percent lower in 2030 than 2010 levels. Not for lack of intent, but because of arithmetic, economics, infrastructure, population, per capita consumption, and extensive benefits of secure energy, among other things.

In 2010, global emissions were ~31 Gt (1 gigatonne = 1 billion tonnes). A 45% reduction would be ~17 Gt—levels last seen in 1976, when global population was ~4 billion and adjusted GWP was about $15 trillion. In 2030, global population will be more than double 1976 at ~8.5 billion, and GWP could be 10 times that of 1976 at $150 trillion (2020 GWP was ~$90 trillion). Emissions from developing economies, especially Asia (led by China and likely to be followed by India) are still increasing. Asia alone emits ~17 Gt of CO_2 today. China and much of Asia continue to build extensive coal capacity, and these plants will last 60 to 80 years. There are *simply too many positive benefits of affordable and reliable energy provided by coal* to developing economies to change. Notwithstanding pledges to the contrary, emissions from Asia will at best plateau by 2030, somewhere around 20 Gt? The rest of the world (Russia, Middle East, South America, Europe, North America…) could eliminate all CO_2, and the world would still not be at 1976 levels.

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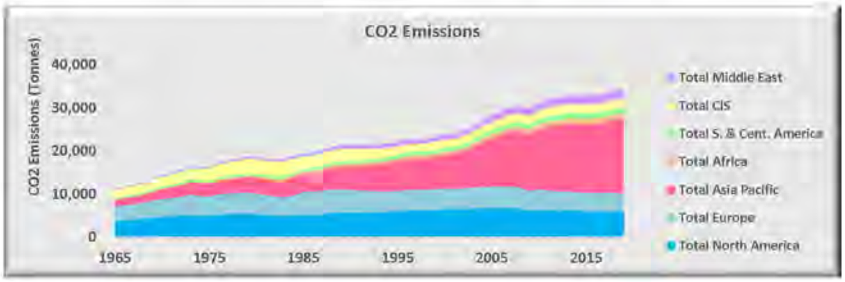

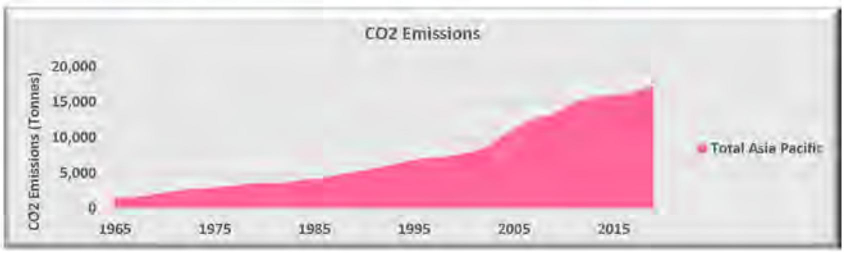

Question 6: You have written "Climate clean can be nature dirty (water and land)." What do you mean by this statement?

Tinker: Carbon neutral—or net zero carbon—is when carbon emissions from an entity are "balanced out" by reducing its own emissions and/or buying carbon dioxide offset credits. Whether there are enough legitimate emissions credits available to offset the pledges—in the case of China, which emits more than 25% of global CO_2 each year, there clearly are not—or whether the time frame of the pledges will be honored, should be matters of significant and warranted discussion. Instead, for a variety of reasons, carbon neutral pledging is the phrase that pays.

But what if well-intended attempts to go net zero result in unintended negative consequences to our water, land, and air on which all nature depends? To address this possibility requires an objective assessment of the options to actually reduce CO_2 emissions at the scale (billions of tons per year), cost (trillions of dollars), and time frame (a decade or two) required. Options favored by some include solar, wind, batteries, biofuels, and efficiency. Other options, arguably as or more scalable and affordable in the time frame required, include hydrogen, nuclear, geothermal, fuel switching, and CCUS (carbon capture, utilization, and storage). Interestingly, with the exception of efficiency, all options have significant negative environmental impacts.

To make enough solar panels, wind turbines, and batteries to replace dispatchable coal, natural gas and nuclear will require non-renewable mining of lithium, cobalt, and other metals. It will also require manufacturing and landfill disposal of massive and toxic materials. Hydroelectric dams could exacerbate

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emissions and impact land and water. To create enough biofuel to replace petroleum will require an inordinate amount of fertilizer, water, and energy, and could exceed the available land. Hydrogen for fuel cells and industrial use requires energy to split methane, water, or other molecules and has greenhouse emissions of its own. Nuclear is a scalable, zero-emissions, high-density option but requires handling of fission products. Geothermal uses the heat of the earth to produce low emissions electricity but requires drilling and has other impacts. Fuel switching from coal to natural gas has been shown effective in the U.S. but requires drilling, pipelines, and has other emissions. CCUS is technically feasible but requires transportation and injection on a large scale.

The reality we face is that humans impact the Earth. In our passion to address climate change, we must balance the major benefits of energy, like ending global poverty and powering all aspects of modern life, while minimizing environmental impacts of all forms of energy on the atmosphere, land, water, and air. Otherwise, carbon neutral could very quickly become nature negative.

Questions from Senator Maria Cantwell

Question 1: Carbon Price

Two years ago, during another hearing in this committee, almost all of the witnesses agreed by a show of hands that putting a price on carbon pollution, either indirectly or directly, is a good thing.

- Do you believe that an economy wide price on carbon, applied upstream where fossil fuels enter the economy, is the most efficient mechanism to decrease carbon emissions at the necessary scale and speed?
- Do you believe that a predictable, market-based carbon price will incentivize the markets to reduce carbon emissions faster and more efficiently than could be achieved through direct regulation of emissions within specific industry sectors?

Tinker: I try to avoid words like "good and bad" and "clean and dirty" when talking about energy. Good for developed nations, or impoverished nations? Clean to the atmosphere, or to the land? You see the dilemma. In 2019 I published a piece in Scientific American on this subject. Rather than try to extract from it, I'll just share it here. It is oddly appropriate for this committee—both sides of the aisle.

> "There is much talk today about carbon pricing to reduce CO_2 emissions and address climate change. Unlike many environmental pollutants that have a local or regional impact, carbon dioxide (CO_2) is global—there is only one atmosphere. If actions taken to reduce atmospheric emissions in one region result in increased emissions elsewhere, then the one atmosphere suffers.
>
> Some form of carbon pricing—a carbon tax, carbon trading, carbon credits—is favored by many politicians, NGOs, academics, and even some in industry. But the reality is that a price on carbon will not be adopted by developing and emerging economies because it makes their energy more expensive, and they are too busy trying to build their economies and lift themselves from poverty.
>
> In the developed world, carbon pricing increases the cost of manufacturing and products, which in turn drives manufacturing to developing nations where it is more affordable because of lower labor costs and less stringent environmental regulations and emissions standards. Global emissions rise in the one atmosphere. Put another way, the good intentions of carbon pricing have an unintended negative impact on climate change. This is not hypothetical. It is happening.

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If carbon pricing won't work, what will? Energy science tells us how to actually lower CO_2 emissions into the one atmosphere in the time frame needed. Unfortunately, those who are the most passionate about addressing climate change seem to not like the answers from the energy experts.

Renewable energy is important to get electricity to people living off-grid in energy poverty. But renewable energy cannot grow large enough or fast enough to put a dent in atmospheric emissions in the time frame needed. Further, although the wind and sun are renewable, the panels, turbines and batteries that collect them are not. They require vastly expanded mining, manufacturing, deployment, and landfill disposal, amounting to major environmental effects on the land.

Biomass and biofuels qualify as "renewable and carbon neutral" in Europe. There may be reasons to burn fuels made from crops to power vehicles or to make electricity, but those reasons are independent of the CO_2 emissions that come from growing, fertilizing, harvesting, converting, transporting, and combusting biomass. That cycle is not a carbon-neutral process.

Electrification of transportation may make sense for short travel, reduced noise, and lowered air emissions locally. But given the reality of the current global electricity mix needed to charge the batteries (coal and natural gas dominate), and the size of the challenge—of the 1.3 billion vehicles on Earth, fewer than 5 million [0.4%] are electric—electrification cannot happen fast enough to matter. Not to mention the environmental effects from mining, manufacturing and eventually disposing of batteries.

So what options does energy science suggest will have a major impact on climate change? Natural gas and nuclear fission replacing coal for power generation in major developing nations such as India, China and Vietnam would have a major impact. Carbon capture, utilization, and storage, direct carbon capture from the atmosphere, and perhaps nature-based solutions such as increasing the size of forests would help, especially in fossil-fuel producing regions such as the U.S., Russia, China, and the Middle East. Distributed renewable energy in rural areas around the world that are currently off-grid will lower emissions and begin to lift more than 1 billion people out of poverty.

Improved energy efficiency across all energy-demand sectors would allow for continued economic growth while lowering emissions. The energy solutions mix will vary geopolitically as a function of resource base, existing infrastructure, political and economic reality, and public perception.

These scientifically sound and economically underpinned energy solutions present a problem. Many are not favored by people who are the most concerned about climate change. Thus, politicians seeking climate votes continue to passionately promote programs and policies that won't actually address climate change.

But we have a remarkable opportunity. The right can acknowledge the need to tackle climate change. The left can acknowledge the energy science needed to accomplish real global emissions reductions into the one atmosphere. And developing and emerging nations can continue to climb out of energy poverty.

Unfortunately, this appears to be far from happening. Climate politics seems to trump energy solutions in Europe and the U.S., and the developing world continues to burn coal."

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Question 2: CCUS and Nuclear.

I strongly support efforts to boost innovation to help bring new forms of energy to the market, but unclear whether carbon capture utilization and storage (CCUS) technologies and nuclear technologies will ever be cost competitive with existing electricity generation sources without an economy wide price signal that accurately reflects the cost of carbon emissions.

- Do you think predictable carbon pricing is important to making CCUS technologies and advanced nuclear technologies economical and getting the private sector investments we need to ramp up these solutions?
- Do you think a predictable price on carbon is more likely to spur energy markets to invest in technologies like CCUS and advanced nuclear than additional funding for more intangible policies like additional R&D?
- Do you think predictable carbon pricing can help keep existing American nuclear reactors open that otherwise will shut down?

Tinker: I spoke to carbon pricing (I favor incentives and investments over pricing) and energy density in prior questions. Given that, I think nuclear and natural gas with carbon capture, utilization, and storage (CCUS) have important roles to play. Each has the potential to scale (meaning have a significant impact on CO_2) in the times frames needed (< two decades). Because they are both energy dense, they provide very significant energy "bang for the buck."

China is building a significant nuclear fleet. I hope India will follow and am working to help with that. Given their government structures (fill in your favorite word), they have the ability to streamline and accelerate deployment. That reduces costs significantly. In my written testimony, I wrote that the U.S. should protect and even expand its nuclear fleet with next-generation technology, streamlined permitting, and deep-borehole nuclear waste disposal. These things are possible but require political agreement. Such agreement would send a stability signal to the markets, and the private sector investment could follow.

CCUS is essentially a cost. It requires a combination of investment flows and enablers from federal (ramped up 45Q, EPA rules, etc.), state (infrastructure, primacy, ownership of liability, etc.), and industry (U = enhanced oil recovery) to go forward.

Geology matters in order to allow for rate, volume, and long-term storage. The U.S. has several excellent CCUS locations, led by the offshore Gulf of Mexico.

Question 3: Aligning National Policies with Business Climate Goals

The past year could be remembered as a turning point in addressing the climate crisis with major corporations committing to decarbonize their operations by ever more aggressive timeframes as the private sector realizes that taking action to decarbonize is not only good socially, but also good for business.

- Why do you think businesses are committing to these bold greenhouse gas emission targets?
- Do these local and corporate emissions reduction activities have an impact on global emissions?
- Do you believe a coordinated national policy will accelerate the commitments we're already seeing at the corporate level?

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Tinker: Pledges and promises should be distinguished from activities and actions. Lots of pledges were made related to the Paris Accord in 2015 and many will not be met. Pledges do not reduce emissions. Pledges should come with very specific action plans to be considered sincere. Buying credits from others to offset your own emissions, or offshoring your supply chain to less regulated countries that emit more on a per unit product basis than the U.S., do not reduce emissions. It just moves the emissions somewhere else. There is only one global atmosphere.

I interact with and have served on corporate boards. Industry is making bold commitments for a variety of reasons, and these vary by company, industry, and geopolitical region. For example, improved access to capital, public license to operate, peer respect, political capital, virtue signaling, improved near-term corporate valuation, process efficiency, and more. For these reasons, pledges have shown to be "good for business" in the near term. Time will tell about the long term. In a globally competitive market, there is significant risk if some countries mandate emissions reductions on their industries while others do not.

I am not interested in accelerating pledges or commitments, but I am interested in reducing actual CO_2 emissions into the single global atmosphere, at scale, in the time frames needed. Thoughtful, bipartisan nationally coordinated incentives, investments, and signals could help with such things as:

- Fuel switching from coal to natural gas in Asia, as has happened in the U.S.
  - Supporting U.S. natural gas development, including pipelines—which are much safer than trucks—trains and boats, and LNG transport
- Nuclear
  - Promoting large-scale nuclear in India and SMRs in emerging economies
  - Expanding the U.S. fleet with next-generation technology
  - Streamlining permitting
  - Deep-borehole disposal
- Efficiency across all U.S. sectors
- Distributed solar and wind and, in certain settings, dispatchable solar and wind
- CCUS, especially in the world-leading Gulf of Mexico hub
- Hydro and geothermal, where global resources are viable
- Hydrogen industry buildout in the U.S.
- For transport, more efficient ICE, CNG, hydrogen FC, and EVs (avoid forcing EVs onto the market)

Question 4: China Winning the Clean Energy Race

There is no doubt that making the clean energy investments we need to stop carbon pollution is going to be a multi-trillion-dollar global market opportunity. The question, I believe, is whether that market—and the millions of associated jobs—will be captured by the U.S., or its foreign competitors.

China is the world's largest producer, exporter and installer of solar panels, wind turbines and electric vehicles. China is investing roughly $100 billion each year, double what the U.S. and the EU combined invest.

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- Is the U.S. losing the clean energy race to China and the rest of the world?
- What does China's clean energy leadership mean in terms of global greenhouse gas emissions?
- One common argument against taking action here in the U.S. is that it won't matter because the rest of the world will just keep on releasing carbon pollution–do you agree with that premise?

Tinker: As I have explained in other questions, there is no clean or dirty energy. Each form impacts the environment significantly, just in different ways. Thus, ***energy of all kinds*** is a multi-trillion-dollar opportunity, and indeed, China is ***winning the energy race***.

China is leading in developing solar, wind, and EV ***capacity***. China is also leading in coal and new nuclear, will soon overtake Japan as the world's top buyer of LNG, and completed the largest dam in the world (Three Gorges) in 2012. China is leading in EVs, but are charging those EVs with 60% coal-fired electricity. China is gaining control of the world's mined resources needed for manufacturing a variety of things, including solar panels, wind turbines and batteries. China is leading in global manufacturing (and associated energy consumption). Etc.

For the U.S. to "capture" solar and wind, which are not particularly high-tech industries, would either require a major acceleration in U.S. mining or the importation of significant raw materials owned by China and others. Global movement of materials has significant emissions implications of its own. At some point, the public will begin to correctly relate solar panels, wind turbines, and batteries to large-scale mining and landfill disposal. Given the growing resistance to almost any energy infrastructure, such as pipelines, which are safer for transporting liquids and gases than ships, trains, and trucks, I am not optimistic that a major U.S. increase in mining is on the horizon.

The U.S. needs to consider the possibility that China and SE Asia might be, quietly, just fine with climate policies that the U.S. and Western Europe are considering. These policies will shut in American and European energy supplies (bans on development of oil and natural gas, selection of transportation market winners (EVs), bans on internal combustion engines, bans on new pipelines, selection of electricity generation winners and losers, etc.). This will make American energy more expensive, accelerate exportation of manufacturing to China and SE Asia, and move the source of transportation fuel control from OPEC (oil) to China (batteries: lithium, cobalt, nickel, etc.).

We may want to do our part to try to keep the planet from warming, but the issue needs careful thought and critical thinking, including such things as: a candid look at global climate action versus often hollow promises; the impacts on U.S. energy security; human rights violations; the significant impacts of nonrenewable solar panels, wind turbines and batteries on land, air and water; and the impact on the U.S. economy.

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Questions from Senator Lisa Murkowski

Question 1: Mr. Mills, in your testimony you state that the U.S. was the top producer of minerals in 1990. Now, the United States is importing at least 50 percent of 47 different minerals. Getting my American Mineral Security Act over the finish line in the Energy Act of 2020 was an important step towards ensuring we reduce our foreign dependence on minerals, but what more can the U.S. do to ensure a reliable supply of critical minerals?

- **Answer:** I think a revisit of the regulatory impediments to mining are still needed. Because mining is both capital-intensive and involves inherently difficult construction projects, the virtual certainity that any venture will see long delays in running the thicket of barriers and permits, and protests, dramatically limits the appetites of private markets to undertake such projects within the United States. And exacerbating that reality, not only are such impediments far less onerous in many other nations, some countries and regions even provide incentives or subsidies to encourage mining.

Question 2: Does the U.S. have the technology and expertise to extract minerals in an environmentally responsible way? What about refining and processing capabilities?

- **Answer:** Yes, the U.S. has both the technology and expertise. However, in order to facilitate the use and expansion of that expertise, and to send the correct signals to the marketplace, the U.S. should resurrect the Bureau of Mines, which was dismantled in 1996. As for refining and processing; the U.S. is deeply deficient in capabilities in that area, though U.S. firms certainly have the expertise. Obviously, without refining/processing, the mining itself is not useful and the critical and high value-added conversion of raw minerals into useful industrial materials will continue to be done elsewhere.

Question 3: Mr. Mills, you mention in your testimony that well-intended efforts to restrict market optionality often result in unintended consequences. The U.S. has reduced its greenhouse gas emissions by significant levels through new technologies instead of burdensome new taxes or regulations. Alaskans are understandably concerned about President Biden's recent executive orders that have been framed as tackling climate change, but in fact are targeting responsible development in Alaska. How realistic are some of the goals that have been set – such as having the electricity sector emission free by 2035? What do these orders mean for communities and states that rely on fossil fuel revenue to fund state budgets?

- **Answer:** The current Administration's goals are profoundly unrealistic, especially in economic terms, when framed in terms of replacing the hydrocarbons that provide over 80% of our economy's energy. For example, the announced plan to fund $2 trillion in climate-related spending across the entire U.S. economy should be compared to the fact that, in order to "decarbonize" the U.S. grid alone—never mind the rest of the economy—would cost something like $4 to $5 trillion using today's wind/solar/battery technologies to replace natural gas and coal plants used to produce electricity. And that's just to take on about 20% of American hydrocarbon consumption. Even were "decarbonizing" the U.S. grid to be achieved, the result would represent, at most, a reduction of about 5% of <u>today's</u> global carbon dioxide emissions and, more likely, a reduction of less than 3% of the greater emissions of the world a couple of decades from now.

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Questions from Senator John Barrasso, M.D.

Question 1:

A. Can you discuss some of the issues surrounding the waste stream from advanced and renewable energy and storage technologies?

- **Answer:** Any full accounting of environmental impacts should included the decommissioning and disposal challenges inherent with the end-of-life of large quantities of hardware, all the worn-out batteries, wind turbines, and solar panels. The massive, reinforced fiberglass (plastic) blades are very expensive to cut up and handle, and are composed of nonrecyclable materials that end up in landfill. Estimates based on the earlier, i.e., less ambitious, wind power plans from several years ago, project that there will be more than three million tons per year of global unrecyclable pastic turbine blades by 2050.[1] Simlarly, the tonnage of waste from decomissioned solar hardware will, for comparision purposes, constitute double the tonnage of all global plastic waste buy 2050, again based on earlier and less ambitious plans for solar hardware.[2]

B. To what extent, is recycling an option to address the waste stream from advanced and renewable energy and storage technologies?

- **Answer:** Recycling is always feasible in theory, but in practice it can be difficult to achieve even modest shares of materials recovery and re-use. We can look to e-waste from the electronics industry for an example of the technical and economic challenges with recycling in a domain that also uses critical minerals, but that entails a vastly smaller total tonnage; the share of materials recycled in e-waste is reportedly about 20%. However, the activities associated with recycling e-waste—and 'green' waste will be very similar—has led to controversies and concerns about labor abuses as well as health and environmental impacts, the latter in large measure beause so much of it occurs in nations with low-cost labor.

Question 2: Many expect renewable and other technologies to improve at rates similar to what we have seen with computers. Is that a reasonable expectation?

- **Answer:** There is a trope in circulation that proposes we should expect that future progress in energy producing technologies could somehow echo the progress in information using technologies seen over the past four decades. It's true that the decline in energy *use* and size of transistors has increased computing power while simultaneously reducing costs; the famously dubbed Moore's Law. The effect of that has been dramatic: it would require the entire U.S. grid to power a single datacenter if it operated at the energy

[1] Pu Liu and Clare Y. Barlow, "Wind Turbine Blade Waste in 2050," Waste Management 62 (April 2017).
[2] Stephanie Weckend, Andreas Wade, and Garvin Heath, "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems Programme (IRENA & IEA-PVPS), June 2016.

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efficiency of computers of 1980. But this Moore's Law effect involves the gains in efficiency of *using* energy for information, and so we now have thousands of datacenters. A similar transformation in how energy is *produced* or *stored* isn't just unlikely, it's not possible unless one can amend the laws of physics. The energy needed to move a ton of people, heat a ton of steel or silicon, or grow a ton of food is determined by properties of nature where limits are set by laws of gravity, inertia, friction, and thermodynamics. If, for example, the performance of silicon solar cells or batteries could follow Moore's Law, a solar panel the size of single postage-stamp-size could power the Empire State Building and a single battery the size of a book would cost 3 cents and power a jumbo jet to Asia; both, obvious, impossibilities.

Question 3: Do you agree that higher energy costs are regressive and inequitable to lower-income people?

- **Answer:** Yes, of course they are. One of the great achievements of civilization has been in making so much energy available to so many people, so inexpensively. Until the age of hydrocarbons, from 70% to 90% of every economy's GDP was associated with obtain fuel and food. That share is roughly 10% now (except in numerous so-called "emerging" economies). Few things in history have had as wide a benefit to people, especially those with low-incomes, as has affordable and abundant energy and food.

Question 4: Much has been made of the fact the some renewable technologies have a lower "levelized cost of electricity" (LCOE) than coal or natural gas, and that these technologies are near or at parity.

A. Is LCOE the proper metric by which to compare these technologies?

- **Answer:** LCOE has some uses but, and I will quote the EIA: "The LCOE values for dispatchable and non-dispatchable technologies are listed separately in the tables because comparing them *must be done carefully*."[3] LCOE calculations do not take into account the array of real, if hidden, costs associated with delivering electricity reliably, 24/7 and 365-day-per-year. It's a useful starting point, but it is in effect a snapshot in time, not a realworld cost for society. To put it simply, if simplistically, imagine planning a daily commute owning an automobile that had a low LCOE *if and when* it was operating, but that could only operated about one-third of the time, and do so somewhat unpredictably.

B. What are some other considerations?

- **Answer:** Again, to put it simply, the key consideration is the overall cost to consumers for supplying electricity when it is needed. The International Energy Agency (IEA) recently proposed the idea of a "value-adjusted" LCOE, or VALCOE, to include such costs; calculated that way, as the share of overall electricity supplied by solar (or wind) rises, the costs associated with ensuring reliability also increases and at some point the result is that the next, or so-called marginal solar kilowatt-hour becomes far more expensive than conventional power.[4]

[3] EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019"

[4] Brent Wanner, "Commentary: Is Exponential Growth of Solar PV the Obvious Conclusion?" IEA, Feb. 6, 2019.

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Question 5: Based on the Intergovernmental Panel on Climate Change "Global Warming of 1.5°" report, the United Nations says that greenhouse gas (GHG) emissions "would need to fall by about 45 percent from 2010 levels by 2030" for the world to be on a path to net zero emissions by 2050. As a consequence, many policymakers in the United States and elsewhere have called for cuts of this magnitude. Based on what you know today, do you expect global emissions in 2030 will be 45 percent lower than 2010 levels? If not, why?

- **Answer:** I do not expect global carbon dioxide emissions will be lower in 2030 because there are no technologies that can be deployed fast enough, cheaply enough, to replace not only troday's uses of hydrocarbons, but the planned increased energy demands for many nations as reported by both the IEA and other reputable forecasts reflecting what countries are doing versus what its leaders are saying or promising. I note as just one example that China alone reportedly still plans to build more coal power plants that will be, in carbon terms, equal to about 20 Keystone Pipelines. About one-third of those new coal plants are already under construction.

Question 6: You testified that:

> *"...the United States is today, and will be for the foreseeable future, a net importer of, either wind, solar and battery machines, or key components for them, or for most of the critical "energy minerals" needed to build them. All these realities have implications for the baseline accounting of carbon dioxide emissions trends. These realities also have economic, geopolitical, environmental and even human rights implications."*

Please expand upon the "human rights implications" that the United States should take into account as it considers reducing GHG emissions through solar, wind, and electric battery technologies.

- **Answer:** The human rights aspects of how other nations obtain and process energy minerals, and manufacture green machines, has obvious relevance given the fact that the U.S. imports roughly 90% of solar panels, about 80% the critical components for wind turbines. we already know there are widespread human rights abuses, including for example widely reportedly cases of child labor in mines in the Congo, where 70% of the world's raw cobalt originates.[5] Companies can make pledges, but unfortunately, the facts suggest that there is often little correlation between such pledges and the frequency of abuses in foreign mines.[6]

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[5] Douglas Broom, "The Dirty Secret of Electric Vehicles," World Economic Forum, Mar. 27, 2019.

[6] Kate Hodal, "'Most Renewable Energy Companies' Linked with Claims of Abuses in Mines," *The Guardian*, Sept. 5, 2019.

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Question 7: The *Washington Free Beacon* has reported that: "One-third of the polysilicon China produced in 2019, for example, came from the Xinjiang region, where more than a million Uighurs are being held in government-run camps."

A. Is this figure accurate?

- **Answer:** It is consistent with other reports I've seen; in addition most analysts see China undertaking the fastest and greatest expansion in polysilicon production capacity.

B. What other components, which are used in solar panels, wind turbines, or electric batteries, are manufactured or processed in the Xinjiang region of China?

- **Answer:** I am not familiar with the specific industrial activities in the various regions in China, though I know from various visits and reading other analyses that the Chinese gonvernment has endeavored to expand the geographic centers of production for all manner of materials. China is one of the major, sometimes dominant, producer of many critical components or materials for so-called clean-tech energy, including for example, the refiing of manganese and cobalt, and the production of high-strength neodymium magnets.

Questions from Senator Maria Cantwell

Question 1: Carbon Price

Two years ago during another hearing in this committee, almost all of the witnesses agreed by a show of hands that putting a price on carbon pollution, either indirectly or directly, is a good thing.

- Do you believe that an economy wide price on carbon, applied upstream where fossil fuels enter the economy, is the most efficient mechanism to decrease carbon emissions at the necessary scale and speed?

- **Answer:** The answer depends on defining "scale and speed." If I may assume that the question is intended to reflect the scale of replacing the use of most hydrocarbons, and at a speed making such possible in the next couple of decades, then my answer is no. It's no, because in my opinion there is no price our society would tolerate to achieve that goal. We have, in effect, undertaken a relevant experiment several times, even if not intentinally, regarding if and how quickly society reduces hydrocarbon use in the face of higher costs. Of course every economics student knows that increasing prices, on average, can decrease demand. But the "elasticity" of that response depends very much on the kind of commodity or product, and in particular if the item/service is essential or discretionary. That food and fuel are essential goes without saying. Even when oil (a useful surrogate for carbon pricing) exceeded $100 a barrel, global demand growth was surprisingly resistant. Instead though, recessions have destroyed energy demand. And increasing the cost of

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oil—via a sufficient carbon tax—to say $200 or $300 a barrel would I'm sure decrease demand, and would doubtless motivate a shift to all manner of cheaper alternatives. But it would also cause a global recession.

- Do you believe that a predictable, market-based carbon price will incentivize the markets to reduce carbon emissions faster and more efficiently than could be achieved through direct regulation of emissions within specific industry sectors?

- **Answer:** I think that both forms of mechanisms of directed regulation would be profoundly less effective at achieving the goals as framed – i.e., a "transition" away from using hydrocarbons – than would market mechanisms based on viable technologies.

<u>Question 2</u>: CCUS and Nuclear

I strongly support efforts to boost innovation to help bring new forms of energy to the market, but unclear whether carbon capture utilization and storage (CCUS) technologies and nuclear technologies will ever be cost competitive with existing electricity generation sources without an economy wide price signal that accurately reflects the cost of carbon emissions.

- Do you think predictable carbon pricing is important to making CCUS technologies and advanced nuclear technologies economical and getting the private sector investments we need to ramp up these solutions?

- **Answer:** As I've indicated above, I don't believe there's a carbon price that society will tolerate that can also make it economically feasible to use the CCUS technology available now. I am, on the other hand very optimistic about the prospects for better nuclear technologies. The incentives to ramp up the latter could be more productively focused on further improving the license/regulatory process, and ensuring that electricity markets are not biased against "baseload" power, wherein the latter is vital for reliability.

- Do you think a predictable price on carbon is more likely to spur energy markets to invest in technologies like CCUS and advanced nuclear than additional funding for more intangible policies like additional R&D?

- **Answer:** The technological difficulty and state-of-the-art for CCUS and nuclear are profoundly different—the former is aspirational while the latter is real. To find realistic technologies for CCUS will require far more basic research which, I recognize, has the unsatisfactory characteristic of no firm promise or deadline for success.

- Do you think predictable carbon pricing can help keep existing American nuclear reactors open that otherwise will shutdown?

- **Answer:** Again, I don't think carbon pricing is the correct mechanism. I think pricing reliability and dispatchability in particular is a better mechanism. If a grid operator were to require an electricity producer

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to supply a specificed number of megawatt-hours when *asked for* over the planning horizons of grids (decades, not hours), in most cases nuclear would beat any combination of wind/solar/batteries for a very long time yet.

Question 3: Aligning National Policies with Business Climate Goals

The past year could be remembered as a turning point in addressing the climate crisis with major corporations committing to decarbonize their operations by ever more aggressive timeframes as the private sector realizes that taking action to decarbonize is not only good socially, but also good for business.

- Why do you think businesses are committing to these bold greenhouse gas emission targets?

- **Answer:** There are of course many incentives—political, regulatory, marketing, social—that induces corporations to make pledges.

- Do these local and corporate emissions reduction activities have an impact on global emissions?

- **Answer:** Often not, if by "impact" we mean anything of significance beyond miniscule changes at the global level, and especially if we include total realworld fuel-cycle impacts.

- Do you believe a coordinated national policy will accelerate the commitments we're already seeing at the corporate level?

- **Answer:** Governments can always provide incentives, or mandates, for corporate behaviors of any kind, and such things can accelerate "commitments." Whether the commitments are realized as eventual outcomes will be eventually determined by economic realities. The debate I would hope we will engage is one of what the incentives really cost and who pays for them. So far, for example, studies show that incentives to buy electric cars or install residential solar have been funded by middle to lower income taxpayers but benefited the highest income earners..

Question 4: China Winning the Clean Energy Race

There is no doubt that making the clean energy investments we need to stop carbon pollution is going to be a multi-trillion dollar global market opportunity. The question, I believe, is whether that market --and the millions of associated jobs-- will be captured by the U.S., or its foreign competitors.

China is the world's largest producer, exporter and installer of solar panels, wind turbines and electric vehicles. China is investing roughly $100 billion each year, double what the US and the EU combined invest.

- Is the U.S. losing the clean energy race to China and the rest of the world?

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- **Answer:** For the record, wind/solar supply about 2% of global energy, after hundreds of billions invested over the past two decades. Those two decades have seen rapid growth from a very small share. The jury is out on whether such growth rates continue; in my view, it is unlikely. In the meantime, China is also world's largest consumer, and importer, of coal and oil. China's grid is about two-thirds coal-fired and those power plants are expected to operate for decades. In addition, China alone reportedly plans to build yet more coal power plants, an additional increase greater than now exists on the entire U.S. grid.

  - What does China's clean energy leadership mean in terms of global greenhouse gas emissions?

Answer: It means, as I've noted earlier, above, that global greenhouse gas emissions will almost certainly rise.

  - One common argument against taking action here in the U.S. is that it won't matter because the rest of the world will just keep on releasing carbon pollution – do you agree with that premise?

Answer: Yes.

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Request from Senator Angus King during the hearing

Note: In my responses to Senator King's questions about the energy costs of battery fabrication and the observation that the associated emissions are "significant," and that studies showed that such fabrication emissions could substantially reduce or "offset" savings from not burning gasoline, Senator King requested: "I would appreciate if you could supply those studies, for the record for the committee."

Answer:

As I pointed out in my answer during the hearing, there are a number of variables that impact emissions attributable to electric vehicles, including, as just two examples, the source of the raw materials that make up the batteries and the primary energy source relied upon to generate the electricity that charges the batteries. Some relevant studies for the record, include the following:

International Council on Clean Transportation. "Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions," February 2018.

Jens F. Peters et al., "The Environmental Impact of Li-Ion Batteries and the Role of Key Parameters: A Review," *Renewable and Sustainable Energy Reviews* 67 (January 2017).

Qinyu Qiao et al., "Cradle-to-Gate Greenhouse Gas Emissions of Battery Electric and Internal Combustion Engine Vehicles in China," *Journal of Applied Energy* 204 (October 2017).

Mia Romare and Lisbeth Dahllöf, "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries: A Study with Focus on Current Technology and Batteries for Light-Duty Vehicles," IVL Swedish Environmental Research Institute, May 2017.

Timothy G. Gutowski, et al. "The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand," Philosophical Transactions of the Royal Society, 2013.

IEA, "Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals," 6 May 2020

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The Honorable Joe Manchin
Chairman
U.S. Senate Committee on
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304 Dirksen Senate Building
Washington, DC 20510

The Honorable John Barrasso
Ranking Member
U.S. Senate Committee on
Energy and Natural Resources
304 Dirksen Senate Building
Washington, DC 20510

Dear Chairman Manchin, Ranking Member Barrasso:

Thank you for holding a full Committee hearing today to examine global climate trends and progress in addressing climate change. I am submitting this letter today on behalf of the American Exploration and Production Council (AXPC), a national trade association representing the largest independent oil and natural gas exploration and production companies in the United States. Many of our member companies provide jobs, tax revenues, and economic benefits in your home states of West Virginia and Wyoming.

Data from IHS Markit shows that U.S. independents combine to produce about 83 percent of the nation's oil production and 90 percent of its natural gas and natural gas liquids (NGL) production.[1] The oil and natural gas industry is one of the most thoroughly regulated industries in the U.S. and we recognize the importance of regulations that balance the essential value of American oil and natural gas production with the global challenge of addressing climate change. As an industry, we have an irreplaceable role in developing and employing the technologies and innovative solutions that further our global climate goals, secure our longer-term energy future, and support our national security.

Reducing Emissions with Innovation and Technology

Our industry recognizes the need for public-private partnerships to create and deploy a broad range of large-scale, low-cost greenhouse gas emissions reduction technologies across the economy. These technologies should help to produce oil and natural gas in ways that are less carbon intensive than current practice. Working as partners, government and business leaders can support the scientific research necessary to develop new technologies, demonstrate the potential of these new technologies in critical applications, incentivize commercial investment in promising innovations, and deploy new technologies in public sector applications.

[1] "The Economic Contribution of Independent Operators in the United States" (May 2019) HIS Markit, for IPAA https://www.ipaa.org/new-study-independent-oil-gas-operators-drive-american-energy-development-by-wide-margin/

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One opportunity would be the research, development and demonstration of carbon capture utilization and storage (CCUS). According to the International Energy Agency (IEA), "Carbon capture, utilization and storage is the only group of technologies that contributes both to reducing emissions in key sectors directly and to removing CO2 to balance emissions that are challenging to avoid – a critical part of "net" zero goals. After years of slow progress, new investment incentives and strengthened climate goals are building new momentum behind CCUS."

This widely recognized technology can be supported by America's policymakers by advancing efficient, modernized, and timely permitting to new CCUS facilities and supporting infrastructure development. In addition, policy makers should count CCUS as an avoided greenhouse gas (GHG) control program, address the liability challenges of long-term storage of CO2, and help mitigate the high costs associated with early development of CCUS.

Significant technology improvements by the industry and our nation's abundance of U.S natural gas supply has led to our country becoming a leader in emissions reductions over the last decade. The deployment of CCUS technology can further reduce emissions.

Increased Natural Gas Production and Use Leads to Emissions Reductions

Over the past decade, natural gas production nearly doubled, while U.S. total energy-related CO2 emissions declined significantly. In part because of our industry, U.S. emissions reductions have outpaced the rest of the world. According to the U.S. Environmental Protection Agency, from 2005 to 2018, total U.S. energy-related CO2 emissions fell by 12 percent, while global energy-related emissions increased nearly 24 percent during this same period. Methane emissions from oil and natural gas systems also are down 23 percent since 1990.

Our environmental progress is recognized globally as well. The IEA reports that in 2019, the U.S. reduced CO2 emissions by 140 million tons, the largest reduction of any country, as a result of increased natural gas production. And, according to the Center for Climate and Energy Solutions, natural gas has been the primary driver[2] in reducing U.S. electric-power sector CO2 emissions to 32-year lows, and they are projected to continue to decline. The increased use of natural gas has also played a role in the reduction in criteria pollutants, including ozone precursors. The progress our country has made should serve as a model for the world—and natural gas is a key component of our success.

U.S. Liquified Natural Gas (LNG) supports climate goals, while helping meet global energy demand

The U.S. has a unique opportunity to meet growing global energy demand while and ensuring it will be filled by an energy source that better serves global climate goals. Even under the IEA Sustainable Development Scenario, which assumes every country meets their Paris commitments, the world will still get almost 50 percent of its energy from oil and natural gas in 2040.

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2 https://www.c2es.org/content/natural-gas/#:~:text=Combustion%20of%20natural%20gas%20emits,emissions%20to%20mid%2D1990%20levels

One of the best ways to reduce global emissions is to promote U.S. liquified natural gas to global markets which currently use more emissions intensive energy sources. For example, China gets about 2/3 of its electricity from coal, India gets about 3/4. U.S. LNG can help reduce emissions by 50 percent. U.S. LNG can also ensure that worldwide energy demand is satisfied in a manner that minimizes GHG emissions while maximizing reliability, and cost-efficiency.

To further domestic and global progress from our increased use of natural gas, AXPC supports efforts by policy leaders to promote increased transportation, use, and exports of natural gas, including:

- **Increasing the use of natural gas in global power generation.** Natural gas is now the largest source of U.S. electric power generation, helping reduce U.S. greenhouse gas emissions from power generation to mid-1990 levels. [3]

- **Providing energy access through natural gas to reduce poverty and improve the standard of living and the environment in impoverished nations.** Nearly a billion people worldwide lack access to electricity which significantly hurts access to health care, life expectancy, economic opportunity, and overall quality of life.

- **Incorporating more natural gas into free trade agreements.** Free trade agreements (FTAs) can be made with select countries to reduce barriers to U.S. natural gas exports. As of March 2019, only 18 countries had a natural gas free trade agreement with the United States. More countries should be added to facilitate natural gas exports.

- **Expediting approvals for U.S. LNG to countries without an FTA.** Shipments of U.S. LNG are automatically approved if the U.S. and the receiving country have a free trade agreement in place. If an FTA is not in force, the Natural Gas Act requires that a company must obtain approval from the Department of Energy (DOE). That approval is dependent on DOE publishing the application in the Federal Register and taking comment to determine if the export is in the public interest.

- **Seeking diplomatic efforts to encourage the consumption of U.S. LNG globally.** Because of the high environmental standards on the industry, and innovations in emissions controls in the production of oil and natural gas; U.S. LNG has significantly lower lifecycle emissions than the second highest global producer, Russia[4]. Promoting U.S. LNG abroad is not only good for lowering emissions, but also for our national security and global stability.

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[3] https://www.c2es.org/content/natural-gas/#:~:text=Combustion%20of%20natural%20gas%20emits,emissions%20to%20mid%2D1990%20levels.

[4] https://www.energy.gov/sites/prod/files/2019/09/f66/2019%20NETL%20LCA-GHG%20Report.pdf

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- **Enhancing U.S. infrastructure by supporting reforms that expedite the permitting process for energy infrastructure and/or provide financing options to bolster options to expand export markets for U.S. LNG.**

We look forward to working together on solutions that ensure a vibrant U.S. oil and natural gas industry, a growing, prosperous economy, and energy security that protects our interests at home and abroad.

Respectfully,

Anne Bradbury
CEO
American Exploration and Production Council

MEMORANDUM

From: Senator Sheldon Whitehouse
Date: March 3, 2020
RE: Economic Risks of Climate Change

Economic Risks of Climate Change

1. Numerous experts are warning of the risk of a carbon bubble:
    - Mark Carney, Governor of the Bank of England: "The exposure of UK investors, including insurance companies, to [stranded assets] is ***potentially huge***." (Page 8)
    - Mark Carney: "The combination of the weight of scientific evidence and the dynamics of the financial system suggest that, in the fullness of time, ***climate change will threaten financial resilience and longer term prosperity***." (Page 11)
    - Paul Fisher, Deputy Head of the Prudential Regulation Authority and Executive Director, Insurance Supervision for the Bank of England: "As the world increasingly limits carbon emissions, and moves to alternative energy sources, ***investments in fossil fuels and related technologies [...] may take a huge hit***." (Page 5)
    - 34 central bank presidents, Network for Greening the Financial System First Comprehensive Report: "Estimates of losses [...] are large and range from $1 trillion to $4 trillion when considering the energy sector alone, or ***up to $20 trillion*** when looking at the economy more broadly." (Page 17)
    - Christopher McGlade & Paul Elkins, University College London, writing in *Nature*: "Our results suggest that, globally, ***a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves*** should remain unused from 2010 to 2050 in order to meet the target of 2 degrees Celsius." (Page 1)
    - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*: "Our conclusions support the existence of a carbon bubble that, if not deflated early, could lead to a discounted global wealth loss of US$1 – 4 trillion, ***a loss comparable to the 2008 financial crisis***." (Page 1)

2. The effects of a carbon bubble on the U.S. economy could be particularly severe:
    - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*:
        i. The U.S. economy could experience more than $3 trillion (2016 dollars) in losses (Page 4, Figure 3a)
        ii. U.S. GDP could shrink by more than 5 percent (Page 4, Figure 3b)
        iii. The U.S. could lose millions of jobs (Page 4, Figure 3c)
        iv. "Regions with higher marginal costs experience a steep decline in production (for example, Russia), or lose almost their entire oil and gas industry (for example, Canada, the United States)." (Page 4)

3. The sooner policy makers act to decarbonize the economy, the less risk from a carbon bubble:
   - Mark Carney: "Risks to financial stability will be minimized if the transition begins early and follows a predictable path, thereby helping the market anticipate the transition to a 2 degree world." (Page 4)
   - Jean-François Mercure, *et al*., Cambridge University, writing in *Nature Climate Change*: "[E]conomic damage from a potential bubble burst could be avoided by decarbonizing early." (Page 1)
   - Jean-François Mercure, *et al*., Cambridge University, writing in *Nature Climate Change*: "[T]he United States is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them." (Page 5)
   - Battiston, *et al*., University of Zurich, writing in *Nature Climate Change*: "The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk." (Page 5)
   - Joseph Stiglitz, Expert Report, *Juliana v. United States of America*: "[T]he more time that passes, the more expensive it becomes to address climate change." (Page 19)

4. Numerous experts are warning of the risk of a coastal real estate crash:
   - Freddie Mac, *Life's a Beach*: "While technical solutions may stave off some of the worst effects of climate change, rising sea levels and spreading flood plains nonetheless appear likely to destroy billions of dollars in property and to displace millions of people. The economic losses and social disruption may happen gradually, but they are likely to be greater in total than those experienced in the housing crisis and Great Recession."
   - Union of Concerned Scientists, *Underwater* (2018): "In the coming decades, the consequences of rising seas will strain many coastal real estate markets – abruptly or gradually, but some eventually ***to the point of collapse – with potential reverberations throughout the national economy***." (Page 2)
   - *Risk & Insurance*: "These bellwether locations [Miami, Atlantic City, and Norfolk] signify a growing and alarming threat; that continually rising seas will damage coastal residential and commercial property values to the point that property owners will flee those markets in droves, thus ***precipitating a mortgage value collapse that could equal or exceed the mortgage crisis that rocked the global economy in 2008***."

5. A coastal real estate crash would have profound economic implications:
   - Freddie Mac, *Life's a Beach*: Between $238 and $507 billion worth of real estate will be below sea level by 2100.

- Union of Concerned Scientists, *Underwater* (2018): "[B]y the end of the 21st century ***nearly 2.5 million residential and commercial properties, collectively valued at $1.07 trillion today***, will be at risk of chronic flooding." (Page 2)
- *Risk & Insurance*: "In the housing crisis of 2008, a significant percentage of borrowers continued to make their mortgage payments even though the value of their homes was less than their mortgages. It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater. As a result, ***lenders, servicers and mortgage insurers are likely to suffer large losses***."
- First Street Foundation: Coastal residential real estate along the East Coast has already lost more than $15 billion in value since 2005 because of sea level rise.
- Moody's: "The growing effects of climate change, including climbing global temperatures, and rising sea levels, are forecast to have an increasing economic impact on US state and local issuers. This will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies."

6. The aggregate economic effects of climate change are systemic and could result in severe economic repercussions:
    - Bank of International Settlements, *The Green Swan*: "[C]limate change is a source of ***major systemic financial risks***." (Page 65); "[C]limate catastrophes are ***even more serious than most systemic financial crises***." (Page 3) "Exceeding climate tipping points could lead to ***catastrophic and irreversible*** impacts that would make quantifying financial damages impossible." (Page 1)
    - McKinsey: Climate change could "make long-duration borrowing unavailable, impact insurance cost and availability, and ***reduce terminal values***." It could "trigger ***capital reallocation and asset repricing***." (Page viii)
    - Fourth National Climate Assessment: "With continued growth in emissions at historic rates, ***annual losses in some economic sectors are projected to reach hundreds of billions of dollars by the end of the century***—more than the current gross domestic product (GDP) of many U.S. states."
    - Standard & Poor's: "***Global warming of 3 degrees Celsius is likely to cost us 2% of global output.*** [… W]e might even be underestimating the costs of climate change. [… T]he higher the temperature, the more damaging climate change will be – and in a nonlinear way."
    - 34 central bank presidents, Network for Greening the Financial System First Comprehensive Report: "Estimates suggest that absent action to reduce emissions, the physical impact of climate change on the global economy in the second half of the century will be substantial. The more sophisticated studies suggest ***average global incomes may be reduced by up to a quarter by the end of the century***." (Page 13)
    - Blackrock: "***Some 58% of U.S. metro areas would see likely [annual] GDP losses of up to 1% or more***, with less than 1% set to enjoy gains of similar magnitude. Florida tops the danger zones, with Naples, Panama City and Key West seeing likely annual GDP losses of up to 15% or more. (Page 9)

- Larry Fink, CEO of BlackRock: "In the near future– and sooner than most anticipate– there will be a ***significant reallocation of capital***."
- Tom Kompas, *et al*., University of Melbourne, writing in *Earth's Future* journal published by the American Geophysical Union: "***The approximate global potential loss is estimated to be US$ 9,593.71 billion or roughly 3% of the 2100 world GDP for 3ºC global warming.*** At 4ºC, losses from global warming increase significantly to US$ 23,149.18 billion." (Page 1160) ***Climate change-related economic losses in the U.S. are estimated to be approximately $224 billion per year in the U.S. in 2100 under a 3ºC scenario*** and $700 billion per year under a 4ºC scenario. (Page 1169)

ECONOMIC RISKS
OF
CLIMATE CHANGE

The pages that follow can also be accessed online at the following web address: https://senwhitehouse.medium.com/economic-risks-of-climate-change-sources-f9626ddff539

Mark Carney: Breaking the tragedy of the horizon – climate change and financial stability

Speech by Mr Mark Carney, Governor of the Bank of England and Chairman of the Financial Stability Board, at Lloyd's of London, London, 29 September 2015.

* * *

I am grateful to Rhys Phillips and Iain de Weymarn for their assistance in preparing these remarks, and to Michael Sheren, Clare Ashton, Matthew Scott and Professor Myles Allen for their comments.

I'm grateful to Lloyd's for the invitation to speak tonight on the occasion of the first City Dinner held in this magnificent, eponymous "Room".

Lloyd's is the bedrock of the UK insurance industry.

An industry whose direct contribution to the UK economy is impressive: 300,000 high-paying jobs and £25bn in annual GDP.

Its economic contribution goes much deeper.

Insurance supports households, companies and investors, safeguarding them from perils they could not otherwise shoulder.

It matches long-term savings and investment, financing the infrastructure essential to productivity.

With its unique perspective and skill set, insurance diversifies the financial system and reinforces its resilience.

Since 1688 Lloyd's has, in the great tradition of the City, served both the UK and the world, providing protection against the perils of the age; helping enterprise and trade to thrive.

From its origins in marine insurance, the Lloyd's market has evolved constantly to meet the needs of a rapidly changing world.

The first excess of loss reinsurance was created here.

Modern catastrophe cover was born with your decision to stand by policyholders after the San Francisco earthquake.

And Lloyd's pioneered aviation insurance.[1]

With eyes constantly on the horizon, Lloyd's has remained at the forefront of global insurance.

Today, you are insuring new classes of risk in new parts of the world – from cyber to climate, from space to specie, from Curitiba to Chengdu.

And you are doing so in market conditions as challenging as any in the last 20 years.

The need to manage emerging, mega risks is as important as ever.

Alongside major technological, demographic and political shifts, our very world is changing. Shifts in our climate bring potentially profound implications for insurers, financial stability and the economy.

I will focus on those risks from climate change this evening.

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[1] The first aviation policy was written in 1911, followed in 1919 by the founding of the British Aviation Insurance Association. That venture closed in 1921, with underwriters concluding that *"there seems to be no immediate future in aviation insurance…"* www.lloyds.com/lloyds/about-us/history/innovation-and-unusual-risks/pioneers-of-travel.

The tragedy of the horizon

There is a growing international consensus that climate change is unequivocal.[2]

Many of the changes in our world since the 1950s are without precedent: not merely over decades but over millennia.

Research tells us with a high degree of confidence that:

- In the Northern Hemisphere the last 30 years have been the warmest since Anglo-Saxon times; indeed, eight of the ten warmest years on record in the UK have occurred since 2002;[3]
- Atmospheric concentrations of greenhouse gases are at levels not seen in 800,000 years; and
- The rate of sea level rise is quicker now than at any time over the last 2 millennia.[4]

Evidence is mounting of man's role in climate change. Human drivers are judged extremely likely to have been the dominant cause of global warming since the mid-20th century.[5] While natural fluctuations may mask it temporarily, the underlying human-induced warming trend of two-tenths of a degree per decade has continued unabated since the 1970s.[6]

While there is always room for scientific disagreement about climate change (as there is with any scientific issue) I have found that insurers are amongst the most determined advocates for tackling it sooner rather than later. And little wonder. While others have been debating the theory, you have been dealing with the reality:

- Since the 1980s the number of registered weather-related loss events has tripled; and
- Inflation-adjusted insurance losses from these events have increased from an annual average of around $10bn in the 1980s to around $50bn over the past decade.[7]

The challenges currently posed by climate change pale in significance compared with what might come. The far-sighted amongst you are anticipating broader global impacts on property, migration and political stability, as well as food and water security.[8]

So why isn't more being done to address it?

A classic problem in environmental economics is the tragedy of the commons. The solution to it lies in property rights and supply management.

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[2] For instance, the IPCC has stated "*Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia*". See IPCC - Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2014).

[3] See www.metoffice.gov.uk/news/releases/archive/2015/Record-UK-temps-2014.

[4] See IPCC (2014).

[5] See IPCC (2014) which notes that the effects of anthropogenic greenhouse gas emissions, together with other anthropogenic drivers are "*extremely likely to have been the dominant cause of observed [global] warming since the mid-20th Century*".

[6] See, for example, Otto et al (2015).

[7] See Munich Re, NatCatSERVICE (2015).

[8] The report "*Risky Business – the economic risks of climate change in the United States*" (2014) suggests that in the USA $238-507bn worth of coastal property could be below sea level by 2100. Research by Lloyd's identifies climate change as an important supply-side issue for food security. See www.lloyds.com/~/media/lloyds/reports/emerging%20risk%20reports/food%20report.pdf. This is consistent with the views expressed by Lloyd's market participants surveyed by the PRA for its report to Defra.

Climate change is the Tragedy of the *Horizon*.

We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

That means beyond:

- the ***business cycle***;[9]
- the ***political cycle***; and
- the ***horizon of technocratic authorities***, like central banks, who are bound by their mandates.

The horizon for monetary policy extends out to 2-3 years. For financial stability it is a bit longer, but typically only to the outer boundaries of the credit cycle – about a decade.[10]

In other words, once climate change becomes a defining issue for financial stability, it may already be too late.

This paradox is deeper, as Lord Stern and others have amply demonstrated. As risks are a function of cumulative emissions, earlier action will mean less costly adjustment.[11]

The desirability of restricting climate change to 2 degrees above pre-industrial levels[12] leads to the notion of a carbon "budget", an assessment of the amount of emissions the world can "afford".

Such a budget - like the one produced by the IPCC[13] – highlights the consequences of inaction today for the scale of reaction required tomorrow.

These actions will be influenced by policy choices that are rightly the responsibility of elected governments, advised by scientific experts. In ten weeks representatives of 196 countries will gather in Paris at the COP21 summit to consider the world's response to climate change. It is governments who must choose whether, and how, to pursue that 2 degree world.

And the role of finance? Earlier this year, G20 Finance Ministers asked the Financial Stability Board to consider how the financial sector could take account of the risks climate change poses to our financial system.

As Chair of the FSB I hosted a meeting last week where the private and public sectors discussed the current and prospective financial stability risks from climate change and what might be done to mitigate them.

I want to share some thoughts on the way forward after providing some context beginning with lessons from the insurance sector.

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[9] Few business leaders list climate change as a near-term pressing risk. See, for instance, PWC's annual survey of CEOs (www.pwc.com/gx/en/ceo-agenda/ceo-survey.html) and the Bank of England's Systemic Risk Survey (www.bankofengland.co.uk/publications/Documents/other/srs/srs2015h1.pdf).

[10] Even credit ratings typically only look out to 3-5 years.

[11] For instance, IPCC (2014) Conclusion SPM 2.1 notes that "*cumulative emissions of CO2 largely determine global mean surface warming by the late 21st century and beyond*". The Stern review observes that "*many greenhouse gases, including carbon dioxide, stay in the atmosphere for more than a century*" (See The Stern Review of the Economic Effects of Climate Change (2006)).

[12] The Cancun Agreement in 2010 committed governments to "*hold the increase in global average temperature below two degrees*". Discussion of this level has been attributed to Nordhaus (1975). Others, including the UNEP Advisory Group on Greenhouse Gasses (1990) have suggested that two degrees could be a point beyond which the damage caused by climate change may become non-linear.

[13] See IPCC (2014).

Climate change and financial stability

There are three broad channels through which climate change can affect financial stability:

– First, ***physical risks***: the impacts today on insurance liabilities and the value of financial assets that arise from climate- and weather-related events, such as floods and storms that damage property or disrupt trade;

– Second, ***liability risks***: the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible. Such claims could come decades in the future, but have the potential to hit carbon extractors and emitters – and, if they have liability cover, their insurers – the hardest;

– Finally, ***transition risks***: the financial risks which could result from the process of adjustment towards a lower-carbon economy. Changes in policy, technology and physical risks could prompt a reassessment of the value of a large range of assets as costs and opportunities become apparent.

The speed at which such re-pricing occurs is uncertain and could be decisive for financial stability. There have already been a few high profile examples of jump-to-distress pricing because of shifts in environmental policy or performance.

Risks to financial stability will be minimised if the transition begins early and follows a predictable path, thereby helping the market anticipate the transition to a 2 degree world.

To draw out these crucial points consider the Bank of England's current approach to the insurance sector.

As regulator of the world's third largest insurance industry, the PRA is responsible for protecting policyholders and ensuring the safety and soundness of insurers.

Our supervision is forward-looking and judgement-based. It is risk-based and proportionate – tailored to different business models around the sector – and considers both business-as-usual and whether a firm can fail safely – recognising that "zero failure" is neither desirable nor realistic.

Our supervisors take a view of your business plans, risk management, governance, and capital models. Where the PRA judges that it is necessary to intervene it does so sooner rather than later.

While our mandate is to protect policyholders – many of whom are local – we are conscious that international competition needs robust and internationally-consistent regulatory standards.

Solvency II is a good example. It is a prudent but proportionate Directive, that embodies the core principles of our domestic standards and embeds them more consistently across Europe while replacing a patchwork of local regimes.

Another example of how best practice is converging globally is the FSB agreement last week on HLA for global systemic insurers, as well as its support for the IASB completing its new insurance contracts standard. The UK insurance industry is well-prepared for such developments.

Forward-looking regulators consider not just the here and now, but emerging vulnerabilities and their impact on business models.

That is why the PRA has worked with regulated firms, many of them represented here tonight, to produce for the Department for Environment, Food and Rural Affairs a review – published today – into the impact of climate change on British insurers.

The Report concludes that insurers stand exposed to each of the three types of risk climate change poses to finance; and while the sector is well-placed to respond in the near-term you should not assume your ability to manage risks today means the future is secure. Longer term risks could have severe impacts on you and your policyholders.

The insurance response to climate change

It stands to reason that general insurers are the most directly exposed to such losses.

Potential increases in the frequency or severity of extreme weather events driven by climate change could mean longer and stronger heat waves; the intensification of droughts; and a greater number of severe storms.

Despite winter 2014 being England's wettest since the time of King George III; forecasts suggest we can expect at least a further 10% increase in rainfall during future winters.[14]

A prospect guaranteed to dampen the spirits and shoes of those who equate climate change with global warming.

While the attribution of increases in claims to specific factors is complex, the ***direct costs*** of climate change are already affecting insurers' underwriting strategies and accounts.

For example, work done here at Lloyd's of London estimated that the 20cm rise in sea-level at the tip of Manhattan since the 1950s, when all other factors are held constant, increased insured losses from Superstorm Sandy by 30% in New York alone.[15]

Beyond these direct costs, there is an upward trend in losses that arise indirectly through second-order events like the disruption of global supply chains.

Insurers are therefore amongst those with the greatest incentives to understand and tackle climate change in the short term. Your motives are sharpened by commercial concern as capitalists and by moral considerations as global citizens. And your response is at the cutting edge of the understanding and management of risks arising from climate change.

Lloyd's underwriters were the first to use storm records to mesh natural science with finance in order to analyse changing weather patterns. Events like Hurricanes Andrew, Katrina and Ike have helped advance catastrophe risk modelling and provisioning.[16] Today Lloyd's underwriters are required to consider climate change explicitly in their business plans and underwriting models.

Your genius has been to recognise that past is not prologue and that the catastrophic norms of the future can be seen in the tail risks of today.

For example, by holding capital at a one in 200 year risk appetite, UK insurers withstood the events of 2011, one of the worst years on record for insurance losses. Your models were validated, claims were paid, and solvency was maintained.

The combination of your forecasting models, a forward-looking capital regime and business models built around short-term policies means general insurers are well-placed to manage physical risks in the near term.

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[14] See Met Office research into climate observations, projections and impacts – http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf.

[15] A Lloyd's report ("*Catastrophe Modelling and Climate Change*" - 2014) looks at factors that influence the impact of hurricanes. It notes the importance of sea-level changes – in addition to wind speed and tides – in the impact of Sandy on New York. See www.lloyds.com/~/media/Lloyds/Reports/Emerging%20Risk%20Reports/CC%20and%20modelling%20template%20V6.pdf.

[16] As the PRA's report to Defra notes, major catastrophe events have often driven innovations in risk management. For example, following Hurricane Andrew (1992, $15.5 billion uninflated insured losses) and the associated insolvency of eight insurance companies, the industry developed a more sophisticated approach to assessing catastrophe risk, and became more resilient to similar events.

But further ahead, increasing levels of physical risk due to climate change could present significant challenges to general insurance business models.

Improvements in risk modelling must be unrelenting as loss frequency and severity shifts with:

- Insurance extending into new markets not covered by existing models;
- Previously unanticipated risks coming to the fore; and
- Increasingly volatile weather trends and hydrological cycles making the future ever-harder to predict.

For example, the extent to which European windstorms occur in clusters[17] could increase the frequency of catastrophes and reduce diversification benefits.

Indeed, there are some estimates that currently modelled losses could be undervalued by as much as 50% if recent weather trends were to prove representative of the new normal.[18] In addition, climate change could prompt increased morbidity and mortality from disease or pandemics.

Such developments have the potential to shift the balance between premiums and claims significantly, and render currently lucrative business non-viable.

Absent actions to mitigate climate change, policyholders will also feel the impact as pricing adjusts and cover is withdrawn.[19]

Insurers' rational responses to physical risks can have very real consequences and pose acute public policy problems.

In some extreme cases, householders in the Caribbean have found storm patterns render them unable to get private cover, prompting mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned.

Thankfully these cases are rare. But the recognition of the potential impact of such risks has prompted a publicly-backed scheme in the UK – Flood Re – to ensure access to affordable flood insurance for half a million homes now considered to be at the highest risk of devastating flooding.

This example underlines a wider point. While the insurance industry is well placed to adapt to a changing climate in the short-term, their response could pose wider issues for society, including whether to nationalise risk.

The passage of time may also reveal risks that even the most advanced models are not able to predict, such as third party liability risks.

Participants in the Lloyd's market know all too well that what appear to be low probability risks can evolve into large and unforeseen costs over a longer timescale.

Claims on third-party liability insurance – in classes like public liability, directors' and officers' and professional indemnity - could be brought if those who have suffered losses show that insured parties have failed to mitigate risks to the climate; failed to account for the damage they cause to the environment; or failed to comply with regulations.

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17 Discussions on correlation are not new. For example, a current issue is the extent to which European windstorms occur in clusters, such as windstorms Daria, Vivian, Wiebke and Herta in 1990 and Lothar, Martin, and Anatol in 1999.

18 See Standard and Poor's – "*Climate Change Could Sting Reinsurers That Underestimate Its Impact*" (2014).

19 In 1992 after Hurricanes Andrew and Iniki hit the US, the price of reinsuring weather risks spiked and several carriers left the market, leading to a rise of up to 40% in premiums in some parts of Florida. A series of hurricanes affecting the Bahamas has prompted several insurers to withdraw flood cover for low-lying areas.

Asbestos alone is expected to cost insurers $85bn on a net ultimate claims basis in the United States – equivalent to almost three Superstorm Sandy-sized loss events.[20]

It would be premature to draw too close an analogy with climate risks, and it is true that court cases have, so far, largely been unsuccessful.

Cases like Arch Coal and Peabody Energy – where it is alleged that the directors of corporate pension schemes failed in their fiduciary duties by not considering financial risks driven at least in part by climate change[21] – illustrate the potential for long-tail risks to be significant, uncertain and non-linear.

And "Loss and Damage" from climate change – and what to do about it – is now formally on the agenda of the United Nations Framework Convention on Climate Change, with some talking openly about the case for compensation.[22]

These risks will only increase as the science and evidence of climate change hardens.

Physical risks from climate change will also become increasingly relevant to the ***asset side*** of insurer's balance sheets.[23]

While the ability to re-price or withdraw cover mitigates some risk to an insurer, as climate change progresses, insurers need to be wary of cognitive dissonance within their organisations whereby prudent decisions by underwriters lead to falls in the value of properties held by the firm's asset managers. This highlights the transition risk from climate change.

Transition risks

The UK insurance sector manages almost £2tn in assets to match liabilities that often span decades.

While a given physical manifestation of climate change – a flood or storm – may not directly affect a corporate bond's value, policy action to promote the transition towards a low-carbon economy could spark a fundamental reassessment.

Take, for example, the IPCC's estimate of a carbon budget that would likely limit global temperature rises to 2 degrees above pre-industrial levels.

That budget amounts to between 1/5th and 1/3rd world's proven reserves of oil, gas and coal.[24]

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[20] See AM Best – *Special Report: Asbestos Losses Fueled by Rising Number of Lung Cancer Cases* (2013) www.ambest.com/ambv/bestnews/presscontent.aspx?altsrc=0&refnum=20451.

[21] See *Roe v Arch Coal Inc et al*, Case: 4:15-cv-00910-NAB, United States District Court, Eastern District of Missouri, 9 June 2015 and *Lynn v Peabody Energy Corporation et al*, Case: 4:15-cv-00916-AGF, United States District Court, Eastern District of Missouri, 11 June 2015. Note that as at 1 September 2015 the defences to these claims were yet to be filed.

[22] Loss and damage refers to impact of climate change not mitigated by reductions in emissions. The UNFCCC Warsaw agreement in 2013 discussed support for measures to address loss and damage. See http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf.

[23] The largest UK insurers hold or manage in excess of £40bn of CRE and infrastructure assets, and have committed to further such investments in future. For instance, six major insurers pledged to invest £25bn into UK domestic infrastructure in 2013 as part of the Government's national infrastructure plan (see http://www.ft.com/cms/s/0/1f74e176-5c41-11e3-b4f3-00144feabdc0.html).

[24] The IPCC gives a range of budgets for future emissions which depends on assumptions about other climate drivers and the level of risk of temperatures going >2 degrees that society is willing to accept. It sets these in the context of existing fossil fuel reserves. See table 2.2 in IPCC (2014).

If that estimate is even approximately correct it would render the vast majority of reserves "stranded" – oil, gas and coal that will be literally unburnable without expensive carbon capture technology, which itself alters fossil fuel economics.[25]

The exposure of UK investors, including insurance companies, to these shifts is potentially huge.

19% of FTSE 100 companies are in natural resource and extraction sectors; and a further 11% by value are in power utilities, chemicals, construction and industrial goods sectors. Globally, these two tiers of companies between them account for around one third of equity and fixed income assets.

On the other hand, financing the de-carbonisation of our economy is a major opportunity for insurers as long-term investors. It implies a sweeping reallocation of resources and a technological revolution, with investment in long-term infrastructure assets at roughly quadruple the present rate.[26]

For this to happen, "green" finance cannot conceivably remain a niche interest over the medium term.

There are a number of factors which could influence the speed of transition to a low carbon economy including public policy, technology, investor preferences and physical events.

From a regulator's perspective the point is not that a reassessment of values is inherently unwelcome. It is not. Capital should be allocated to reflect fundamentals, including externalities.

But a wholesale reassessment of prospects, especially if it were to occur suddenly, could potentially destabilise markets, spark a pro-cyclical crystallisation of losses and a persistent tightening of financial conditions.

In other words, an abrupt resolution of the tragedy of horizons is in itself a financial stability risk.

The more we invest with foresight; the less we will regret in hindsight.

And there are ways to make that more likely.

Financial policy implications

Financial policymakers will not drive the transition to a low-carbon economy. It is not for a central banker to advocate for one policy response over another. That is for governments to decide.

But the risks that I have outlined mean financial policymakers do, however, have a clear interest in ensuring the financial system is resilient to any transition hastened by those decisions, and that it can finance the transition efficiently.

Some have suggested we ought to accelerate the financing of a low carbon economy by adjusting the capital regime for banks and insurers. That is flawed. History shows the danger

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[25] The IPCC makes clear that, without this critical technology, the cost of meeting the two degree goal more than doubles – if it can be achieved at all. Canada is home to the world's first *commercial*-scale CCS plant at Boundary Dam. Other projects rely on government subsidies which can prove unreliable. If companies are relying on CCS to achieve net zero carbon emissions, investors will want to assess how they plan to get there – and who they expect to pay for it.

[26] The IPCC estimates that additional investment of US$ 190-900bn is required annually in the energy sector alone if the rise in average global temperature is to be capped at 2C. www.ipcc.ch/report/ar5/ Mercer estimates that additional cumulative investment in efficiency improvements, renewable energy, biofuels and nuclear, and carbon capture and storage could be in the range of US$3-5trn by 2030. www.mercer.com/insights/point/2014/climate-change-scenarios-implications-for-strategic-asset-allocation.html

of attempting to use such changes in prudential rules – designed to protect financial stability – for other ends.

More properly our role can be in developing the frameworks that help the market itself to adjust efficiently.

Any efficient market reaction to climate change risks as well as the technologies and policies to address them must be founded on transparency of information.

A "market" in the transition to a 2 degree world can be built. It has the potential to pull forward adjustment – but only if information is available and *crucially* if the policy responses of governments and the technological breakthroughs of the private sector are credible.

That is why, following our discussions at the FSB last week, we are considering recommending to the G20 summit that more be done to develop consistent, comparable, reliable and clear disclosure around the carbon intensity of different assets.

Better information to allow investors to take a view

An old adage is that which is measured can be managed.

Information about the carbon intensity of investments allows investors to assess risks to companies' business models and to express their views in the market.

A well-known dictum of macroeconomics is Say's Law: that supply creates demand.

This means that the act of producing new products creates income and profits that ultimately finance the demand for them.

By analogy, a framework for firms to publish information about their climate change footprint, and how they manage their risks and prepare (or not) for a 2 degree world, could encourage a virtuous circle of analyst demand and greater use by investors in their decision making. It would also improve policymaker understanding of the sources of CO2 and corporate preparedness.

A carbon budget – like the one produced by the IPCC – is hugely valuable, but can only really be brought to life by disclosure, giving policymakers the context they need to make choices, and firms and investors the ability to anticipate and respond to those choices.

Given the uncertainties around climate, not everyone will agree. Some might dispute the IPCC's calculations. Others might despair that there will never be financial consequences of burning fossil fuels. Still others could take a view that the stakes make political action inevitable.

The right information allows sceptics and evangelists alike to back their convictions with their capital.

It will reveal how the valuations of companies that produce and use fossil fuels might change over time.

It will expose the likely future cost of doing business, paying for emissions, changing processes to avoid those charges, and tighter regulation.

It will help smooth price adjustments as opinions change, rather than concentrating them at a single climate "Minsky moment".

Crucially, it would also allow feedback between the market and policymaking, making climate policy a bit more like monetary policy.

Policymakers could learn from markets' reactions and refine their stance, with better information allowing more informed reactions, and supporting better policy decisions including on targets and instruments.

A climate disclosure task force

That better information – about the costs, opportunities and risks created by climate change – can promote timely responses is not a new idea.

Much the opposite: there are already nearly 400 initiatives to provide such information.

Existing schemes vary in their status (from laws to voluntary guidance); scope (from greenhouse gas emissions to broader environmental risks); and ambition (from simple disclosure to full explanations of mitigation and divestment strategies).[27]

In aggregate over 90% of FTSE 100 firms and 80% of Fortune Global 500 firms participate in these various initiatives. For instance, the Carbon Disclosure Project makes available disclosure from 5,000 companies to investment managers responsible for over $90 trillion of assets.

The existing surfeit of existing schemes and fragmented disclosures means a risk of getting "lost in the right direction".

In any field, financial, scientific or other, the most effective disclosures are:

- ***Consistent*** – in scope and objective across the relevant industries and sectors;
- ***Comparable*** – to allow investors to assess peers and aggregate risks;
- ***Reliable*** – to ensure users can trust data;
- ***Clear*** – presented in a way that makes complex information understandable; and
- ***Efficient*** – minimising costs and burdens while maximising benefits.

Meeting these standards requires coordination, something the G20 and FSB are uniquely placed to provide.

The logical starting point is a co-ordinated assessment of what constitutes effective disclosure, by those who understand what is valuable and feasible.

One idea is to establish an industry-led group, a ***Climate Disclosure Task Force***, to design and deliver a voluntary standard for disclosure by those companies that produce or emit carbon.

Companies would disclose not only what they are emitting today, but how they plan their transition to the net-zero world of the future. The G20 – whose member states account for around 85% of global emissions[28] – has a unique ability to make this possible.

This kind of proposal takes its lead from the FSB's successful catalysing of improved disclosure by the world's largest banks following the financial crisis, via the Enhanced Disclosure Task Force.

The EDTF's recommendations, published in October 2012, were the product of collaboration between banks, analysts and investors. This has given the providers of capital the disclosures they need – specifically how banks manage risks and make profits – in a format that the banks can readily supply.

That shows that private industry can improve disclosure and build market discipline without the need for detailed or costly regulatory interventions.

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[27] A non-exhaustive list of some of the more prominent initiatives in this space includes the Carbon Standards Disclosure Board, Integrated Reporting, the Carbon Disclosure Project, and the UN Principles for Responsible Investment.

[28] See www.pwc.co.uk/assets/pdf/low-carbon-economy-index-2014.pdf

Like the EDTF, a CDTF could be comprised of private providers of capital, major issuers, accounting firms and rating agencies.

Complementing static disclosures

Static disclosure is a necessary first step. There are two ways its impact could be amplified.

First, governments, potentially sparked by COP21, could complement disclosure by giving guidance on possible carbon price paths.

Such a carbon price *corridor* involves an indicative minimum and maximum price for carbon, calibrated to reflect both price and non-price policy actions, and increasing over time until the price converges towards the level required to offset fully the externality. [29]

Even if the initial indicative price is set far below the "true" cost of carbon, the price signal itself holds great power. It would link climate exposures to a monetary value and provide a perspective on the potential impacts of future policy changes on asset values and business models.

Second, stress testing could be used to profile the size of the skews from climate change to the returns of various businesses.[30]

This is another area where insurers are at the cutting edge.

Your capital requirements are based on evaluating the impact of severe but plausible scenarios. You peer into the future, building your defences against a world where extreme events become the norm.

This stress-testing technology is well-suited to analysing tail risks likely to grow fatter with time, casting light on the future implications of environmental exposures embedded in a wide range of firms and investments.

Stress testing, built off better disclosure and a price corridor, could act as a time machine, shining a light not just on today's risks, but on those that may otherwise lurk in the darkness for years to come.

Conclusion

Our societies face a series of profound environmental and social challenges.

The combination of the weight of scientific evidence and the dynamics of the financial system suggest that, in the fullness of time, climate change will threaten financial resilience and longer-term prosperity.

While there is still time to act, the window of opportunity is finite and shrinking.[31]

Others will need to learn from Lloyd's example in combining data, technology and expert judgment to measure and manage risks.

The December meetings in Paris will work towards plans to curb carbon emissions and encourage the funding of new technologies.

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[29] For instance, the report of the Canfin-Grandjean Commission (2015) discusses the merits of an indicative price corridor with a maximum and minimum price that can be increased over time. See www.elysee.fr/assets/Report-Commission-Canfin-Grandjean-ENG.pdf

[30] These skews could be upside or downside, depending on business model and the point in the transition path.

[31] Already our failure to act since 2010 has increased the task – since emissions persist – and the pace of de-carbonisation required – for instance see http://site.thomsonreuters.com/corporate/pdf/global-500-greenhouse-gases-performance-trends-2010-2013.pdf

We will need the market to work alongside in order to maximise their impact.

With better information as a foundation, we can build a virtuous circle of better understanding of tomorrow's risks, better pricing for investors, better decisions by policymakers, and a smoother transition to a lower-carbon economy.

By managing what gets measured, we can break the Tragedy of the Horizon.

BANK OF ENGLAND

Speech

Confronting the challenges of tomorrow's world

Speech given by
Paul Fisher, Deputy Head of the Prudential Regulation Authority and Executive Director, Insurance Supervision

Economist's Insurance Summit 2015, London
Tuesday 3 March 2015

Thank you for inviting me to speak to you today. As many of you will know I have been covering as Executive Director of Insurance, in addition to my responsibilities as Deputy Head of the PRA, since August last year whilst a search was made for a permanent appointment. At long last I will be passing the baton over to Sam Woods at Easter. So this is likely to be my final speech made as Insurance Director.

I would like to take the opportunity to offer up some personal observations about the current and prospective state of the insurance industry, as well as comment more generally on the role regulation will play in 'confronting the challenges of tomorrow'.

The insurance sector, by absorbing and laying off risk, plays a fundamental role in fostering a stable economy. A successful industry is therefore key to achieving the Bank of England's financial and monetary stability objectives. And as society and its economy evolve, it is vital that the insurance sector also responds to that changing environment.

Tomorrow's world inevitably brings change. Some changes can be forecast, or guessed by extrapolating from what we know today. But there are, inevitably, the unknown unknowns which will help shape the future. That means that a successful industry needs to be both dynamic and robust.

Uncertainty generates challenges but also represents opportunity. I want to discuss these risk/reward trade-offs and the importance of understanding the potential for new exposures that changing risk profiles can bring.

Insurance fulfils important social functions: the provision of income security in retirement; income protection whilst in work; funding for health care services and preserving the continuity of businesses subject to unexpected shocks. Indeed, in some areas, insurance is compulsory such as with motor insurance and employers' liability. Disruption to these functions is unlikely to be tolerated by wider society, not only because of the social benefits, but because risk transfer and pooling are crucial for sustainable economic growth and development. It is for this reason that the need to protect the interests of policy holders and to preserve long-term critical cover is so important.

Although one cannot be sure what the future may bring, we can learn from past mistakes to avoid their repetition. That is particularly apposite given that the residual effects of the great financial crisis are still being felt across the global economy. One of the things we appreciate very well at the PRA is that insurance business is very different to banking, and I have seen that at first hand over the past six months or so. I have also seen that there are lessons to be learnt from the banking crisis that can directly read across to the world of insurance.

Let me express a clear personal opinion: financial crises of the past were often, in large part, created by the people at the top making poor decisions – people not possessing the right information; not having due regard for risk; not being properly incentivised. Significant failures have often had their roots in poor governance with insufficient checks and balances to the decisions of powerful individuals. Strong, effective systems of oversight and risk management are paramount in meeting the PRA's objectives for the safety and soundness of firms and insurance policyholder protection. Not surprisingly, governance issues are consistently at, or near the top, of the PRA's agenda whether for banks or insurers. I can safely predict that this focus is not about to lessen any time soon. Firms in tomorrow's world need to aim for governance best practice.

The recent banking crises further illustrated that one of the most obvious ways in which financial stability can be undermined is through disorderly firm failure and the consequent disruption of financial services. The PRA's stance is that unsuccessful business models need to be allowed to fail, but that failure should be in an orderly manner so as not to disrupt the provision of core financial services. And I think we would all agree that the taxpayer should not be asked to bail out a failed firm.

One difference from banking is that failing insurers usually do exit in an orderly manner. Actually, about a third of the PRA's authorised firms are in run-off. But that is in part a testament to the successful regulatory regime that the UK has been running for the insurance sector. And, whatever the regime, we cannot be certain this will be the case in every conceivable circumstance. For this reason, the PRA continues to place the resolution arrangements for insurers on both the domestic and international agendas.

The banking crisis further taught us all that we need to be looking at potential storms ahead and not to be misled by periods of fair weather. For the PRA this means it will assess firms not just against current risks, but also against those that could plausibly arise in the future, carrying out increased business model analysis. For insurers, this involves monitoring emerging risks and taking preparatory steps to deal with what may result, with firms holding capital commensurate to their evolving risk profile. This approach is embedded as part of Solvency II, for example with the requirement for each undertaking to conduct a forward looking assessment of its own risk and solvency needs.

The fallout from the global financial crisis has accentuated the need for an open, two-way dialogue between regulator and regulated. This is especially true in times of change or stress. To ensure policyholder protection, regulators need to be alert to emerging risks and this is best achieved through a 'cards on the table' approach. Indeed, where the PRA judges it is necessary to intervene, we will seek to do so at an early stage. Firms should be open and straightforward in their dealings with the PRA and we in turn will take a risk-based and proportionate approach.

This is being put into practice. For example, enhanced communication is particularly pertinent as we transition to the Solvency II world. From April, firms will be able to make formal applications and we don't need a crystal ball to predict a very busy year for both regulator and regulated. The PRA has had an extensive on-going dialogue with firms, giving detailed feedback on, for example, their internal model developments or their matching adjustment applications. Just over a week ago we issued guidance on how equity release mortgages might be structured for use in the matching adjustment. Right now, the PRA is aiming to provide both general and individual firm feedback, recognising the importance of timely communication allowing firms to prepare thoroughly.

As a consequence of the financial crisis, financial regulation in all its forms has been through a major transition. In the UK we have seen the split of prudential and conduct regulation, the establishment of a single Insurance Directorate at the PRA with an insurance specific secondary objective, and we have moved forward in our application of 'judgement-based regulation'. The next few years will be about embedding this new approach through Solvency II.

I would like to move on now from regulation to a number of other developments and challenges that are currently on the horizon and to discuss the possible impacts these could have on insurers' business models.

The nature of insurance and the risk transfer role it provides means that insurance cuts across all aspects of society; whether providing at retirement solutions to pensioners to insuring the latest iPhone. It is for this reason that insurers find themselves innovating in step with wider society. As insurers are directly exposed to social changes, the changing world is the very stuff on which they should thrive. There are a number of such societal, regulatory or environmental changes currently at play such as global warming, globalisation, digitisation, demographic changes and cyber risk to name but a few.

Societal and Environmental Changes

A topical environmental change that is quickly moving up the agenda for insurers is that of climate change.

Climate change impacts insurers on both sides of their balance sheets. Insurers may be impacted by increased claims experience - particularly so given the London Market's prominence in areas like catastrophe risk. But it appears that the asset side may also give rise to unexpected risks.

Let's take these in turn.

We are seeing evermore frequent "record" weather events; storms; floods; hotter summers; intense rainfall; not to mention global concerns such as higher sea levels. Insurers are having to respond to these shifts. However, increases in catastrophic risk events can provide both an opportunity and a threat to insurers. There is an opportunity for growth in underwriting new products. But the combination of concentrated exposures to large catastrophe losses, inadequate risk management and/or the potential for mis-pricing could undermine the sustainability of businesses.

The insurance industry is already taking steps to stay ahead of the climate curve on the liability side with the establishment of Flood Re; ClimateWise forums; more sophisticated underwriting techniques; the development of climate change products and carbon offsets. However, it is worth bearing in mind that, even though the full impacts of climate change often may not be visible in the short term, it is well worth insurers being alert to the emerging risks, including those emanating from policy makers.

But insurers, as long term investors, are also exposed to changes in public policy as this affects the investment side. One live risk right now is of insurers investing in assets that could be left 'stranded' by policy changes which limit the use of fossil fuels. As the world increasingly limits carbon emissions, and moves to alternative energy sources, investments in fossil fuels and related technologies – a growing financial market in recent decades – may take a huge hit. There are already a few specific examples of this having happened.

The Bank of England has been carrying out analysis to better understand these risks. The Bank of England voluntarily accepted DEFRA's invitation to compile a Climate Change Adaptation Report, due for delivery later this year. A project team was established to inquire into the topics of climate change and stranded assets. We are seeking to understand how these changes may impact upon the PRA's objectives and how that could shape our role going forward.

We have noted that change to an insurers' business model can be driven from many sources – which include changing consumer expectations.

Today the consumer demands more control, flexibility and automatism having become accustomed to interactive, accessible and digitised services. Increasingly consumers – that's you and I in our personal lives – expect the same digitised experience for all their buying needs, including insurance.

Digitisation and the prominence of 'smart tech' cannot be ignored and already innovation in technology is leading insurers to do business differently. This shift can be felt across the value-chain, whether it be changes in distribution channels and use of cloud-based infrastructure, to enhanced underwriting processes and use of 'black boxes'.

For the most part, digital includes putting the customer experience at the centre of insurers' strategies. Whilst positive, as with any shift in business model and strategy, business developments need to be carefully managed and monitored to ensure the core objectives of enhancing the customer experience are indeed achieved. And new IT systems don't come cheap, nor are they riskless.

Digitisation and enhanced technology can be a double-edged sword. Technological enhancements bring new opportunities to businesses but the pace of innovation must be met by the pace of corresponding safeguards to deal with the risks. In particular, the risk of cyber-attack is a great concern. The pace here is really changing very rapidly.

As with the other risks, insurers are affected for both good and ill: with ever more frequent and increasingly sophisticated cyber-attacks on businesses and individuals, insurers are being relied upon more and more for protection. A new business opportunity for sure. But, unlike most other insured risks, insurance firms could themselves be significant victims.

It is difficult to predict how cyber-crime – or even cyber accidents – will evolve, and it is very challenging to obtain data for losses that arise out of cyber-events. This makes it all the more difficult to quantify reserves, models and prices as well as develop operational safeguards internally.

An Insurer wishing to expand into any new business area needs to demonstrate to the PRA that new risk exposures are well understood and that the required capital for an altered risk profile has been fully considered. As stated previously, business model analysis forms an important part of the PRA's supervisory approach and a focus for its supervisory activity. Insurers will need to deal with the PRA in an open, co-operative and constructive manner to allow us to understand whether the business model is sustainable and to identify key vulnerabilities. This will ensure a more informed, focussed and proportionate supervisory approach.

Into the unknown

Over the past 25 years we have seen: the introduction of the Euro; break-up of the Soviet Union; a shift from West to East; the introduction of the world wide web to ordinary life; and smart technology – so what will happen over the next 25 years?

As an ex-forecaster I can tell you confidently that the only thing we can be certain of is that there will be changes that no one will predict.

I did not think, some six years ago, when sat at the table of the Monetary Policy Committee for my first meeting, that Bank Rate would continue to be 0.5% this far down the line. One can never be sure what tomorrow will bring and interest rates is a case in point.

The low level of real interest rates today is, in large part, a product of spare capacity in the real economy and low levels of growth and productivity across the developed world. This presents a number of issues for insurers who rely on interest income from their assets as part of their basic business model, especially where these returns back contractual guarantees. Without making any implied comment about monetary policy, just looking at today's yield curve, it is not plausible for insurers to expect high nominal or real rates of return in the near future from low-risk assets. Firms relying on high income streams from their assets may find themselves taking ever greater risks to their balance sheets.

Earlier on I mentioned the importance of governance in the work of the PRA. It is one thing that can help generate robustness in the face of these uncertain developments. Good governance should lie at the heart of every organisation. It is not just about the role of the board but includes management, controls, oversight and management information. Good governance encourages better business practices and outcomes. Of course, well intentioned people can make sub-optimal structures work – just as good structures can be run poorly. But a better structure gives a firm a better chance of avoiding a big business mistake and of surviving an unexpected shock.

Insurance retains highly talented and competent individuals. However, I have observed that the sector can be a bit of a 'closed field'. I hear some firms – not all – talk of the difficulty in being able to appoint successful executives and even more difficulty in finding qualified, independent non-executives. Insurers also talk about the challenges of attracting young and ambitious individuals to supply the talent of the future. These people issues become particularly relevant in an environment under the Solvency II regime when the system of governance will be given even more prominence. I hope that the new Senior Insurance Managers Regime will be seen as both appropriate and proportionate to the needs of the industry and policy holders alike. To be clear, the Senior Insurance Managers Regime should not be operated in such a way so as to put good people off. The desired outcome is that of effective governance, not enforcement.

Insurance innovation and regulation

Preparedness for what tomorrow's world may bring will likely involve a degree of change – greater risk-awareness, ensuring good governance, collaboration with the regulator – but is the insurance industry capable of that change?

The insurance industry has been founded upon taking the long term view. This is a concept that perhaps evokes a perception of consistency rather than innovation. However, the UK industry has traditionally not shied away from changing with the times, with the London market being a particular example.

Already, in response to changes on the horizon, we are seeing shifts in business models. Insurers are refreshing their product offerings, altering operational structures and enhancing distribution channels. The PRA has an important role to play in this so let me return to the subject of regulation.

To be clear, regulators have no intrinsic reason to stifle innovation. Far better to supervise a successful, profitable, innovating enterprise than a declining out-dated one. Underpinning that view, I would say that there should not be a prohibitive trade-off between insurers' ability to innovate versus their ability to manage risks.

Instead, the PRA will need to work with its regulated entities closely and early in the process of innovation. Let's be clear that the business model and the risk are owned by the firm – the PRA's job is make sure that a firm's approach to risk management is sound and that their policy holders are adequately protected.

I believe Solvency II will help to do this. It will introduce greater risk-sensitivity; co-operation across jurisdictions; and consistency in approach. Being a risk-based regime means that insurers should be able to evolve and adapt to capture all risks they are exposed to and the qualitative risk assessment introduced under Pillar II will further support this move towards a more responsive, reflective and adaptable solvency regime. This in turn will mean that insurers will need to think carefully about the risks they are exposed to and how this is captured and managed. This does not mean that Solvency II should dictate firms' business models. Rather, market forces and expectations of policy holders will inform insurers' pricing and strategies.

As referred to earlier, there is much we can do to prepare for the future by learning from mistakes of the past. One such area where this should be borne in mind is in the use of risk models which will play a huge role in Solvency II for the larger, more complicated firms. Firms need to be able to understand their models and their limitations, and be able to challenge them. As the Governor said last year: "*The dangers of using poorly designed models were made all too clear in the banking sector. So the Bank won't hesitate to withhold approval of inadequate or opaque models*".

There are many things I could say about Solvency II, but I want to concentrate on what it means for the future. One particular aspect is that it sensibly allows for a smooth transition, over a period of 16 years in some cases. It is recognised that for insurers (particularly life insurers), Solvency II with the introduction of a 'going concern' regime, is a considerable shift. In particular, firms will have to hold a risk margin to ensure that the insurance liabilities reflect the value for which they could be transferred to a third party. To allow for the gradual introduction of the risk margin, firms will be able to make a transitional deduction from their technical provisions. Together, the various transitional measures within Solvency II should ensure a smooth progression, avoiding the market dislocation, volatility and increased costs that could result should a number of firms have to augment their capital base at the same time. They rightly recognise that the underlying risks have not changed overnight, even if the regime has.

Firms making use of transitional measures will be afforded time to reach the level of financial resources required by the full Solvency II regime. In the meantime we can be sure that the transitional deduction from technical provisions will not result in a firm's resources falling below those required under the existing UK regime. This is because Solvency II caps the amount of transitional benefit a firm may derive. Bearing in mind this cap, and the benefits to be gained from a smooth transition, the take-up of transitional measures should be seen as a viable option for firms to take to assist with their capital planning, and are a feature that the UK authorities strongly supported during the development of Solvency II. They are there to be used where appropriate.

As we shift to a Solvency II world, I think it is worth bearing in mind that, like a smartphone, regulation tends to get new "updates" and "apps" in response to changes in the external environment. Indeed, the path of the future is in global policy development, including the insurance capital standard (ICS) under the aegis of the International Association of Insurance Supervisors (IAIS) which will look to develop risk-based global standards.

Insurance business is fast becoming globalised and interlinked. It naturally follows that so too should regulation. Introducing global capital standards would enhance global cooperation, ensure a level playing field and limit regulatory arbitrage.

For this reason, the PRA supports the development of global capital standards and the establishment of a long term vision in order to achieve a single insurance capital standard predicated on a single valuation basis which is genuinely comparable across jurisdictions.

Concluding remarks

Insurance sits at frontline of innovation and, as seen with climate change and digitisation, insurers can be directly exposed to changes in regulation, public policy and other shifts in society. This is because insurance forms one of the foundations to our daily lives, providing a risk transfer role for all facets of human activity. Risk transfer allows society as we know it to function effectively and as such, insurers oil the wheels for the engine of the economy to function. On the basis of what I have seen since last August, the UK insurance industry is one of the most advanced and successful in the world. The key to meeting the challenges of tomorrow's world is for the industry and regulator to continue to develop and work together.

NGFS
Central Banks and Supervisors
Network for Greening the Financial System

Foreword by Frank Elderson, Chair of the NGFS

We collectively face the effects of climate change, as it reaches beyond economies, borders, cultures, and languages. In 2017, air pollution was a cause of almost 5 million deaths worldwide while 62 million people in 2018 were affected by natural hazards, with 2 million needing to move elsewhere due to climate events. A transition to a green and low-carbon economy is not a niche nor is it a "nice to have" for the happy few. It is crucial for our own survival. There is no alternative. Therefore, we need to come together and take action to create a bright, sustainable future.

Understanding what the magnitude of climate change heralds for financial stability, at the initiative of Banque de France, eight central banks and supervisors established a Network of Central Banks and Supervisors for Greening the Financial System (NGFS) at the Paris "One Planet Summit" in December 2017. Since then, the NGFS has grown to 34 Members and 5 Observers from all over the globe.

Climate-related risks are a source of financial risk and it therefore falls squarely within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks. This significant breakthrough was already acknowledged in the NGFS progress report, published in October 2018. With this first NGFS comprehensive report, we build upon this insight to issue six recommendations: the first four apply to the work of central banks and supervisors while the last two address policymakers. However, all six call for collective action and draw a focus to integrating and implementing previously identified needs and best practices for a smooth transition towards a low-carbon economy. These recommendations are aimed at inspiring central banks and supervisors – NGFS members and non-members – to take the necessary measures to foster a greener financial system. We need to take action and we cannot and will not do this alone. We will globally cooperate with policy makers, the financial sector, academia and other stakeholders to distill best practices in addressing climate-related risks.

The achievements of the NGFS and the rapid expansion of its membership within a year have exceeded my expectations. However, we are not there yet. These recommendations represent only the Network's beginnings, as there is much work to be done in order to equip these aforementioned actors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. Future deliverables include a handbook on climate and environmental risk management, voluntary guidelines on scenario-based risk analysis and best practices for incorporating sustainability criteria into central banks' portfolio management. Going forward, the NGFS also expects to dedicate more resources to the analysis of environmental risks.

I am confident that the brain trust of the NGFS will continue to grow and evolve, keeping in mind the aim of having the financial sector worldwide contribute toward a greener future. As chair, I am very proud of what the NGFS has accomplished in only 16 months since its creation, and I look forward to consolidating our work during the coming years.

Finally, I would like to extend my thanks to the tremendous amount of work done by everyone involved in this endeavour, the chairs and members of the three working groups and my team at De Nederlandsche Bank. In particular I would like to thank the secretariat at the Banque de France, without whom we would not have stood where we stand today.

Contents

Executive summary

In the October 2018 progress report, NGFS members acknowledged that ***"climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks."*** The legal mandates of central banks and financial supervisors vary throughout the NGFS membership, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions. Even though the prime responsibility for ensuring the success of the Paris Agreement rests with governments, it is up to central banks and supervisors to shape and deliver on their substantial role in addressing climate-related risks within the remit of their mandates. Understanding how structural changes affect the financial system and the economy is core to fulfilling these responsibilities.

Climate change is one of many sources of structural change affecting the financial system.[1] However, it has distinctive characteristics that mean it needs to be considered and managed differently. These include:

- **Far-reaching impact in breadth and magnitude:** climate change will affect all agents in the economy (households, businesses, governments), across all sectors and geographies. The risks will likely be correlated with and potentially aggravated by tipping points, in a non-linear fashion. This means the impacts could be much larger, and more widespread and diverse than those of other structural changes.
- **Foreseeable nature:** while the exact outcomes, time horizon and future pathway are uncertain, there is a high degree of certainty that some combination of physical and transition risks will materialise in the future.
- **Irreversibility:** the impact of climate change is determined by the concentration of greenhouse gas (GHG) emissions in the atmosphere and there is currently no mature technology to reverse the process. Above a certain threshold, scientists have shown with a high degree of confidence that climate change will have irreversible consequences on our planet, though uncertainty remains about the exact severity and time horizon.
- **Dependency on short-term actions:** the magnitude and nature of the future impacts will be determined by actions taken today, which thus need to follow a credible and forward-looking policy path. This includes actions by governments, central banks and supervisors, financial market participants, firms and households.

While today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change, climate science leaves little doubt: action to mitigate and adapt to climate change is needed now. The NGFS recognises that there is **a strong risk that climate-related financial risks are not fully reflected in asset valuations.** There is **a need for collective leadership and globally coordinated action** and, therefore, the role of international organisations and platforms is critical.

The NGFS, as a coalition of the willing and a voluntary, consensus-based forum provides **six recommendations** for central banks, supervisors, policymakers and financial institutions to enhance their role in the greening of the financial system and the managing of environment and climate-related risks. The recommendations are not binding and reflect the best practices identified by NGFS members to facilitate the role of the financial sector in achieving the objectives of the Paris Agreement.

Recommendations n°1 to 4 *are aimed at inspiring central banks and supervisors – NGFS members and non-members – to take these best practices on board when it fits within their mandate. Parts of these recommendations may also be applicable to financial institutions.*

Recommendation n°1: Integrating climate-related risks into financial stability monitoring and micro-supervision.

Important steps in this regard include:

a) Assessing climate-related financial risks in the financial system by:

- mapping physical and transition risk transmission channels within the financial system and adopting key risk indicators to monitor these risks;

1 The report focuses on climate-related risks rather than environment-related risks.

- conducting quantitative climate-related risk analysis to size the risks across the financial system, using a consistent and comparable set of data-driven scenarios encompassing a range of different plausible future states of the world;
- considering how the physical and transition impact of climate change can be included in macroeconomic forecasting and financial stability monitoring.

b) Integrating climate-related risks into prudential supervision, including:

- Engaging with financial firms:
  - to ensure that climate-related risks are understood and discussed at board level, considered in risk management and investment decisions and embedded into firms' strategy;
  - to ensure the identification, analysis, and, as applicable, management and reporting of climate-related financial risks.
- Setting supervisory expectations to provide guidance to financial firms as understanding evolves.

Recommendation n°2: Integrating sustainability factors into own-portfolio management.

Acknowledging the different institutional arrangements in each jurisdiction, the NGFS encourages central banks to lead by example in their own operations. Without prejudice to their mandates and status, this includes integrating sustainability factors into the management of some of the portfolios at hand (own funds, pension funds and reserves to the extent possible).

Notwithstanding that the focus of central banks incorporating environmental, social and governance (ESG) aspects into their portfolio management has been on own funds and pension portfolios, some voices have called for an extension of this approach to monetary policy. Going forward, the NGFS considers exploring the interaction between climate change and central banks' mandates (beyond financial stability) and the effects of climate-related risks on the monetary policy frameworks, paying due regard to their respective legal mandates.

Recommendation n°3: Bridging the data gaps.

The NGFS recommends that the appropriate public authorities share data of relevance to Climate Risk Assessment (CRA) and, whenever possible, make them publicly available in a data repository. In that respect, the NGFS sees merit in setting up a joint working group with interested parties to bridge the existing data gaps.

Recommendation n°4: Building awareness and intellectual capacity and encouraging technical assistance and knowledge sharing.

The NGFS encourages central banks, supervisors and financial institutions to build in-house capacity and to collaborate within their institutions, with each other and with wider stakeholders to improve their understanding of how climate-related factors translate into financial risks and opportunities. The NGFS also encourages relevant parties to offer technical assistance to raise awareness and build capacity in emerging and developing economies.

***Recommendations n°5 and 6** do not fall directly within the remit of central banks and supervisors but point to actions that can be taken by policymakers to facilitate the work of central banks and supervisors. Parts of these recommendations may also be applicable to the private sector.*

Recommendation n°5: Achieving robust and internationally consistent climate and environment-related disclosure.

The NGFS emphasises the importance of a robust and internationally consistent climate and environmental disclosure framework. NGFS members collectively pledge their support for the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD). The NGFS encourages all companies issuing public debt or equity as well as financial sector institutions to disclose in line with the TCFD recommendations. The NGFS recommends that policymakers and supervisors consider further actions to foster a broader adoption of the TCFD recommendations and the development of an internationally consistent environmental disclosure framework.

Recommendation n°6: Supporting the development of a taxonomy of economic activities.

The NGFS encourages policymakers to bring together the relevant stakeholders and experts to develop a taxonomy that enhances the transparency around which economic activities (i) contribute to the transition to a green and low-carbon economy and (ii) are more exposed to climate and environment-related risks (both physical and transition). Such a taxonomy would:
- facilitate financial institutions' identification, assessment and management of climate and environment-related risks;
- help gain a better understanding of potential risk differentials between different types of assets;
- mobilise capital for green and low-carbon investments consistent with the Paris Agreement.

To some extent, recommendations n°1-4 require the implementation of recommendations n°5-6, but this does not preclude central banks and supervisors from acting now.

Going forward, the NGFS will continue its work as long as its members deem it necessary and useful. The lesson drawn from the first sixteen months of NGFS activity is that climate change presents significant financial risks that are best mitigated through an early and orderly transition.

To ensure such a smooth transition, there is still a significant amount of analytical work to be done in order to equip central banks and supervisors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. This calls for a close and specific dialogue with academia and for further technical work to translate the NGFS recommendations or observations into operational policies and processes.

More precisely, the NGFS is planning to develop:
(i) a handbook on climate and environment-related risk management for supervisory authorities and financial institutions;
(ii) voluntary guidelines on scenario-based risk analysis;
(iii) best practices for incorporating sustainability criteria into central banks' portfolio management (particularly with regard to climate-friendly investments).

This report has been coordinated by the NGFS Secretariat/Banque de France.
For more details, go to *https://www.banque-france.fr*
or contact the NGFS Secretariat *sec.ngfs@banque-france.fr*

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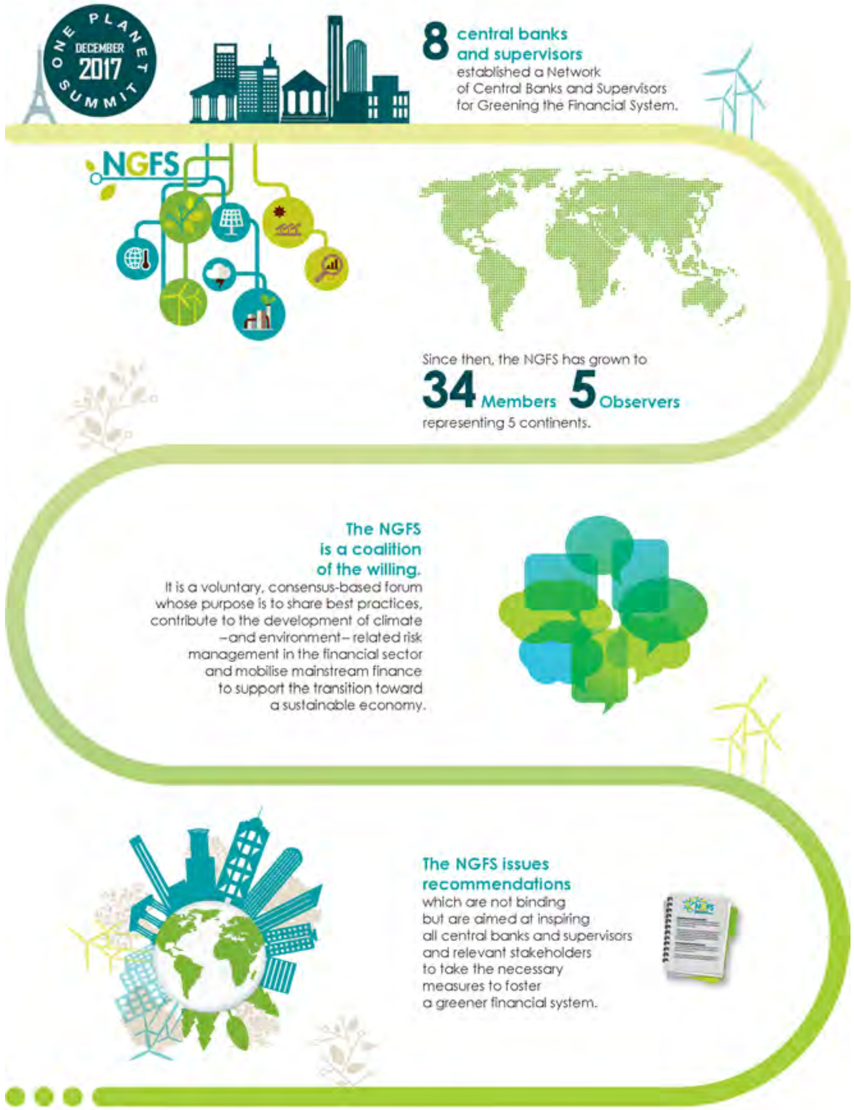
Origin of the NGFS



NGFS composition and governance

NGFS members' jurisdictions cover:

31%
of the global population

Source: United Nations, 2017.

Supervision of **2/3**
of the global systemically important banks and insurers

Source: Financial Stability Board, 2018.

45%
of global greenhouse gas emissions

Source: Global Carbon Budget, 2017.

44%
of the global GDP

Source: World Bank, 2017.

Functioning of the NGFS

The NGFS aims to accelerate the work of central banks and supervisors on climate and environmental risk and on scaling up green finance. The NGFS' work could feed into the work of existing international regulatory bodies. It does not aim to replicate the work conducted elsewhere, but to build on and enrich it where necessary. The NGFS' diverse membership allows for close coordination between the various ongoing international initiatives on issues of common interest. To this end, the NGFS has kept close contact with the Sustainable Banking Network (SBN), the Sustainable Insurance Forum (SIF) and the recently created Sustainable Finance Network (SFN), initiated by IOSCO, and the UNEP Financial Initiative.

The NGFS has structured its work into **three workstreams** dedicated to:

- **supervising of climate and environmental risks** (WS1, chaired by Ma Jun from the People's Bank of China);
- **analysing the macrofinancial impact of climate change** (WS2, chaired by Sarah Breeden from the Bank of England);
- **scaling up green finance** (WS3, chaired by Joachim Wuermeling from the Deutsche Bundesbank).[2]

2 Joachim Wuermeling will be replaced by Sabine Mauderer, Member of the Executive Board of the Deutsche Bundesbank, as chair of the WS3 as of April 2019.

1 Climate change as a source of economic and financial risks

The Intergovernmental Panel on Climate Change (IPCC) has concluded that anthropogenic emissions have increased since the pre-industrial era, driven largely by economic and population growth. This has led to increased concentrations of GHGs which are unprecedented in at least 800,000 years.[3] This is extremely likely to have been the dominant cause of the observed warming since the mid-20th century. Temperatures are now at least 1°C above pre-industrial levels.

Climate scientists have concluded that continued emissions in line with historical rates would lead to warming of 1.5°C between 2030 and 2052.[4] This would cause long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.

BOX 1

Distinguishing between climate and environment-related risks

The NGFS aims to contribute to the development of environment and climate-related risk management in the financial sector. By **environment-related risks**, this report refers to risks (credit, market, operational and legal risks, etc.) posed by the exposure of financial firms and/or the financial sector to activities that may potentially cause or be affected by environmental degradation (such as air pollution, water pollution and scarcity of fresh water, land contamination, reduced biodiversity and deforestation). By **climate-related risks**, the report refers to risks posed by the exposure of financial firms and/or the financial sector to physical or transition risks caused by or related to climate change (such as damage caused by extreme weather events or a decline of asset value in carbon-intensive sectors).

This report focuses on climate-related risks rather than environmental risks for two main reasons: first, the transition to a low-carbon economy consistent with the objectives of the Paris Agreement requires a radical shift of resource allocation and, thus, a seminal response by the financial sector. It was first against this background that the NGFS was founded. Second, climate change itself poses a major challenge – if not the major challenge – of our time and its impact will be felt globally, thus demanding a strong international response and multilateral cooperation, particularly given that the impacts of climate change may only be felt many years into the future, and yet are determined by the actions we take today.

Nevertheless, there are compelling reasons why the NGFS should also look at environmental risks relevant to the financial system. For instance, environmental degradation could cascade to risks for financial institutions, as reduced availability of fresh water or a lack of biodiversity could limit the operations of businesses in a specific region. These could turn into drivers of financial risks and affect financial institutions' exposures to those businesses.[i] Also, it is important to be aware of potential greater impacts due to the combined effects of climate and environmental risks. Against this background, the NGFS expects to dedicate more resources to the analysis of environmental risks going forward.

i Schellekens, Van Toor (DNB), *Values at risk? Sustainability risks and goals in the Dutch financial sector*, 2019.

3 IPCC, *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.

4 IPCC, *Global Warming of 1.5°C, Summary for Policymakers*, 2018.

1.1 Climate change is a source of structural change in the economy and financial system and therefore falls within the mandate of central banks and supervisors

The legal mandates of central banks and financial supervisors vary throughout the NGFS membership, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions. Understanding structural changes to the financial system and the economy is core to fulfilling these responsibilities. Climate change is one source of structural change.[5] As highlighted by the NGFS October 2018 progress report, climate change may result in physical and transition risks that can have system-wide impacts on financial stability and might adversely affect macroeconomic conditions.

Physical impacts include the economic costs and financial losses resulting from the increasing severity and frequency of extreme climate change-related weather events (such as heat waves, landslides, floods, wildfires and storms) as well as longer term progressive shifts of the climate (such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures).

Transition impacts relate to the process of adjustment towards a low-carbon economy.[6] Emissions must eventually reach "net zero" to prevent further climate change. The process of reducing emissions is likely to have significant impact on all sectors of the economy affecting financial assets values. While urgent action is desirable, an abrupt transition could also have an impact on financial stability and the economy more broadly.

These risks might have persistent impacts on macroeconomic and financial variables (for instance, growth, productivity, food and energy prices, inflation expectations and insurance costs) **that are fundamental to achieving central banks' monetary policy mandates.**[7] Nevertheless, the prime responsibility for ensuring the success of the Paris Agreement rests with governments. Yet, it is up to the central banks and supervisors to shape and deliver on their substantial role in addressing climate-related risks, although the NGFS remains mindful that not all its member-central banks have the same mandates for action. An understanding of the links between broader climate policy and the mandates of central banks and supervisors is therefore necessary.

1.2 Climate change is different from other sources of structural change

Climate change is one of many sources of structural change. However, it has distinctive characteristics that mean it needs to be considered and managed differently.

These include:

- **Far-reaching impact in breadth and magnitude:** climate change will affect all agents in the economy (households, businesses, governments), across all sectors and geographies. The risks will likely be correlated and, potentially aggravated by tipping points, in a non-linear fashion. This means the impacts could be much larger, and more widespread and diverse than those of other structural changes.
- **Foreseeable nature:** while the exact outcomes, time horizon and future pathway are uncertain, there is a high degree of certainty that some combination of increasing physical and transition risks will materialise in the future.
- **Irreversibility:** the impact of climate change is determined by the concentration of greenhouse gas (GHG) emissions in the atmosphere and there is currently no mature technology to reverse the process. Above a certain threshold, scientists have shown with a high degree of confidence that climate change will have irreversible consequences on our planet, though uncertainty remains about the exact severity and time horizon.
- **Dependency on short-term actions:** the magnitude and nature of the future impacts will be determined by

5 Some NGFS members have extended this analysis to broader environmental risks, which are also considered within supervisory and financial stability mandates.

6 In its work, the NGFS has incorporated the risk associated with emerging legal cases related to climate change for governments, firms and investors, e.g. liability risks, as a subset of physical and transition risks.

7 See, for instance, the speech by Benoît Cœuré, Member of the Executive Board of the European Central Bank, at a conference on "Scaling up Green Finance: The Role of Central Banks", organised by the Network for Greening the Financial System, the Deutsche Bundesbank and the Council on Economic Policies, Berlin, 8 November 2018.

actions taken today which thus need to follow a credible and forward-looking policy path. This includes actions by governments, central banks and supervisors, financial market participants, firms and households.

1.3 How climate change might affect the economy and financial stability

1.3.1 Understanding the possible impacts of physical risks

Extreme weather events impact health and damage infrastructure and private property, reducing wealth and decreasing productivity. These events can disrupt economic activity and trade, creating resource shortages and diverting capital from more productive uses (e.g. technology and innovation) to reconstruction and replacement. Uncertainty about future losses could also lead to higher precautionary savings and lower investment.

Physical impacts are not just risks for the future; they are already impacting the economy and financial system today. Overall, worldwide economic costs from natural disasters have exceeded the 30-year average of USD 140 billion per annum in 7 of the last 10 years.[8] Since the 1980s, the number of extreme weather events has more than tripled.[9]

Over a longer time horizon, progressive changes in the natural environment will impact the liveability of different regions, particularly if mean temperatures rise by more than 1.5 to 2°C compared to pre-industrial levels. This is due to the significant risks related to human health, food security, water resources, heat exposure and sea level rise.[10]

Estimates suggest that absent action to reduce emissions, the physical impact of climate change on the global economy in the second half of the century will be substantial. The more sophisticated studies suggest average global incomes may be reduced by up to a quarter by the end of the century.[11] In addition, the increased probability of disruptive events such as mass migration, political instability and conflict in these scenarios means that economic estimates are likely to understate the size and timing of the associated risks.

8 Munich Reinsurance Company (2019), "Natural Catastrophe Review 2018" *Geo Risks Research*, NatCatSERVICE.

9 Munich Reinsurance Company (2018), "A stormy year: Natural catastrophe 2017" *Geo Risks Research*, NatCatSERVICE.

10 IPCC (2018), Chapter 3.

11 See, for example, Burke, Hsiang and Miguel, "Global Non-Linear Effect of Temperature on Economic Production", *Nature* Vol. 527, pp. 235-239 (12 November 2015).

There have been fewer attempts to quantify the physical risks to financial stability rather than for the economy as a whole, but again losses are likely to be significant. Studies estimate that the financial value at risk could be up to 17% depending on the mean average temperature rise.[12]

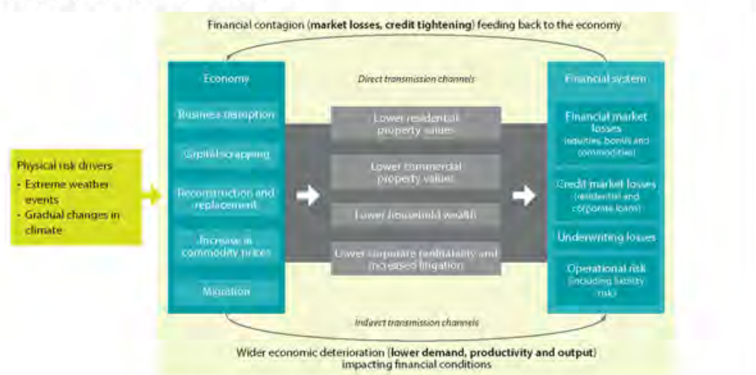
If losses are insured, more frequent and severe weather events affect insurance firms directly through higher claims and their customers indirectly via higher premiums. If losses are uninsured, the burden falls on households, companies and ultimately governments' budgets. A change in the debt repayment capacity of borrowers or a fall in collateral values can increase credit risks for banks and other lenders. A change in lenders' projected earnings would also be reflected in financial markets, impacting investors and asset owners.

Feedback loops between the financial system and the macroeconomy could further exacerbate these impacts and risks. For example, damage to assets serving as collateral could create losses that prompt banks to restrict their lending in certain regions, reducing the financing available for reconstruction in affected areas. At the same time, these losses weaken household wealth and could in turn reduce consumption.

The broad, global averages referenced above mask significant differences in the distribution of economic impacts and financial risks across regions and sectors. This variation is driven not only by differences in the gross exposure to physical risks, but also by the level of resilience and adaptation (action taken to prevent or minimise damage). Countries with less economic diversification, less climate resilient public infrastructure, less capital market flexibility and lower capacity to adapt will be at greater risk. Particular sectors could be at greater risk too, depending on their regional footprint.

These estimates represent a lower bound. Currently, physical impact models for both the economy and financial stability are partial. They typically cover only a handful of the possible transmission channels in order to make them tractable and neglect wider socio-economic impacts. Non-modelled impacts are also often estimated separately. A more holistic approach is needed to understand the relationship between different levels of risks, resilience and adaptation. The non-linearities stemming from the increasing risk of tipping points, and the potential for these to accelerate in the near term, are a core part of climate modelling that need to be better captured in economic and financial risk models.

Figure 1 **From physical risk to financial stability risks**



12 One study found that almost 2% of the world's financial assets are at risk if the global mean surface temperature rises by 2.5°C compared to pre-industrial levels (Dietz, Bowen, Dixon and Gradwell "Climate value at risk' of global financial assets" *Nature Climate Change*, 2016). Warming of 5°C could result in losses equal to 5% of the global stock of manageable assets ("The cost of inaction: Recognising the value at risk from climate change", *The Economist Intelligence Unit*, 2015).

1.3.2 Understanding the possible impacts of transition risks

The potential severity of the physical impacts of climate change and the direct correlation with the concentration of greenhouse gases (GHG) motivated the international community to commit to reducing emissions in Paris in December 2015. The Paris Agreement aims to limit the rise in global average temperatures to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C. Signatories agreed to reach global peaking of GHG emissions as soon as possible and to undertake rapid reductions thereafter, so as to achieve net zero emissions in the second half of this century.

The transition to a low GHG economy requires rapid and far-reaching transitions in energy, land, urban, infrastructure and industrial systems. **The scale of the economic and financial transformation related to this transition is significant, bringing both risks and opportunities for the economy and the financial system.** The Intergovernmental Panel on Climate Change (IPCC) projects the necessary additional energy-related investments compatible with a 1.5°C scenario for the period 2016-2050 to reach USD 830 billion annually.[13] The European Union alone has identified an annual investment gap amounting to almost EUR 180 billion to achieve its climate and energy targets.[14] Although the incremental change in total investment is not large, it would require a significant redirection of capital toward green finance.[15] For example, the OECD estimates that to achieve the 2°C target, bonds financing and refinancing in the renewable energy, energy efficiency and low-emission vehicle sectors have the potential to reach USD 620 billion to USD 720 billion in annual issuance and USD 4.7 trillion to USD 5.6 trillion in outstanding securities by 2035.[16]

Despite its rapid growth in the last few years, this is well beyond what the green bond market amounts to nowadays, namely an issuance volume of about USD 168 billion in 2018 after USD 162 billion in 2017 and USD 85 billion in 2016.[17] Although the green bond market does not account for all green investments, it provides a signal of the scaling up of green finance. The increase in volume has spurred the development of new green financial assets: for example, in addition to the already dynamic green bond market, new products have emerged such as green covered bonds and green securities.

This shift in investment would result in significant structural changes in the economy compared to today and some studies have sought to quantify the impacts of such a transition. Summarising the results of 31 models, the IPCC (2014) concluded that the costs of limiting warming to 2°C (with a 66% probability) would be between 1-4% of global aggregate consumption by 2030 compared to current economic forecasts.

Intuitively, the economic costs of the transition would stem from a disruptive transition and the need to switch to – initially more expensive – low-carbon technologies in some sectors, for instance, aviation or cement and steel production. However, these costs and the precise transition pathways will vary from country to country depending on the existing capital stock and may be more or less likely due to different political, technological and socioeconomic conditions. Moreover the costs and pathway for the transition can change over time depending on future choices made (e.g. infrastructure investment, a sudden decision by policy makers to cut subsidies for renewables energy or a sudden shift of consumers towards greener choices). **Nevertheless, the estimated costs are likely to be small compared to the costs of no climate action.**

In addition, these cost estimates are not universally accepted and **some argue that the economic costs of the transition to a low-carbon economy would be offset by a positive "green growth" effect.** According to this theory, ambitious climate policies aimed at achieving structural reforms would boost innovation and job creation and lower production costs.[18]

13 IPCC, *Global Warming of 1.5°C, Summary for Policymakers* 2018.

14 European Commission, *Action Plan: Financing Sustainable Growth*, 2018.

15 The G20 Green Finance Study Group (GFSG, 2016) defines "green finance" as "financing of investments that provide [climate and] environmental benefits in the broader context of environmentally sustainable development".

16 OECD, *Mobilising Bond Markets for a Low-Carbon Transition*, Paris, 2017.

17 Sustainable Banking Network, *Creating green bond markets insight, innovations and tools from the emerging markets*, October 2018. Green bond issuances have been stable in 2018, but the sustainable bond universe grew steadily (Climate Bonds Initiative, *Green bonds: The state of the market 2018*, 2019).

18 ESRB, *Too late, too sudden: Transition to a low-carbon economy and systemic risk*, 2016; Finansinspektionen, *Climate change and financial stability*, 2016.

This would benefit the global economy in the short and medium term in aggregate.[19] This notion is called the **"Porter Hypothesis"**.[20] However, empirical evidence of this effect, focusing on smaller scale case studies, is mixed.[21]

What the literature does show is that, firstly, while the transition would result in a significant structural change in the economy – and some regions and sectors will fare better than others – the overall costs of the transition would be much lower than those that would arise absent action, i.e. in a "hot house world". Secondly, infrastructure decisions today affect choices in the future. Delaying the transition to a low-carbon stock means that sharper (and more costly) emissions cuts would be required in the future to meet a given policy target. The speed and timing of the transition is crucial: an orderly scenario, with clear policy signalling, would allow adequate time for existing infrastructure to be replaced and for technological progress to keep energy costs at a reasonable level.[22] In contrast, a disorderly, sudden, uncoordinated, unanticipated or discontinuous transition would be disruptive and costly, particularly for those sectors and regions that are more vulnerable to structural change.

Comparing economic estimates is, however, difficult because the models define a wide range of possible values for employment, investment, population, productivity and growth. Further research is needed to narrow the range of plausible values to be incorporated into economic models, particularly taking into account country and sectoral differences.

The potential risks to the financial system from the transition are greatest in scenarios where the redirection of capital and policy measures such as the introduction of a carbon tax occur in an unexpected or otherwise disorderly way. So far, scenarios have largely focussed on the potential for assets to become stranded when infrastructure has to be retired before the end of its useful life in order to meet emissions reduction targets. Stranded assets will fall in value leading to losses of both capital and

19 OECD, *Investing in Climate, Investing in Growth*, 2017.

20 Porter and van der Linde, "Toward a New Conception of the Environment-Competitiveness Relationship" *Journal of Economic Perspectives*, Vol. 9 (4): pp. 97-118, 1995.

21 Jaffe, Newell and Stavins, "Technological Change and the Environment", *Working Paper* No. 7970, National Bureau of Economic Research, 2000; Berman and Bui, "Environmental Regulation and Productivity: Evidence from Oil Refineries", *NBER Working Paper* No. 6776, November 1998; Gray and Shadbegian, "Environmental Regulation, Investment Timing, and Technology Choice", *Working Paper* No. 6036, National Bureau of Economic Research, May 1997.

22 ESRB, *Too late, too sudden: Transition to a low-carbon economy and systemic risk*, 2016; Finansinspektionen, *Climate change and financial stability*, 2016.

Figure 2 **From transition risk to financial stability risks**

income for owners but also to increased market and credit risks for lenders and investors.

Many of these studies on the transition risks of climate change are partial and often focus on the energy sector. A smaller number of studies are broader in scope, covering transition impacts to entire economic segments. **Estimates of losses in these studies are large and range from USD 1 trillion to USD 4 trillion when considering the energy sector alone,[23] or up to USD 20 trillion when looking at the economy more broadly.[24]** More research is needed to understand how these impacts translate into systemic risks for financial markets, particularly taking second order effects into account. A wholesale reassessment could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions, which would constitute a climate Minsky moment.[25]

Translating economic transition loss estimates into financial risks is challenging because often the macroeconomic models used were developed for a different purpose, such as calculating the social cost of carbon or the cost of meeting a particular emissions target. Linking these macroeconomic models to financial portfolios requires granular and holistic outputs at a firm, regional and sectoral level to better support bottom-up analysis.

1.4 The future impacts provide a loud wake-up call

If we continue along our current global emissions trajectory, the physical risks from climate change are likely to significantly change where and how we live in the second half of the century. Even though considerable effects of climate change on the economy are widely expected, due to various limitations in our economic models, quantitative estimates today can only give an indication of how big the impacts on the economy and the financial system might be.

Measures to smooth the climate-related structural changes towards a low GHG economy would minimise these risks. As mentioned before, the overall costs of the transition would be much lower than those in a "hot-house world". The size and nature of the risks will therefore be dependent on actions today.

23 See IEA and IRENA, *Perspectives for the Energy Transition*, 2017.

24 See IEA and IRENA (2017). There is also a difference in the methodology used. The IEA estimates stranded *capital* while IRENA estimates stranded *value*. For instance, in the upstream oil and gas sector, the IEA considers investments that oil & gas firms have made into exploration, which may not be recouped. IRENA, on the other hand, considers the potential priced-in market value of explored reserves, which, as one might expect, is higher than the cost of exploration.

25 Bank of England Prudential Regulation Authority (2018), *Transition in Thinking: The impact of climate change on the UK banking sector*.

2 A call for action: what central banks and supervisors can do and how policymakers can facilitate our work

While today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change, **climate science leaves little doubt: action to mitigate and adapt to climate change is needed now**. At the country level, governments and agencies should step up their efforts to implement effective policies that incentivise sustainable practices, while firms should develop business strategies and risk management controls that achieve sustainability in the long term.

There is a need for global collective leadership and coordinated action and, therefore, the role of international organisations and fora is critical. The NGFS, as a coalition of the willing and a voluntary, consensus-based forum, acknowledges this fact. **It is within this context that we set out a number of recommendations for central banks, supervisors and policymakers to do more.**

The following six non-binding recommendations reflect the best practices identified so far by NGFS members to facilitate the role of the financial sector in achieving the objectives of the Paris Agreement.

- **Recommendations n°1 to 4 are aimed at inspiring central banks and supervisors** – NGFS members and non-members – to take these best practices on board as it fits within their mandate. Parts of these recommendations may also be applicable to financial institutions.

- **Recommendations n°5 and 6 do not fall directly within the remit of central banks and supervisors** but point to actions that can be taken by policymakers to facilitate the work of central banks and supervisors. Parts of these recommendations may also be applicable to the private sector.

2.1 Recommendation n°1
Integrating climate-related risks into financial stability monitoring and micro-supervision

The NGFS acknowledges that climate-related risks are a source of financial risk and therefore calls on central banks and supervisors to start integrating climate-related risks into micro-supervision and financial stability monitoring. Important steps in this regard include:

1) Assessing climate-related financial risks in the financial system by:
- **mapping physical and transition risk transmission channels within the financial system and adopting key risk indicators to monitor these risks;**
- **conducting quantitative climate-related risk analysis to size the risks across the financial system, using a consistent and comparable set of data-driven scenarios encompassing a range of different plausible future states of the world;**
- **considering how the physical and transition impact of climate change can be included in macroeconomic forecasting and financial stability monitoring.**

2) Integrating climate-related risks into prudential supervision, including:
- **engaging with financial firms:**
  - **to ensure that climate-related risks are understood and discussed at board level, considered in risk management and investment decisions and embedded into firms' strategy;**
  - **to ensure the identification, analysis, and, as applicable, management and reporting of climate-related financial risks.**
- **setting supervisory expectations to provide guidance to financial firms, as understanding evolves.**

2.1.1 Assessing climate-related financial risks in the financial system

Scenario analysis is an important tool to help central banks and supervisors assess how climate change will impact the macroeconomy, financial system and safety and soundness of financial firms. The NGFS has therefore been considering how it could be implemented into authorities' toolkits.

There are several challenges that need to be highlighted in the development of workable scenarios for the financial impact of climate change. Assessing the impacts of climate change can be challenging because of the uncertainties around the course of climate change itself, the breadth and complexity of transmission channels, the primary and secondary impacts and the need to consider, in aggregate, some combination of both physical and transition risks. Even if all these challenges were addressed, over long time horizons, estimates will be highly dependent on the assumptions made about how climate policy and technology will evolve.

The future of climate policy is highly uncertain especially given the extended time horizons and political economy considerations. Policies must be initiated far in advance of the benefits being realised, while costs typically occur more immediately. Furthermore, the rate of progress in low-carbon technologies will be instrumental in determining the emissions reductions that are technically and economically feasible. It will also determine the extent of disruption to current business models in various sectors. Scenario analysis requires assumptions about whether emissions targets are met and when and how policymakers choose to act. These decisions may of course not be uniform in every region.

Given the sensitivity of results to these underlying assumptions, **hypothetical transition scenarios can be used to explore the direction and broad scale of outcomes.**

BOX 2

Designing a scenario analysis framework for central banks and supervisors

To contribute to central banks' and supervisors' ongoing work in this area, **the NGFS is developing an analytical framework for assessing climate-related risks, in order to size the impact of climate-related risks on the economy and the financial stability**. This includes looking at the different possible outcomes for climate change and the policies to mitigate it, assessing the financial impact and determining the timeframes during which risks could materialise.

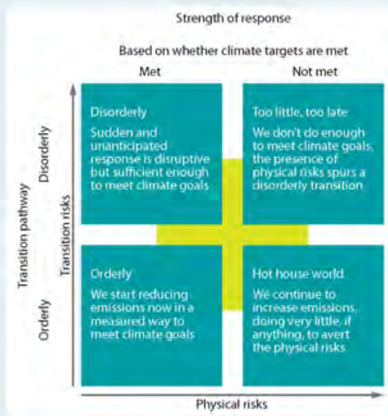
In its work so far, the NGFS has undertaken a **literature review** of existing scenarios to consider the most important design decisions when sizing macrofinancial risks. The NGFS has concluded that there are two important dimensions to consider when assessing the impact of physical risks and transition risks on the economy and the financial system.

- The total level of mitigation or, in other words, **how much action is taken** to reduce greenhouse gas emissions (leading to a particular climate outcome).
- Whether the transition occurs in an orderly or disorderly way, i.e. **how smoothly and foreseeably the actions are taken.**

Across these two dimensions there is a continuum of different outcomes and transition pathways to achieve them. However, to simplify the analytical exercise, four representative **high-level scenarios** have been developed that take both these dimensions into consideration.

The bottom-right scenario can help central banks and supervisors consider the long-term physical risks to the economy and financial system if we continue on our current "hot house world" pathway. The bottom-left orderly scenario can help us understand how climate policy (such as a carbon price) and other shifts in technology and sentiment to reduce emissions would affect the economy and the financial system.

The two scenarios at the top can help central banks and supervisors consider how physical and transition risks could crystallise in the economy and the financial system over a short time period (for example, in response to extreme weather events or a shift in climate policy leading to a sudden reassessment of future developments).



In the next phase, **the NGFS will develop a more detailed data-driven narrative and quantitative parameters as a foundation to these scenarios** and enable central banks and supervisors to explore some of these questions in their own jurisdictions. This will include proposing key assumptions for policy and technological change. During this design phase, the NGFS will work with academic experts, scenario designers and financial firms to ensure the scenarios are fit for purpose.

Looking ahead, NGFS members may incorporate these scenarios into their domestic work programmes. This would provide a case study for other central banks and supervisors that are considering running similar exercises and provide some feedback for the calibration of the scenarios.

Although these scenarios are primarily being developed by central banks and supervisors in support of their own work and objectives, these scenarios may provide a useful input for other stakeholders, such as financial and non-financial firms, in considering how they may be impacted by climate change.

These scenarios should have a clear, plausible, qualitative narrative but also be data-driven and provide quantitative parameters to help anchor assessments of economic costs and financial risks. They can help identify sectors or geographies which are particularly vulnerable either to physical or transition risks or a combination thereof. Ultimately, they should be suitable to help explore materially different plausible future states of the world over different time horizons.

The different states of the world that feature prominently in the existing literature on scenario analysis (and are key determinants of risk) include those where international climate targets are either met or not, and those where the transition to a low-carbon economy occurs in an orderly or disorderly way.

Using a consistent set of transition scenarios can help to enhance the comparability of different analyses. Work to standardise some of the macroeconomic assumptions in transition scenarios is already underway and could be developed further.[26] However, it is vital that common scenarios do not unduly constrain or narrow the analysis and results.

Further work is also required to translate these economic scenarios into financial risk parameters for financial stability analysis. This would help supervisors assess the financial stability risks across the system. Key risk indicators allow us to track which future scenarios are most likely to materialise and whether the economy and financial system need to adjust to minimise the potential risks.

Common scenarios should only provide a starting point for supervisors and firms to carry out bespoke analyses on the risks to their balance sheet. Financial firms should not wait for central banks or supervisors (or others) to deliver some kind of universal, perfect model. Rather, they should initiate their own structured analytical work to identify risks and vulnerabilities, which, successively, can become more and more quantified and sophisticated.

2.1.2 Integrating climate-related risks into prudential supervision

The NGFS stock-taking exercise on national supervisory frameworks and practices concluded that **the integration of climate-related factors into prudential supervision is at an early stage.** However, it also shows that over the last few years, many authorities have made significant progress within this area, and methods and tools to assess the financial risks of climate change from both physical and transition risks are gradually developing.

To contribute to central banks' and supervisors' ongoing work to integrate these issues into their operations, and based on the experiences and best practices identified within its membership, the NGFS proposes a high-level framework summarised in Figure 3.

Raising awareness and building capacity

The first step is for national and supra-national competent authorities **to build in-house capacity and to collaborate within their institutions.**

This in-house capacity building needs to happen concurrently with integration of climate change into risk assessment to ensure engagement with firms is effective. Initiatives to achieve this include:

- **Increasing awareness of climate issues within institutions** through outreach presentations and bringing together expertise from multiple departments.
- **Providing training courses for frontline supervisors** and financial stability experts. Training can provide an understanding of both the financial risks stemming from climate change, as well as the distinct characteristics of climate issues, e.g. regarding the timing mismatch between action and impact.

Collaboration with other supervisors and with wider stakeholders (think-tanks, NGOs, government departments, environment and climate science experts, and industry bodies from the financial sector) is also important.

26 See the Shared Socioeconomic Pathways (SSPs) project by the International Institute for Applied Systems Analysis (IIASA).

Figure 3 **High-level framework for the integration of climate-related factors into prudential supervision**

Courses of action	Possible measures by supervisors
Raising awareness and building capacity among firms	• Raise awareness of the relevance of climate-related risks publicly and during bilateral meetings; survey firms on the impact of these risks; lay out a strategic roadmap for the handling of climate-related risks. • Build capacity by convening events to progress the translation of scientific findings to financial analysis; set up working groups with firms, for example, on incorporating climate issues into risk management or scenario analysis.
Assessing climate-related risks	• Develop analytical tools and methods for assessing physical and transition risks related to climate change both at a micro- (financial institutions) and macro-level (i.e. the financial system). • Conduct and publish an assessment of these risks at a macro- and micro-level. • Analyse potential underlying risk differentials of "green" and "brown" assets. This pre-supposes that the supervisor and/or jurisdiction have agreed on definitions and classifications for "green" and "brown" activities.
Setting supervisory expectations	• Issue guidance on the appropriate governance, strategy and risk management of climate-related risks by regulated firms. • Train supervisors to assess firms' management of these risks.
Requiring transparency to promote market discipline	• Set out expectations for firms' climate-related disclosures in line with the TCFD recommendations. • Consider integrating climate-related disclosures into Pillar 3.
Mitigating risk through financial resources	• Consider applying capital measures in Pillar 2 for firms that do not meet supervisory expectations or with concentrated exposures. • Based on the risk assessment outlined above, possibly consider integrating it into Pillar 1 capital requirements.

As a next step, most authorities are focusing on engaging with firms to raise awareness and foster capacity building and discussing how the governance structure and strategy of the firm ensures a proper identification, assessment, management and reporting of climate and environment-related risks. In this regard, some central banks and supervisors have undertaken formal information gathering by sending out surveys to regulated firms.[27] Such a survey process can prompt firms to consider the risks more fully and then feed into an analysis of the approaches to address climate-related risks across the industry.[28]

27 See Appendix A of *The impact of climate change on the UK insurance sector A Climate Change Adaptation* Report by the Bank of England Prudential Regulation Authority (PRA), September 2015 and Section 4 of *Transition in thinking: The impact of climate change on the UK banking sector*, PRA, September 2018.

28 See e.g. Bank of England PRA, *Transition in thinking: The impact of climate change on the UK banking sector*, September 2018 and Finansinspektionen, *Integration of Sustainability into Corporate Governance; A survey of financial firms' public sustainability information*, 7 November 2018.

Developing tools and methods to identify and assess climate-related financial risks

Climate Risk Assessment

Climate Risk Assessment (CRA) refers to the methods and practices used to size the financial impact of climate-related risks to micro-prudential objectives, including:

- **Qualitative CRA** explores the longer-term impacts of different scenarios and provides a descriptive assessment, for example of risk transmission channels to the financial sector. Most member supervisors have undertaken some form of qualitative analysis.
- **Quantitative CRA** represents a numerical approach to sizing the financial risks. It is most effective at assessing the shorter-term financial exposures to physical and transition risks. Fewer authorities have performed quantitative analysis and in general, these studies have been partial, focusing on narrow channels of impact although wider methodologies are being developed.

Over the last few years, there has been significant progress on attempts to size the financial risks from both physical and transition risks. When combined, qualitative and quantitative assessments can provide a fuller picture of the risks the financial sector faces. The list below provides some examples of quantitative CRA.

On the transition risk side:

- Assessing financial institutions' exposures to high-carbon sectors.[29]
- Estimating the impact of a bank's exposure at risk to energy inefficient homes against the background of tightening energy efficiency regulation.
- Incorporating climate-related stresses into sector – or even market – wide stress tests.[30,31]

On the physical risk side:

- Developing climate scenarios based on specific temperature rises and estimating the climate-related claims burden for insurers (see the case studies in Box 3).
- Analysing the consequences of flood scenarios by linking estimated damage to residential and commercial buildings to financial institutions' exposures.
- Calculating a vulnerability index for firms' assets based on their geographical distribution.[32]

29 Regelink, Reinders, Vleeschhouwer, van de Wiel (DNB), *Waterproof? An exploration of climate-related risks for the Dutch financial sector*, 2017.

30 According to a stress test conducted by DNB, transition risk could lead to substantial losses for banks, leading to a reduction in the banks' CET 1 capital ratios of up to 4.3 percentage points. Vermeulen, Schets, Lohuis, Kölbl, Jansen, Heeringa, *An energy transition risk stress test for the financial system of the Netherlands*, 2018.

31 Bank of England PRA, *General Insurance Stress Test 2017, Scenario Specification, Guidelines and Instructions*, 11 April 2017.

32 Regelink, Reinders, Vleeschhouwer, van de Wiel (DNB), *Waterproof? An exploration of climate-related risks for the Dutch financial sector*, 2017.

BOX 3

Case study of quantitative analysis – DNB physical risk CRA tool

Dutch non-life insurers cover most of the economic damage caused by storms, hail and rain. Therefore, changing weather patterns are an important consideration for the insurance sector. In the Netherlands, more than 95% of all non-life insurance policies cover objects within domestic borders. Hence, insurers' claims are heavily related to regional climate change.

The 2017 Waterproof report explored the potential of a changing climate on climate-related claims. Based on scenarios from the Intergovernmental Panel on Climate Change (IPCC), the Dutch Meteorological Institute (KNMI) developed climate scenarios for the Netherlands for a 1.5°C and 3.5°C temperature rise in 2085. These scenarios include more frequent and severe hail and thunder, an increase in the intensity of rainfall and sea level rise. Based on these scenarios, the De Nederlandsche Bank (DNB) calculated the climate-related claims burden in 2085. Lower and higher estimates reflect the substantial uncertainty about the impact of changes in frequency and intensity of weather.

.../...

All scenarios showed an increase in climate-related claims as a result of climate change.

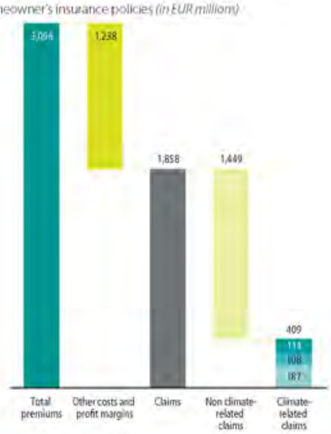
Since products of non-life insurance companies are typically on a one-year horizon, the sector might be able to adapt to the new circumstances on a relatively short notice. However, this would lead to additional pressure on premiums. Supervisors can use these scenario analyses to challenge insurance firms' risk model and climate strategies.

Other institutions have performed CRA exercises as well. According to an internal study by the Deutsche Bundesbank, in early 2018, **German banks' credit exposure to a limited set of carbon intensive industries was relatively small** (with an aggregated exposure of around EUR 157 billion or 4.7% of total loans to domestic households and non-financial corporations). According to a study by the ACPR, **in France, 13% of banks' total net credit was exposed to sectors vulnerable to transition risks** in 2016.[1]

Increase in climate-related claims in 1.5°C and 3.5°C scenarios

C1 Estimated climate-related claims burden as a proportion of premiums in 2016

Homeowner's insurance policies *(in EUR millions)*



Source: DNB, 2017 Waterproof Report.

C2 Estimated climate-related claims burden in 2085

Homeowner's insurance policies *(in EUR millions)*

Source: DNB, 2017 Waterproof Report.

1 French Treasury, ACPR, Banque de France, *Evaluating Climate Change Risks in the Banking Sector*, April 2017.

Analysis of the potential risk differentials between profiles of green, non-green, brown and non-brown assets

From a supervisory perspective, there is a need to understand the potential risk differentials between green, non-green, brown and non-brown assets. If risk differentials are detected, further analysis needs to be performed to assess if the differentials can be attributed to (non-) green or (non-) brown characteristics, or if they are driven by other factors. Important prerequisites for this are clear definitions of which assets can be considered green or brown. Owing to the lack of taxonomies elsewhere, the default rates of these types of assets have not been evaluated in any jurisdiction, except for China.

BOX 4

The China Banking and Insurance Regulatory Commission analysis of default rates of green loans compared to the overall loan portfolio[1]

Data from the China Banking and Insurance Regulatory Commission (CBIRC, formerly the CBRC)[2] showed that, for the **21 largest banks in China as of June 2017, green loans had a non-performing loan (NPL) ratio that is 1.32 percentage points lower on average (at 0.37%) than that of all loans.** CBIRC data also showed that the NPL ratios of green loans were consistently lower than those of all loans for each of the previous four years (2013-16). However, further work is needed to assess whether the differences in performance can be attributed purely to the green/brown characteristics of the related loans.[3]

China was able to conduct this study following the introduction of official definitions for green loans in 2012, and official definitions for green bonds in 2015.[4] Other than China, Brazil is the only other G20 country to have adopted a green loan definition, but no data has been collected in Brazil.

1 This simple statistical analysis does provide first insights about the relative performances of green and brown assets, but it does not allow inferring broader conclusions about their relative intrinsic riskiness. The study does not indeed control for other factors which influence NPL ratios (different states of the sectoral cycle, average characteristics of counterparties or the loan, etc.). Further data analysis is therefore warranted.

2 *www.cbrc.gov.cn/*

3 As an example, borrowers with high profitability and cash flow (i.e. low PD) may be the same borrowers who have the means to invest in modern, "green" production capacity.

4 In China, the definition of green loans could be traced back to July 2007 in the *Opinions on Implementing Environmental Protection Policies and Regulations to Prevent Credit Risks* (MEP Document No. 108 2007) issued by the Ministry of Environment Protection (MEP), CBRC (the banking regulator) and the PBC, and has been further improved in the *Guidelines on Green Loans* (CBRC Document No. 4 2012) issued in February 2012.

Under prudential frameworks, risk weights are allocated to different asset classes or each individual exposure based on the riskiness of the underlying asset(s), in accordance with local supervisory requirements, usually based on BCBS and IAIS standards.[33] **No jurisdiction, however, has thus far explicitly taken into account the (non-) green or (non-) brown nature of the underlying assets when computing their perceived riskiness.**

The NGFS has performed a preliminary stock-take of studies conducted by market participants on credit risk differentials between green and non-green assets. These studies used either international or local definitions of "green". The preliminary finding of the stock-take is that **it is currently impossible to draw general conclusions on potential risk differentials.** Some studies, based on national and sectoral data found that green loans had lower default and non-performing[34] ratios than non-green loans while others did not.

The studies have covered several types of assets:

- Several studies point to a lower arrears frequency for **residential mortgages** on energy-efficient properties, although borrowers' financial ability and thus repayment capacity is only one of the factors controlled for.[35,36]
- There are fewer studies on **corporate loans.** The China Green Finance Committee (CGFC) found lower NPL ratios for green corporate loans across most corporate industry portfolios. Moody's carried out a study in 2018 on infrastructure transactions from 1983 to 2016 in both

33 The definition of "non-performing" in these studies is based only on arrears, which differs from other definitions such as in the EU, where the NPL definition includes loans where the borrower has been assessed as "unlikely to pay" by the lender.

34 The Basel Committee on Banking Supervision (BCBS) is the primary global standard setter for the prudential regulation of banks. The International Association of Insurance Supervisors (IAIS) is responsible for the regulatory cooperation regarding the supervision of the insurance sector.

35 "Home Energy Efficiency and Mortgage Risks" (2013), by the Institute for Market Transformation (IMT).

36 E.g. "Impact of energy use and price variations on default risk in commercial mortgages: Case studies" (2017) by Mathew et al., "Insulated from risk? The relationship between energy efficiency of properties and mortgage defaults" (2018), by Guin and Korhonen and *Transition in Thinking: The impact of climate change on the UK banking sector*, case study 1: "Tightening energy efficiency standards and the UK buy-to-let market" (2018), by the Bank of England.

advanced and developing economies.[37] It found that green use-of-proceeds projects exhibit lower cumulative default risk (5.7%) than non-green use-of-proceeds projects (8.5%) in advanced economies. However, Moody´s suggests that the difference is likely to be due to subsample characteristics other than greenness.

- Some studies assess the default implications **from the perspective of loan/bond pricing**, on the basis that companies with lower default probabilities tend to enjoy lower funding costs. One study, based on data of 5,600 loans from the Thomson Reuters DealScan Database, finds that borrowers with better green management have more stable income streams. This makes them less likely to default on loans, violate covenants or file bankruptcy. As a result, the borrowing costs for "greener" companies tend to be lower than those of other companies.[38]
- Two studies found that a premium (ranging from 1 to 7 basis points) exists for **green bonds**. However, the study that found a larger premium has not isolated the "green factor".[39] Another study found no systematic evidence that green bonds would be issued or traded at lower yields than comparable non-green bonds. It highlighted the excess of demand for green bonds as the main driver behind the perceived premium of 1-2 basis points, rather than the explicit "greenness".[40]

However, the number of these studies is small and they typically have three types of limitations:

- most do not fully take into account other variables on borrower characteristics that may affect the default probability;
- country and sectoral coverage is limited;
- the definitions of green/non-green and brown/non-brown assets are not harmonised across the studies, therefore it is not possible to draw a general conclusion on their risk profiles.

The stock-take points to the need for a more thorough examination of existing studies as well as further fact-gathering and analyses. This should pay due regard to non-climate variables that might affect the default rates and performance of green assets. The NGFS intends to perform an exploratory data collection from selected banks in 2019. The objective is to analyse the collected data and assess if there is a risk differential between green and non-green assets (loans and bonds), taking into account the above mentioned constraints. The NGFS is aware that historical data is not always a good indicator of future performances, in particular given the likelihood of unprecedented disruptions to the economy caused by climate change. Therefore, as a possible next step after the collection and analysis of historical data, it may be expedient to introduce a more forward-looking perspective into the analysis, for example, through scenario analysis and/or stress tests.

Setting supervisory expectations

Some central banks and supervisors have further integrated climate-related risks into the supervisory framework by adjusting and communicating their supervisory expectations.[41] These expectations can set out how financial institutions should monitor and manage the financial risks associated with their climate exposures, anchored in the qualitative aspects of Pillar 2. This includes ensuring that consideration of these risks is integrated into governance, strategy and risk management assessments. The majority of authorities plan to assess climate-related financial risks through established financial risk categories, rather than to introduce new policy or frameworks.

Promoting transparency to enhance market discipline

In addition, authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues. Through the promotion of climate-related disclosure via Pillar 3, for example in line with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations (see recommendation n°5); authorities can contribute to an improvement of the pricing mechanisms for climate-related risks and a more efficient allocation of capital.

37 "Default and recovery rates for project finance bank loans, 1983-2016: Green projects demonstrate lower default risk" (2018).

38 Dawei Jin, Jun Ma, Liuling Liu, Haizhi Wang, Desheng Yin, "Are green companies less risky and getting lower cost bank loans? A stakeholder-management perspective" *Working Paper*, 2018.

39 "Is there a Green Bond Premium?" (2018), by O.D. Zerbib and "The Pricing and Ownership of U.S. Green Bonds" (2018), by Baker et al.

40 UBS Wealth Management Sustainable Investing – Green Bonds (2018).

41 See e.g. *https://www.bankofengland.co.uk/*

Mitigating climate-related risks through financial resources

Climate-related risks could be integrated further via the quantitative aspects of the prudential framework. In particular, the Pillar 2 framework could be enhanced to assess the adequateness of firms' governance and risk management processes for dealing with climate and environment-related risks, or with concentrated exposures. If a risk differential and causation is established, it might be appropriate to include it in Pillar 1 capital requirements.

2.2 Recommendation n°2 Integrating sustainability factors into own-portfolio management

Acknowledging the different institutional arrangements in each jurisdiction, the NGFS encourages central banks to lead by example in their own operations. Without prejudice to their mandates and status, this includes integrating sustainability factors into the management of some of the portfolios at hand (own funds, pension funds and reserves to the extent possible).

NGFS members may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates.[42] **This approach could have several benefits:**

- The assessment of sustainability factors, in addition to traditional financial factors, can **improve investors' understanding of long-term risks and opportunities** and thereby enhance the risk-return profile of long-term investments. To the extent that sustainability factors, such as the exposure of a security to climate change, can pose financial risks, it is natural for investors to seek to capture them.

- **Central banks can reduce reputational risks** by acknowledging financial risks related to the transition towards a carbon-neutral economy and by addressing these risks proactively in their own (risk) frameworks. Against this backdrop, central banks could be scrutinised for not "walking the talk" if they fail to appropriately address climate-related risks in their own (risk) frameworks. Reputational risk could also arise when central banks invest in companies that are exposed to these risks.

- Central banks may decide to employ part of their investments to pursue non-financial sustainability goals in order to **generate positive (societal) impacts**, in addition to traditional financial return goals. In this way, central banks can also actively support the development of the market for green and sustainable assets.

Many NGFS members are, however, limited by their mandates and/or investment objectives, such that, overall, sustainability criteria currently still play a minor role in most central banks' portfolio management. **Nevertheless, a number of central banks have established themselves as frontrunners** in this field and have adopted sustainability strategies for all or at least part of their investments.

If other central banks were to follow, it seems expedient for them to first establish their fundamental strategy based on their motivation and rationale, then to establish sustainability policies for their different given portfolios and finally decide on the necessary implementation measures and how to evaluate and report on their progress towards achieving their set objectives. As central banks are not a homogeneous group of investors with one shared doctrine, it is up to each central bank to set the appropriate goals and scope for their respective sustainable investment approach.

42. NGFS members' efforts to work towards mainstreaming green finance also include various steps they take as corporates to green their core business activities and to reduce their environmental impact. There is broad consensus among NGFS members that leadership also requires dedicated environmental strategies, well-defined sustainability targets – such as reducing resource, water and energy use as well as waste production – and transparency regarding the measures taken and the degree to which these targets have been met.

BOX 5

Sustainable investment at the Banque de France

In March 2018, the Banque de France (BdF) released its responsible investment charter for its portfolios backed to own funds and to the pension liability. This investment charter is in line with the BdF's corporate social responsibility (CSR) charter and its fiduciary duty as a long-term investor.

One year later, **the BdF released its first responsible investment report** based on the provisions of Article 173 of the French Law on the energy transition for green growth (LTECV) and recommendations from the Task Force on Climate-related Financial Disclosures (TCFD).[1] It describes the extra-financial performance of its portfolios and sets up the objectives of the BdF responsible investment strategy. The BdF committed to harmonise its investments with France's climate targets by getting aligned with a 2°C trajectory and by financing the energy and ecological transition through green bonds and dedicated funds. Moreover, the BdF will include environmental, social and governance (ESG) criteria in its asset management and a best-in-class approach based on firms' ESG score and climate performance will be applied. Lastly, the BdF will adopt a voting policy that includes provisions on non-financial transparency and will increase its general meeting attendance rate.

1 *https://www.banque-france.fr/sites/*

Notwithstanding that the focus of central banks incorporating ESG aspects into their portfolio management has been on own funds and pension liability portfolios, **some voices have called for an extension of this approach to monetary policy.** Among NGFS members, so far only one central bank, the People's Bank of China, has a dedicated policy to promote green finance via monetary policy.

Going forward, the NGFS will consider exploring the interaction between climate change and central banks' mandates (other than financial stability) and the effects of climate-related risks on the monetary policy frameworks, paying due respect to their respective legal mandates.

2.3 Recommendation n°3 Bridging the data gaps

Building on the G20 GFSG/UNEP initiatives, the NGFS recommends that the appropriate public authorities share data of relevance to Climate Risk Assessment (CRA) and, whenever possible, make them publicly available in a data repository.

In that respect, the NGFS sees merit in setting up a joint working group with interested parties to bridge existing data gaps. The deliverable of this group would be a detailed list of data items that are currently lacking but which are needed by authorities and financial institutions to enhance the assessment of climate-related risks and opportunities – for example, physical asset level data, physical and transition risk data or financial assets data.

In the course of its work, the NGFS observed, like other institutions and academic papers before, that **data scarcity and inconsistency are substantial obstacles to the development of analytical work on climate risk.** The associated challenges include:

- **Data availability**: data covering the exposure to climate-related risks, risk-return profiles of green financial products as well as "brown" assets (loans, bonds and equity instruments) are critical to undertaking risk assessment and carrying out climate disclosure. Granular data is also needed to conduct bottom-up, quantitative analysis of the macrofinancial impacts of climate-related risks. Finally, such data is also needed to assess and quantify the development of green asset markets, which is of particular interest in a portfolio management context.
- **Time horizon**: the period covered by available data is currently too short. Risk-weighted assets, for example, are calculated on a one-year forward-looking basis only.
- **Lack of expertise**: there is a need to bring together the relevant expertise to gain a complete and integrated understanding of data needs, covering climate, environmental and financial data.

In order to move from observation to action, the NGFS is ready to initiate work with interested parties on setting out a detailed list of currently lacking data items, which authorities and financial institutions would need to enhance the assessment of climate-related risks and opportunities such as physical asset level data, physical and transition risk data and financial assets data. The aim of this initiative is to allow data providers to mine the relevant data and progressively bridge the gaps.

2.4 Recommendation n°4
Building awareness and intellectual capacity and encouraging technical assistance and knowledge sharing

The NGFS encourages central banks, supervisors and financial institutions to build in-house capacity and to collaborate within their institutions, with each other and with wider stakeholders to improve their understanding of how climate-related factors translate into financial risks and opportunities.

The NGFS therefore encourages central banks, supervisors and financial institutions to:

- **allocate sufficient internal resources to address climate-related risks and opportunities;**
- **develop training to equip employees with the necessary skills and knowledge;**
- **work closely together with academics and think-tanks to inform thinking;**
- **raise awareness by sharing knowledge within the financial system.**

The NGFS also encourages relevant parties to offer technical assistance to raise awareness and build capacity in emerging and developing economies when possible.

A key element to achieving effective consideration of climate risks across the financial system is to support internal and external collaboration. Internally, the distinct cross-cutting nature of climate-related risks has led to innovative ways of working across supervisory institutions. Central banks and supervisors have typically formed internal "hubs" or "networks" to bring together the relevant expertise within their organisations.

Externally, there are examples of collaboration with academia, think-tanks, NGOs, government departments, other local supervisors, climate science experts, and financial industry bodies. Examples of international collaboration include:

- ESRB – European Systemic Risk Board and the Analysis Working Group (AWG) Project Team on Sustainable Finance;
- G20 – the G20 Sustainable Finance Study Group;
- IOSCO – Sustainable Finance Network;
- OECD – Centre on Green Finance and Investment, including its annual Forum on Green Finance and Investment;
- SBN – Sustainable Banking Network supported by the IFC;
- SIF – Sustainable Insurance Forum;
- TCFD – Task Force on Climate-related Financial Disclosures.

NGFS members also promote market growth as facilitators between the financial industry and legislators. Many are involved in various national and/or international private sector or public-private initiatives such as the Network of Financial Centres for Sustainability, the Prudential Regulation Authority (PRA)-Financial Conduct Authority (FCA) Climate Financial Risk Forum, Finance for Tomorrow in Paris, the DNB's sustainable finance platform, and the Chinese Green Finance Committee. Participating in such initiatives allows for continuous dialogue with market participants and enables central banks and supervisors to contribute to the improvement of existing green market infrastructure and the development of new green financial instruments.

To foster international exchange on the topic, the NGFS organised an industry dialogue in Singapore in June 2018 which was instrumental in understanding the expectations of the private sector with regards to the role of the NGFS and its members in scaling up green finance. Some participants called for policymakers to set minimum transparency standards regarding the methodologies of second opinion providers for green assets, to provide guidelines (for example, for green bonds) or to simplify approval processes (facilitating green issuances).

Furthermore, the NGFS hosted a conference at the Bank of England in January 2019 bringing together academia, think-tanks, central banks and supervisors and financial institutions to better understand how to size the risks.

Going forward, NGFS members will scale up their efforts for capacity building and technical assistance in emerging economies. Emerging economies are often disproportionately affected by the effects of climate change and they often lack the resources to assess the associated risks. During its work, the NGFS has therefore initiated a dialogue with authorities in developing and emerging countries outside of its membership, and will continue to do so. The NGFS also encourages other relevant parties, such as multilateral institutions, to offer technical assistance to raise awareness and build capacity in emerging and developing economies when possible.

2.5 Recommendation n°5 Achieving robust and internationally consistent climate and environment-related disclosure

The NGFS emphasises the importance of a robust and internationally consistent climate and environmental disclosure framework.

NGFS members collectively pledge their support for the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD). The TCFD recommendations provide a framework for consistent, comparable and decision-useful disclosure of firms' exposures to climate-related risks and opportunities. The NGFS encourages all companies issuing public debt or equity as well as financial sector institutions to disclose in line with the TCFD recommendations.

The NGFS recommends that policymakers and supervisors consider further actions to foster a broader adoption of the TCFD recommendations and the development of an internationally consistent environment disclosure framework. This includes authorities engaging with financial institutions on the topic of environment and climate-related information disclosures, aligning expectations regarding the type of information to be disclosed and sharing good disclosure practices.

As stated in the NGFS October 2018 progress report, **robust disclosure of climate-related information by financial institutions has a number of important benefits:**

- It is integral to an efficient, well-functioning capital market, as it can improve the pricing mechanisms for climate-related risks. It also facilitates the surveillance of the financial system.
- Better disclosure can lead to better risk management. The discipline of public disclosure requires financial institutions to establish the necessary data collection and procedures to better identify and manage their risks.
- It enables market players and policymakers to quickly identify and capitalise on sustainable opportunities, thereby contributing to the continued growth of the green finance ecosystem.

Climate-related disclosure practices differ across jurisdictions, both in terms of what and how to disclose.

The majority of jurisdictions surveyed by the NGFS already have in place, or are planning to implement, some form of climate-related disclosure requirements for their entities. **There are various approaches to encourage disclosure**, including:

- **Non-mandatory approaches**: supporting industry-led or non-binding disclosure guidelines, including cross-border collaboration[43] and surveying disclosure practices. This approach can help financial institutions comply with broader disclosure requirements applied to listed entities and/or entities considered to be of significant public relevance within the jurisdiction.
- **A "comply or explain" approach**: a firm would be considered non-compliant if it does not disclose and fails to provide an adequate explanation.[44] This approach provides firms with clarity and guidance on disclosure requirements but with greater flexibility and possibly reduced compliance costs compared to a one-size-fits-all disclosure rule. Additional non-binding recommendations can support the standardisation of firms' disclosure.[45]
- **A mandatory approach**, specifying a catalogue of data items detailing the quantitative and qualitative data that need to be disclosed.

Most jurisdictions with disclosure requirements set out the type of information that entities must disclose, but allow flexibility on how to comply with the requirements. While the scope and extent of information disclosed varies across entities and jurisdictions, the reporting components broadly include:

- the firm's policies and practices in relation to climate matters;
- climate targets, metrics and performance (including the impact of their activities on the environment);
- material climate risk exposures as well as measures taken to mitigate such risks. In some entities and jurisdictions, this may include the entity's environmental impacts, and how it seeks to identify, prevent and mitigate those impacts.

The absence of a global standardised framework for disclosures results in two main drawbacks:

- the lack of comparability and consistency across jurisdictions, especially on the level of granularity and transparency;
- the lack of a level playing field across jurisdictions, which may lead to increased and skewed compliance costs.

This impedes the proper and globally consistent assessment of climate risks at a firm level as well as the analysis of financial stability risks.

A common international standard on climate information disclosure would foster comparable high-quality disclosures and provide greater clarity to the industry on how to align their reporting internationally. **The recommendations provided by the TCFD with support from the Financial Stability Board (FSB) are an obvious avenue of convergence for a global standardised framework on climate disclosures.** Unlike existing disclosure requirements, the TCFD proposal mainly focuses on climate rather than more broadly on sustainability.

There is a significant level of awareness amongst central banks, supervisors and regulated entities of the TCFD

43 Led by the China Green Finance Committee and the City of London Green Finance Initiative, and in collaboration with the Principles for Responsible Investment, the China-UK Pilot TCFD group, comprising ten Chinese and UK financial institutions, launched a pilot TCFD reporting programme and developed templates for disclosure by banks. The three-year action plan of this pilot exercise was published in November 2018.

44 An example of this is Article 173 of the French Energy Transition Law.

45 EU law requires large companies to disclose certain information on the way they operate and manage social and environmental challenges. While Directive 2014/95/EU, as implemented into national law, is mandatory, the EU Commission issues non-binding guidelines on non-financial reporting which refine the disclosure obligation set out in the Directive.

recommendations, and support from the private sector has grown rapidly, particularly considering that the recommendations were only released in mid-2017. As of February 2019, the TCFD had the support of over 580 firms, with market capitalisations of over USD 7.9 trillion, and including financial firms responsible for assets of nearly USD 100 trillion. The most recent status report, from September 2018, highlighted that many firms are already disclosing in line with the recommendations, but there is still a need for progress in key areas, including scenario analysis and disclosing the financial impacts of climate change on the firms' operations. Increasing awareness and sharing best practices can help encourage wider implementation of the recommendations. For example, the United Nations Environment Programme Finance Initiative (UNEP FI)/TCFD pilot project involves 16 global banks working to assess how they can best adopt key elements of the recommendations.

Supervisors could support the development of a disclosure framework by proposing additional standardised metrics for the financial sector. This includes:

- engaging with financial institutions on the topic of environment and climate-related information disclosures to align expectations regarding the type of information to be disclosed and share good disclosure practices;
- issuing additional guidance on materiality assessment for their respective financial institutions and jurisdictions in order to help firms' comprehensively capture the climate-related risk factors to be considered and disclosed.

In jurisdictions where prudential and market supervision are conducted by different authorities, collaboration on disclosure is also very important.

The NGFS considers that disclosure of climate-related information and enhanced market discipline cannot emerge rapidly enough without action by policymakers or supervisory authorities. While acknowledging the need to move forward on this issue, the NGFS is also mindful of the remaining challenges, including the current lack of data, the scope of reporting, and methodological issues.

2.6 Recommendation n°6
Supporting the development of a taxonomy of economic activities

The NGFS encourages policymakers to bring together the relevant stakeholders and experts to develop a taxonomy that enhances the transparency around which economic activities (i) contribute to the transition to a green and low-carbon economy and (ii) are more exposed to climate and environment-related risks (both physical and transition). Such a taxonomy would:

- **facilitate financial institutions' identification, assessment and management of climate and environment-related risks;**
- **help gain a better understanding of potential risk differentials between different types of assets;**
- **mobilise capital for green and low-carbon investments consistent with the Paris Agreement.**

Policymakers would thus need to:

- **ensure that the taxonomy is robust and detailed enough to (i) prevent green washing, (ii) allow for the certification of green assets and investments projects and (iii) facilitate risk analysis;**
- **leverage existing taxonomies available in other jurisdictions and in the market and ensure that the taxonomy is dynamic and reviewed regularly to account for technological changes and international policy developments;**
- **make the taxonomy publicly available and underline the commonalities with other available taxonomies. Eventually, it should strengthen global harmonisation to ensure a level playing field and prevent the dilution of green labelling.**

BOX 6

Green taxonomies and the cases of China and Europe

Green finance taxonomies provide the basis for defining and classifying green financial assets (e.g., green loans, green bonds and green funds). **In China, the definition of green loans was introduced as early as 2013 by the China Banking and Insurance Regulatory Commission** (CBIRC, formerly CBRC) **in the *Guidance on Green Loans*.** This green loan definition included 12 categories, such as renewable energy, green transportation, green building, etc. Since then, the CBIRC has requested all major banks to report on a semi-annual basis the balance of green loans and the environmental benefits these loans delivered. Green loan default data are also collected by the CBIRC. As of end-2018, the outstanding amount of green loans held by the 21 largest commercial banks in China reached RMB 8.23 trillion, accounting for about 10% of their total aggregate loan balance.

In 2015, China introduced the world's first national-level green bond taxonomy, the Green Bond Endorsed Project Catalogue (2015), which was published by the Green Finance Committee of China Society for Finance and Banking, an institution under the People's Bank of China (PBoC). The Catalogue defined six main categories and 31 sub-categories of projects as eligible for green bond financing. The six main categories included (i) energy saving, (ii) pollution prevention and control, (iii) resource conservation and recycling, (iv) clean transport, (v) clean energy, and (vi) ecological protection and climate change adaptation. The Catalogue was used by virtually all issuers, investors and verifiers in China, even though it was not intended to be "mandatory". Based on the green bond taxonomy, Chinese regulators have also introduced rules and guidelines on green bond verification, as well as environmental information disclosure by green bond issuers. The Catalogue is now under revision and a new version is expected to be released in 2019. Thanks in part to the green taxonomies and the green bond eco-system developed on the basis of the taxonomy, Chinese institutions have issued over USD 100 billion in green bonds from 2016 to 2018, becoming one of the largest green bond markets in the world.

In Europe, the European Commission has tabled a legislative proposal to develop a unified EU classification system – or taxonomy – to determine which economic activities can be regarded as environmentally sustainable for investment purposes. Such a list of environmentally sustainable economic activities would be a useful tool to help financial market participants identify sustainable companies and assets. The proposal identifies six environmental objectives. For an economic activity to be environmentally sustainable, it needs to (i) substantially contribute to at least one of the environmental objectives, (ii) do no significant harm to any of these objectives, (iii) comply with minimum safeguards, and (iv) comply with technical screening criteria. These criteria are meant to determine when an activity can be considered to "substantially contribute" to the objectives, while doing "no significant harm". The Commission has set-up a Technical Expert Group on Sustainable Finance to advise the Commission on the technical screening criteria. The taxonomy will be instrumental to many other actions that the Commission plans to take to move towards more sustainable growth. For example, the Technical Expert Group is also working on a potential EU Green Bond Standard, which will build on the EU Sustainability Taxonomy.

It is important to exploit potential synergies between taxonomies in different jurisdictions. For example, the China Green Finance Committee and the European Investment Bank (EIB) have already made such an attempt by publishing a White Paper called "The Need for a Common Language in Green Finance" in November 2017, followed by a second edition in December 2018. The White Papers compared and mapped the differences and similarities between different green bond taxonomies and highlighted the need for and a potential pathway towards harmonisation of green taxonomies.

The NGFS identified a clear taxonomy around green, non-green, brown and non-brown products as a prerequisite for deepening its analytical work.

- **A taxonomy of "brown" assets** based on clearly defined criteria is important to identify **which assets will be impacted by the Paris Agreement** and the low-carbon and climate-resilient transition. It is a preliminary step to better assess the risk profile of "brown" assets and ensure that disclosures by financial institutions are consistent and comprehensive.
- **A taxonomy of "green" assets** enables policymakers and supervisors to **assess their risk** profile. Like any other investor, central banks will benefit from these taxonomies when implementing sustainable investment strategies.
- **A taxonomy of "green" assets is also of particular use for scaling up green finance**, as it provides financial markets with more transparency, consistency and uniformity and, therefore, confidence in green characteristics. It provides the basis for labelling green financial assets and verifying the "green" feature of the underlying activities, for collecting statistics in green financial flows and stocks, such as green loans or bonds extended or issued during a certain period of time as well as the outstanding volume of green loans and green bonds at any point in time.

The practical challenge is for all affected stakeholders to come together and implement this taxonomy. This calls for policymakers to bring together the relevant stakeholders and experts and to structure and facilitate the debate.

Until now, no regulatory taxonomy has been implemented globally, except market-driven taxonomies which are, by definition, not binding. The NGFS acknowledges the trade-off between, on the one hand, the fragmentation of regional or national approaches, diversity of jurisdictions' collective preference and differing stages of development and, on the other hand, harmonisation in order to avoid level-playing-field problems and to facilitate global assessment of risk profiles. **Although the space for a global taxonomy is limited, the NGFS is supportive of ensuring comparability and consistency across different taxonomies.**

3 Looking forward: operationalising the work and strengthening the dialogue

The NGFS is an open-ended initiative and will continue its work as long as its members deem it necessary and useful. The lesson drawn from the first sixteen months of NGFS activity is that climate change presents significant financial risks that can only be mitigated through an early and orderly transition.

To ensure such a smooth transition, there is still a significant amount of analytical work to be done in order to equip central banks and supervisors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. This calls for a close and specific dialogue with academia and for further technical work to translate the NGFS recommendations or observations into operational policies and processes.

The NGFS will continue to leverage the best practices identified within its membership to help central banks and supervisors to better assess and mitigate climate-related risks.

More precisely, in terms of concrete deliverables, the NGFS is planning to develop:

- **A handbook on climate and environmental risk management for supervisory authorities and financial institutions:** this document would set out some detailed and concrete steps to be taken by supervisors and financial institutions to better understand, measure and mitigate exposures to climate and environmental risks. The handbook will build on the recommendations of this report. It would also provide some detailed case studies of climate/environmental risk analyses carried out by financial institutions and/or supervisory authorities. The focus will be primarily on climate-related risks but will also cover environmental risks.
- **Voluntary guidelines on scenario-based risk analysis:** scenario-based risk analysis is complex, requiring further research and analytical input. The NGFS is working to develop data-driven scenarios for use by central banks and supervisors in assessing climate-related risks. The next step will consist in providing practical advice and guidelines for authorities willing to conduct their own analyses.
- **Best practices for incorporating sustainability criteria into central banks' portfolio management (particularly with regard to climate-friendly investments):** building on some concrete case studies, NGFS members will further delve into the topic and develop a hands-on practical guide for central banks to integrate sustainability principles into their portfolio management.

The NGFS is also aware that addressing climate-related risks calls for a collective response with the relevant stakeholders, namely:

- **With non-NGFS central banks or supervisors, regional and/or international supervisory authorities and standard setting bodies and international organisations, governments and policymakers** in order to contribute to developing the appropriate policy framework. International standard setting bodies could consider how the NGFS recommendations could feed into their work and assess their current set of standards/best practices with respect to the relevance of climate-related risks. To this end, the NGFS will present this report to the BCBS in 2019. Specific regional outreach exercises, following the example of the Mexico Green Finance Conference in January 2019, will be arranged to strengthen the global reach of the NGFS.
- **With academia** in order to identify analytical blind spots and gaps in our collective knowledge. In 2019, the NGFS will set up a specific dialogue with academia and hold periodic academic events to discuss the most pressing research questions.
- **With the financial industry and NGOs** in order to ensure a mutually beneficial exchange of experience and information. To that end, the NGFS has entered into a close dialogue with a number of stakeholders relevant to its work.

Conclusion

Over barely sixteen months of existence, the NGFS has grown from eight founding members to more than thirty members from five continents including emerging and developed countries alike. **As time is running out to ensure a smooth transition to a low-carbon economy, and to mitigate climate change impacts on the world's economy and the global financial system, the momentum among the central bank and supervisory community to respond to this challenge is growing rapidly.** This first comprehensive report lays the foundations for the more technical deliverables the NGFS is going to produce in the coming months. The NGFS membership is collectively determined to develop practical tools and methodologies for its membership and beyond, while continuing to raise awareness and to reach out to the various stakeholders relevant to its work.

List of acronyms

BCBS The Basel Committee on Banking Supervision is the primary global standard setter for the prudential regulation of banks.

CRA Climate Risk Assessment refers to the methods and practices used to size the financial impact of climate-related risks to micro-prudential objectives, including qualitative and quantitative analysis.

CSR Corporate social responsibility.

ESG Environmental, social and governance criteria are used by responsible investors and can be financially material.

GFSG/SFSG The G20 Green/Sustainable Finance Study Group was launched under China's Presidency of the G20 in 2016. The Study Group is co-chaired by China and the United Kingdom and has published three reports in 2016, 2017 and 2018.

GHG According to the IPCC[1] the greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds.

IAIS The International Association of Insurance Supervisors is responsible for regulatory cooperation regarding the supervision of the insurance sector.

IPCC The Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change.

NGFS Network for Greening the Financial System.

NPL A non-performing loan is a loan for which the debtor has not met the scheduled payments for a defined period.

PD The probability of default refers to the likelihood of default on a financial asset over a defined time horizon.

SFN The Sustainable Finance Network is an initiative of the International Organization of Securities Commissions (IOSCO) bringing together securities and markets authorities. The Network is currently chaired by Erik Thedéen, Director General, Finansinspektionen (Swedish Financial Supervisory Authority).

TCFD The Task Force on Climate-related Financial Disclosures is a private-sector led task force, chaired by Michael R. Bloomberg with support from the Financial Stability Board, which provides a global standardised framework on climate disclosures.

UNEP FI The United Nations Environment Programme – Finance Initiative is a partnership between UNEP and the global financial sector created in the wake of the 1992 Earth Summit with a mission to promote sustainable finance.

1 IPCC, Special Report: Global Warming of 1.5°C, Glossary, 2018.

LETTER

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The geographical distribution of fossil fuels unused when limiting global warming to 2 °C

Christophe McGlade[1] & Paul Ekins[1]

Policy makers have generally agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above the average global temperature of pre-industrial times[1]. It has been estimated that to have at least a 50 per cent chance of keeping warming below 2 °C throughout the twenty-first century, the cumulative carbon emissions between 2011 and 2050 need to be limited to around 1,100 gigatonnes of carbon dioxide (Gt CO_2)[2,3]. However, the greenhouse gas emissions contained in present estimates of global fossil fuel reserves are around three times higher than this[2,4], and so the unabated use of all current fossil fuel reserves is incompatible with a warming limit of 2 °C. Here we use a single integrated assessment model that contains estimates of the quantities, locations and nature of the world's oil, gas and coal reserves and resources, and which is shown to be consistent with a wide variety of modelling approaches with different assumptions[5], to explore the implications of this emissions limit for fossil fuel production in different regions. Our results suggest that, globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C. We show that development of resources in the Arctic and any increase in unconventional oil production are incommensurate with efforts to limit average global warming to 2 °C. Our results show that policy makers' instincts to exploit rapidly and completely their territorial fossil fuels are, in aggregate, inconsistent with their commitments to this temperature limit. Implementation of this policy commitment would also render unnecessary continued substantial expenditure on fossil fuel exploration, because any new discoveries could not lead to increased aggregate production.

Recent climate studies have demonstrated that average global temperature rises are closely related to cumulative emissions of greenhouse gases emitted over a given timeframe[2,6,7]. This has resulted in the concept of the remaining global 'carbon budget' associated with the probability of successfully keeping the global temperature rise below a certain level[4,8,9]. The Intergovernmental Panel on Climate Change (IPCC)[3] recently suggested that to have a better-than-even chance of avoiding more than a 2 °C temperature rise, the carbon budget between 2011 and 2050 is around 870–1,240 Gt CO_2.

Such a carbon budget will have profound implications for the future utilization of oil, gas and coal. However, to understand the quantities that are required, and are not required, under different scenarios, we first

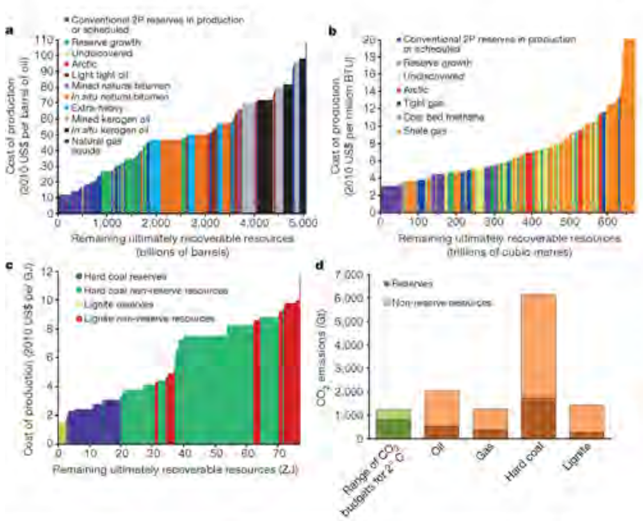

Figure 1 | Supply cost curves for oil, gas and coal and the combustion CO_2 emissions for these resources. **a–c**, Supply cost curves for oil (**a**), gas (**b**) and coal (**c**). **d**, The combustion CO_2 emissions for these resources. Within these resource estimates, 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 Gt of hard coal, and 276 Gt of lignite are classified as reserves globally. These reserves would result in 2,900 Gt of CO_2 if combusted unabated. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting the temperature rise to 2 °C (870–1,240 Gt of CO_2) is also shown. 2P, 'proved plus probable' reserves; BTU, British thermal units (one BTU is equal to 1,055 J). One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules. Annual global primary energy production is approximately 0.5 ZJ.

[1]University College London (UCL), Institute for Sustainable Resources, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK.

need to establish the quantities and location of those currently estimated to exist. A variety of metrics with disparate nomenclature are relied upon to report the availability of fossil fuels[10,11], but the two most common are 'resources' and 'reserves'. In this work 'resources' are taken to be the remaining ultimately recoverable resources (RURR)—the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of current economic conditions. 'Reserves' are a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced[11]. Our best estimates of the reserves and resources are presented in Fig. 1 and, at the regional level, in Extended Data Table 1.

Figure 1 also compares the above carbon budget with the CO_2 emissions that would result from the combustion of our estimate of remaining fossil fuel resources (nearly 11,000 Gt CO_2). With the combustion emissions of the remaining reserves alone totalling nearly 2,900 Gt CO_2, the disparity between what resources and reserves exist and what can be emitted while avoiding a temperature rise greater than the agreed 2 °C limit is therefore stark.

Although previous research[12] has examined the implications that emissions mitigation might have on the rents collected by fossil fuel resource owners, more pertinent to policy and industry are the quantities of fossil fuel that are not used before 2050 in scenarios that limit the average global surface temperature rise to 2 °C. Such geographically disaggregated estimates of 'unburnable' reserves and resources are provided here using the linear optimization, integrated assessment model TIAM-UCL[13].

To provide context to the issue of unburnable fossil fuels and our results, it is useful to examine scenarios provided by other models that quantify separately the volumes of oil, gas and coal produced globally under a range of future emissions trajectories[5]. Cumulative production between 2010 and 2050 from these are presented in Fig. 2. Since they have very different future greenhouse gas emissions profiles, we have converted them to approximate temperature rise trajectories. These have been calculated using the climate model MAGICC[14], which generates a probability distribution over temperature rise trajectories for a given emissions profile. We use the 60th percentile temperature trajectory (to correspond with assumptions within TIAM-UCL) and then group the scenarios by the final temperature rise in 2100: below 2 °C, between 2 °C and 3 °C, or exceeding 3 °C.

In this work we have constructed three core scenarios that are constrained to limit the average surface temperature rise in all time periods to 2 °C, to 3 °C, and to 5 °C. Cumulative production of each fossil fuel between 2010 and 2050 in each of these scenarios can be identified within each of the three temperature groupings in Fig. 2.

The global reserves of oil, gas and coal included in Fig. 1 total approximately 7.4 ZJ, 7.1 ZJ and 20 ZJ, respectively. With narrow inter-quartile ranges, relative to the level of reserves available, Fig. 2 shows good agreement on the levels of fossil fuels produced within the temperature groups, despite the range of modelling methodologies and assumptions included.

Since assumptions in modelling the energy system are subject to wide bands of uncertainty[15], we further constructed a number of sensitivity scenarios using TIAM-UCL that remain within a 2 °C temperature rise. These span a broad range of assumptions on production costs, the availability of bio-energy, oil and gas, demand projections, and technology availability (one with no negative emissions technologies, and one with no carbon capture and storage (CCS)) (Extended Data Table 2). The availability of CCS has the largest effect on cumulative production levels (Extended Data Fig. 1); however, there is little variability in the total production of fossil fuels if the world is to have a good chance of staying within the agreed 2 °C limit.

Global production of oil, gas and coal over time in our main 2 °C scenario is given in Fig. 3. This separates production by category, that is, by the individual kinds of oil and gas that make up the global resource base, and compares total production with the projections from the 2 °C scenarios in Fig. 2. The results generated using TIAM-UCL are a product

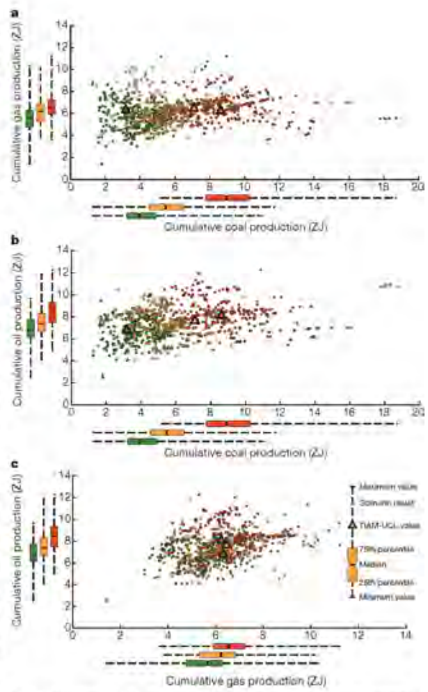

Figure 2 | Cumulative production between 2010 and 2050 from a range of long-term energy scenarios. Panels refer to coal and gas (**a**), coal and oil (**b**), and gas and oil (**c**). Scenarios[5] are coloured according to their approximate resultant 2100 temperature rise above pre-industrial levels. 379 individual scenarios result in a temperature rise of less than 2 °C (green), 366 of between 2 °C and 3 °C (orange), and 284 of more than 3 °C (red). Triangles are the values from the 2 °C (with CCS), 3 °C and 5 °C TIAM-UCL scenarios. Ranges and symbols are as shown in the key in **c**.

of the economically-optimal solution, and other regional distributions of unburnable reserves are possible while still remaining within the 2 °C limit (even though these would have a lower social welfare). A future multi-model analysis could therefore usefully build on and extend the work that is presented here, but results at the aggregate level can be seen to lie within range of the ensemble of models and scenarios that also give no more than a 2 °C temperature rise.

In the TIAM-UCL scenarios, production of reserves and non-reserve resources occurs contemporaneously. It is therefore important to recognize that it would be inappropriate simply to compare the cumulative production figures in Fig. 2 with the reserve estimates from Fig. 1 and declare any reserves not used as 'unburnable'. Although there may be sufficient reserves to cover cumulative production between 2010 and 2050, it does not follow that only reserves should be developed and all other resources should remain unused. For oil and gas, resources that are not currently reserves may turn out to be cheaper to produce than some reserves, while new resources will also be developed to maintain

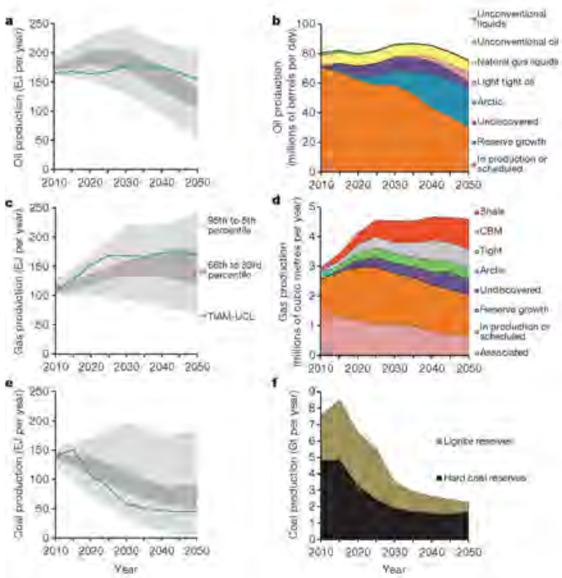

Figure 3 | Oil, gas and coal production in the TIAM-UCL 2 °C scenario (with CCS) and comparison with all other 2 °C scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) database[9]. **a**, **c** and **e** compare total production by oil, gas and coal with the AR5 database; **b**, **d** and **f** provide a disaggregated view of production for the TIAM-UCL 2 °C scenario separated by category. Associated gas is gas produced alongside crude oil from oil fields. One exajoule (EJ) is equal to one quintillion (10^{18}) joules.

the flow rates demanded by end-use sectors. However, if resources that are currently non-reserves are produced, a greater proportion of reserves must not be produced to stay within the carbon budget.

The reserves of oil, gas and coal that should be classified as unburnable within each region, and the percentage of current reserves that remain unused, are set out in Table 1. Since total production is most sensitive to assumptions on CCS, and since it has been suggested that the deployment of CCS will permit wider exploitation of the fossil fuel resource base[16], Table 1 includes the unburnable reserves from two alternative 2 °C scenarios. One scenario permits the widespread deployment of CCS from 2025 onwards, and the other assumes that CCS is unavailable in any time period.

Globally, when CCS is permitted, over 430 billion barrels of oil and 95 trillion cubic metres of gas currently classified as reserves should remain unburned by 2050. The Middle East, although using over 60% of its oil reserves, carries over half of the unburnable oil globally, leaving over 260 billions of barrels in the ground. Canada has the lowest utilization of its oil reserves (25%), as its natural bitumen[17] deposits remain largely undeveloped (see below) while the United States has the highest, given the proximity of supply and demand centres. The Middle East also holds half of unburnable global gas reserves, with Former Soviet Union countries accounting for another third, meaning that they can use only half their current reserves.

Coal reserves are by far the least-used fossil fuel, with a global total of 82% remaining unburned before 2050. The United States and the Former Soviet Union countries each use less than 10% of their current reserves, meaning that they should leave over 200 billion tonnes (Gt) coal (both hard and lignite) reserves unburned. Coal reserve utilization

Table 1 | Regional distribution of reserves unburnable before 2050 for the 2 °C scenarios with and without CCS

	2 °C with CCS						2 °C without CCS					
	Oil		Gas		Coal		Oil		Gas		Coal	
Country or region	Billions of barrels	%	Trillions of cubic metres	%	Gt	%	Billions of barrels	%	Trillions of cubic metres	%	Gt	%
Africa	23	21%	4.4	33%	28	85%	28	26%	4.4	34%	30	90%
Canada	39	74%	0.3	24%	5.0	75%	40	75%	0.3	24%	5.4	82%
China and India	9	25%	2.9	63%	180	66%	9	25%	2.5	53%	207	77%
FSU	27	18%	31	50%	203	94%	28	19%	36	59%	209	97%
CSA	58	39%	4.8	53%	8	51%	63	42%	5.0	56%	11	73%
Europe	5.0	20%	0.6	11%	65	78%	5.3	21%	0.3	6%	74	89%
Middle East	263	38%	46	61%	3.4	99%	264	38%	47	61%	3.4	99%
OECD Pacific	2.1	37%	2.2	56%	83	93%	2.7	46%	2.0	51%	85	95%
ODA	2.0	9%	2.2	24%	10	34%	2.8	12%	2.1	22%	17	60%
United States of America	2.8	6%	0.3	4%	235	92%	4.6	9%	0.5	6%	245	95%
Global	431	33%	95	49%	819	82%	449	35%	100	52%	887	88%

FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3. %, Reserves unburnable before 2050 as a percentage of current reserves.

is twenty-five percentage points higher in China and India, but still they should also leave nearly 200 Gt of their current coal reserves unburned.

The utilization of current reserves is lower in nearly all regions for all of the fossil fuels when CCS is not available, although there is a slight increase in gas production in some regions to offset some of the larger drop in coal production. Nevertheless, Table 1 demonstrates that the reserves of coal that can be burned are only six percentage points higher when CCS is allowed, with the utilization of gas and oil increasing by an even smaller fraction (around two percentage points). Because of the expense of CCS, its relatively late date of introduction (2025), and the assumed maximum rate at which it can be built, CCS has a relatively modest effect on the overall levels of fossil fuel that can be produced before 2050 in a 2 °C scenario.

As shown in Fig. 3, there is substantial production of many of the non-reserve resource categories of oil and gas. Extended Data Table 3 sets out the regional unburnable resources of all coal, gas and oil in the scenario that allows CCS by comparing cumulative production of all fossil fuel resources with the resource estimates in Fig. 1.

The RURR of both types of coal and unconventional oil vastly exceed cumulative production between 2010 and 2050, with the overwhelming majority remaining unburned. Resources of conventional oil are used to the greatest extent, with just under 350 billion barrels of non-reserve resources produced over the model timeframe. The Middle East again holds the largest share of the unburnable resources of conventional oil, but there is a much wider geographical distribution of these unburnable resources than was the case for oil reserves.

Regarding the production of unconventional oil, open-pit mining of natural bitumen in Canada soon drops to negligible levels after 2020 in all scenarios because it is considerably less economic than other methods of production. Production by *in situ* technologies continues in the 2 °C scenario that allows CCS, but this is accompanied by a rapid and total decarbonization of the auxiliary energy inputs required (Extended Data Fig. 2). Although such a decarbonization would be extremely challenging in reality, cumulative production of Canadian bitumen between 2010 and 2050 is still only 7.5 billion barrels. 85% of its 48 billion of barrels of bitumen reserves thus remain unburnable if the 2 °C limit is not to be exceeded. When CCS is not available, all bitumen production ceases by 2040. In both cases, the RURR of Canadian bitumen dwarfs cumulative production, so that around 99% of our estimate of its resources (640 billion barrels), remains unburnable. Similar results are seen for extra-heavy oil in Venezuela. Cumulative production is 3 billion barrels, meaning that almost 95% of its extra-heavy reserves and 99% of the RURR are unburnable, even when CCS is available.

The utilization of unconventional gas resources is considerably higher than unconventional oil. Under the 2 °C scenario, gas plays an important part in displacing coal from the electrical and industrial sectors and so there is over 50 trillion cubic metres unconventional gas production globally, over half of which occurs in North America. Nevertheless, there is a low level of utilization of the large potential unconventional gas resources held by China and India, Africa and the Middle East, and so over 80% of unconventional gas resources (247 trillion cubic metres) are unburnable before 2050. Production of these unconventional gas resources is, however, only possible if the levels of coal reserves identified in Table 1 are not developed: that is, it is not possible for unconventional gas to be additional to current levels of coal production.

Finally, we estimate there to be 100 billion barrels of oil (including natural gas liquids) and 35 trillion cubic metres of gas in fields within the Arctic Circle that are not being produced as of 2010. However, none is produced in any region in either of the 2 °C scenarios before 2050. These results indicate to us that all Arctic resources should be classified as unburnable.

To conclude, these results demonstrate that a stark transformation in our understanding of fossil fuel availability is necessary. Although there have previously been fears over the scarcity of fossil fuels[18], in a climate-constrained world this is no longer a relevant concern: large portions of the reserve base and an even greater proportion of the resource base should not be produced if the temperature rise is to remain below 2 °C.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

Fossil fuel definitions. A 'McKelvey' box[19] is often used to provide an overview of the relationship between different resource and reserve estimates[20]. The best estimates of current oil and gas reserves in Extended Data Table 1 were of the 'proved plus probable' or '2P' quantities. Since 2P reserve estimates are rare for coal and none are in the public domain, the best estimates shown for coal were of the 'proved' or '1P' reserves. Broadly speaking, 1P estimates are more conservative, often corresponding to an estimate with a 90% probability of being exceeded, while 2P estimates are the median estimate of the reserves for a given field or region[11].

Oil and gas can be further separated into 'conventional' and 'unconventional' reserves and resources. Again, there is no single definition of these terms, but here we define oil with density greater than water (often standardized as '10° API') to be unconventional and all other quantities as conventional. We therefore categorize the 'light tight oil' extracted from impermeable shale formations using hydraulic fracturing as conventional oil.

For gas, tight gas (gas trapped in relatively impermeable hard rock, limestone or sandstone), coal-bed methane (gas trapped in coal seams that is adsorbed in the solid matrix of the coal), and shale gas (gas trapped in fine-grained shale) are considered as the three 'unconventional gases'; all other quantities are considered to be conventional.

Coal is distinguished by its energy density following the definitions used by the Federal Institute for Geosciences and Natural Resources (BGR)[21]. Hard coal has an energy density greater than 16.5 $MJ\,kg^{-1}$; any quantities with energy density less than this are classified as lignite.

Derivation of reserve and resource estimates. The estimated oil and gas reserves and resources shown in Extended Data Table 1 were derived in the following manner[22]. We first identified the individual elements or categories of oil and gas that make up the global resource base. For oil these are: current conventional 2P reserves in fields that are in production or are scheduled to be developed, reserve growth, undiscovered oil, Arctic oil, light tight oil, natural gas liquids, natural bitumen, extra-heavy oil, and kerogen oil. The latter three of these are the unconventional oil categories.

Reserve growth is defined to be 'the commonly observed increase in recoverable resources in previously discovered fields through time'[23]. Quantities in this category here include any contributions from reserves in fields that have been discovered but are not scheduled to be developed ('fallow fields'), the new implementation of advanced production technologies such as enhanced oil recovery, changes in geological understanding, and changes in regional definitions.

There are eight categories of conventional and unconventional gas: current conventional 2P reserves that are in fields in production or are scheduled to be developed, reserve growth, undiscovered gas, Arctic gas, associated gas, tight gas, coal-bed methane, and shale gas. As noted above, the latter three of these are collectively referred to as unconventional gas.

We then selected the most robust data sources that provide estimates of the resource potential of each individual category within each country; these sources are set out in Extended Data Table 4. Taken together, differences between these sources provide a spread of discrete quantitative resource estimates for each category within each country. We also differentiated between the quantities of conventional oil that are natural gas liquids, and the quantities of natural gas that are associated with oil fields; these distinctions are important for modelling purposes but are rarely made in the literature.

For unconventional oil, we first generated a range of estimates for the in-place resources of natural bitumen, extra-heavy oil, and kerogen oil, and a range of potential recovery factors for different extraction technologies. We separately characterized the natural bitumen and kerogen oil resources that are extractable using mining technologies and those resources that are extractable using *in situ* technologies because the resource potential, costs, and energy requirements of these technologies are very different.

Continuous distributions were next constructed across these data ranges. Since there is no empirical basis for the choice of a suitable shape or form for such distributions, we used both the triangular and the beta distributions, chosen because they can be skewed both positively and negatively, and because they allow identical distributions to be used across all of the ranges derived. With equal weighting for each distribution, we combined these into a single individual resource distribution for each category within each country.

We then estimated the production costs of each of the oil and gas resource categories. Taking account of the resource uncertainty, these were used to develop supply cost curves for each category of oil and gas within each country.

We finally used a Monte Carlo selection process to combine these country-level supply cost curves. Regional supply cost curves were thus formed from aggregated supply cost curves for individual countries, and similarly supply cost curves formed for multiple categories of oil or gas within one or more countries. Data in Fig. 1 are the median values from these aggregate distributions with Extended Data Table 4 giving high (95th percentile), median, and low (5th percentile) estimates for each category at the global level.

In most industry databases of oil and gas reserves (for example, the database produced by the consultancy IHS CERA[24,25]), some of the quantities classified as reserves lie in fields that were discovered over ten years ago, yet these fields have not been developed and there are no plans at present to do so. These are sometimes referred to as 'fallow fields'. For gas these quantities can also be called 'stranded gas', and they can be quite substantial; for example ref. 24 suggests that 50% gas reserves outside of North America are in stranded fields. Strictly, oil and gas in such fields should not be classified as reserves (for example, ref. 11 states that reserve quantities must have a 'reasonable timetable for development'). However, in this work, to ensure that the reserve estimates provided in Table 1 are not substantially different from the global totals provided by these industry databases, we follow their convention of classifying these quantities as reserves.

There are fewer independent estimates of reserves for coal and so we simply relied upon the estimates provided by the BGR[21] for the reserve figures in Extended Data Table 1. The RURR of coal are more problematic to characterize, however. The 'resource' estimates provided by the BGR are not estimates of the quantities that can actually be extracted but are the in-place quantities; large portions of these are unlikely ever to be technically recoverable.

We therefore used the proved, probable and possible reserve estimates for hard coal and lignite provided by the World Energy Council[26] for a selection of countries. The sum of these three figures gives an estimate of the 'tonnage within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future' (the definition provided by the World Energy Council). Since the sum of these three figures takes account of technical recoverability, we consider that, while imperfect, they provide a better estimate of the ultimately recoverable resources of coal than either the (narrower) proved reserve or the (broader) in-place resource estimates.

There are a number of countries that are estimated by the BGR to hold large quantities of coal in place but for which no probable and possible reserve estimates are provided by the World Energy Council. The ratio of the World Energy Council resource estimate to the BGR in-place estimate in countries that have estimates provided by both sources can vary substantially, but the average ratio is 16% for hard coal and 31% for lignite. We therefore assumed this ratio to generate resource estimates for all countries for which only BGR in-place estimates are provided. The proved reserve estimates of coal are so large themselves that the resource estimates are less important than is the case for oil and gas resource estimates.

There are few other sources providing a comprehensive overview of fossil fuel availability. Further, these often do not provide their sources or the methods used to generate estimates, do not define fully what categories or elements are included or excluded, and do not indicate sufficient conversion factors that would allow a like-with-like comparison. Some exceptions, however, are the IEA[27,28], the IIASA Global Energy Assessment (GEA)[29], and the BGR[21]. Their estimates are shown together with our aggregated reserve and resource estimates in Extended Data Table 5.

A number of factors contribute to the large variation between these estimates. A key reason is that the definitions of 'reserves' and 'resources' differ among sources, and so it is problematic to seek to compare them directly. For example, as noted above, the BGR, whose estimates are followed closely by the other sources, gives the total coal in place rather than an estimate of the resources that can be recovered, as in our study. Other reasons for the differences seen include: (1) the exclusion or inclusion of certain categories of fossil fuels such as light tight oil, aquifer gas, and methane hydrates; (2) whether proved (1P) or proved plus probable (2P) reserves are reported, and the methods used to generate the 1P reserve estimates; (3) the potential inflation of reserve estimates for political reasons, and whether they should consequently be increased or reduced[30]; (4) the inclusion of stranded gas volumes in gas reserve estimates; (5) differences in the functional form used to estimate volumes of reserve growth (if reserve growth is included at all); (6) the difficulty in estimating current recovery factors (the ratio of recoverable resources to total resources in place), and how these may increase in the future; (7) differences between the methods used to estimate undiscovered oil and gas volumes; (8) the scarcity of reports providing reliable estimates of the potential resources of Arctic oil and gas, light tight oil, tight gas and coal bed methane, and the frequent consequent reliance upon expert judgement; (9) variation in what unconventional oil production technologies, which vary considerably in their recovery factors, will be used in the future; and (10) the chosen cut-off 'yield' (the volume of synthetic oil produced from a given weight of shale rock) for kerogen oil.

The estimates considered in our model are the result of careful and explicit consideration of all these issues, with our choices justified in the light of available knowledge. It can be seen in Extended Data Table 5, however, that our median figures are generally lower than the estimates provided by the other sources shown there. Therefore, although we consider our median resource estimates to be more robust than the figures used by these other sources, if in fact these other estimates were found to be closer to being correct, then the unburnable resources given in Extended Data Table 3 would also be larger. For example, if total gas resources are actually at the GEA high estimate, then the percentage that should be classified as unburnable before 2050 under the 2 °C scenario would increase to 99% rather than our estimate of 75%.

The cut-off date after which quantities that have not been produced should be considered 'unburnable' is also an important assumption. While there are no specific timeframes attached to the definition of reserves, quantities are usually required to be developed within, for example, a 'reasonable timeframe'[19]. It is doubtful whether any reserves not produced by 2050 would fulfil this criterion. We therefore take cumulative production of reserves between 2010 and 2050 as the reserve 'utilization', and classify any quantities not used within this time as those that should be 'unburnable' if a certain temperature rise is not to be exceeded. Similarly, if none, or only a minor proportion, of a certain non-reserve resource is produced before 2050, then any current interest in developing it would be questionable. We thus also rely on 2050 as the cut-off date for classifying resources that should be considered as unburnable.

Description and key assumptions in TIAM-UCL. The TIMES Integrated Assessment Model in University College London ('TIAM-UCL') is a technology-rich, bottom-up, whole-system model that maximizes social welfare under a number of imposed constraints. It models all primary energy sources (oil, gas, coal, nuclear, biomass and renewables) from resource production through to their conversion, infrastructure requirements, and finally to sectoral end-use. An extended explanation of input assumptions, approaches and data sources can be found in ref. 13. The base year of TIAM-UCL is 2005, the model is run in full to 2100, and thereafter the climate module is run to 2200. Results are presented here only between 2010 and 2050 (and are reported in five-year increments). All scenarios in this paper are run with the assumption of perfect foresight.

Resources and costs of all primary energy production are specified separately within 16 regions covering the world, and separately within the regions that contain members of the Organisation of Petroleum Exporting Countries (OPEC); the names of these are presented in Extended Data Table 6. For clarity in the main text, we have aggregated some of these regions into ten more-encompassing groups.

The climate module of TIAM-UCL is calibrated to the MAGICC model[14]. This module can be used to project the effects of greenhouse gas emissions on: atmospheric concentrations of greenhouse gas, radiative forcing, and average global temperature rises. It can also be used to constrain the model to certain bounds on these variables. In this work, the climate module is used to restrict the temperature rise to certain levels (as explained below). For the calibration to MAGICC, values from the probability distributions of climate parameters in MAGICC were selected so that there is a 60% chance that the temperature rise will remain below any level reported. Any constraints imposed using the TIAM-UCL climate module thus also correspond to this probability.

The emissions profiles[3] used in Fig. 2 were converted to temperature rises using MAGICC. To ensure consistency with TIAM-UCL, we use the 60th percentile temperature trajectory from MAGICC and then group by the final temperature rise in 2100; there is therefore also a 60% chance that the temperature rise will be below the level indicated.

For each of the scenarios run in this paper using TIAM-UCL, a 'base case' is first formed that incorporates no greenhouse gas abatement policies. This base case uses the standard version of the model that relies upon minimizing the discounted system cost. This is used to generate base prices for each commodity in the model. TIAM-UCL is then re-run using the elastic demand version with the greenhouse gas abatement policies introduced. This version of the model maximizes social welfare (the sum of consumer and producer surplus) and allows the energy-service demands to respond to changes in the endogenously determined prices resulting from these new constraints.

Fossil fuel modelling in TIAM-UCL. Oil and gas are both modelled in a similar manner in TIAM-UCL. The nine categories of conventional and unconventional oil and eight categories of conventional and unconventional gas identified above are all modelled separately. Coal production in TIAM-UCL is modelled more collectively, with only two categories, reserves and resources, for hard coal and lignite.

Natural bitumen and kerogen oil resources can be produced using either mining or *in situ* means, the technologies for which have different costs, efficiencies, and energy inputs. Although natural gas is predominantly used at present for the energy inputs to these unconventional resources, the model is free to choose any source of heat, electricity and hydrogen to allow greater flexibility. The costs of the auxiliary energy inputs required to extract and upgrade the native unconventional oils are determined endogenously by the model.

Each of the coal, gas and oil categories are modelled separately within the regions listed in Extended Data Table 6, with each resource category within each region split into three cost steps. As discussed above, the supply cost curves given in Fig. 1 comprise the data input to TIAM-UCL.

After processing, oil is next refined into products (gasoline, diesel, naphtha and so on), whereas processed gas and coal can be used directly. Fuel switching to and from all of the fossil fuels is possible. Trade of hard coal, crude oil, refined products, natural gas, both in pipelines and as liquefied natural gas, is allowed. Lignite cannot be traded between the regions.

Refined oil products can also be produced directly using Fischer–Tropsch processes with possible feedstocks of coal, gas, or biomass; these technologies can also be employed either with or without carbon capture and storage. Regional coal, oil and gas prices are generated endogenously within the model. These incorporate the marginal cost of production, scarcity rents, rents arising from other imposed constraints, and transportation costs.

A new key aspect of TIAM-UCL is the imposition of asymmetric constraints on the rate of production of oil and gas given a certain resource availability; these are intended to represent 'depletion rate constraints'. In TIAM-UCL, these constraints are modelled through introducing maximum annual production growth and maximum 'decline rate' restrictions. These are imposed on each cost step of each category of both oil and gas in each region, and ensure that the production follows a more realistic profile over time.

Data for these constraints are available at the field level from the bottom-up economic and geological oil field production model ('BUEGO')[11]. BUEGO contains a data-rich representation of 7,000 producing 'undiscovered' and discovered but undeveloped oil fields. These data include each field's 2P reserves, potential production capacity increases, water depth, capital and operating costs, and natural decline rate (the rate at which production would decline in the absence of any additional capital investment).

We used production-weighted averages (as of 2010) of the individual fields within each region to give average regional natural decline rates, which were imposed as maximum decline constraints in TIAM-UCL in the form of equal maximum annual percentage reductions. Although data on gas natural decline rates are much more sparse, some are available at a regional level[17], which can be compared with similar results for oil natural decline rates[22]. This comparison suggests that gas natural decline rates are on average 1% per year greater than for oil, with similar distributions for location (onshore/offshore) and size. The constraints placed on the maximum annual reductions in natural gas production were thus assumed to be 1% higher than those derived for oil.

As identified in the main text, to understand the quantities of reserves of oil and gas that are unburnable, production of reserve sources only should be compared with reserve estimates, while cumulative production of all sources should be compared with the resource estimates. For coal, the reserves are so much greater than cumulative production under any scenario that this distinction is not as important.

The base year of TIAM-UCL is 2005, but the base year of this study is 2010. Since reserves have grown, and oil and gas have been discovered in the intervening five years, some quantities that were classified as reserve growth and undiscovered oil and gas in 2005 should be classified as reserves in 2010. Within each region, the cumulative production figures to which the reserve estimates in Extended Data Table 1 are compared therefore contain production from the conventional 2P reserves in the 'fields in production or scheduled to be developed' category, as well as some portions of production from the 'reserve growth' and 'undiscovered' categories. In addition, since, for example, reserves of natural bitumen are included in the reserves figures of Canada and unconventional gas reserves are included in the reserves figures of the United States, production of some of the unconventional categories are also included in these cumulative production figures. To ensure consistency within each region, the maximum production potentials over the modelling period from the categories included in the cumulative production figures are equal to the reserve estimates given in Extended Data Table 1.

Overview of scenarios implemented. A brief overview of the main assumptions within the four scenarios run as part of this work is provided in Extended Data Table 7. For the emissions mitigation scenarios (those that limit the temperature rise to 3 °C and 2 °C), we assume that there are only relatively modest efforts to limit emissions in early periods as explained. The assumptions within the 2 °C sensitivity scenarios used to construct Extended Data Fig. 1 are provided in Extended Data Table 2.

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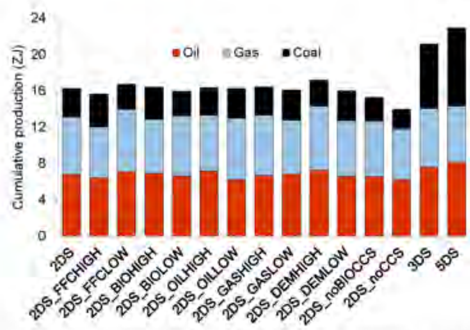
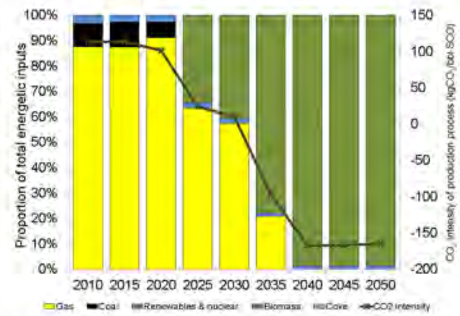


Extended Data Figure 1 | Cumulative fossil fuel production under a range of sensitivity scenarios run using TIAM-UCL. Scenario names and characteristics are given in Extended Data Table 2.



Extended Data Figure 2 | The auxiliary energy inputs for natural bitumen production in Canada by *in situ* technologies in the 2 °C scenario and the CO_2 intensity of these. bbl SCO, a barrel of synthetic crude oil, the oil that results after upgrading the natural bitumen.

Extended Data Table 1 | Best estimates of remaining reserves and remaining ultimately recoverable resources from 2010

	Oil (Gb)			Gas (Tcm)			Hard coal (Gt)		Lignite (Gt)	
Country or region	Res	Con RURR	Uncon RURR	Res	Con RURR	Uncon RURR	Res	RURR	Res	RURR
Africa	111	280	70	13	45	35	31	45	2	5
Canada	53	60	640	1	5	25	4	35	2	40
China and India	38	90	110	5	10	40	255	1,080	16	120
FSU	152	370	360	61	95	30	123	580	94	490
CSA	148	360	450	9	30	55	10	25	5	10
Europe	25	110	30	6	25	20	17	70	66	160
Middle East	689	1,050	10	76	105	20	2	10	2	5
OECD Pacific	6	30	130	4	10	20	45	120	44	200
ODA	23	75	5	9	25	15	15	40	14	155
United States	50	190	650	8	25	40	226	560	31	335
Global	1,294	2,615	2,455	192	375	300	728	2,565	276	1,520

'Con' and 'Uncon' stand for conventional and unconventional sources, respectively. Coal is specified in billions of tonnes (Gt), gas in trillions of cubic metres (Tcm) and oil in billions of barrels (Gb). Res, reserves

Extended Data Table 2 | Labels and description of the sensitivity scenarios modelled in this project

Sensitivity Name	Description
2DS_FFCHIGH	Production costs of all fossil fuel technologies are 50% larger in 2015 and 100% larger in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_FFCLOW	Production costs of all fossil fuel technologies are 33% lower in 2015 and 50% lower in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_BIOHIGH	The maximum annual production of solid biomass and bio-crops in 2050 is assumed to be 350 EJ. This is close to the highest level of production of bio-energy in any of the scenarios from the AR5 scenario database[5] and is around three times the equivalent figure in 2DS (119 EJ).
2DS_BIOLOW	The maximum annual production of solid biomass and bio-crop in 2050 is assumed to be 38 EJ. This is similar to the figure given in the central scenario from [33] and is around a third of the equivalent figure in 2DS (119 EJ).
2DS_OILHIGH	Uses the high values of each category of oil in each region from the aggregate resource distributions described in the methods section (Extended Data Table 4)
2DS_OILLOW	Uses the low values of each category of oil in each region (Extended Data Table 4)
2DS_GASHIGH	Uses the high values of each category of gas in each region (Extended Data Table 4)
2DS_GASLOW	Uses the low values of each category of gas in each region (Extended Data Table 4)
2DS_DEMHIGH	The major drivers of energy service demands in TIAM-UCL are growth in GDP, population, and GDP/capita. Future regional growth in GDP and population are therefore modified to the values given in Shared Socioeconomic Pathway (SSP) number 5[34] the SSP with the highest GDP and GDP/capita growth by 2050 (a 240% increase in the global average; cf. a 120% increase in 2DS). All other energy service demands (not relying on GDP or population) are also modified commensurately.
2DS_DEMLOW	Future regional growth in GDP and population are modified to the values given in Shared Socioeconomic Pathway (SSP) number 3:[34] the SSP with the lowest GDP and GDP/capita growth by 2050 (a 50% increase in the global average).
2DS_NOBIOCCS	No negative emissions technologies are permitted i.e. carbon capture and storage (CCS) cannot be applied to any electrical or industrial process that uses biomass or bio-energy as feedstock in any period.
2DS_NOCCS	CCS is not permitted to be applied to any electrical or industrial process in any period.

Data for bio-energy sensitivities from refs 5 and 33, and for demand sensitivities from ref. 34.

Extended Data Table 3 | Regional distribution of resources unburnable before 2050 in absolute terms and as a percentage of current resources under the 2 °C scenario that allows CCS

	Conven oil		Unconven oil		Conven Gas		Unconven Gas		Hard Coal		Lignite	
Country or region	Gb	%	Gb	%	Tcm	%	Tcm	%	Gt	%	Gt	%
Africa	141	50%	70	100%	28	61%	35	100%	42	94%	2.8	56%
Canada	43	72%	633	99%	3.6	73%	18	71%	34	98%	39	97%
China and India	54	60%	110	100%	8.0	80%	35	88%	1,003	93%	106	88%
FSU	201	54%	360	100%	63	67%	27	89%	576	99%	480	98%
CSA	198	55%	447	99%	23	76%	51	92%	21	85%	6.3	63%
Europe	64	58%	30	100%	18	72%	16	78%	69	99%	142	89%
Middle East	554	53%	10	100%	72	68%	20	100%	10	100%	5.0	99%
OECD Pacific	23	77%	130	100%	9.0	90%	15	74%	116	97%	198	99%
ODA	38	51%	5.0	100%	14	55%	12	78%	34	84%	142	92%
United States	99	52%	650	100%	19	75%	20	50%	556	99%	317	95%
Global	1,417	54%	2,445	100%	257	69%	247	82%	2,462	96%	1,438	95%

'Conven' and 'Unconven' stand for conventional and unconventional resources, respectively.

Extended Data Table 4 | Principal data sources used to derive reserve and resource estimates and estimates at the global level for each category of production

Category	Data sources used to provide country-level estimates of resources	Aggregated high estimate	Aggregated median estimate	Aggregated low estimate
Oil		(in Gb)	(in Gb)	(in Gb)
Current conventional 2P reserves in fields in production or scheduled to be developed	[21,31,35,38]	950	820	620
Reserve growth	[37,38]	1,200	850	610
Undiscovered oil	Fact sheets since USGS World Petroleum Assessment [39] and [35,40,41]	580	300	180
Arctic oil	[42,43]	80	65	40
Light tight oil	[10]	470	300	150
Natural gas liquids (NGL)	[26] Ancillary data associated with [39]	380	280	170
Natural bitumen	Oil in place estimates [17,26]	Mined RURR 130	Mined RURR 100	Mined RURR 70
	Extraction technologies [44–46]	*In situ* RURR 1290	*In situ* RURR 840	*In situ* RURR 520
Extra-heavy oil	Oil in place estimates [47,48] Extraction technologies [47] and refs for bitumen	750	440	230
Kerogen oil	Oil in place estimates [49,50]	Mined RURR 740	Mined RURR 485	Mined RURR 270
	Extraction technologies [51]	*In situ* RURR 1,080	*In situ* RURR 590	*In situ* RURR 190
Total		7,650	5,070	3,050
Gas		(in tcm)	(in tcm)	(in tcm)
Current conventional 2P reserves in fields in production or scheduled to be developed	[35,52]	140	130	110
Reserve growth	[24,37,38]	125	90	60
Undiscovered gas	Fact sheets since USGS World Petroleum Assessment [39] and [35,41]	180	120	80
Arctic gas	[42,43]	40	35	25
Tight gas	[20]	60	60	60
Coal-bed methane	[20]	45	40	20
Shale gas	[20]	310	200	120
Associated gas	[36,37,44]	Included in the above		
Total		900	675	475

High and low values are the aggregated 95th and 5th percentile estimates, respectively. 'tcm', trillions of cubic metres. Data are from references 10, 17, 20, 21, 31, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50 and 51.

Extended Data Table 5 | Global aggregated oil, gas and coal reserve and resource estimates from a selection of data sources

	Oil (Gb)		Gas (Tcm)		Coal (Gt)	
Organisation	Reserves	Resources	Reserves	Resources	Reserves	Resources
BGR	1,600	4,750	195	825	1,000	23,500
IEA	1,700	5,950	190	810	1,000	21,000
GEA	1,500 - 2,300	4,200 - 6,000	670 - 2,000	2,000 - 12,500	850 - 1,000	14,000 - 20,000
This study's median figures	1,300	5,070	190	675	1,000	4,085

BGR, Federal Institute for Geosciences and Natural Resources; IEA, International Energy Agency; GEA, Global Energy Assessment

Extended Data Table 6 | Regions included in TIAM-UCL and their aggregation to the regions given in the main text

Region	Aggregated region in main text
Non-OPEC Africa	Africa
OPEC Africa	Africa
Australia	OECD Pacific
Canada	Canada
Non-OPEC Central and South America	Central and South America (CSA)
OPEC Central and South America	Central and South America (CSA)
China	China and India
Eastern Europe	Europe
Former Soviet Union	Former Soviet Union (FSU)
India	China and India
Japan	OECD Pacific
Non-OPEC Middle	Middle East
OPEC Middle East	Middle East
Mexico	Central and South America (CSA)
Other Developing Asia	Other Developing Asia (ODA)
South Korea	OECD Pacific
United Kingdom	Europe
United States	United States
Western Europe	Europe

Extended Data Table 7 | Labels and description of the four core scenarios modelled in this project

Scenario Name	Description
5DS	The model is constrained to keep the average global surface temperature rise to less than 5°C in all years to 2200. No other emissions constraints are imposed, and since allowed emissions under this scenario are so high (i.e. the constraint is very lax), no real emissions mitigation is required. These constraints result in 2050 GHG emissions of 71 Gt CO_2-eq (up from around 48 Gt CO_2-eq in 2010).
3DS	From 2005 to 2010, the model is fixed to the solution given in the 5°C temperature i.e. we assume that no emissions reductions are required. From 2010-2015, it is assumed that the model must be on track to achieve the emissions reduction pledges set out in the Copenhagen Accord[1], but no other emissions reductions are required. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 3°C in all years to 2200. These constraints result in 2050 GHG emissions of 54 Gt CO_2-eq
2DS	The constraints between 2005 and 2015 in this scenario are identical to the 3DS. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 2°C in all years to 2200. These constraints result in 2050 GHG emissions of 21 Gt CO_2-eq
2DS-noCCS	Emissions reduction requirements are identical to 2DS. Carbon capture and storage (CCS) is not permitted to be applied to any electricity or industrial process in any period.

GHG, greenhouse gas measured in tonnes of CO_2 equivalent (CO_2-eq). Data from ref. 1.

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Macroeconomic impact of stranded fossil fuel assets

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Several major economies rely heavily on fossil fuel production and exports, yet current low-carbon technology diffusion, energy efficiency and climate policy may be substantially reducing global demand for fossil fuels[1–4]. This trend is inconsistent with observed investment in new fossil fuel ventures[1,2], which could become stranded as a result. Here, we use an integrated global economy–environment simulation model to study the macroeconomic impact of stranded fossil fuel assets (SFFA). Our analysis suggests that part of the SFFA would occur as a result of an already ongoing technological trajectory, irrespective of whether or not new climate policies are adopted; the loss would be amplified if new climate policies to reach the 2 °C target of the Paris Agreement are adopted and/or if low-cost producers (some OPEC countries) maintain their level of production ('sell out') despite declining demand; the magnitude of the loss from SFFA may amount to a discounted global wealth loss of US$1–4 trillion; and there are clear distributional impacts, with winners (for example, net importers such as China or the EU) and losers (for example, Russia, the United States or Canada, which could see their fossil fuel industries nearly shut down), although the two effects would largely offset each other at the level of aggregate global GDP.

The Paris Agreement aims to limit the increase in global average temperature to "well below 2 °C above pre-industrial levels"[5]. This requires that a fraction of existing reserves of fossil fuels and production capacity remain unused, hence becoming SFFA[6–10]. Where investors assume that these reserves will be commercialized, the stocks of listed fossil fuel companies may be overvalued. This gives rise to a 'carbon bubble', which has been emphasized or downplayed by reference to the credibility of climate policy[6,8,11–14]. Here, we show that climate policy is not the only driver of stranding. Stranding results from an ongoing technological transition, which remains robust even if major fossil fuel producers (for example, the United States) refrain from adopting climate mitigation policies. Such refusal would only aggravate the macroeconomic impact on producers because of their increased exposure to stranding as global demand decreases, potentially amplified by a likely asset sell-out by lower-cost fossil fuel producers and new climate policies. For importing countries, a scenario that leads to stranding has moderate positive effects on GDP (gross domestic product) and employment levels. Our conclusions support the existence of a carbon bubble that, if not deflated early, could lead to a discounted global wealth loss of US$1–4 trillion, a loss comparable to the 2008 financial crisis. Further economic damage from a potential bubble burst could be avoided by decarbonizing early.

The existence of a carbon bubble has been questioned on grounds of credibility or timing of climate policies[11,12]. That would explain investors' relative confidence in fossil fuel stocks[11,12] and the projected increase in fossil fuel prices until 2040[3]. Yet, there is evidence that climate mitigation policies may intensify in the future. A report covering 99 countries concludes that over 75% of global emissions are subject to an economy-wide emissions-reduction or climate policy scheme[15]. Moreover, the ratification of the Paris Agreement and its reaffirmation at COP22 (the 22nd Conference of the Parties) have added momentum to climate action despite the position of the new US administration[16]. Furthermore, low fossil fuel prices may reflect the intention of producer countries to sell out their assets, that is, to maintain or increase their level of production despite declining demand for fossil fuel assets[17]. But that is not all.

Irrespective of whether or not new climate policies are adopted, global demand growth for fossil fuels is already slowing in the current technological transition[1,2]. The question then is whether, under the current pace of low-carbon technology diffusion, fossil fuel assets are bound to become stranded due to the trajectories in renewable-energy deployment, transport fuel efficiency and transport electrification. Indeed, the technological transition currently underway has major implications for the value of fossil fuels, due to investment and policy decisions made in the past. Faced with SFFA of potentially massive proportions, the financial sector's response to the low-carbon transition will largely determine whether the carbon bubble burst will prompt a 2008-like crisis[11,13,14,18].

We use a simulation-based integrated energy–economy–carbon-cycle–climate model, E3ME-FTT-GENIE (Energy-Environment-Economy Macroeconomic–Future Technology Transformations–Grid Enabled Integrated Earth) (see Methods and Supplementary Table 1), to calculate the macroeconomic implications of future SFFA. Integrated assessment models generally rely on general-equilibrium methods and systems optimization[19–21]. Such models struggle to represent the effects of imperfect information and foresight for real-world agents and investors. By contrast, a dynamic simulation-based model relying on empirical data on socio-economic and technology diffusion trajectories can better serve this purpose (see Supplementary Note 1). In this method, investments in new technology and the interactional effects of changing social preferences generate momentum for technology diffusion that can be quantitatively estimated for specific policy sets. Our model, E3ME-FTT-GENIE, is currently the only such

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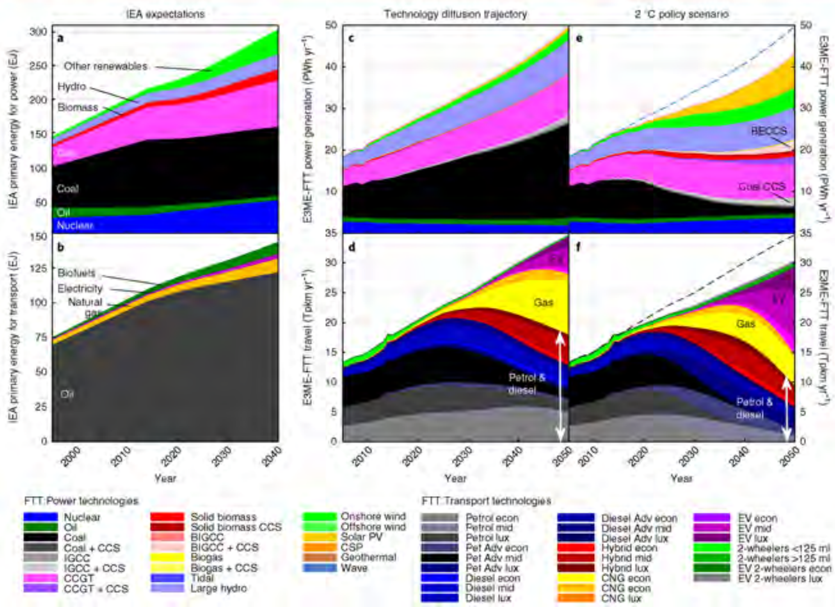

Fig. 1 | Projections of future energy use for power generation and transport. a,b, Global IEA fuel demand in the IEA expectations scenario. **c–f**, Technology composition in electricity generation (**c**,**e**) and road transport (in terms of trillion passenger kilometres travelled, Tpkm; **d**,**f**) in our Technology Diffusion Trajectory (**c**,**d**) and 2 °C (**e**,**f**) scenarios. IEA fuel demand is taken from ref. . Dashed lines refer to our Technology Diffusion Trajectory scenario for comparison. CCS, carbon capture and storage; CC, combined cycle; IGCC, integrated gasification CC; CCGT, CC gas turbine; BIGCC, biomass IGCC; PV, photovoltaic; CSP, concentrated solar power; CNG, compressed natural gas; EV, electric vehicle; Adv, higher-efficiency combustion; Econ, engine size < 1,400 cc; Mid, 1,400cc ≤ engine size < 3,000 cc; Lux, engine size ≥ 3,000 cc.

Table 1 | Scenarios and models

Sector			Power generation	Road transport	Household heating	Other transport	Industry	Rest
Model			FiT	FT	FT	E3ME	E3ME	E3ME
Scenario	IEA expectations		Energy sector not modelled; replaced by fuel use data taken from IEA					
	Technology Diffusion Trajectory	No sell-out	CO_2P, FiT, Reg	Implicit in data	Implicit in data	Implicit in data	Implicit in data	Implicit in data
		Sell-out	Same, with exogenous assumptions over fossil fuel production (production/reserve ratio)					
	2 °C	No sell-out	CO_2P, Sub, FiT, Reg, K-S	FiT, RT, BioM, Reg, K-S	FiT, Sub	CO_2P, Reg	CO_2P, Reg	CO_2P, Reg
		Sell-out	Same, with exogenous assumptions over fossil fuel production (production/reserve ratio)					

Abbreviations: CO_2P, carbon price; FiT, feed-in tariff; Sub, capital cost subsidies; RT, registration carbon tax; Reg, regulations; K-S, kick-start programme; BioM, biofuel mandates; FT, fuel tax. Policy details available in the Methods. For carbon prices, sell-out assumptions and a sell-out sensitivity analysis, see Supplementary Figs. 5 and 6. For key model characteristics, see Methods, Supplementary Table 1 and Supplementary Note 1. For sensitivity analyses on key technology parameters, see Supplementary Note 2, Supplementary Tables 3 and 4 and Supplementary Fig. 8. Supplementary Table 5 and Supplementary Figs. 7–11 compare our scenarios with others in the literature. Supplementary Table 6 compares GENIE outputs with other models. For fossil fuel prices, see Supplementary Table 7. For sectoral impacts, see Supplementary Note 5 and Supplementary Table 8. The IEA expectations scenario corresponds to the IEA's new policies scenario. Detailed policies can be obtained from the Supplementary Information.

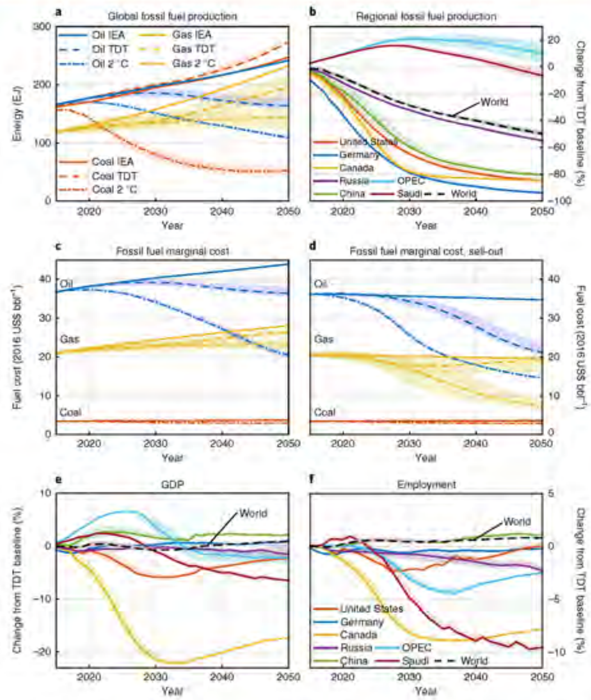

Fig. 2 | Change in fossil fuel asset value and production across countries, and in macroeconomic indicators. a, Global production of fossil fuels, for the IEA expectations (IEA) scenario, our Technology Diffusion Trajectory scenario (TDT) and our 2 °C policies scenario. **b**, Change in total fossil fuel production between the 2 °C policies scenario and TDT. **c**,**d**, Marginal costs of fossil fuels in the same three scenarios, without sell-out (**c**) and with sell-out (**d**). **e**,**f**, Changes in GDP and employment between the 2 °C policies sell-out scenario and TDT without sell-out (negative means a loss). The width of traces represents maximum uncertainty generated by varying technology parameters (see Supplementary Table 3 and Supplementary Note 2). OPEC excludes Saudi Arabia for higher detail. Macro impacts for Canada feature higher levels of economic uncertainty (not shown), because such high impacts could be mitigated in reality by various policies such as deficit spending by the government; however, we exclude studying deficit spending here for simplicity of interpretation (we assume balanced budgets).

simulation-based integrated assessment model that couples the macroeconomy, energy and the environment covering the entire global energy and transport systems with detailed sectoral and geographical resolution[22–24].

We study and compare three main scenarios (see Table 1 and Methods for details): fuel use from the International Energy Agency's (IEA) 'new policies scenario', which we call 'IEA expectations' to reflect the influence of the IEA's projections on the formation of investor and policymaker expectations as to future demand (see Fig. 1a,b for electricity generation and transport); our own E3ME-FTT 'Technology Diffusion Trajectory' projection with energy demand derived from our technology diffusion modelling in the power[25], road transport[26], buildings and other sectors under the ongoing technological trajectory (Fig. 1c,d); and a projection, which we call the '2 °C' scenario, under a chosen set of policies that achieve 75% probability of remaining below 2 °C (Fig. 1e,f; see Supplementary Fig. 1 for climate modelling), while keeping the use of bioenergy below 95 EJ yr^{-1} and thereby limiting excessive land-use change[27]. Only the Technology Diffusion Trajectory and 2 °C scenarios rely on FTT technology diffusion modelling.

Unlike the IEA expectations scenario, our Technology Diffusion Trajectory scenario captures technology diffusion phenomena by relying on historical data and projecting these data into the future. Importantly, historical data implicitly include the effects of past policies and investment decisions. On that basis, the Technology Diffusion Trajectory scenario reflects higher energy efficiency and leads to lower demand. Liquid fossil fuel use in transport peaks

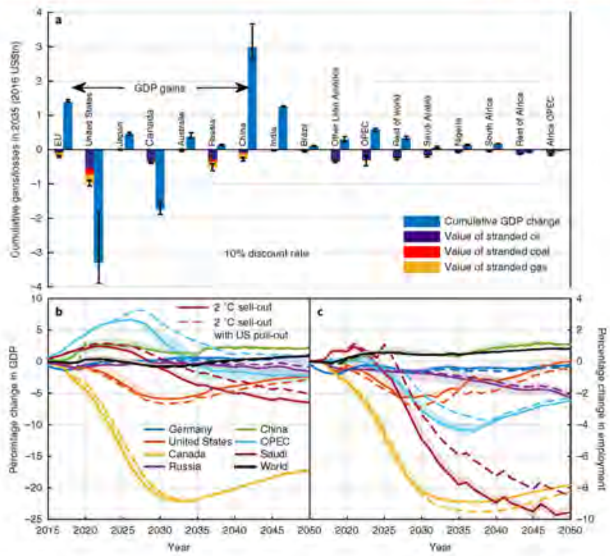

Fig. 3 | SFFA losses and impacts across countries. **a**, Discounted cumulated fossil fuel value loss to 2035 for oil, gas and coal, and GDP changes up to 2035, between the 2 °C sell-out scenario and the IEA expectations scenario (see Supplementary Table 2 and Supplementary Fig. 4 for other scenarios and aggregation methods). Negative bars indicate losses. Error bars represent maximum uncertainty on total SFFA generated by varying technology parameters (see Supplementary Table 3 and Supplementary Note 2; Supplementary Table 4 provides a breakdown for individual fuels). **b**,**c** Percent change in GDP (**b**) and labour force employment (**c**) between the 2 °C sell-out scenario and our Technology Diffusion Trajectory non-sell-out scenario (solid lines), and between the 2 °C sell-out scenario with a US withdrawal from climate policy and our Technology Diffusion Trajectory non-sell-out scenario (dashed lines)

in both the Technology Diffusion Trajectory and 2 °C scenarios before 2050 (Figs. 1 and 2a; for sectoral fuel use and emissions, see Supplementary Fig. 2). Solar energy partially displaces the use of coal and natural gas for power generation. On the basis of recent diffusion data (see Methods and Supplementary Table 1), our model suggests that a low-carbon transition is already underway in both sectors. Our sensitivity analysis (Supplementary Note 2 and Supplementary Table 3) confirms that these results are robust and driven by historical data rather than by exogenous modelling assumptions.

Importantly, the lower demand for fossil fuels leads to substantial SFFA, whether or not 2 °C policies are adopted (Fig. 2d). For individual countries, the effects vary depending on regional marginal costs of fossil fuel production, with concentration of production in OPEC (Organization of the Petroleum Exporting Countries) members where costs are lower (Fig. 2b). Regions with higher marginal costs experience a steep decline in production (for example, Russia), or lose almost their entire oil and gas industry (for example, Canada, the United States).

The magnitude of the loss depends on a variety of factors. Our analysis suggests that the behaviour of low-cost producers and/or the adoption of 2 °C policies can lead to an amplification of the loss (see Table 1 and Supplementary Table 2). The magnitude of the loss may indeed be amplified if low-cost producers decide to increase their ratio of production relative to reserves to outplay other asset owners and minimize their losses ('selling out'; a detailed definition is given in Methods and Supplementary Note 3) (Fig. 2c,d). Slowing or peaking demand leads to fossil fuel prices peaking (without sell-out) or immediately declining (with sell-out). In the 2 °C scenario, fossil fuel markets substantially shrink and the prices fall abruptly between 2020 and 2030, a potentially disastrous scenario with substantial wealth losses to asset owners (investors, companies) but not to consumer countries. This result highlights the important strategic implications of decarbonization for the EU (European Union), China and India (consumers) compared with the United States, Canada or Russia (producers).

At the global level, it is possible to quantify the potential loss in value of fossil fuel assets (see Supplementary Note 4). If we assume that investment in fossil fuels in the present day continues on the basis of questioning commitments to policy, the return expectations derived from the IEA expectations projection and the assets' rigid lifespan with expected returns until 2035, and then if, contrary to investors' expectations, policies to achieve the 2 °C target are adopted, and low-cost producers sell-out their assets, then approximately US$12 trillion (in 2016 US dollars, which amounts to US$4 trillion present value when discounted with a 10% corporate rate) of financial value could vanish off their balance sheets globally in the form of stranded assets (see Supplementary Table 2). This is over 15% of global GDP in 2016 (US$75 trillion). This quantification arises from pairing the IEA expectations scenario with the 2 °C scenario with sell-out. If instead of the IEA expectations, we pair our own baseline (the Technology Diffusion Trajectory scenario) with the 2 °C scenario under the sell-out assumption, the total value loss from SFFA is approximately US$9 trillion (in 2016 US dollars; US$3 trillion with 10% discount rate; see Supplementary Table 2). Our quantification is broadly consistent with recent financial exposure estimates calculated at a regional and country level for the EU and the United States[14] (detailed explanation in Supplementary Note 4). Note that a 10% discount rate represents an investment horizon of about 10–15 years, and that fossil fuel ventures have lifetimes ranging between 2 (shale oil) and 50 (pipelines) years (oil wells: 15–30 years; oil tankers: 20–30 years; coal mines: >50 years). For reference, the subprime mortgage market value loss that took place following the 2008 financial crisis was around US$0.25 trillion, leading to global stock market capitalization decline of about US$25 trillion[18].

Regarding the impact of SFFA on GDP and employment, Fig. 2e,f show the change in GDP and employment between the Technology Diffusion Trajectory scenario without sell-out and the 2 °C scenario with sell-out, for several major economies/groups. The low-carbon transition generates a modest GDP and employment increase in regions with limited exposure to fossil fuel production (for example, Germany and most EU countries, and Japan). This is due to a reduction of the trade imbalance arising from fossil fuel imports, and higher employment arising from new investment in low-carbon technologies. The improvement occurs despite the general increase of energy prices and hence costs for energy-intensive industries[7,20]. Meanwhile, fossil fuel exporters experience a steep decline in their output and employment due to the near shutdown of their fossil fuel industry. These patterns emerge alongside a <1% overall impact of the transition on global GDP (<1% GDP change), indicating that impacts are primarily distributional, with clear winners (for example, the EU and China) and losers (for example, the United States and Canada, but also Russia and OPEC countries).

In both the Technology Diffusion Trajectory and 2 °C scenarios, a substantial fraction of the global fossil fuel industry eventually becomes stranded. In reality, these impacts should be felt in two independent ways (see Supplementary Note 4): through wealth losses and value of fossil fuel companies and their shareholders, and through macroeconomic change (GDP and employment losses in the fossil fuel industry, structural change), leaving winners and losers. Figure 3a compares cumulative GDP changes with the cumulative 2016 value of SFFA between the present and 2035. Due to different country reliance on the fossil fuel industry, impacts have different magnitudes and directions (see Supplementary Note 5).

Reducing fossil fuel demand generates an overall positive effect for the EU and China and a negative one for Canada and the United States. Figure 3b,c shows, however, that since impacts on the Canadian and US economies primarily depend on decisions taken in the rest of the world, the United States is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them. This is due to the way global fossil fuel prices are formed. If the rest of the world reduces fossil fuel consumption and there is a sell-out, then lower fuel prices will make much US production non-viable, regardless of its own policy, meaning that its assets become stranded. If the United States promotes a fossil fuel-intensive economy, then the situation becomes worse, as it ends up importing this fuel from low-cost producers in the Middle East, while it forgoes the benefits of investment in low-carbon technology (for other countries, see Supplementary Fig. 3, Supplementary Table 8 and Supplementary Note 5).

Importantly, the macroeconomic impacts of SFFA on producer countries are primarily determined by climate mitigation decisions taken by the sum of consuming countries (for example, China or the EU), and thus a single country, however large, cannot alter this trajectory on its own. Also, critically, this finding contradicts the conventional assumption that global climate action is accurately described by the prisoner's dilemma game, which would allow a country to free-ride. But an exposed country can mitigate the impact of stranding, by divesting from fossil fuels as an insurance policy against what the rest of the world does. What remains to be known, however, is the degree to which SFFAs impose a risk to regional and global financial stability.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0182-1.

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Author contributions

J.-F.M. designed and coordinated the research. J.-F.M., J.E.V., N.R.E., H.P. and J.S. wrote the article. J.-F.M., H.P. and U.C. ran simulations. U.C. and H.P. managed E3ME. J.-F.M. and A.L. developed FTT:Transport. J.-F.M. and P.S. developed FTT:Power and the resource depletion model. F.K. and J.-F.M. developed FTT:Heat. P.B.H. and N.R.E. ran GENIE simulations and provided scientific support on climate change. J.E.V. contributed geopolitical expertise.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Detailed scenario definitions. *IEA expectations.* In the IEA expectations scenario, we replace our energy model (FTT and E3ME estimations) by exogenous fuel use data from the IEA's new policies scenario. We derive macroeconomic variables from the evolution of a fixed energy system (FTT is turned off). We use our fossil fuel resource depletion model to estimate changes in the marginal cost of production of fossil fuels. This enables us to calculate fossil fuel asset values. Given that this scenario does not make use of our technology projections with FTT, we use this scenario with the interpretation that it represents the expectations of investors who do not fully realize the state of change of technology, in particular electric vehicles and renewables, that, as we argue in the text, is taking place.

Technology Diffusion Trajectory. In the Technology Diffusion Trajectory scenario, we use the three FTT diffusion models and our own E3ME energy sector model (see Supplementary Table 1) to estimate changes in fuel use due to the diffusion of new technologies. This is the baseline of the E3ME-FTT-GENIE model, which differs substantially from the IEA's. We interpret this scenario as that which, we argue, is likely to be realized instead of the IEA expectations scenario, according to the current technological trajectory observed in historical data that parameterize our models, if no climate policies are adopted. Policies are not specified explicitly, but instead are implicitly taken into consideration through the data.

In the 2 °C scenario, we choose a set of policies that achieve 75% chance of not exceeding 2 °C of peak warming, according to the GENIE model, itself validated with respect to Coupled Model Intercomparison Project Phase 5 models (see Supplementary Fig. 1). We estimate the diffusion of new low-carbon technologies and evolution of the energy sector under these policies using E3ME-FTT. Policies (for example, subsidies, taxes, regulations) are specified explicitly.

Sell-out versions of all scenarios. In both the Technology Diffusion Trajectory and 2 °C scenarios, the issue of the sell-out of fossil fuel resources by low-cost producers is a real but not inevitable possibility. We therefore present both sell-out and non-sell-out versions for each scenario. The sell-out is defined by increasing production-to-reserve ratios of producer countries, which concentrates production to OPEC and other low-cost production areas. Meanwhile, in the non-sell-out scenarios, these ratios are constant, as they have been until recently. These assumptions are exogenous (see Supplementary Note 3). SFFAs are given for all combinations in Supplementary Table 2.

Policy assumptions for achieving a 2 °C target. The set of policies that we use to reach the Paris targets constitutes one of many possible sets that could theoretically reach the targets. They achieve emissions reductions consistent with a 75% probability of reaching the 2 °C target, and include the following.

Multiple sectors. CO_2 pricing is used to incentivize technological change across sectors in E3ME-FTT. One price/tax is defined exogenously, in nominal US dollars, at every year for every country, shown in Supplementary Fig. 5a. This policy applies to power generation and all heavy industry sectors (oil and gas, metals, cement, paper and so on). It is not applied to households or to road transport.

Electricity generation. Combinations of policies are used to efficiently decarbonize electricity generation, following earlier work. These involve CO_2 pricing (see above) to incentivize technological change away from fossil fuel generators, subsidies to some renewables (biomass, geothermal, carbon capture and storage) and nuclear to level the playing field, feed-in tariffs for wind and solar-based technologies, and regulations to phase out the use of coal-based generators (none newly built). In some countries (foremost the United States, China, India), a kick-start programme for carbon capture and storage and bioenergy with carbon capture and storage is implemented to accelerate its uptake. All new policies are introduced in or after 2020.

Road transport. Combinations of policies are used to incentivize the adoption of vehicles with lower emissions, following earlier work. These include (1) fuel efficiency regulations for new liquid-fuel vehicles; (2) a phase-out of older models with lower efficiency; (3) kick-start procurement programmes for electric vehicles where they are not available (by public authorities or private institutions, for example, municipality vehicles and taxis); (4) a tax starting at US$50 per gCO_2 per km (2012 values) to incentivize vehicle choice; (5) a fuel tax (increasing from US$0.10 per litre of fuel in 2018 to US$1.00 in 2050; 2012 prices) to curb the total amount of driving; (6) biofuel mandates that increase from current values to between 10% and 30% (40% in Brazil) in 2050, different for every country, extrapolating IEA projections.

Industrial sectors. Fuel efficiency policy and regulations are used, requiring firms to invest in more recent, higher-efficiency production capital and processes, beyond what is delivered by the carbon price. These measures are publicly funded, following the IEA's 450 ppm scenario assumptions. Further regulations are used that ban newly built coal-based processes (for example, boilers) in all sectors.

Buildings. For households, we assume a tax on the residential use of fossil fuels (starting at US$60 per tCO_2 in 2020, linearly increasing by US$6 per tCO_2 per year; 2016 prices), and subsidies on modern renewable heating technologies (starting at −25% in 2020, gradual phase-out after 2030). Commercial buildings increase energy efficiency rates, following the assumptions in the IEA's 450 ppm scenario.

The simulation-based integrated assessment model. E3ME-FTT-GENIE is an integrated assessment simulation model that comprises a model of the global economy and energy sector (E3ME), three subcomponents for modelling technological change with higher detail than E3ME (the FTT family), a global model of fossil fuel supply and an integrated model of the carbon cycle and climate system (GENIE). E3ME, FTT and the fossil fuel supply model are hard-linked in the same computer simulation, while GENIE is run separately, connected to the former group by soft coupling (transferring data). A peer-reviewed description of the model with fully detailed equations is available with open access; key model codes and datasets can be obtained from the authors upon request.

The E3ME model. E3ME is a highly disaggregated demand-led global macroeconometric model based on post-Keynesian foundations, which implies a non-equilibrium simulation framework (see Supplementary Table 1). It assumes that commercial banks lend according to bank reserves, which are created on demand by the central bank. This means that increased demand for technologies and intermediate products in the process of decarbonization is financed (at least in part) by bank loans, and that spare production capacity in the economy and existing unemployment lead to possible output boosts during major building periods and to slumps during debt repayment periods. In the jargon of the field, whereas computable general-equilibrium models normally 'crowd out' finance (additional investment in a given asset class implies a compensating reduction in investment in other asset classes), E3ME assumes a full availability of finance through credit creation by banks (additional investment in one sector does not require cancelling investment elsewhere; see ref. for a discussion). E3ME does not feature an explicit representation of the sectoral detail of the financial sector (it is not stock-flow consistent) or model financial contagion; however, it does feature endogenous money through its investment equations, which is necessary and sufficient for this paper.

E3ME has 43 sectors of production, 22 users of fuels, 12 fuels and 59 regions. It uses a chosen set of 28 econometric relationships (including employment, trade, prices, investment, household consumption, energy demand) regressed over a corresponding high-dimension dataset covering the past 45 years, and extrapolates these econometric relationships self-consistently up to 2050. E3ME includes endogenous technological change in the form of technology progress indicators in each industrial sector and fuel user, providing the source of endogenous growth. It is not an equilibrium model; it is path-dependent and demand-led in the Keynesian sense. E3ME has been used in numerous policy analyses and impact assessments for the European Commission and elsewhere internationally (for example, see refs). Recent discussions of the implications for results of the choice of an economic model for assessing the impacts of energy and climate policies are given in refs. Previously, such debates have often concerned simpler types of integrated assessment models (for example, the Dynamic Integrated Climate-Economy model), while newer debates are emerging that address issues of framing and philosophy of science. Recent empirical studies appear to find no evidence for crowding-out in the finance of innovation, from the perspective of access to finance. E3ME has been validated against historical data by reproducing history between 1972 and 2006, on the basis of the normal regression parameters.

The FTT model. Technology diffusion is not well described by time-series econometrics, as it involves nonlinear diffusion dynamics (S-shaped diffusion). To improve our resolution of technological change in the fossil fuel-intensive sectors of electricity and transport, we use the FTT family of sectoral evolutionary bottom-up models of technological change dynamically integrated to E3ME. FTT projects existing low-carbon technology diffusion trajectories on the basis of observationally determined preferences of heterogeneous consumers and investors, using a diffusion algorithm.

FTT models market share exchanges between competing technologies in the power, road transport and household heating sectors on the basis of technology 'fitness' to consumer/investor preferences. Agents have probabilistically distributed preferences calibrated on cross-sectional market datasets. Choices are evaluated using chains of binary logits, weighted by their market share. The diffusion patterns of technologies are functions of their own market share and those of others, which reproduce standard observed S-shaped diffusion profiles (a so-called evolutionary replicator dynamics equation, or Lotka–Volterra competition equation). FTT does not use optimization algorithms, and it is a time-step path-dependent simulation model (see Supplementary Table 1).

It is crucial to note that FTT projects the evolution of technology in the future by extending the current technological trajectory with a diffusion algorithm calibrated on recent history. The key property of FTT, strong path-dependence (or strong autocorrelation in time), typically found in technology transitions, is given to the model by two features. (1) Technologies with larger market shares have a proportionally greater propensity to increase their market share, until they reach market domination. This is a key stylized feature of the diffusion of innovations. (2) Continuity of the technological trajectory at the transition year from historical data to the projection (2013 ± 3–5 years) is obtained by empirically determining cost factors (denoted γ, see below and Supplementary Fig. 8). Since the diffusion of innovations typically evolves continuously, there should not be a change of trajectory at the transition from history to projection. By ensuring that this is so, we obtain a baseline trajectory in which some new low-carbon technologies (for example, hybrid and electric vehicles, solar photovoltaics) already diffuse to non-negligible or substantial market shares, and some traditional vehicle types decline (for example, small motorcycles in China). This baseline (the Technology Diffusion Trajectory scenario) includes current policies implicitly in the data; that is, they are not specified explicitly. The introduction of additional policy, in later years, results in further gradual changes to the technological trajectory, typically after 2025, differences that become further from the baseline along the simulation time span. Sensitivity analysis (Supplementary Table 3) shows that these trajectories are robust under substantial changes of all relevant technological parameters.

The γ factors are determined in the following way. Historical databases were carefully constructed by the authors by combining various data sources (transport and household heating; see Supplementary Table 1) or taken from IEA statistics (power generation). The γ values are added to the respective levelized cost that is compared among options by hypothetical (heterogeneous) agents in the model. One and only one set of γ values ensures that the first 3–5 years of projected diffusion features the same trajectory (time-derivative of market shares) as the last 3–5 years of historical data from the start date of the various simulations (2012 for transport, 2013 for power, 2015 for heat; see Supplementary Fig. 8 for an example). This is the sole purpose of γ. The interpretation of γ is a sum of all pecuniary or non-pecuniary cost factors not explicitly defined in the model, which includes agent preferences and existing incentives from current policy frameworks, as well as implicit valuations of non-pecuniary factors such as (for vehicles) engine power, comfort and status. While the heterogeneity of agents is explicitly specified in FTT cost data and handled by the model (through empirical cost distributions; see for example ref.), γ are constant scalar values (not distributed or time-dependent). As is the case for any parameter determined with historical data, the further we model in the future, the less reliable the γ values are, but, just as with regression parameters, they do represent our best current knowledge as inferred from history.

The fossil fuel supply model. The supply of oil, coal and gas, in primary form, is modelled using a dynamical resource depletion algorithm. It is equivalent in function and theory to that recently used by McGlade and Ekins. Cost distributions of non-renewable resources are used, on the basis of an extensive survey of global fossil fuel reserves and resources. The algorithm is then used to evaluate how resources are depleted, and how their marginal cost changes as the demand changes (that is, which is the most costly extraction venture, given extraction rates for all other extraction sites in production, supplying demand). As reserves are consumed and/or demand increases, fossil fuel resources previously considered to be uneconomic come online, requesting price increases. Meanwhile, when demand slumps, the most costly extraction ventures are first to shut down production (for example, deep offshore, oil sands). The data are disaggregated geographically following the E3ME regional classification.

The model assumes that the marginal cost sets the price, thus excluding effects on the price by events such as armed conflicts, processing bottlenecks (for example, refineries coming online and offline) and time delays associated with new projects coming online. While fossil fuel price changes may not always immediately follow changes in the marginal cost in reality, differences are cyclical (due to the ability of firms to cross-subsidize and produce at a loss for a limited time), and the long-term trend is robust. Taxes and duties on fuels, which differ in every region of the world, are not included in Fig. 2 or in the calculation of SFFA. E3ME includes end-user fuel prices from the IEA database, including taxes. The source for energy price data is the IEA. In the scenarios, we do not explicitly include the phase-out of fossil fuel subsidies, but the carbon price, when applied to fuels, effectively turns the subsidies into taxes. It is noted that some of the largest fuel subsidies are in countries that are energy exporters and that reducing or removing the subsidies would help to support public budgets (although doing so increases pressure on households). End-user prices are updated during the simulation to reflect changes in fossil fuel marginal costs from the fossil fuel supply model; however, end-user prices are not used in the calculation of SFFA. Behavioural assumptions over production decisions have important impacts in this submodel, described further below.

The GENIE model. GENIE is a global climate–carbon-cycle model, applied in the configuration of ref., comprising the GOLDSTEIN (Global Ocean Linear Drag Salt and Temperature Equation INtegrator) three-dimensional ocean coupled to a two-dimensional energy–moisture-balance atmosphere, with models of sea ice, the ENTSML (Efficient Numerical Terrestrial Scheme with Managed Land) terrestrial carbon storage and land-use change, BIOGEM (BIOGEochemistry Model) ocean biogeochemistry, weathering and SEDGEM (SEDiment GEochemistry Model) sediment modules. Resolution is 10°×5° on average with 16 depth levels in the ocean. To provide probabilistic projections, we perform ensembles of simulations using an 86-member set that varies 28 model parameters and is constrained to give plausible post-industrial climate and CO_2 concentrations. Simulations are continued from AD 850 to 2005 historical transients. Post-2005 CO_2 emissions are from E3ME, scaled by 9.82/8.62, to match estimated total emissions, accounting for sources not represented in E3ME, and extrapolated to zero at 2079. For the 2 °C scenario, non-CO_2 trace gas radiative forcing and land-use-change maps are taken from Representative Concentration Pathway 2.6 (ref.). For the purposes of validation, the GENIE ensemble has been forced with the Representative Concentration Pathway scenarios, and these simulations are compared with the CMIP5 (Coupled Model Intercomparison Project Phase 5) and AR5 (IPCC Fifth Assessment Report) EMIC (Earth system Model of Intermediate Complexity) ensembles in Supplementary Table 6.

In the 2 °C scenario, median peak warming relative to 2005 is 1.00 °C, with 10% and 90% percentiles of 0.74 °C and 1.45 °C, respectively. Corresponding values for peak CO_2 concentration are 457, 437 and 479 ppm, respectively. Total warming from 1850–1900 to 2003–2012 is estimated as 0.78 ± 0.06 °C (ref.), giving median peak warming relative to pre-industrial levels of 1.78 °C. Ensemble distributions of warming and CO_2 are plotted in Supplementary Fig. 1. Oscillations are associated with reorganizations of ocean circulation or snow-albedo feedbacks rendered visible by the lack of chaotic variability in the simplified atmosphere.

It could be questioned why such a detailed climate model is needed in this analysis. One key aspect of our analysis is the quantification of additional SFFA that arise due to climate policy. For this quantification to be meaningful, it is also necessary to quantify the climate and carbon-cycle uncertainties that are associated with these policies (here, a 75% probability of avoiding 2 °C warming). Rapid decarbonization pathways lie outside the Representative Concentration Pathways framework, so that our physically based climate–carbon-cycle model is a more appropriate and robust tool than, for example, an emulator under extrapolation.

Data availability. The data that support the findings of this study are available from Cambridge Econometrics, but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with the permission of Cambridge Econometrics.

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ARTICLES

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A climate stress-test of the financial system

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The urgency of estimating the impact of climate risks on the financial system is increasingly recognized among scholars and practitioners. By adopting a network approach to financial dependencies, we look at how climate policy risk might propagate through the financial system. We develop a network-based climate stress-test methodology and apply it to large Euro Area banks in a 'green' and a 'brown' scenario. We find that direct and indirect exposures to climate-policy-relevant sectors represent a large portion of investors' equity portfolios, especially for investment and pension funds. Additionally, the portion of banks' loan portfolios exposed to these sectors is comparable to banks' capital. Our results suggest that climate policy timing matters. An early and stable policy framework would allow for smooth asset value adjustments and lead to potential net winners and losers. In contrast, a late and abrupt policy framework could have adverse systemic consequences.

Assessing the impact of climate risks and climate policies on the financial system is currently seen as one of the most urgent and prominent policy issues[1,2]. In particular, there is a debate on whether the implementation of climate policies to meet the 2 °C target generates systemic risk or, instead, opportunities for low-carbon investments and economic growth. However, data are scarce and there is no consensus on the appropriate methodologies to use to address this issue. The magnitude of so-called stranded assets of fossil-fuel companies (in a 2 °C economy) has been estimated to be around 82% of global coal reserves, 49% of global gas reserves and 33% of global oil reserves[3]. Moreover, several studies have investigated the role of stranded assets in specific sectors and countries[4–9]. By investing in fossil-fuel companies, financial institutions hold direct 'high-carbon exposures', which for European actors have been estimated to be, relative to their total assets, about 1.3% for banks, 5% for pension funds and 4.4% for insurances[10]. One can compute the value at risk (VaR) associated with climate shocks[11] in the context of integrated assessment models[12] in which aggregate financial losses are derived top-down from estimated GDP (gross domestic product) losses due to physical risks resulting from climate change. Yet, assessing the financial risk of climate policies (often referred to as transition risks) requires estimations of the likelihood of the introduction of a specific policy. However, the likelihood that a climate policy is introduced depends on the expectations of the agents on that very likelihood. Thus, the intrinsic uncertainty of the policy cycle undermines the reliability of the probability distributions of asset returns, also due to the presence of fat tails[13]. Further, it is now understood that interlinkages among financial institutions can amplify both positive and negative shocks[14–16] and significantly decrease the accuracy of our estimation of default probabilities in an interconnected financial system[17]. As a result, calculations of expected losses/gains from climate policies carried out with traditional risk analysis methodologies have to be taken with caution. Here, we develop a complementary approach, rooted in complex systems science, and consisting of a network analysis of the exposures of financial actors[18,19] to all climate-policy-relevant sectors of the economy, as well as the exposures among financial actors themselves, across several types of financial instruments. This analysis is meant as a tool to support further investigations of the potential impact and the political feasibility of specific climate policies[20,21]. To go beyond the mere exposure to the fossil-fuels extraction sector, we remap an existing standard classification of economic sectors (NACE Rev2) according to their relevance to climate mitigation policies, and we analyse empirical microeconomic data for shareholders of listed firms in the European Union and in the United States. We find (see Supplementary Table 6) that while direct exposures via equity holdings to the fossil-fuel sector are small (4–13% across financial actor types), the combined exposures to climate-policy-relevant sectors are large (36–48%) and heterogeneous. In addition, financial actors hold equity exposures to the financial sector (13–25%), implying indirect exposures to climate-policy-relevant sectors.

Results

By targeting the reduction of greenhouse gas (GHG) emissions, climate policies can affect (positively or negatively) revenues and costs of various sectors in the real economy with indirect effects on financial actors holding securities of firms in those sectors. However, the existing classifications of economic sectors such as NACE Rev2 (ref. 22) or NAICS (ref. 23) were not designed to estimate financial exposures to climate-policy-relevant sectors. Therefore, we define a correspondence between sectors of economic activities at NACE Rev2 4-digit level and five newly defined climate-policy-relevant sectors (fossil fuel, utilities, energy-intensive, transport and housing) based on their GHG emissions, their role in the energy supply chain, and the existence in most countries of related climate policy institutions (see Methods and Fig. 1).

The exposures of financial actors (classified according to the standard European Systems of Accounts, ESA (ref. 24)) can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). By combining the breakdown of exposures across instruments with the reclassification

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Table 1 | Absolute (first row, in US$ billions) and relative (second row, percentage of aggregate equity portfolio) exposure of each financial actor type to each sector.

	OCIs (955)	GOV (125)	Individuals (33,733)	Banks (798)	IPFs (6,392)	OFSs (3,081)	NFCs (14,851)	IFs (5,124)
Fossil-fuel	31.17	66.17	98.17	173.29	230.21	185.15	377.30	549.85
(767)	6.02%	11.43%	3.77%	6.34%	7.09%	5.33%	8.06%	6.05%
Utilities	19.32	63.58	21.16	77.02	55.53	65.46	93.09	249.32
(216)	3.73%	10.99%	0.81%	2.82%	1.71%	1.88%	1.99%	2.74%
Energy-intensive	172.84	147.53	766.33	708.30	865.87	1,019.84	1,408.65	2,701.69
(3,956)	33.40%	25.49%	29.47%	25.92%	26.68%	29.36%	30.08%	29.71%
Housing	13.26	15.88	100.57	59.07	85.28	76.60	146.72	189.36
(797)	2.56%	2.74%	3.87%	2.16%	2.63%	2.21%	3.13%	2.08%
Transport	11.43	18.48	55.38	47.67	54.48	69.96	106.67	173.02
(224)	2.21%	3.19%	2.13%	1.74%	1.68%	2.01%	2.28%	1.90%
Finance	127.01	95.33	419.63	684.72	609.11	669.82	702.44	1,532.08
(2,659)	24.54%	16.47%	16.14%	25.06%	18.77%	19.29%	15.00%	16.85%
Other	142.44	171.80	1,139.53	982.46	1,345.08	1,386.27	1,847.40	3,698.41
(6,259)	27.53%	29.68%	43.82%	35.95%	41.44%	39.91%	39.46%	40.67%

Numbers in brackets indicate the number of firms in this group of actors or sectors. OCIs, Other Credit Institutions; GOV, Government; IPFs, Insurance and Pension Funds; OFSs, Other Financial Services; NFCs, Non-Financial Corporations; IFs, Investment Funds.

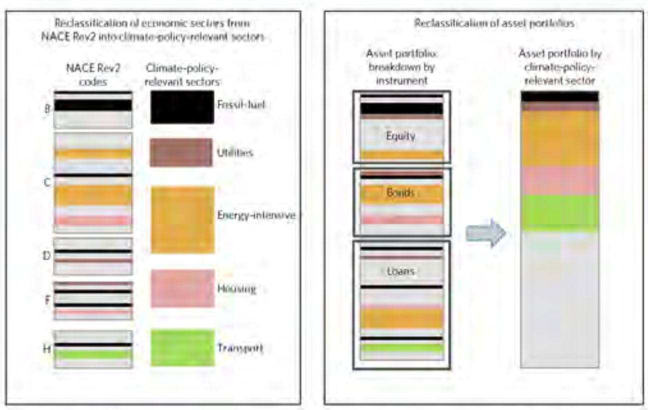

Figure 1 | Diagram illustrating the reclassification of sectors from NACE Rev2 codes into climate-policy-relevant sectors. For more information see the Methods and Supplementary Table 3.

of securities, we compute the total direct exposure of a given financial actor to each climate-policy-relevant sector (see Methods).

Direct financial exposure through equity holdings

To provide empirical estimates of exposures to climate-policy-relevant sectors, we apply our methodology to recent available data sets. Despite their relevance for policy purposes, data about securities holdings of financial institutions, in particular to climate-policy-relevant sectors, is generally scarce, inconsistent or even undisclosed. Along the three main instrument types mentioned above (equity, bonds and loans), at the level of individual institutions only some data of equity holdings are publicly available.

We thus first analyse a sample obtained from the Bureau Van Dijk Orbis database covering all EU and US listed companies and their disclosed shareholders (14,878 companies and 65,059 shareholders) at the last available year, that is, 2015. On the basis of our methodology, we construct the portfolio of each shareholder and we compute its exposure to each climate-policy-relevant sector. To gain insights into the magnitude of indirect exposures we further classify equity holdings in companies belonging to the financial sector. We group shareholders by financial actor type to include, besides the institutional financial sectors from the ESA classification (that is, Banks, Investment Funds, Insurance and Pension Funds) also Individuals, Governments, Non-Financial Companies, Other Credit Institutions and Other Financial Services (Table 1).

Figure 2a shows the result of the aggregated exposures in terms of equity holdings in listed companies for each financial actor type. The combined shares of equity holdings held by the financial sector (that is, Investment Funds, Insurance and Pension Funds, Banks, Other Credit Institutions, and Other Financial Services) amount to about 32.4 trillion US dollars, equivalent to 58.7% of total market capitalization.

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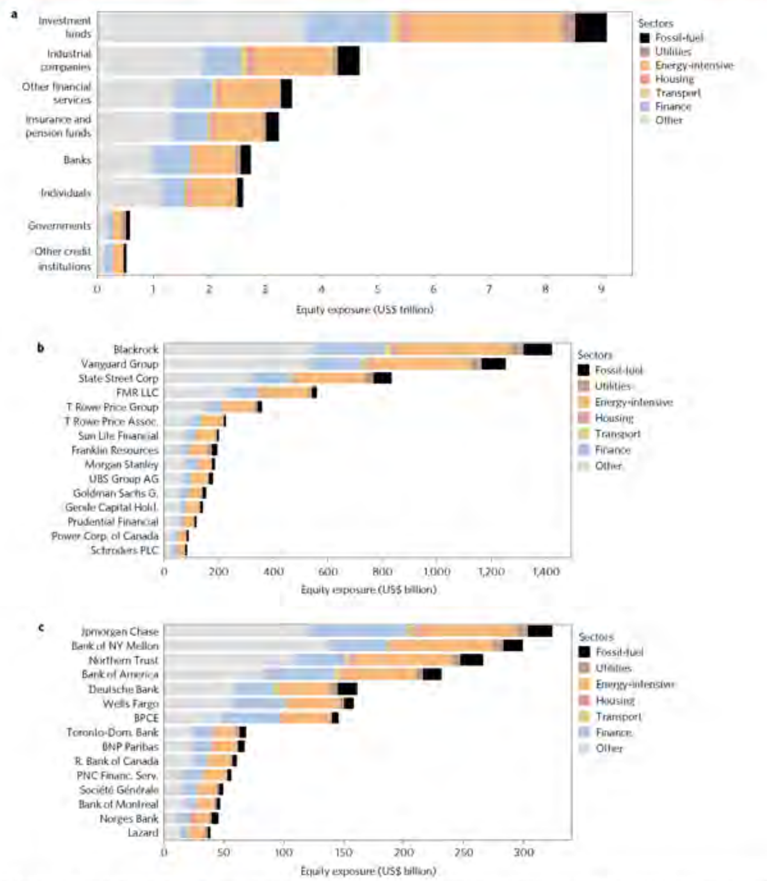

Figure 2 | Equity holdings in EU and US listed companies in 2015 (data from Bureau Van Dijk Orbis). **a**, Exposures to climate-policy-relevant sectors of aggregate financial actors worldwide. **b**, Exposures to climate-policy-relevant sectors of selected investment funds worldwide (top 15 by size of equity portfolio in the data). **c**, Exposures to climate-policy-relevant sectors of selected banks worldwide (top 15 by size of equity portfolio in the data).

The following findings emerge. First, the relative equity portfolio exposures of all financial actors types to the fossil-fuel sector are limited (that is, ranging from 4.4% for Individuals to 12.9% for Governments) (see Supplementary Table 6). Second, their relative equity portfolio exposures to all climate-policy-relevant sectors are large (that is, ranging from 45.2% for Insurance and Pension Funds, to 47.7% for Governments), and mostly accounted for by the energy-intensive sector. Third, since financial actors' exposures to the financial sector itself range from 13% for Industrial Companies up to 25.8% for Other Credit Institutions, they bear additional indirect exposures to climate-policy-relevant sectors. Within each financial actor type, the standard deviation of exposures across individuals (see Supplementary Table 6) reflects the level of heterogeneity across individuals' portfolio compositions. Examples of individual equity holdings' compositions are shown in Fig. 2b,c for the twenty largest players among investment funds and banks.

Climate stress-testing EU largest banks

Several quantitative estimates exist for the macroeconomic impacts of climate change and climate policies[25,26], as well as for the value

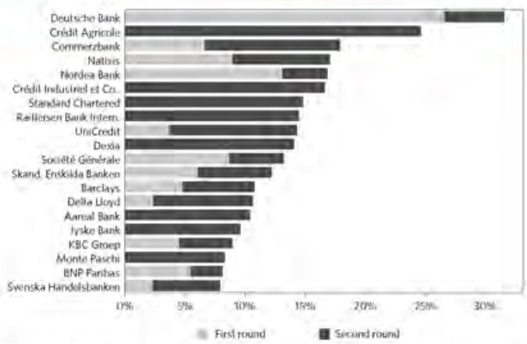

Figure 3 | First- and second-round losses in banks' equity for the 20 most-severely affected EU listed banks, under the Fossil fuel + Utilities 100% shock. Subsidiaries have not been taken into account.

of stranded assets[6]. Accordingly, probabilistic estimates of the climate VaR can be carried out from an aggregate perspective[11]. However, these estimates are too broad to define shock scenarios for individual institutions. At a more granular level, estimates of the value of stranded assets are available in the literature but their sectoral coverage is currently too narrow to inform an analysis of systemic impacts.

To overcome these limitations, we extend the stress-test methodology developed in refs 27,28, which allows one to disentangle the two main contributions to systemic losses. First-round losses are defined as losses in banks' equity due to direct exposures to shocks. Second-round losses are defined as indirect losses in banks' equity due to the devaluation of counterparties' debt obligations on the interbank credit market. The magnitude of second-round effects can vary significantly. Traditional methods (based on ref. 29), yielding small second-round effects, are appropriate only under specific market conditions (that is, full recovery from counterparties' asset liquidation and no mark-to-market valuation of debt obligations). In general, instead, second-round effects can be comparable in magnitude to first-round effects[15,27,28,30].

We illustrate how our methodology can be used to conduct a climate stress-test of the banking system based on microeconomic data at the level of individual banks, by carrying out two exercises on the set of the top 50 listed European banks by total assets (see Methods).

In the first exercise we aim to determine an upper bound on the magnitude of the losses induced by climate policies by considering a set of scenarios in which the whole equity value of the firms in the shocked sector would be lost. We can then compute for each bank the ratio of the exposures to climate-policy-relevant sectors over the banks' capital (that is, banks' equity on the liability side of their balance sheets). Different scenarios consist of different combinations of sectors as indicated in Supplementary Table 8, by increasing levels of shocks' severity. For instance, in the second scenario, 100% of the market capitalization of listed firms both in the fossil-fuel sector and in the utilities sector is lost. Figure 3 shows the losses as a percentage of the banks' capital across the 20 most affected banks as a result of the second scenario from Supplementary Table 8. Light (dark) grey bars indicate the losses from the first- (second-) round shocks. Notice that some banks have no first-round losses but have important losses at the second round. None of the largest banks could default solely due to their exposures to climate-policy-relevant sectors on the equity market. This result implies that even in a severe scenario, there is no systemic impact when considering only the equity holdings channel.

More refined scenarios, allowing one to compute a VaR for each bank, require one to have distributions of shocks across climate-policy-relevant sectors, which are not available in the literature at this stage. As a first step in this direction, in our second exercise, we construct distributions of shocks for the fossil-fuel and utility sectors based on the economic impact assessment of climate policies provided by the LIMITS database[26] and we consider several scenarios of banks' exposures to climate-policy-relevant sectors (see Methods).

In particular, we interpret scenarios (2) and (4) in terms of distributions of losses suffered by a 'representative' (average) bank adopting one of two different investment strategies:

- (2) a 'green' bank having all its equity holdings in utilities invested in renewables-based utilities and having no equity holdings in the fossil-fuel sector,
- (4) a 'brown' bank having all its equity holdings in utilities invested in fossil-fuel-based utilities and keeping its equity holdings in the fossil-fuel sector.

Supplementary Table 10 reports the main statistics on the global relative equity loss in the banking system. The results of the two exercises are consistent: the system's VaR in the brown scenario is less than 1% of the total banks' capital. Supplementary Table 3 reports the statistics for the 'representative' brown and green bank: depending on whether their exposure to utilities is mainly concentrated on renewables-based utilities or on fossil-fuel ones and if they are exposed to the fossil-fuel sector, banks might face very different impacts from climate policies. Further, Supplementary Fig. 6 shows the distribution of first-round losses: the brown bank incurs more losses than the green one, but these losses are small in comparison with the equity of the average bank (that is, US$32 billion) and with its total asset (that is, US$604 billion). Finally, Fig. 4a,b reports the VaR for the 20 most affected banks both in the brown and in the green scenario.

The limited magnitude of banks' losses in this exercise is due to the fact that Euro Area banks bear little equity holdings compared with their balance sheet (about 1.2T EUR, that is, 3.8% of total assets and 48% of capital), probably due to higher capital requirements for equity holdings[31]. However, banks bear larger exposures on loans to non-financial corporations (about 4.8T EUR = 13.8% of total assets and 192% of their capital). Unfortunately, Euro Area banks' loans are only available at 1-digit NACE Rev2 aggregation[32]. At this stage,

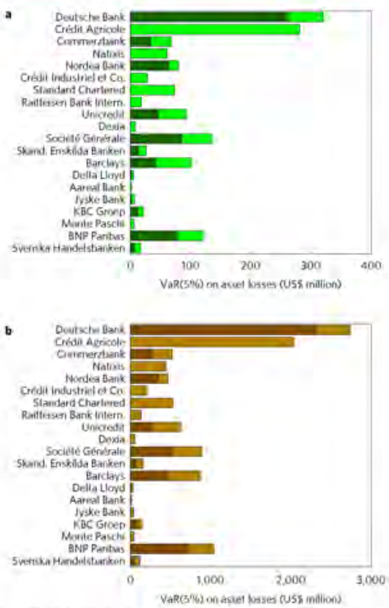

Figure 4 | Individual banks' value at risk under green and brown investment strategies. Value-at-risk at the 5% significance level of the 20 most-severely affected EU listed banks in the data set, under the scenario that they follow the green investment strategy (**a**) or the brown investment strategy (**b**). Darker colour refers to VaR(5%) computed on the distribution of first-round losses only, while lighter colour refers to VaR(5%) computed on the sum of first- and second-round losses.

we cannot compute individual exposures of banks to climate-policy-relevant sectors via their loans. Sector level data for 2014 from the ECB Data Warehouse provide the following aggregate estimations for the banks' exposures on loans as a fraction of banks' capital: 11.4% for fossil and utilities; 28% for energy-intensive; 16% for transportation; 73% for housing. We also need to consider banks' loans to households (presumably mostly granted for mortgages), which add a further 208% of exposures in the housing sector as a fraction of capital.

Better disclosure of climate-related financial exposures[33] would allow one to improve calculations for individual banks. The above considerations suggest that banks would not default solely due to their loan exposures to firms in the fossil-fuel and utilities sectors. However, if climate policies imply higher volatility of loans' values in the energy-intensive and transport sector or in the housing sector and for mortgages, this would translate into volatility of large portions of banks' assets, relative to their capital (16% + 28% = 44% and 73% + 208% = 281%, respectively).

Indirect exposures of European financial actors

By cross-matching aggregate balance sheet information for financial actors (from ECB Data Warehouse) with equity holdings (from Orbis), the following findings emerge for the Euro Area. First, the major direct exposures to climate-policy-relevant sectors of investment funds and pension funds are concentrated in equity holdings, while for banks they are concentrated on loans. Interestingly, bond holdings are only a minor channel of direct exposure to climate-policy-relevant sectors because outstanding bonds issued by non-financial firms in the Euro Area amount to about 1 trillion Euro, that is, about only one-fifth of the values of equity shares issued by the same type of firms. Indeed, only less than 7% of bonds are issued by firms in the real sectors, with roughly 40% issued by governments and another 45% issued by financial institutions.

Second, financial actors bear also indirect exposures to climate-policy-relevant sectors. For instance, pension funds hold an exposure of about 25% of their total assets in equity shares of investment funds, which in turn have an estimated exposure of about 25% of total assets in equity holdings of climate-policy-relevant sectors. Pension funds also hold an exposure of 15% of their total assets in bonds and loans to banks, which, on the basis of the previous section, hold an estimated exposure of about 14% of total assets to climate-policy-relevant sectors. In contrast, the direct exposure of pension funds to climate-policy-relevant sectors through equity holdings is about 8% of total assets. These findings imply that shocks on the fossil sector and increased volatility on asset values in the other climate-policy-relevant sectors could affect non-negligible portions of pension funds' assets through both direct (8.3%) as well as indirect exposures (about 8%).

Conclusions

By remapping the existing classification of economic activities (NACE Rev2) into newly defined climate-policy-relevant sectors, we find that direct and indirect exposures to such sectors represent a large portion of financial actors' equity holdings portfolios (in particular for investment funds and pension funds). Moreover, exposures represent a portion of banks' loan portfolios comparable to banks' capital. Further, we develop a network-based climate stress-test methodology that can be used to derive statistics of losses for individual financial actors, including VaR. We illustrate the methodology on a sample of the top 50 largest EU banks taking into account first- and second-round effects of shocks to their equity portfolios.

Our findings suggest that the implementation of climate mitigation policies is key, both in terms of timing and expectations. The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk. In contrast, in a scenario in which the implementation of climate policies is uncertain, delayed and sudden[2,10] (for example, as a reaction to increased frequency of extreme weather events and to align with the COP21 agreement), market participants would not be able to fully anticipate the impact of policies. In this case, given the large direct and indirect exposures of financial actors to climate-policy-relevant sectors, this might entail a systemic risk because price adjustments are abrupt and portfolio losses from the fossil-fuel sector and fossil-based utilities do not have the time to be compensated by the increase in value of renewable-based utilities. These two scenarios and their corresponding VaR are illustrated by the loss distributions for a 'green' and a 'brown' investing strategy in our climate stress-test on EU banks.

Moreover, the fact that financial actors bear large exposures to climate-policy-relevant sectors implies that climate mitigation policies could increase volatility on large portions of their portfolios. Climate mitigation policies are commonly thought to have an adverse effect on the value of assets in the fossil-fuel sector[5], as well as an adverse effect on the whole economy (see Ch. 6 of ref. 25). However, a transition to a low-carbon economy could also have net positive aggregate effects[34]. Overall, the effects of climate policies are likely to vary across firms and sectors: for example, the renewable energy and the energy efficiency sectors are expected to increase massively in market share (see ref. 35, IEA report 2015; IRENA Annual Review 2016), while real-estate assets can increase or decrease in value, depending on their energy performance (see Supplementary Table 6.7 in ref. 25). Further, stock price volatility in climate-policy-relevant sectors can increase as a result of: technological innovation[36,37], increased competition[38] and policy uncertainty[39]. Therefore, climate policy could lead to winners and losers (in absolute terms) across financial actors, depending on the composition of their portfolios.

Overall, our network analysis of financial exposures highlights that financial actors' portfolios are both interdependent and largely exposed to the outcome of the climate policy cycle. This implies the possibility of multiple equilibria without a clear way to assign *ex ante* probabilities for each equilibrium to occur. Therefore, while climate-related financial information disclosure is crucial for risk evaluation, a stable policy framework is necessary to resolve the multiplicity of possible outcomes. To this end, a network-based, conditional VaR approach represents an advancement in the analysis of climate-policy risks and their implications for the financial sector.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

All authors contributed to the writing of the manuscript, as well as material and analysis tools. G.V. and S.B. also performed the data analysis.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to S.B.

Competing financial interests

The authors declare no competing financial interests.

Methods

Identifying climate-policy-relevant sectors in the real economy. Many climate policies target the reduction of GHG emissions (in particular in non-carbon neutral processes). To identify the climate-policy-relevant sectors we group economic activities with the following logic. We start from the top sectors by direct GHG emissions according to Eurostat (scope 1 CO_2 equivalent), which includes activities across sectors such as utilities, transports, agriculture, manufacturing and households. We also include the mining sector, although it has small direct emissions according to the scope 1 classification, because all the emissions of the three above sectors derive directly or indirectly from the fossil-fuel extraction when accounting from the supply side[40]. We then take into account the so-called carbon leakage risk classification, which according to the EC Directive 2014[41] identifies activities (mostly within manufacturing) for which either costs or competitiveness is heavily affected by introduction of a carbon price. It can be easily verified that the traditional NACE Rev2 (but the same holds for NAICS) classification of economic activities is not well-suited for a climate-policy analysis. For instance, some activities classified under B-Mining and quarrying, such as 'B7.1-Mining of iron ores', are not so relevant for climate policies. In contrast, some activities classified under C-Manufacturing, such as 'C19.2-Manufacture of refined petroleum products' or transport 'H49.5-Transport via pipeline', are more relevant to the fossil-fuel sector from the criterion of economic scenarios resulting from climate policies. Furthermore, some activities that pertain to the housing sector from a policy perspective fall into different NACE Rev2 sectors such as F—Construction and L—Real estate.

All the considered economic activities can be divided into three categories: (1) suppliers of fossil fuels, (2) suppliers of electricity (3) users of either fossil fuels or electricity. We can further divide the third category according to the traditional policy areas: transport, housing and manufacturing. While suppliers of fossil fuels are mostly negatively affected by GHG emission reduction policies, the other categories can be affected positively or negatively depending on the energy source utilized (fossil fuel versus renewable). On the basis of all the above information, we can finally remap all the economic activities from the 4-digit NACE Rev2 classification into the following climate-policy-relevant sectors: fossil, utilities, transport, energy-intensive, housing. The complete mapping from NACE Rev2 4-digits codes is provided in Supplementary Information.

Assessing direct exposures of financial actors. Since our goal is to assess the exposure of financial actors to the climate-policy-relevant sectors in the real economy, we group financial actors into financial institutional sectors according to the standard ESA classification: banks, investment funds, insurance and pension funds. The exposures of each financial actor can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). More formally, denoting by A_i the total assets of financial actor i, and by $\mathbb{S}$ the set of climate-policy-relevant sectors, we can write

$$A_i = \left(\sum_{S\in\mathbb{S}}\sum_{j\in S} \alpha_{ij}^{\text{equity}} + \alpha_{ij}^{\text{bond}} + \alpha_{ij}^{\text{loan}}\right) + R_i \tag{1}$$

where the terms α_{ij} denote the monetary values of the exposures of i in the securities associated with economic actors j for the different types of instruments and R_i is a residual accounting for the exposure to other sectors and instruments not considered in our analysis.

Although instrument types have different risk profiles, it is informative to look at the total exposure of financial actors to a given sector across all instruments. For instance, we can compute in this way the full exposure of a given bank to the fossil sector, by summing up all of its equity holdings, bonds and loans exposures to this sector. If we denote by α_{iS} the total exposure of actor i to sector S, we can write $\alpha_{iS} = \sum_{j\in S} \alpha_{ij}^{\text{equity}} + \alpha_{ij}^{\text{bond}} + \alpha_{ij}^{\text{loan}}$.

In addition to the exposures of individual financial actors, we are also interested in the aggregate exposure of an entire financial institutional sector F to a given climate-policy-relevant sector, $A_{FS} = \sum_{i\in F} \alpha_{iS}$. Finally, the total direct exposure of the financial system in the totality of climate-policy-relevant sectors is $A_{\mathcal{F}\mathbb{S}} = \sum_{F\in\mathcal{F}} \sum_{S\in\mathbb{S}} \alpha_{FS}$, where $\mathcal{F}$ denotes the set of institutional financial actors.

Assessing indirect exposures of financial actors. A large portion of total assets held by financial institutions are in fact securities issued by other financial institutions (for example, about 40% for banks in the Euro Area). Moreover, about 25% of total market capitalization is invested in equity issued by companies in the financial sectors, and about 40% of the bond market is represented by outstanding obligations issued by financial institutions.

As a result, there is a potential systemic risk that can materialize through the so-called second-round effects[11,17]. For instance, first-round effects may induce directly the bankruptcy of a financial institution that then defaults on its obligations towards its financial counterparties. Second-round effects refer to financial contagion effects including, but not necessarily, further defaults. More generally, the accounting practice of mark-to-market implies that the deterioration of the balance sheet of a financial institution has a negative impact on the market value of its obligations held by its counterparties. Mark-to-market and, in particular, credit valuation adjustment, is recognized as a major mechanism of financial distress propagation: during the 2007/2008 financial crisis, it accounted for two-thirds of losses among many financial institutions (see ref. 42). More formally, in the breakdown of total assets, we can distinguish the securities issued by firms in the financial sectors (whose values depend on their own assets' values) from those issued by firms in the climate-policy-relevant sectors to obtain

$$A_i = \left(\sum_{j\in\mathcal{F}} \alpha_{ij}^{\text{equity}}(A_j) + \alpha_{ij}^{\text{bond}}(A_j) + \alpha_{ij}^{\text{loan}}(A_j)\right) + \left(\sum_{j\in\mathcal{A}\setminus\mathcal{F}} \alpha_{ij}^{\text{equity}} + \alpha_{ij}^{\text{bond}} + \alpha_{ij}^{\text{loan}}\right) + R_i \tag{2}$$

where $\mathcal{A}$ denotes the set of all actors and, again, $\mathcal{F}$ denotes the set of institutional financial actors. When we consider the above equation for many financial actors simultaneously, equation (2) becomes a system of coupled equations in the asset values. In the spirit of analysing the short-term effects of a deviation in the values from an initial face value of the securities, the terms $\alpha_{ij}^{\text{instrument}}(A_j)$ can be written as the product $\alpha_{ij}^0 f_{ij}(A_j)$, where α_{ij}^0 represents the face value of the security at the initial time and $f_{ij}(A_j)$ represents the valuation of the security with respect to its face value. While the exact functional form of f_{ij} depends on the instrument type and the pricing model used for the valuation of the security, it is possible nevertheless to infer certain useful properties. Consider for instance a chain of exposure in which the financial actor i holds bond securities issued by the financial actor j, who in turn holds securities issued by a firm k in the climate-policy-relevant sector. From the equations above it follows that

$$\frac{\partial A_i(A_j(A_k))}{\partial A_k} = \frac{\partial A_i(A_j)}{\partial A_j}\frac{\partial (A_j)}{\partial A_k} = \alpha_{ij}^0\alpha_{jk}^0 \frac{\partial f_{ij}}{\partial A_j}\frac{\partial f_{jk}}{\partial A_k} \tag{3}$$

Without loss of generality, in line with widely used pricing models such as those based on the Merton model for the value of debt obligations, the functions f_{ij} are non-decreasing in the value of the assets of the issuer j, that is, $df_{ij}/dA_j \geq 0$, because the ability of the issuer to pay either dividends or interest rates to its creditor generally increases with the issuer's total assets, everything else the same.

It follows that, as long as the terms df_{ij}/dA_j are not too small and comparable across instruments, the indirect exposure to a climate-policy-relevant sector along chains of financial actors is determined by the product of the face value of the exposures along the chain, $\alpha_{ij}^0\alpha_{jk}^0$, where each exposure corresponds to the strength of the link between the two nodes. The result can be generalized to longer chains, although we focus on length two in this work. Therefore, the problem of identifying the largest indirect exposure of a given path length is mathematically equivalent to the graph-theoretical problem of finding the path(s) with the largest product of link weights along the path in a weighted graph.

Distribution of shocks. To infer a distribution of shocks on the fossil-fuel and utilities sector we use the LIMITS database[25], which provides economic impact assessments of climate policies using a set of economic models and several scenarios that take into account the stringency of climate policy and the timing of its implementation. Results are reported as time series of forecasted production level for each sub-sector with a five-year interval up to 2050. In particular we analyse the estimated time series of the share of fossil fuels and renewables in primary and secondary (electricity) energy consumption. Out of the time series, one can infer a distribution of shocks by considering each change in market share from one period to the next as corresponding to an observation of a shock for the respective sub-sector. Hence, one obtains one shock per period per scenario and per model, for a total of 5,421 shocks. From an economic viewpoint, interpreting these shocks on market shares as shocks on equities amounts to make the following simplifying assumptions. First, the share of nominal expenses on energy is constant (that is, the demand elasticity of substitution is 1). Second, the value of equity in a sub-sector is proportional to total income. Third, market valuation is based on one-period (five years) ahead expectations. The shocks can then be interpreted as the impact on market valuation of a previously unanticipated policy measure. The extent to which these shocks will materialize depends on the ability of agents to anticipate policy measures. The shock scenario we describe in the paper corresponds to a setting in which informational imperfections prevent agents from smoothly adjusting their expectations. The alternative scenario emphasized in the

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conclusion corresponds to a situation where a stable policy framework would allow financial actors to smoothly adjust their expectations. In this case, climate-induced systemic risk would not materialize. Supplementary Fig. 6 shows the resulting distribution of the variation in asset value for a brown bank (investing in fossil-fuel primary sector and fossil-fuel-based utilities) and a green bank (investing in the renewable utilities sector only).

Data. Data on equity holding were obtained through the Bureau Van Dijk Orbis database. We collected a sample covering all EU and US listed companies and their disclosed shareholders with voting rights as of the end of the last available year, that is, 2014. After some consistency checks, we end up with 14,878 companies and 65,059 shareholders. By grouping the exposures by investor we thus reconstruct portions of their equity holding portfolios, within the limitations of the available data. Further details on the data set and the methodology are provided in the Supplementary Information. Data on the balance sheets of the top 50 listed European banks are obtained from the Bureau Van Dijk Bankscope database. Data include for each bank its total lending and borrowing to other banks. Exposures of a bank to individual other banks are not publicly available and have been estimated on the basis of existing methodologies (see literature in ref. 28). Data on GHG and CO_2 emissions of sectors have been obtained from Eurostat statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics). Data on financial exposures at the sectoral level have been obtained from the ECB Data Warehouse (http://sdw.ecb.europa.eu).

Data availability. The data that support the findings of this study are available from Bureau Van Dijk (Orbis database) but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors on reasonable request and with permission of Bureau Van Dijk.

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EXPERT REPORT
OF
JOSEPH E. STIGLITZ, PH.D.

University Professor, Columbia University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M., through his Guardian Tamara Roske-Martinez; et al., Plaintiffs,

v.

The United States of America; Donald Trump, in his official capacity as President of the United States; et al., Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

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TABLE OF ACRONYMS AND ABBREVIATIONS

C:	Celsius
CAFE:	Corporate Average Fuel Economy
CAD:	Canadian Dollar
CBO:	Congressional Budget Office
CO_2:	carbon dioxide
CPI:	consumer price index
EPA:	U.S. Environmental Protection Agency
GDP:	gross domestic product
GHGs:	greenhouse gases
IMF:	International Monetary Fund
IPCC:	Intergovernmental Panel on Climate Change
NASA:	National Aeronautics and Space Administration
NOAA:	National Oceanic and Atmospheric Administration
OECD:	Organisation for Economic Co-operation and Development
OMB:	Office of Management and Budget
ppm:	parts per million
R&D:	research and development
USGCRP:	U.S. Global Change Research Program

I. QUALIFICATIONS AND PROFESSIONAL BACKGROUND

1. I am one of sixteen University Professors at Columbia University with joint appointments in the Faculty of Arts and Sciences (Department of Economics), the Graduate School of Business (Department of Finance), and the School of International and Public Affairs. Prior to assuming this position, I held professorships at Stanford University, Yale University, Princeton University, and the University of Oxford, where I taught a wide variety of graduate and undergraduate courses in economics and finance. I received my Ph.D. in Economics from MIT in 1967.

2. Over the course of my career I have published hundreds of peer-reviewed articles, written or edited more than 50 academic and popular books, testified several times before Congress, and written numerous opinion pieces for newspapers and magazines. My publications and research have extended into many different areas, including macroeconomics and monetary theory, development economics and trade theory, public and corporate finance, industrial organization and rural organization, welfare economics, and income and wealth distribution, many of which are germane to this case. Oxford University Press is in the process of publishing a six-volume set based on my research, *Selected Works of Joseph E. Stiglitz*. The first two volumes have been published and are entitled *Information and Economic Analysis: Basic Principles and Information and Economic Analysis: Applications to Capital, Labor, and Products Markets*.

3. Public economics and public finance, which study how governments raise funds and make expenditures, have been major pillars of my academic work. I served as a co-editor of the *Journal of Public Economics*, the leading economics journal dealing with matters of taxation and public economics, and have published broadly in this area. My textbook, *Economics of the Public Sector*, is a leading text first published in 1986 with the most-recent version released in 2015. Another of my books, *Lectures on Public Economics*, published in 1980 and reprinted in 2015 with a new introduction, has been widely translated. Many of my popular texts, including my recent books *The Great Divide* and *The Price of Inequality*, published in 2015 and 2012, respectively, critically examine our public institutions, and comment on public finance and public economics generally.

4. Environmental economics and economic policy around natural resources has been another focus of my academic and professional work. I was one of the lead authors of the 1995 Report of the Intergovernmental Panel on Climate Change, which shared the 2007 Nobel Peace Prize with former Vice President Gore. I was co-chair of the High-Level Commission on Carbon Prices (we released our report in May 2017). I was also involved in environmental economic policy during my time on the Council of Economic Advisors, where one of my responsibilities was evaluating, designing, and implementing public policies that affect the environment, and while Chief Economist of the World Bank, where one of my responsibilities was evaluating and designing environmentally sustainable economic policies. I have also published many peer-reviewed articles that examine how we treat externalities (e.g., pollution) and public goods (e.g., the environment).

5. I have received numerous fellowships and honors over my career. In 2001, I was awarded the Nobel Memorial Prize in Economics for my work on Information Economics. This work includes the study of how information asymmetries affect economic behavior, the determination of the conditions under which efficient sharing of risk occurs, and the economics of financial markets, which are directly relevant to this case. In 1979, I was awarded the John Bates Clark Medal by the American Economic Association, given biennially to the economist under 40 who has made the most significant contribution to economics.[1]

6. I was the founding editor of the *Journal of Economic Perspectives*. I have served (or am currently serving) on the Editorial Board of numerous journals, including *The Economists' Voice*, the *Journal of Globalization and Development*, the *World Bank Economic Review*, the *Journal of Public Economics*, the *American Economic Review*, the *Journal of Economic Theory*, *The Review of Industrial Organization*, *Managerial and Decision Economics*, *Energy Economics*, the *Review of Economic Design*, and the *Review of Economic Studies*.

[1] The John Bates Clark Medal has been given annually since 2009.

7. I served as President of the International Economic Association from 2011–2014 and as President of the Eastern Economic Association in 2008. I also served as Vice President of the American Economic Association in 1985.

8. I have received more than 40 honorary degrees, and have received awards from foreign governments, including the Legion of Honor from France. I have also been elected to numerous academic and scientific societies in the United States and abroad, including the National Academy of Sciences, the Royal Society, the American Academy of Arts and Sciences, the American Philosophical Society, and the British Academy. In 2011, *Time* magazine named me to their *Time 100* list as one of the 100 most influential people in the world.

9. From 1993 to 1997, I served as a member of President Clinton's Council of Economic Advisers, and from 1995 to 1997, as Chairman of the Council and a member of the President's Cabinet. As Chairman and Cabinet Member, I was heavily involved in formulating fiscal policy, sustainable economic policies (including environmental economic policies), financial sector regulation and banking policy, and coordinating policy with the U.S. Treasury.

10. From 1997 to 2000, I served as Chief Economist and Senior Vice President of the World Bank, in which capacity I had the responsibility of advising countries around the world on the design of fiscal, tax, and monetary policies, competition policies, sustainable economic policies (including those regarding natural resources and the environment), intellectual property regimes, financial regulations, and trade policy.

11. I have served or am serving currently on many commissions and advisory committees addressing a myriad of economic policy issues, both in the U.S. and abroad, including the Joint CFTC-SEC Advisory Committee on Emerging Regulatory Issues, the United Nations' International Labour Organization World Commission on the Social Dimensions of Globalization, the High Level Panel of the African Development Bank, and the Economic Advisory Panel in South Africa.

12. At the behest of the President of the General Assembly of the United Nations, I served as Chair of the Commission of Experts on Reforms of the International Monetary and Financial System, to review the workings of the global financial system in the wake of

the 2008 economic crisis and suggest steps for U.N. member states to secure a sustainable economic future. Our final report was published in September 2009. In addition, I was appointed President of the Commission on the Measurement of Economic Performance and Social Progress by President Sarkozy of France, in 2008. This commission was formed to consider flaws in traditional macroeconomic indicators measuring economic performance and social progress and consider what might be the more relevant metrics, which are relevant to this case. Our final report was released in September 2009.

13. In 2000, I founded the Initiative for Policy Dialogue, for which I continue to serve as co-President. The Initiative for Policy Dialogue is a global network of academics and practitioners to enhance democratic processes for decision-making in developing countries. I am also Co-Chair of the High-Level Expert Group on the Measurement of Economic Performance and Social Progress, Organisation for Economic Co-operation and Development (OECD) and the Chief Economist of, and a Senior Fellow at, the Roosevelt Institute.

14. Previously, I served as Chair of the Management Board at the Brooks World Poverty Institute at the University of Manchester, on the Board of Trustees of Amherst College, my undergraduate *alma mater*, and as Co-Chair of Columbia University's Committee on Global Thought.

15. I have provided expert testimony in various fora throughout the United States, and before foreign courts and international tribunals. I have submitted *amicus curiae* briefs before the Supreme Court of the United States and before U.S. Circuit Courts of Appeal. My expert testimonies have related broadly to financial markets and derivatives, taxes, antitrust and competition, patent enforcement, and public interest generally (e.g., promotion of efficiency and/or minimization of welfare costs). I have also offered testimony regarding environmental economics, specifically, around offshore drilling.

16. My curriculum vitae, which provides more details of my qualifications, including a list of my publications, is attached as **Exhibit A**. **Exhibit B** contains a list of my previous expert testimony within the last five years. The materials that I, and volunteers supporting me at my direction, considered in preparing this report are cited in the footnotes and listed in **Exhibit C**.

17. I am working *pro bono* to prepare this expert report. My usual rate for work in litigation matters is $2,000 per hour, which is the rate I will charge if another party seeks discovery under Federal Rule 26(b). I have no present or intended financial interest in the outcome of this matter. My work in this matter is ongoing, and I reserve the right to revise or augment the opinions set forth in this report should additional relevant information become available to me, or as I perform further analysis.

II. ASSIGNMENT AND SUMMARY OF CONCLUSIONS

18. Julia Olson and Philip Gregory, counsel for Plaintiffs in this matter, have asked me to provide my expert opinion on the economics of transitioning to a non-fossil fuel economy.[2] In particular, I have been asked: (a) to analyze from an economic perspective how climate change will harm the Youth Plaintiffs (and Affected Children) if Defendants continue to pursue policies that perpetuate a fossil-fuel-based energy system and defer action to mitigate climate change; and (b) to assess the economic benefits of transitioning to a non-fossil-fuel economy now rather than later. The opinions expressed in this report are my own. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated.

19. I have formed four primary conclusions in this case, the bases for which are set forth more fully below:

   a. Scientific evidence shows further incremental increases in global temperature will lead to disproportionately greater costs imposed on our society. This has important consequences for how Defendants' actions harm the Youth Plaintiffs and Affected Children more generally. Continuation of the national fossil fuel-based energy system by Defendants is causing imminent, significant, and irreparable harm to the Youth Plaintiffs and Affected Children more generally. This kind of environmental harm, by its nature, cannot be adequately remedied by money damages and is often permanent or at least of long duration, i.e., irreparable. There is a point at which, once this harm occurs, it cannot be undone at any reasonable cost or in any reasonable period of time. Based on the best available science, our country is close to approaching that point.[3]

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2 I understand that the plaintiffs in this litigation are young people, who I will refer to as the "Youth Plaintiffs." However, my analysis also looks at the impact on other young people who are not named plaintiffs (and as-yet-unborn youth, the so-called future generations), but are just as (or even more) affected, whom I collectively refer to as "Affected Children."

3 This is a global problem. However, as I discuss below in Section V.B, the U.S. is a significant contributor to GHG emissions, and so actions by the U.S., have a significant impact on these global outcomes.

b. Defendants' continuing support and perpetuation of a national fossil fuel-based energy system and continuing delay in addressing climate change is saddling and will continue to saddle Youth Plaintiffs with an enormous cost burden, as well as tremendous risks, which is causing substantial harm to the economic and personal well-being and security of Youth Plaintiffs. These costs and risks will be borne over each ensuing year that progress towards remediation is not undertaken by Defendants. Such costs and risks arise both from damage caused by accumulated greenhouse gas emissions and from the required outlays on future remediation and adaptation efforts, which grow more expensive as the accumulation of greenhouse gases in the atmosphere increases. There are particularly consequential risks arising from the potentially catastrophic impacts of climate change, which increase each year that Defendants defer action on greenhouse-gas mitigation efforts.

c. Moving the U.S. economy away from fossil fuels is both feasible and beneficial, especially over the next 30 years (as technological and scientific evidence discussed below makes clear). Defendants could facilitate this transition with standard economic tools for dealing with externalities, for example a tax or levy on carbon (a price on the externality) and the elimination of subsidies on fossil-fuel production. Relatedly, decisions concerning the transition off of fossil fuels can be reached more systematically and efficiently by revising current government discounting practices, the methodology by which future costs are compared to present costs. Current and historical government decision making practices based on incorrect discount rates lead to inefficient and inequitable outcomes that impose undue burdens on Youth Plaintiffs and future generations. Basing decisions (policies, programs, and actions) on appropriate discount rates would help minimize the burdens that Defendants' current policies place on Youth Plaintiffs and future generations. That is to say, if Defendants' discounting policies and practices more accurately reflected the expected changes in relative prices over time (and their distribution, implicitly putting a lower discount rate on climate change benefits), the basis for Defendants' policy-making decisions would more closely align with economic principles and yield more efficient outcomes.

d. Based on this reasoning, I conclude that Defendants can and should take meaningful actions to reduce GHG emissions from fossil fuels and mitigate climate change impacts now rather than defer action to some future date. Acting now will yield benefits for both Defendants and Youth Plaintiffs and reduce harm to Youth Plaintiffs, and the costs of mitigating climate change now are manageable. Defendants could make meaningful progress on climate change mitigation by acting today in accordance with the best available science. Moreover, Defendants meeting their constitutional and public trust obligations to redress climate change would improve societal well-being by any reasonable economic standard. In fact, some of the actions that Defendants could take to meet these obligations would actually have a negative cost. That is to say, in the long run, the net present value of benefits to society would exceed the net present value of costs that society would have to incur.[4] This is referred to as Kaldor–Hicks efficiency in standard economic analysis, typically a hallmark of sound policymaking, from an economic perspective, whereby the net benefits of a policy change outweigh the net costs of such policy change. Thus, if Defendants were to make such changes as are argued for by other of Plaintiffs' experts, the net societal gain would more than outweigh the net societal loss. In contrast, Defendants' current policies of perpetuating the fossil fuel-based energy system impose unacceptably high costs and risks on the Youth Plaintiffs specifically and Affected Children more generally, and will continue to do so, well out of portion to the amounts that Defendants save currently by avoiding taking the appropriate actions.

20. The body of my report sets out the factual and analytical bases for my conclusions and opinions. The balance of my report proceeds as follows: Section III summarizes the scientific evidence on increasing greenhouse gases affecting global temperatures and why the time to act is now; Section IV discusses the costs that Youth Plaintiffs will face if Defendants continue to promote and permit a fossil-fuel-based energy system and no

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[4] This is not to say that each party is better off (which would be a Pareto improvement); but those parties who are better off by the policy change (e.g.., non-polluters) are made better off by more than the parties made worse off by the policy change (e.g.., polluters) are made worse off.

actions (or insufficient actions) are taken to wean society off fossil fuels; Section V analyzes how the transition away from fossil fuels is feasible and can be facilitated with standard economic tools; and, finally, Section VI concludes.

III. BACKGROUND ON THE RELATIONSHIP BETWEEN ATMOSPHERIC CONCENTRATIONS OF GREENHOUSE GASES AND CLIMATE CHANGE

21. The climate change young people are experiencing today is caused by the historic emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs), primarily from burning fossil fuels and other anthropogenic activities, including deforestation and agricultural practices.[5] It is scientifically established that human activities produce GHG emissions, which accumulate in the atmosphere and the oceans, resulting in warming of Earth's surface and the oceans[6], acidification of the oceans,[7] increased variability of climate, with a higher incidence of extreme weather events, and other changes in the climate.

22. Dangerous impacts are already occurring from the current level of global warming of around 1°C above preindustrial temperatures. Climate scientists have established through the paleo record that warming of 1.5°C or 2°C above pre-industrial levels would be well outside the Holocene range of global temperatures within which humans have lived and

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[5] See, for example, Intergovernmental Panel on Climate Change, "Climate Change 2014: Synthesis Report Summary for Policymakers," pp. 4-5. Other Greenhouse Gases, like Methane, also trap heat within the earth. They differ in key technical properties, like the rate of dissipation. Throughout this report, I use the terms GHG and CO_2 emissions interchangeably.

There is a popular but misguided debate among so-called climate "skeptics" about the extent to which the observed increase in temperature is a result of the emissions of CO_2 and other GHGs. The scientific literature is clear (and has been clear for a long time): the increase in atmospheric concentration of GHGs predictably increases the Earth's temperature in the manner observed. This has been most recently reaffirmed by "Climate Science Special Report: Fourth National Climate Assessment, Volume I" U.S. Global Change Research Program, November 2017, pp. 96-97 https://science2017.globalchange.gov/downloads/CSSR2017_FullReport.pdf. (Hereinafter USGCRP Climate Science Special Report).

But even if there were other factors contributing to climate change, the analysis here is unchanged: Defendants could, with mild costs, take actions now that would avoid imposing the undue and excessive burdens and risks imposed on the Youth Plaintiffs in this case.

[6] USGCRP Climate Science Special Report, p. 364.

[7] USGCRP Climate Science Special Report, pp. 371-372.

societies developed.[8] Moreover, leading experts believe that there is already more than enough excess heat in the climate system to do severe damage and that 2°C of warming would have very significant adverse effects, including resulting in multi-meter sea level rise.[9] NOAA projects up to 0.63 m (2.1 feet) of sea level rise by 2050, 1.2 m (3.9 feet) by 2070, 2.5 m (8.2 feet) by 2100, 5.5 m (18 feet) by 2150, and 9.7 m (31.8 feet) by 2200.[10] A 2-3 foot sea level rise would inundate and render uninhabitable large portions of the world's barrier islands and deltas and place major pressures on the infrastructure of low-lying coastal zones like South Florida, and 3 feet of seal level rise would "permanently inundate 2 million American's homes and communities."[11] Sea level rise of this magnitude would impose irreversible harm and an immense financial burden on young people in coastal areas, along with significant indirect costs on young people elsewhere.

23. Experts have identified a number of known "feedback loops" in the climate system. These feedback loops cause warming to catalyze still further warming. For example, warmer arctic temperatures result in melting permafrost that releases methane, a GHG that further warms the planet. These feedbacks, in conjunction with the fact that CO_2 persists in the atmosphere for centuries, mean that the longer we delay action, the greater the risk that warming will trigger tipping points in the climate system and become irreversible, or reversible only at much increased cost. Given the self-reinforcing nature

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[8] J. Hansen et al., "Assessing ''Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature," *PLOS One*, 8:12, e81648, 2013, p. 9.

[9] J. Hansen, et al., "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2C global warming is highly dangerous," *Atmospheric Chemistry and Physics Discussions*, 15, 20059-179, 2015, http://faculty.sites.uci.edu/erignot/files/2017/06/Ice-melt-sea-level-rise-and-superstorms-evidence-from-paleoclimate-data-climate-modeling-and-modern-observations-that-2C-global-warming-is-highly-dangerous.pdf.

[10] "Global and regional sea level rise scenarios for the United States," NOAA Technical Report NOS CO-OPS 083, January 2017, p. 23, https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

[11] H. Wanless, "Declaration of Dr. Harold R. Wanless in Support of Answer of Real Parties in Interest to Petition for Writ of Mandamus", *in United States of America et al. v. United States District Court for the District of Oregon et al.*, Case No. 17-71692, Doc. No. 14-3, paras. 31-32, *citing* "Global and regional sea level rise scenarios for the United States," NOAA Technical Report NOS CO-OPS 083, January 2017.

of climate change, prompt action is needed to both minimize future emissions and reduce the effects of historic emissions.

24. Experts have observed an increased incidence of climate-related extreme weather events, including increased frequency and intensity of extreme heat and heavy precipitation events and more severe droughts and associated heatwaves. Experts have also observed an increased incidence of large forest fires, and reduced snowpack affecting water resources in the western U.S. The most recent National Climate Assessment projects these climate impacts will continue to worsen in the future as global temperatures increase.[12]

25. Although the scale of the problems and risks that we face are immense, it is possible to reduce these risks by acting now to avoid irreversible harm to essential natural systems with its catastrophic consequences such as sea level rise, increased ocean temperatures, ocean acidification, heat waves, increased drought, and the associated impacts on water quality and availability, human health, and agriculture. Such impacts would harm our economy directly and introduce much increased risk in the form of variability in and uncertainty around climate outcomes.

26. Dr. Hansen and other experts in this case have provided a prescription for an emissions reduction and carbon sequestration pathway back to CO_2 levels below 350 ppm by 2100, which they say would substantially lessen the risk of catastrophic sea level rise and other climate harms.[13] Returning to temperatures and atmospheric CO_2 levels that avoid dangerous anthropogenic climate change has a limited window (because of tipping points in the climate system), which is still open but is closing rapidly. Defendants must take action now to reduce these risks.

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[12] USGCRP Climate Science Special Report, pp. 19-22.

[13] James Hansen et al., "Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature," *PLOS One*, 8:12, e81648, 2013.

IV. DEFENDANTS' ACTIONS THAT PERPETUATE A FOSSIL FUEL ENERGY SYSTEM AND INSUFFICIENT ACTION ON CLIMATE CHANGE ARE IMPOSING AND WILL CONTINUE TO IMPOSE ENORMOUS COSTS ON YOUTH PLAINTIFFS

27. The current national energy system, in which approximately 80 percent of energy comes from fossil fuels, is a direct result of decisions and actions taken by Defendants.[14] Defendants control and dictate the U.S. national energy policy in a myriad of ways. For example, they provide billions of dollars annually in subsidies to the fossil fuel industry;[15] control the fuel economy of cars and trucks through the Corporate Average Fuel Economy ("CAFE") standard; set efficiency standards for appliances; permit the extraction, transportation, import, export, and combustion of fossil fuels; and provide funding for research and development.[16] The fact that the U.S. national energy system is so predominately fossil fuel-based is not an inevitable consequence of history. With the oil crises of the 1970s, recognition of the risks of dependence on oil was developed (though these risks were markedly different from those with which we are concerned today). Even then, it was clear that there were viable alternatives, and with the appropriate allocation of further resources to R&D, it is likely that these alternatives would have been even more competitive. Thus, the current level of dependence of our energy system on fossil fuels is a result of intentional actions taken by Defendants over many years (including subsidization of fossil fuels and *inactions* in the form of not providing adequate support for alternatives).[17] Cumulatively, these actions promote the use of fossil fuels, contribute to dangerous levels of CO_2 emissions, and cause climate change. The economic impacts of these actions are deleterious to Youth Plaintiffs and the nation as a whole. In other words, Defendants' actions promoting a fossil fuel based

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[14] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, August 2017 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

[15] See, Section V, below.

[16] "Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2013", U.S. Energy Information Administration, March 2015, https://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf.

[17] I would note that inactions in this sense are affirmative decisions by Defendants not to act.

energy system are serving to undermine the legitimate government interests of national security and economic prosperity that they purport to advance.[18]

28. When conducting an economic analysis of the effects of climate change and appropriate responses thereto, Defendants must take into account a number of salient aspects of climate change. I have already noted some of these aspects: not just global warming in the sense of on-average increases in temperature, but also an increase in extreme (and damaging) weather events, rising sea levels, the public health consequences, and many other direct and indirect impacts of climate change. Still another aspect of climate change that is crucial in framing an appropriate response are the long lag times inherent in the climate system, implying that the full climate impact of any given accumulation of GHGs may not be apparent for many years.[19] Moreover, critical to the effects (as already noted) is the increase in concentration of GHGs. The fact that GHGs dissipate very slowly from the atmosphere (particularly in the case of CO_2[20]) and that the costs of taking

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[18] Daniel R. Coats, Director of National Intelligence, "Statement for the Record: Worldwide Threat Assessment of the US Intelligence Community," *Office of the Director of National Intelligence*, February 13, 2018, https://www.intelligence.senate.gov/sites/default/files/documents/os-dcoats-021318.PDF (at page 16: "The impacts of the long-term trends toward a warming climate, more air pollution, biodiversity loss, and water scarcity are likely to fuel economic and social discontent—and possibly upheaval….").

[19] Because of these lags, we have not yet seen the full rise in temperature that will occur as a result of the CO_2 that has already been emitted. As noted above, the Earth's average surface temperature has already risen by approximately 1°C since the Industrial Revolution. The concentration of CO_2 in the atmosphere is increasing at the rate of 2-3 ppm per year. Scientists tell us that even if CO_2 were stabilized at current levels, there would be at least another 0.5°C "in the pipeline." The delayed response is known as climate lag. The reason the planet takes several decades to respond to increased CO_2 is the thermal inertia of the oceans. Consider a saucepan of water placed on a gas stove. Although the flame has a temperature measured in hundreds of degrees C, the water takes a few minutes to reach boiling point. This simple analogy explains climate lag. The mass of the oceans is around 500 times that of the atmosphere. The time that it takes to warm up is measured in decades. For example, a paper by Dr. Hansen (and others) estimates the time required for 60 percent of global warming to take place in response to increased emissions to be in the range of 25 to 50 years. See, Hansen, J.E. et al., "Earth's Energy Imbalance: Confirmation and Implications," *Sciencexpress*, April 28, 2004, http://science.sciencemag.org/content/early/2005/04/28/science.1110252.

[20] Accumulations of CO_2 are particularly problematic because they dissipate so slowly. See, e.g., "Carbon is forever," *Nature Reports Climate Change*, November 20, 2008. This article discusses results from Dr. Hansen's research, stating: "Several long-term climate models, though their details differ, all agree that anthropogenic CO_2 takes an enormously long time to dissipate. If all recoverable fossil fuels were burnt up using today's technologies, after 1,000 years the air would still hold around

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CO_2 out of the atmosphere through non-biological carbon capture and storage are very high[21] means that the consequences of GHG emissions should be viewed as effectively irreversible. Accordingly, if Defendants do not take serious action to mitigate climate change now, Youth Plaintiffs and Affected Children will largely shoulder the costs caused by Defendants' actions that contribute to the further accumulation of GHGs and Defendants' failure to act to redress the harm. We can expect these burdens to manifest themselves in at least four ways.

29. ***First***, despite their relative lack of economic power in society today, Youth Plaintiffs themselves will suffer the disproportionate, increased financial burdens of climate change as the impacts of climate change propagate throughout the economy. For example, rising sea levels will lead to massive reductions in property value (indeed, the value of land that is underwater will fall to zero). Some Youth Plaintiffs, such as Levi D., and Affected Children will (with high probability) be deprived of the use of submerged lands, and many of them will almost surely experience large capital losses, as markets eventually fully reflect the realities of climate change. In addition, Youth Plaintiffs and Affected Children will, as future taxpayers, help bear the enormous cost of relocating the people and infrastructure that are now on this land to higher ground. Youth Plaintiffs and Affected Children will also bear the cost of instituting temporary stopgap measures, such as dikes to hold back rising sea levels, and some of them will have to bear directly themselves relocation costs.

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a third to a half of the CO_2 emissions. 'For practical purposes, 500 to 1000 years is 'forever,'' as Hansen and colleagues put it. In this time, civilizations can rise and fall, and the Greenland and West Antarctic ice sheets could melt substantially, raising sea levels enough to transform the face of the planet."

21 See, for example, House, K.Z., et al., "Economic and energetic analysis of capturing CO_2 from ambient air," *Proceedings of the National Academy of Sciences*, 108(51) (December 2011): 20428-20433, http://www.pnas.org/content/108/51/20428.full.pdf. The authors concluded: "Our empirical analysis of energetic and capital costs of existing, mature, gas separation systems indicates that air capture processes will be significantly more expensive than mitigation technologies aimed at decarbonizing the electricity sector. Unless a technological breakthrough that departs from humankind's accumulated experience with dilute gas separation can be shown to "break" the Sherwood plot and the second-law efficiency plot—and the burden of proof for such a process will lie with the inventor—direct air capture is unlikely to be cost competitive with CO_2 capture at power plants and other large point sources."

30. ***Second***, Youth Plaintiffs and Affected Children will face increased burdens as taxpayers because, as Defendants and climate scientists project, climate change will increase future losses related to climate variability, sometimes of a catastrophic nature.[22] In previous cases of catastrophic loss, society as a whole has borne much of the cost in the form of disaster relief payments from the public sector.[23] Recent examples of catastrophes in which a large proportion of the losses were borne by the public sector include Hurricane Katrina, Hurricane Sandy, Hurricane Harvey, Hurricane Irma, and Hurricane Maria. Each of these disasters has (or will) cost the public sector billions of dollars in disaster relief. For instance, Hurricane Sandy cost the U.S. government over $50 billion, which is three times larger than the $18.7 billion of insured losses from that disaster, and over 70

[22] "The Impact of Climate Change on Natural Disasters," NASA, https://earthobservatory.nasa.gov/Features/RisingCost/rising_cost5.php. "Global Warming and Hurricanes," National Oceanic and Atmospheric Association, https://www.gfdl.noaa.gov/global-warming-and-hurricanes/. "Climate Change Indicators: Weather and Climate," EPA, https://www.epa.gov/climate-indicators/weather-climate. See also, K. Trenberth et al., "Attribution of climate extreme events," *Nature Climate Change* 5 (2015): 725-730.

[23] "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget", Congressional Budget Office (CBO), June 2016, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

Public sector relief is needed in these cases because private risk-pooling solutions, such as property and casualty insurers, do not and cannot cover even a majority of the realized losses. This is true for three primary reasons. *First*, a significant portion of the population is uninsured or underinsured for certain types of losses such as the risk of flood, especially in areas that have not been historically prone to flooding. *Second*, public property may not be insured at all. *Third*, property and casualty insurers are sometimes insufficiently capitalized to cover the enormous losses that such events can potentially cause, and their insolvency forces policyholders to turn to the government for assistance.

This point is illustrated by Hurricane Harvey in 2017, where some estimates of the costs run to nearly $200 billion, which represents about 1 percent of gross national product. See, e.g., Doyle Rice, "Harvey to be costliest natural disaster in U.S. history, estimated cost of $190 billion," *USA Today*, August 31, 2017, https://www.usatoday.com/story/weather/2017/08/30/harvey-costliest-natural-disaster-u-s-history-estimated-cost-160-billion/615708001/ and Reuters, "Hurricane Harvey Damages Could Cost up to $180 Billion," *Fortune*, September 3, 2017, http://fortune.com/2017/09/03/hurricane-harvey-damages-cost/. The Treasury Secretary went so far as to speculate that the Federal government's debt limit would have to be raised to free up spending for disaster recovery, and the Governor of Texas estimated that such relief could require $180 billion. *Id.*

Estimates for Hurricane Maria have been on the order of $100 billion. See, Jill Disis, "Hurricane Maria could be a $95 billion storm for Puerto Rico," *CNN*, September 28, 2017, http://money.cnn.com/2017/09/28/news/economy/puerto-rico-hurricane-maria-damage-estimate/index.html.

percent of the total economic damage of the disaster as estimated by the CBO.[24] Hurricane Katrina cost the U.S. government over $110 billion, 75 percent of the total economic damages of the disaster.[25] With increased catastrophic losses due to climate change, we can expect that the U.S. government's role as a safety net will expand.[26] As this trend continues, taxpayers of the future, including Youth Plaintiffs, will have to make whole the losses of property owners. The continuation, let alone the expansion, of the public sector's role as a safety net will be enormously costly, impose an increased burden and economic disadvantage on Youth Plaintiffs and Affected Children compared to older generations, and result in fewer government resources to be spent on public services.[27]

31. The National Centers for Environmental Information tracks the impact of weather events on the United States. As they report, from 1980 to 2017 the U.S. has experienced "219 weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2017). **The total cost of these 219 events exceeds $1.5 trillion.**"[28] (Emphasis in original.) In describing the impact on the U.S. in 2017 (the last full year):[29]

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[24] "Catastrophes: U.S.," Insurance Information Institute, http://www.iii.org/fact-statistic/catastrophes-us. "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget", Congressional Budget Office (CBO), June 2016, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[25] "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget," Congressional Budget Office (CBO), p. 17, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[26] "Underinsurance of Property Risks: Closing the Gap," Swiss Re, No. 5/2015, http://institute.swissre.com/research/overview/sigma/5_2015.html.

[27] The CBO estimates that, by 2075, hurricane losses alone will total 0.22 percent of GDP, or $39 billion in 2016 dollars, an increase of 40 percent from today's annual levels, and over half of that loss will be borne by the U.S. government. "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget," Congressional Budget Office, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[28] "Billion-Dollar Weather and Climate Disasters: Overview," National Centers for Environmental Information, 2018, https://www.ncdc.noaa.gov/billions/.

[29] *Id.*

> In 2017, there were 16 weather and climate disaster events with losses exceeding $1 billion each across the United States. These events included 1 drought event, 2 flooding events, 1 freeze event, 8 severe storm events, 3 tropical cyclone events, and 1 wildfire event. Overall, these events resulted in the deaths of 362 people and had significant economic effects on the areas impacted.

32. As the above makes clear, it is not just hurricanes that can cause such costly events. The 2017 wildfire season in California was particularly harsh. Insurance claims at the end of 2017 were approximately $9.4 billion (with many properties being underinsured or not insured, the total damage is higher),[30] and estimates of the total impact on economic activity were $180 billion (including damages, closures, costs to fight fires, lost sales, etc.).[31] In 2016, Canada had a similar experience in Fort McMurray, Alberta; insurance payments were the costliest in Canadian history at CAD 3.58 billion,[32] and this covered only 70 percent of the total economic loss.[33] Particularly insidious with forest fires is that they also lead to massive injections of CO_2 into the atmosphere. As the Climate Science Special Report (a compilation by the U.S. Global Change Research Program, spanning multiple government agencies) noted about the Alberta wild fires specifically: "They can also radically increase emissions of greenhouse gases, as demonstrated by the amount of carbon dioxide produced by the Fort McMurray fires of May 2016—more than 10% of Canada's annual emissions."[34] The federal government expends significant financial

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30 W. Richter, "We may never be able to know the true cost of California's massive wildfires," *Business Insider*, December 7, 2017, http://www.businessinsider.com/santa-rosa-california-fires-cost-damage-2017-12.

31 "AccuWeather predicts 2017 California wildfire season cost to rise to $180 billion," *AccuWeather*, December 8, 2017, https://www.accuweather.com/en/weather-news/accuweather-predicts-2017-california-wildfire-season-cost-to-rise-to-180-billion/70003495.

32 "Northern Alberta Wildfire Costliest Insured Natural Disaster in Canadian History – Estimate of insured losses: $3.58 billion." Insurance Bureau of Canada, July 7, 2016, http://www.ibc.ca/ab/resources/media-centre/media-releases/northern-alberta-wildfire-costliest-insured-natural-disaster-in-canadian-history.

33 W. Koblensky, "Fort McMurray in top 10 worst insured losses globally," Insurance Business Canada, March 29, 2017, http://www.insurancebusinessmag.com/ca/news/environmental/fort-mcmurray-in-top-10-worst-insured-losses-globally-63960.aspx.

34 USGCRP Climate Science Special Report, p. 415.

resources each year on both fire suppression efforts and in the aftermath of wildfires, and while costs do vary from year to year, in general, they are rising.[35]

33. Other potential examples include agricultural losses. Whether or not insurance reimburses farmers for their crops, there can be food shortages that lead to higher food prices (that will be borne by consumers, that is, Youth Plaintiffs and Affected Children). There is a further risk that as our climate and land use pattern changes, disease vectors may also move (e.g., diseases formerly only in tropical climates move northward).[36] This could lead to material increases in public health costs in terms of vaccinations and treatments, at least some portion of which will be borne by future taxpayers, i.e., Youth Plaintiffs and Affected Children. Moreover, the Youth Plaintiffs and Affected Children will be at risk of experiencing directly one or more of these increased health hazards, only a portion of the costs of which will be picked up by insurance or public assistance. There is a risk too that the increased health costs will be reflected in increased insurance premiums, affecting all those relying on private insurance, including some or all of the Youth Plaintiffs and Affected Children.

34. All of these factors will also lead to increasing inequality, as those with financial means are more able to privately bear the costs of these disasters, while those without financial means will not. Those with means will also be able to relocate, perhaps avoiding (for themselves) the burdens of rising sea levels. This will impose a greater burden on those less able to pay for the direct, local consequences of climate change. Such increasing inequality is bad not only for those made worse off, but also for society as a whole, as a more unequal society is one with poorer economic performance.[37] This will impose

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[35] See, e.g., K. Hoover & B. Lindsay, "Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress," Congressional Research Service, October 5, 2017, https://fas.org/sgp/crs/misc/R44966.pdf.

[36] See, e.g., G. Mercer, "The Link Between Zika and Climate Change," *The Atlantic*, February 24, 2016, https://www.theatlantic.com/health/archive/2016/02/zika-and-climate-change/470643/.

[37] See, e.g., OECD, "Inequality hurts economic growth, finds OECD research," September 12, 2014, http://www.oecd.org/newsroom/inequality-hurts-economic-growth.htm and Prakash Loungani and Jonathan D. Ostry, "The IMF's Work on Inequality: Bridging Research and Reality," IMF, February 22, 2017, https://blogs.imf.org/2017/02/22/the-imfs-work-on-inequality-bridging-research-and-reality/ ("Another important conclusion of IMF research: rising inequality poses risks to durable

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further costs on the Youth Plaintiffs and Affected Children as they have to adapt to a structurally weaker economy due to increasing inequality (as elaborated on below, inequality is also exacerbated by Defendants' subsidy system that takes from taxpayers and gives to fossil-fuel corporations).

35. ***Third***, Youth Plaintiffs will face increased burdens because the more time that passes, the more expensive it becomes to address climate change.[38] It is highly likely that, as the consequences and magnitude of climate change become manifest, there will finally be a global consensus for a globally equitable and efficient response.[39] At that juncture, the only way to prevent the accumulation of greenhouse gases beyond a tolerable level will be "negative emissions," i.e. taking carbon out of the atmosphere, effectively attempting to undo the damage that is currently being done.[40] That will be enormously expensive relative to what it would have cost to begin curtailing emissions today.[41] Further, there is no guarantee that Youth Plaintiffs will be able to timely and effectively repair this

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economic growth. This puts addressing inequality squarely within the IMF's mandate to help countries improve economic performance.").

[38] See, e.g., "Climate change in the United States: Benefits of Global Action", EPA. Beccherle, Julien and Tirole, Jean, "Regional Initiatives and the Cost of Delaying Binding Climate Change Agreements", *Journal of Public Economics* 95 (December 2011): 1339-1348. Jakob, Michael and Tavoni, Massimo, "Time to act now? Assessing the costs of delaying climate measures and benefits of early action", *Climate Change* 114 (2012): 79-99.

[39] See, for example, Climate change in the United States: Benefits of Global Action, EPA, https://www.epa.gov/sites/production/files/2015-06/documents/cirareport.pdf.

[40] See, for example, "The cost of delaying action to stem climate change," Executive Office of the President of the United States, July 2014, p. 13, https://obamawhitehouse.archives.gov/sites/default/files/docs/the_cost_of_delaying_action_to_stem_climate_change.pdf.

[41] Even as these costly actions to undo the damage are undertaken, the effects of failing to act now will likely be felt, in ways described earlier in this report. Each and every one of the Youth Plaintiffs will face a risk of being personally affected, e.g., by increased taxes, increased direct losses, and increased exposure to health risks and to climate variability itself.

A recent estimate pegged the costs of CO_2 extraction to be on the order of $8 to $18.5 trillion, or over $100 billion per year over 80 years, to return to a 350 ppm target by 2100. These costs are much higher with continued high emissions (i.e., if we do not cease fossil fuel use and rely only on carbon capture and storage), being on the order of $100 *trillion* or more. See, J. Hansen et al., "Young People's Burden: Requirement of Negative CO_2 Emissions," *Earth System Dynamics*, vol. 8, 2017, pp. 577-616, at 591-592.

damage. In other words, the actions of Defendants in promoting and perpetuating a fossil fuel-based energy system impose a disproportionately higher financial burden and economic disadvantage on Youth Plaintiffs and Affected Children, undermining their economic security and depriving them of the stronger economy that they would have had in the absence of unmitigated climate change.

36. ***Fourth***, in the absence of mitigation efforts, there is a significant risk of catastrophic impacts of climate change; indeed, there is overwhelming evidence that such catastrophic impacts are likely to result. Defendants' failure to invest in climate change mitigation and thereby insure against that outcome imposes an enormous degree of risk on Youth Plaintiffs, not experienced by older generations. Events such as the rapid melting of ice sheets and consequent increases in global sea levels or temperature increases on the higher end of the range of scientific forecasts have the potential to entail severe, perhaps even irreparable, consequences.[42] To confront properly the possibility of climate catastrophes, Defendants must take prudent steps now to reduce the chance of the most severe consequences of climate change. The longer Defendants postpone such action, the greater will be the atmospheric concentration of GHGs and the risk (due to the self-reinforcing and path-dependent[43] nature of climate systems and long lags between actions and results, as discussed above). Just as businesses and individuals guard against severe financial risks by purchasing various forms of insurance, Defendants can take actions now that reduce the chances of triggering the most severe climate events. There is no third party from which Defendants could purchase insurance to protect Youth Plaintiffs from the damages that are consequent to Defendants' actions. The only alternative for Defendants is to take actions without delay to reduce the atmospheric concentration of CO_2 in order to restore Earth's energy balance and avert catastrophic and irreversible

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[42] See, Section III, above.

[43] By path dependence, I mean that prior actions affect the future trajectory of the economy in ways that are not irreversible, or reversible only at high costs. Accordingly, what is a prudent strategy today depends on decisions made yesterday (and many years ago). Put differently, prior decisions are not something that we can now just walk away from; those prior decisions directly affect the world we live in today and affect the analysis of what is a prudent strategy going forward.

climate change impacts.[44] Unlike conventional insurance policies, climate and energy policy that serves the purpose of climate insurance also results in cleaner air, improved energy security, and other benefits, many of which are difficult to monetize, like biological diversity or preserving culturally important places, but are nonetheless significant.

37. The benefits of undertaking such actions are disproportionate to the costs, even without taking account of the huge benefits that arise from the reduction of risk itself. This has been documented, for example, in the High-Level Commission on Carbon Prices.[45] Due to feedback loops, the magnitude of climate change may change much more than the proportionate increase in atmospheric concentrations of GHGs. Likewise, the increases in atmospheric concentrations of GHGs may increase disproportionately relative to emissions,[46] and the cost of damage wrought by climate change can increase much faster still.[47] More is being learned about the behavior of the climate system, including the potential timing and likelihood of these worst-case scenarios. However, the paleo-climate record gives scientists at least one good indication of the consequences of different levels of atmospheric CO_2. The last time in the geologic record that CO_2 levels were over 400 ppm, the seas were 70-90 feet higher than sea level today.[48] The experience of the last

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44 J. Hansen, "Exhibit A: Declaration of Dr. James E. Hansen in Support of Plaintiffs' Complaint for Declaratory and Injunctive Relief," in *Juliana et al. v. United States et al.*, Case No. 6:15-cv-01517-TC, Doc. No. 7-1., 2015, paras. 39, 67, 85.

45 The Commission showed that even a modest tax on carbon combined with the elimination of subsidies and certain other regulatory measures and modest public investments would be able to prevent a rise of temperature beyond the 1.5°C to 2°C.

46 See, for example, "The study of Earth as an integrated system," NASA, https://climate.nasa.gov/nasa_science/science/ and National Research Council of the National Academies, "Climate Change: Evidence, Impacts, and Choices," *The National Academies of Sciences, Engineering, and Medicine*, 2012, http://nas-sites.org/americasclimatechoices/files/2012/06/19014_cvtx_R1.pdf.

47 This is discussed in the Stern Review. See, for example, Figure 6.6 showing the exponential increase in reduced GDP per capita as global mean temperature increases. Nicholas Stern, "Stern Review: The Economics of Climate Change", p. 159, http://unionsforenergydemocracy.org/wp-content/uploads/2015/08/sternreview_report_complete.pdf.

48 H. Wanless, "Declaration of Dr. Harold R. Wanless in Support of Answer of Real Parties in Interest to Petition for Writ of Mandamus", *in United States of America et al. v. United States District Court for the District of Oregon et al.*, Case No. 17-71692, Doc. No. 14-3, para. 52.

quarter century is that there have been many surprises of underestimating adverse climate impacts (e.g., early estimates of sea level rise had not taken into account the effect of the melting of the arctic icecap or the release of methane gases from the tundra).[49]

38. Fair treatment of Youth Plaintiffs by Defendants requires taking due account of some of the worst, but still plausibly possible, cases. In such cases, national income will be lower because of the adverse effects of climate change,[50] imposing doubly an increased financial burden and economic disadvantage on Youth Plaintiffs and Affected Children: they will face the costs of remediation and adaptation with fewer resources with which to do so. Even if national incomes continue to rise in real terms, the costs of taking remedial climate action are an ever-increasing burden on Youth Plaintiffs and Affected Children as well. Moreover, as discussed in the climate science summary above, we are quickly approaching (or some argue we may have already passed) certain "tipping points" that will dramatically increase costs in a non-linear fashion.[51] Thus, it is not a practical solution to say Youth Plaintiffs and future generations may be more wealthy in the future (in fact, GDP may be lower in the future because of climate effects) and can bear the costs more efficiently than Defendants today (because those costs continue to increase disproportionately and have long-lasting adverse effects). The assumption of ever-increasing national income has significant implications for Defendants' cost-benefit

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[49] See, for example, Schneider, Stephen H. and Root, Terry L. Ecological implications of climate change will include surprises, *Biodiversity and Conservation* 5 (1996): 1109-1119.

[50] In one recent study, researchers found that temperature change due to unmitigated global warming will leave global GDP per capita 23 percent lower in 2100 than it would be without any warming. See Burke, M., Hsiang, S. M., & Miguel, E., (2015) "Global non-linear effect of temperature on economic production," *Nature*, 527 (7577): 235-239.

A per capita 23 percent lowering of GDP is the on-average result, which understates the full potential impact in two ways (much as the on-average temperature increases understate the increase in catastrophic events, as I discussed above). *First*, a 23 percent on-average result includes many states of the world where the average may be much worse. *Second*, a 23 percent on-average result will not affect all persons or all regions equally; those near the bottom of the income distribution that have no savings will suffer from lack of ability to consume, and almost surely these effects will be felt more in coastal regions, from which those near the bottom of the income distribution will lack the financial resources to relocate, further exacerbating their financial difficulties.

[51] See also, "The study of Earth as an integrated system," NASA, https://climate.nasa.gov/nasa_science/science/.

analysis and development of discount rates and the social cost of carbon, as described in more detail in Section V.C, below.

39. Moreover, it will be necessary to devote a significant proportion of national income to dealing with the consequences of climate change; the standard term is that there will be high costs of adaptation.[52] Especially disturbing are the impacts on developing countries, many of which are in tropical zones, which will be particularly hard hit. In the U.S., Youth Plaintiffs will not be able to insulate themselves from the global repercussions. The costs of adaptation to climate change by developing countries are well beyond anything that those countries can afford (or will be able to afford in the future). Youth Plaintiffs may recognize that they have a moral responsibility to global citizens elsewhere in the world because of the actions of the U.S., including Defendants, and thus they will bear a burden because of the failure of Defendants to take appropriate actions.[53] However, even were they not to do so, the markedly lower incomes in developing countries will set off large migration pressures, which we are already seeing today.[54]

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52 According to the United Nations Environment (UNEP) report, the cost of adapting to climate change in developing countries could rise to between $280 and $500 billion per year by 2050. There will be a significant financing gap unless new and additional finance for adaptation is made available. See UNEP 2016. The Adaptation Finance Gap Report 2016. United Nations Environment Programme (UNEP), Nairobi, Kenya.

53 Of course, Defendants do not control global climate emissions. The U.S. is the second-largest current emitter of CO_2 at 15 percent of global emissions (behind only China), and by far the largest historical emitter of CO_2 and GHGs. See, EPA, "Global Greenhouse Gas Emissions Data," *United States Environmental Protection Agency*, data as of 2014, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Country and J. Gillis and N. Popovich, "The U.S. Is the Biggest Carbon Polluter in History. It Just Walked Away From the Paris Climate Deal," *The New York Times*, June 1, 2017, https://www.nytimes.com/interactive/2017/06/01/climate/us-biggest-carbon-polluter-in-history-will-it-walk-away-from-the-paris-climate-deal.html.

However, action by the world's largest historical contributor of GHGs and the world's largest economy (the U.S.) would help further the goals of the Paris agreement and other countries' efforts to reduce GHG emissions. Moreover, it could reduce the incentive for other countries to shirk their climate change efforts by attempting to gain a competitive edge by not addressing climate change (a race to the bottom, so to speak). In any event, however, the fact that other countries, particularly developing countries, may not take as strong as action as is needed is not justification for Defendants using out-dated economic models and analysis to foist high costs on Youth Plaintiffs and Affected Children more generally.

54 See, for example, Coral Davenport and Campbell Robertson, "Resettling the First American 'Climate Refugees,'" *The New York Times*, May 3, 2016, https://www.nytimes.com/2016/05/03/us/resettling-

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Managing this migration (including possibly putting up hard-and costly-to-enforce barriers to it) will impose large costs on Youth Plaintiffs, undermining their economic security.[55] Moreover, in a globally interconnected system, lower incomes abroad will adversely affect the demand for American goods and services, thereby reducing U.S. GDP from what it otherwise would be, with consequent risks for Youth Plaintiffs and Affected Children.

40. I understand that Defendants argue their policies were necessary for the economic and national security of the U.S.[56] Such arguments do not withstand economic scrutiny. Whatever benefits might have existed in the middle of the 20th century, it has been decades since such policies were rational. This has been recognized by leading security experts. For example, since at least 2007, members of the U.S. military have recognized that "serious consequences to our national security ... are likely from unmitigated climate

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the-first-american-climate-refugees.html and Aryn Baker, "How Climate Change is Behind the Surge of Migrants to Europe," *Time*, September 7, 2015, http://time.com/4024210/climate-change-migrants/.

55 As discussed in the Stern Review, some estimates suggested up to 200 million people may become permanently displaced by climate change by the middle of this century, noting that almost as many people leave their homes because of environmental disasters as flee political oppression. See, Nicholas Stern, "Stern Review: The Economics of Climate Change", p. 77, http://unionsforenergydemocracy.org/wp-content/uploads/2015/08/sternreview_report_complete.pdf. See also, K. Burrows & P. Kinney, "Exploring the Climate Change, Migration and Conflict Nexus," *International Journal of Environmental Research and Public Health* 13(4) (2016): 443, noting that the number of people displaced by climate change by 2050 is estimated to be between 50 million, on the low end, and 1 billion, on the high end.

56 See, e.g., "Office of Fossil Energy FY 2019 Budget," U.S. Department of Energy, https://www.energy.gov/fe/about-us/our-budget ("The Office of Fossil Energy (FE) programs are focused on activities related to the reliable, efficient, affordable, and environmentally sound use of fossil fuels that are essential to our Nation's security and economic prosperity.").

See also, Jason Furman and Gene Sperling, "Reducing America's Dependence on Foreign Oil As a Strategy to Increase Economic Growth and Reduce Economic Vulnerability," Obama White House Archives, August 29, 2013, https://obamawhitehouse.archives.gov/blog/2013/08/29/reducing-america-s-dependence-foreign-oil-strategy-increase-economic-growth-and-redu ("...the President's focus on increasing America's energy independence is not just a critical national security strategy, it is also part of an economic plan to create jobs, expand growth and cut the trade deficit." The first element of President's Obama plan was "Increasing domestic production of oil.").

change."[57] In a report released in 2007, eleven retired military generals and admirals detailed the variety of threats to America's national and economic security that climate change poses:[58]

> In already-weakened states, extreme weather events, drought, flooding, sea level rise, retreating glaciers, and the rapid spread of life-threatening diseases will themselves have likely effects: increased migrations, further weakened and failed states, expanded ungoverned spaces, exacerbated underlying conditions that terrorist groups seek to exploit, and increased internal conflicts. In developed countries, these conditions threaten to disrupt economic trade and introduce new security challenges, such as increased spread of infectious disease and increased immigration. Overall, climate change has the potential to disrupt our way of life and force changes in how we keep ourselves safe and secure by adding a new hostile and stressing factor into the national and international security environment.

41. From an economic perspective, one of the key insights is that, just at the time when money is scarce (and our economy is weak) because of climate change, there will be greater need for funds. Thus, government will be less able to provide the requisite finance for key public services, depriving Youth Plaintiffs and Affected Children of the economic benefits enjoyed by older generations. This makes it even more compelling for Defendants to take all the precautionary measures today that they can.

42. As noted by the High-Level Commission on Carbon Prices (the "High-Level Commission"), which I co-chaired, the estimated economic costs of climate change in many of the standard models, and in particular Defendants' estimates of the social cost of carbon (under the Obama administration), are:[59]

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57 "National Security and the Threat of Climate Change," The CNA Corporation, 2007, p. 44, https://www.cna.org/cna_files/pdf/national%20security%20and%20the%20threat%20of%20climate%20change.pdf.

58 "National Security and the Threat of Climate Change," The CNA Corporation, 2007, pp. 44-45, https://www.cna.org/cna_files/pdf/national%20security%20and%20the%20threat%20of%20climate%20change.pdf.

59 High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices", 2017, Washington, DC: World Bank, Appendix A.

> …biased downward because they fail to consider many vitally important risks and costs associated with climate change—particularly the widespread biodiversity losses, long-term impacts on labor productivity and economic growth, impacts on the poorest and most vulnerable, rising political instability and the spread of violent conflicts, ocean acidification, large migration movements, as well as the possibility of extreme and irreversible changes.

43. Thus, it is prudent for Defendants to take precautionary actions, not based on the "average" estimate of what the damage might be, but rather based on estimates of realistically plausibly possible "worst cases." Because, as detailed below, Defendants could take actions at modest costs, and it would be reckless not to undertake those actions; it would be needlessly endangering the future prospects and the economic and personal security of Youth Plaintiffs and Affected Children.

V. TRANSITIONING THE U.S. ECONOMY OFF OF FOSSIL FUELS IS NOT ONLY FEASIBLE BUT WILL BENEFIT THE ECONOMY

A. TRANSITIONING OFF OF FOSSIL FUELS IS FEASIBLE

44. There is broad consensus among economists, and the High-Level Commission concluded, that limiting temperature increase to "well below 2°C" is achievable with reasonable and modest measures, and that the costs of those measures are far smaller than the costs of the damage that climate change could inflict.[60]

45. The High-Level Commission estimated that the costs of curtailing emissions to a level to achieve the goals set forth by the Paris Agreement ("well below 2°C") would be modest.[61] The High-Level Commission noted that the carbon tax, that they explained could induce the requisite change in emissions, could substitute for other more distortionary taxes. If governments made such a substitution, the aggregate cost of curtailing carbon emissions could even be less than zero, providing net benefits to the economy. Furthermore, at a time when so much discussion focuses on the Federal government's deficit spending (and our national debt), the elimination of billions of dollars of often-hidden subsidies to the fossil fuel industry would improve the country's fiscal situation and economic performance generally. As discussed below in Section V.B, the full amount of post-tax subsidies in the U.S. has been estimated at nearly $700 billion a year, more than half of the Federal government's forecasted deficit for the next fiscal year.[62] Eliminating all fossil fuel subsidies (implicit and explicit, many of which

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[60] High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices", 2017, Washington, DC: World Bank, p. 1.

[61] When I use the term "costs" here, I refer to the net effect of undertaking such policy changes—that is, such costs can be negative (when the benefits outweigh the costs). As is standard in economic analysis, I analyze the *marginal* effects, that is, the marginal (i.e., additional as compared to the *status quo*) net outlays that will be required for effectuating a given policy choice. Because certain policy choices can have long-term benefits that outweigh long-term costs, negative costs are a distinct possibility.

[62] Coady et al., "How Large Are Global Energy Subsidies?", IMF Working Paper, Fiscal Affairs Department, 2015, paper and underlying data available at: https://www.imf.org/en/News/Articles/2015/09/28/04/53/sonew070215a.

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go to large corporations) could, therefore, both curtail fossil-fuel production, through forcing companies to bear more of the true costs of fossil-fuel production, and substantially reduce our national deficit in one fell swoop. Equity would also be improved with corporations paying more and individuals, such as the Youth Plaintiffs and Affected Children, benefiting.

46. There are many reasons to be optimistic that emissions could be curtailed further than previously thought. These benefits are a result of continued technological development in the renewables sector. Because of technological improvements, the costs of renewables and storage are decreasing. The price of solar panels has dropped by more than half in recent years (80 percent reduction from 2008 to 2016).[63] In 2016 alone, the average dollar capital expenditure per megawatt for solar photovoltaics and wind dropped by over 10 percent.[64] As these technologies continue to improve and the efficiency increases, while manufacturing costs drop, these technologies will more easily substitute for existing fossil fuel infrastructure.

47. Transitioning to a non-fossil-fuel-based economy will require additional investment in our energy sector. Such sectoral shifts in our economy are not uncommon. In fact, a hallmark of a well-functioning market economy is its ability to shift between sectors as

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See also a report published by the Overseas Development Institute and Oil Change International, which found that as of 2014, the U.S. government provides approximately $20 billion annually in producer side subsidies through various tax exceptions/deductions.

Doukas, Alex, "G20 subsidies to oil, gas and coal production: United States", Overseas Development Institute, 2015, https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9979.pdf).

With the recent tax cuts, the deficit is currently forecasted to be about $1 trillion in the next fiscal year. See, Associated Press in Washington, "US deficit to approach $1tn after Trump tax cuts and spending bill, CBO says," *The Guardian*, April 9, 2018, https://www.theguardian.com/us-news/2018/apr/09/us-deficit-trump-tax-cuts-trillion-cbo-projection.

63 See, e.g., Ryan Whitman, "We could be headed for a solar power renaissance as costs keep dropping," *ExtremeTech*, December 19, 2016, https://www.extremetech.com/extreme/241300-headed-solar-power-renaissance-costs-keep-dropping.

64 Frankfurt School-UNEP Centre/BNEF, "Global Trends in Renewable Energy Investment 2017," 2017, http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

technology changes and demand fluctuates. For example, we have seen shifts from agriculture to manufacturing to services over the course of the twentieth century, and we saw a shift towards the financial sector (from less than 3 percent to over 8 percent of GDP) from the 1950s to its peak in 2006 (immediately before the financial crisis).[65] Our spending on our energy sector has also fluctuated, as the chart below shows energy expenditures as a percent of GDP from 1970 to 2015. While the high levels of spending in the early 1980s (over 10 percent) were during periods of economic turbulence with high inflation and an energy crisis, there have been other periods, such as the 2000s and the early 1970s where there was economic growth and high spending on our energy system. Moreover, our economy has endured sudden, unplanned disruptions in the past (again, for example, the financial crisis); moving our economy to one without fossil fuels would come with a slight cost, but would be an event we can plan for to minimize disruptions (and would bring net benefits in the form of risk reduction).

[65] See, e.g., Robin Greenwood and David Scharfstein, "The Growth of Finance," *Journal of Economic Perspectives*, 27(2) (Spring 2013): 3-28.

Figure 1: Energy Expenditures as Share of GDP (Percent)

Source: U.S. Energy Information Administration, March 2018 Monthly Energy Review, Table 1.7 Primary Energy Consumption, Energy Expenditures, and Carbon Dioxide Emissions Indicators.

48. There are a number of important new "energy smart" technologies that can play a role in reducing dependence on energy, making our existing energy infrastructure more efficient.[66] Smart grids, for example, can turn on appliances when renewable electricity is plentiful—and ramp down electric loads when renewable power wanes. Advanced energy storage technologies are increasingly diverse and many, like ice energy storage, are simpler and can be more cost effective than chemical batteries. Electric vehicles can also be considered "energy smart" technology, as their charging and discharging of batteries can be flexible, creating great potential to improve the efficiency of our national energy infrastructure. These technologies reduce overall energy consumption, so that even without the introduction of less carbon intensive energy sources, they can reduce

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[66] Frankfurt School, UNEP Centre, "Global Trends In Renewable Energy Investment 2017," http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

carbon emissions. Many energy efficiency technologies actually have a negative cost to implement, especially if one includes in the costs the implicit costs associated with GHG emissions (costs to society that are currently externalized).[67]

49. The major U.S. corporations that have committed themselves to dramatic emissions reductions—as well as state and local governments that have committed to emissions reductions—support the feasibility of a swift transition.[68] Creating predictability is of significant economic value in aggressively seeking to reduce emissions; i.e., it makes clear to players in the future economy that they can plan accordingly with very high confidence. In addition, this greater certainty facilitates the production of goods and services at lower costs. For instance, the Chief Executive Officers of Apple, BHP Billiton, BP, DuPont, General Mills, Google, Intel, Microsoft, National Grid, Novartis Corporation, Rio Tinto, Schneider Electric, Shell, Unilever, and Walmart all called on the President to stay the course with respect to United States' participation in the Paris Agreement.[69] So too, were the Defendants to adopt a high and reliable price of carbon, households and firms would know that it paid economically to adopt low- or zero-emission technologies and products.

50. In pursuing clean-energy technology, there is also the potential for increasing overall economic production and stimulating aggregate demand and economic growth. As I

[67] See, e.g., European Commission, "The Macroeconomic and Other Benefits of Energy Efficiency", https://ec.europa.eu/energy/sites/ener/files/documents/final_report_v4_final.pdf.

[68] In 2017, for example, nine states making up the Regional Greenhouse Gas Initiative consortium agreed to a cap-and-trade program that seeks a 30 percent reduction in carbon pollution from energy plants by 2030. See, Colin Young, "9 states, including Mass., Agree to Accelerate Emission Reductions in Next Decade," *WBUR*, August 23, 2017, http://www.wbur.org/news/2017/08/23/9-states-including-mass-agree-to-extend-carbon-reduction-goals-to-2030.

Other state-driven strategies include California's January 2018 announcement to have 5 million zero-emission vehicles in use by 2030; Hawaii mandating that all of the state's electricity come from renewable sources by the mid-21st century; and Vermont's commitment to reduce emissions to 80-95 percent below 1990 levels by 2050. See, "U.S. Leads in Greenhouse Gas Reductions, but Some States are Falling Behind," Environmental and Energy Study Institute, March 27, 2018, http://www.eesi.org/articles/view/u.s.-leads-in-greenhouse-gas-reductions-but-some-states-are-falling-behind.

[69] See, e.g., Center for Climate and Energy Solutions, "Top companies urge White House to stay in the Paris Agreement," Center for Climate and Energy Solutions Press Release, April 2017, https://www.c2es.org/newsroom/releases/major-companies-urge-white-house-stay-paris.

wrote a few years ago in *The Guardian*, "retrofitting the global economy for climate change would help to restore aggregate demand and growth."[70] Consistent with this, the High-Level Commission, which I co-chaired with Lord Stern,[71] found that "climate policies, if well designed and implemented, are consistent with growth, development, and poverty reduction. The transition to a low-carbon economy is potentially a powerful, attractive, and sustainable growth story, marked by higher resilience, more innovation, more livable cities, robust agriculture, and stronger ecosystems."[72]

51. However, instead of supporting existing clean energy technology that would benefit the economy and create jobs, Defendants are acting in ways to suppress and hinder clean energy, which also leads to job losses and harms the economy. For example, in January 2018, President Trump approved tariffs on imported solar cells that start at 30 percent. The tariffs are unlikely to benefit American solar manufacturing jobs, but, according to the Solar Energy Industries Association, are likely to result in the loss of 23,000 American jobs this year and the delay or cancelation of billions in solar investments. The tariffs are also expected to lead to a net reduction in solar installations by roughly 11 percent between 2018 and 2022, a 7.6-gigawatt reduction in solar PV capacity, which means approximately 1.2 million homes will not be powered by renewable solar energy. Such tariffs are both harmful for the environment and the economy.[73]

52. Not promptly undertaking actions to pursue clean-energy technology continues to expose Youth Plaintiffs and Affected Children to the risk of extreme costs and damages, not just from climate change itself, but from the required outlays on future remediation and adaptation efforts and a weaker, less efficient, and more expensive U.S. economy.

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70 Stiglitz, J., "Climate Change and Poverty Have Not Gone Away," *The Guardian*, January 7, 2013, https://www.theguardian.com/business/2013/jan/07/climate-change-poverty-inequality

71 Lord Stern succeeded me as Chief Economist of the World Bank and subsequently was a leading economic advisor to the UK Treasury, as Second Permanent Secretary and head of the Government Economic Service.

72 High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices," 2017, Washington, DC: World Bank, p. 1.

73 Julia Pyper, "New Tariffs to Curb US Solar Installations by 11% Through 2022," *Greentech Media*, January 23, 2018, https://www.greentechmedia.com/articles/read/tariffs-to-curb-solar-installations-by-11-through-2022#gs.YNvvdYQ

B. POLLUTION IS A CLASSIC EXTERNALITY THAT CAN BE COMBATED WITH STANDARD ECONOMIC TOOLS THAT PROMOTE SOCIAL WELFARE

53. Currently, around 80 percent of the energy consumed in the U.S. comes from fossil fuels.[74] In contrast, renewable energy sources comprise 11 percent of total energy consumption. That percentage has only risen by 2 percent (9 to 11 percent) from 1949 to 2017.[75]

54. The burning of fossil fuels generates large amounts of pollution. Pollution is the archetypal negative externality. In economics, an externality arises when the cost or benefit of an activity of one party imposes a cost or benefit on another. In the pollution example, the polluter makes a good (its primary activity), but in the course of doing so generates pollution that imposes a cost or burden on another (e.g., a fisherman who fishes in the waters that become polluted will catch fewer fish). A positive externality example might be a technological development that benefits more than the inventor alone (e.g., the developer of the worldwide web who made it freely available).

55. The issue that arises with a negative externality is that the producer of the externality (e.g., the polluter) considers only their private costs when making production decisions and not the total costs of their activity (the costs borne by the polluter and the fisherman). Standard economic theory argues that private markets can be relied on to make efficient decisions, if, and only if, the (marginal private) costs confronting individuals equal the (marginal) social costs, and the (marginal private) benefits confronting them equal the (marginal) social benefits. When there is an externality, social and private costs and/or benefits are not aligned. A classic way to intervene in this situation is for government to tax the causes of negative externalities (thereby raising the effective private cost closer to

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[74] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, March 2018 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

[75] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, March 2018 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

the social cost and forcing the producer to bear the full cost of their actions).[76] Having a well-functioning price system—where price setters take into account all costs—is important for economic efficiency and overall social welfare.

56. At present, the U.S. lacks a comprehensive carbon-pricing regime that accounts for the negative externalities of burning fossil fuels such that private markets can be relied on to make efficient decisions. Thus, producers and sellers of fossil fuels consider only their private costs and benefits, and the costs that their activities are imposing on society through, among other factors, increased GHG emissions and long-term climate effects of the sort I discussed earlier are not considered or internalized as part of the price.

57. Beyond the lack of a comprehensive carbon-pricing regime, a faulty system that is full of hidden subsidies for fossil fuels, as noted above, hinders the transition towards a less carbon-intensive economy. These subsidies also accelerate and exacerbate the costs to Youth Plaintiffs from climate change.

58. These subsidies take many forms. For instance, upstream oil and gas exploration and production companies in the U.S. receive several tax breaks that go beyond those afforded to businesses generally, such as deducting intangible drilling costs as a current business expense (not capitalized over the life of the well), depletion allowances,[77] and offshore drilling tax royalty relief (which permits the claiming of foreign royalties as taxes (and makes them creditable against U.S. taxes) for taxpayers taxed in two countries). When companies make an investment, it is natural that they be allowed to depreciate the cost of the capital as a tax-deductible expense over the lifetime of the asset.

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[76] Sometimes, governments have to rely on "second best" interventions. Thus, government can subsidize alternatives (or positive-externality activities), which lowers the effective price of substitute products. Lowering the price of a substitute product can have the effect of increasing demand for the substitute (e.g., clean energy) and reducing the demand for the original product (e.g., fossil fuel-based energy). But leaving the negative externality-generating activity without a "charge" for its external effects leaves a distortion in place.

[77] I have studied the economics of depletion allowances, together with Sir Partha Dasgupta, in my academic work. See, J.E. Stiglitz, "Monopoly and the Rate of Extraction of Exhaustible Resources," *The American Economic Review* 66(4) (September 1976): 655-661 and P. Dasgupta and J.E. Stiglitz, "Uncertainty and the Rate of Extraction Under Alternative Arrangements," *Institute Mathematical Studies in the Social Sciences*, tech. rep. no. 179 (September 1975).

But with depletion allowances, an oil company can deduct 15 percent of the revenue as a "depletion allowance," regardless of the amount of investment it made to find the oil.[78] The company receives the depletion allowance—as if it invested money—even if it makes no investment. The value of this provision itself is enormous; some estimates say it could save the U.S. Treasury over $11 billion in 10 years if it were eliminated.[79] (Money not received by Treasury is, in effect, money given to the fossil fuel industry.) Coal companies can receive similar corporate tax reductions, and are able to purchase or lease land from Defendants at below market rates.[80] These tax breaks artificially reduce the private cost of fossil fuels to producers and consumers (but not the social cost), which makes renewable sources of energy appear less competitive to consumers.[81] In the U.S., these tax breaks for fossil fuel companies have resulted in an economy heavily dependent on fossil fuels and infrastructure designed around fossil fuels.

59. Similarly, at various times, oil, gas, and coal leases have been conducted in ways in which fossil fuel companies are able to obtain leases at prices far below what the competitive equilibrium price would be, depriving taxpayers of money they need for a variety of public purposes, while distorting the market to make participation in oil, gas, and coal more economically attractive.[82] The efficient auctions that have been used in

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78 This provision dates to 1913. See, e.g., Rebecca Leber, "Happy 100th Birthday, Big Oil Tax Breaks," *Think Progress*, March 1, 2013, https://thinkprogress.org/happy-100th-birthday-big-oil-tax-breaks-3c9731c4bc85/. See also, Seth Hanlon, "Big Oil's Misbegotten Tax Gusher," *Center for American Progress*, May 5, 2011, https://www.americanprogress.org/issues/economy/news/2011/05/05/9663/big-oils-misbegotten-tax-gusher/.

79 See, Seth Hanlon, "Big Oil's Misbegotten Tax Gusher," *Center for American Progress*, May 5, 2011, https://www.americanprogress.org/issues/economy/news/2011/05/05/9663/big-oils-misbegotten-tax-gusher/.

80 Doukas, Alex, "G20 subsidies to oil, gas and coal production: United States", Overseas Development Institute, 2015, https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9979.pdf.

81 Bridle, Richard, Kitson, Lucy, "The Impact of Fossil-Fuel Subsidies on Renewable Electricity Generation", International Institute for Sustainable Development, December 2014, http://www.iisd.org/sites/default/files/publications/impact-fossil-fuel-subsidies-renewable-electricity-generation.pdf.

82 This was the case, for instance, in the early 1980s, when large numbers of tracts were simultaneously put up for auctions, so many that the average tract had less than two bidders. I discussed some of the

Continued on next page

other areas (e.g., for the auctioning of the electro-magnetic spectrum) were typically never used. A 2016 report from the President's Council of Economic Advisors regarding coal leases recognized several of these points explicitly, noting, for example, that the coal leasing program "has been widely criticized in recent years by economic and environmental experts for providing a poor return to the taxpayer and for not adequately addressing the environmental costs of coal extraction, processing, and combustion."[83] The report also found that previous and then-current policies of Defendants had misaligned incentives: "the program has been structured in a way that misaligns incentives going back decades, resulting in a distorted coal market with an artificially low price for most Federal coal and unnecessarily low government revenue from the leasing program."[84] The report suggests that to fully reflect the social costs of coal extraction—i.e., price the externality completely—the costs are so high that the resulting royalty rate may be "well-over 100 percent."[85]

Continued from previous page

research in this instance in my Nobel lecture. See, J.E. Stiglitz, "Information and the Change in the Paradigm in Economics," Prize Lecture, December 8, 2001, pp. 489-490, https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/2001/stiglitz-lecture.pdf.

See also, J.J. Leitzinger and J.E. Stiglitz, "Information Externalities in Oil and Gas Leasing," *Contemporary Policy Issues* 5 (March 1984): 44-57 and J.E. Stiglitz, "What is the Role of the State?" Chapter 2 in M. Humphreys, J.D. Sachs, and J.E. Stiglitz (eds.) "Escaping the Resource Curse," 2007, Columbia University Press, pp. 23-52 at p. 31: "When competition for the resources is limited—and especially when it is known that it is limited—then the prices that prevail will be lower. There are three ways of limiting competition. The first is suddenly to put up for lease a large number of tracts—increase the supply so that the bidding on each tract is limited. This is what President Reagan did in the early 1980s. It was like a fire sale—as if the government had to get rid of its holdings immediately. But in fact, there was no reason for it; it was not as if the oil was going to disappear, or as if the United States needed to raise cash quickly. On a very large fraction of tracts, there was only one bidder (and, of course, the oil companies knew this). In a study I conducted with Jeff Leitzinger (1984) we quantified the impact on the price the government received. The government got a fraction of what it would have earned had the tracts been put up in a more orderly process, and the extra profits went into the coffers of the oil companies."

83 "The Economics of Coal Leasing on Federal Lands: Ensuring a Fair Return to Taxpayers," Executive Office of the President of the United States, June 2016, at p. 2, https://obamawhitehouse.archives.gov/sites/default/files/page/files/20160622_cea_coal_leasing.pdf.

84 *Id.*

85 *Id.* at p. 29.

60. An important source of protection against global warming is carbon-sequestration—holding carbon in trees, plants, wetlands, or soils. Carbon molecules that are thus held are carbon molecules that are not in the atmosphere.[86] There are large amounts of public land holding millions of acres of trees, but the government has an industry-driven policy framework in which (a) the timber industry, which acquires the right to cut down the timber, does not pay for the carbon costs of their activities; (b) the timber industry is typically subsidized through roads constructed by the Department of Agriculture, which manages these public forests; (c) the timber industry, like the fossil fuel industry, receives favorable tax benefits; and (d) the timber industry acquires these assets at prices that are below prices that would prevail in a competitive market that accounted for all private and public costs of logging.[87]

61. The provision of these tax benefits and the sale and/or lease of these public assets at below competitive market prices by Defendants harms the U.S. today, and these Youth Plaintiffs and Affected Children, in multiple ways. The harm to the U.S. arises because improper pricing that ignores the externalities of logging leads to inefficient uses of forests, logs, and wood products that would not materialize if the price of logs reflected the carbon costs of cutting down the trees and releasing CO_2 into the atmosphere. These actions by Defendants support the destruction of forests, which are needed to sequester CO_2 (not to mention all the critical ecosystem benefits forests provide). The poorly functioning price mechanism deprives our society of governmental revenues that could be used for multiple purposes, including investment in emission reductions and investments in R&D that would facilitate the transition towards a green economy; and forces taxes to be imposed elsewhere, with distortionary costs—so that total costs to society are well in excess of the losses of tax revenues. The resulting weaker economy

86 For a more thorough articulation of this framework, see J.E. Stiglitz, "Sharing the Burden of Saving the Planet: Global Social Justice for Sustainable Development: Lessons from the Theory of Public Finance," Columbia University Academic Commons, https://doi.org/10.7916/D8KD24MX and Mary Kaldor and Joseph E. Stiglitz, eds., *The Quest for Security: Protection without Protectionism and the Challenge of Global Governance*, New York: Columbia University Press, pp. 161-190.

87 See, e.g., "Congressional Subsidies for Private Logging," Taxpayers for Common Sense, December 13, 2001, http://www.taxpayer.net/library/article/congressional-subsidies-for-private-logging.

means that Youth Plaintiffs are inheriting an economy that is not only dirtier than it otherwise would have been, but also weaker.

62. There are also indirect explicit subsidies that contribute to the continued reliance on fossil fuels, such as government investments and policies that promote emission producing methods of transportation or manufacturing.

63. Another implicit subsidy granted by governments is to not charge the fossil fuel industry for the negative externalities they create, such as carbon emissions. As discussed above, carbon emissions, and pollution in general, are negative externalities that can affect society and the economy, yet the vast majority of negative-externality carbon emissions across the globe are not priced.[88] Pricing CO_2 emissions and emissions of other GHGs would greatly enhance revenues available to government to address a variety of societal needs, as I discussed in Section IV above. A basic principle of taxation is that it is better to tax bad things like pollution than good things like savings and work. Again, the resulting weaker economy means that Youth Plaintiffs are inheriting an economy that is not only dirtier than it otherwise would have been, but also weaker. In this instance, not only are Defendants not raising revenue in an efficient way (subsidizing rather than taxing carbon emissions), Youth Plaintiffs are burdened with the socioeconomic costs that arise with pollution, such as additional healthcare costs.

64. Defendants have recognized for at least 40 years that these direct and indirect subsidies to fossil fuel producers hinder the adoption of renewable energy and improvements in

88 See, e.g., High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices," 2017, Washington, DC: World Bank, at p. 35: "The carbon prices observed span from less than US$1/tCO2e to US$126/tCO2e, 85 percent of global emissions are not priced today…"

Because all emissions generate externalities, for an efficient economy, all emissions should be taxed. In a few instances, the adverse effects of not taxing the emissions can be mitigated by the imposition of regulations.

renewable energy technologies. For example, a 1978 memo to President Carter regarding solar power found that:[89]

> Widespread use of solar energy is also hindered by Federal and state policies and market imperfections that effectively subsidize competing energy sources. These policies include Federal price controls on oil and gas, a wide variety of direct and indirect subsidies, and utility rate structures that are based on average, rather than marginal costs. Also, the market system fails to reflect the full social benefits and costs of competing energy sources, such as the costs of air and water pollution.

65. If Defendants stopped providing subsidies and/or implemented carbon pricing policies that allow the U.S. government to further fund research and development of green technologies to decarbonize the economy, such measures would have a large positive impact in the long term. These positive effects are not limited to mitigating the environmental effects; there are monetary gains, too. Some estimates of the financial benefit to the U.S. economy of accelerating technological developments for lowering carbon emissions suggest that they would amount to $1 trillion by 2050.[90]

66. This monetary estimate does not take into account possible spillover effects from advancing technology that could provide further value to the economy (e.g., in the same way that the space race or developments in the world wars brought us many advancements in basic science that made their way into consumer and industrial products). Even without technological change, the net financial costs to the economy may be negative, taking into account the financial benefits of eliminating carbon subsidies and replacing them with carbon taxes and the consequent development of a more efficient low-carbon energy system.

67. A short-term measure Defendants can readily implement is to cease approvals for any new fossil fuel infrastructure, pending completion of a national climate recovery plan. Any new coal projects or coal extraction harms Youth Plaintiffs. For example, it

[89] Attachment to Memorandum from Jim Schlesinger to The President, "Domestic Policy Review of Solar Energy: A Response Memorandum to The President of the United States," December 5, 1978, at p. iv.

[90] Richard G. Richels, Geoffrey J. Blanford, "The value of technological advance in decarbonizing the U.S. economy," *Energy Economics* 30(6) (2008): 2930-2946, ISSN 0140-988.3.

increases GHG emissions locking in higher concentrations of GHGs in the atmosphere as Youth Plaintiffs grow up and live their lives, with all the attendant costs and impacts that I have described thus far. Enabling investments in long-lasting "fossil" infrastructure (like coal-burning power plants and oil and natural gas pipelines) means that for decades going forward, there will continue to be incentives to engage in costly carbon emissions. Once the plants are built, the owners have an incentive to continue using it to recover their investment (and in so doing, generate GHG emissions). Furthermore, should a fossil-fuel plant be shut down before the natural end of its economic life, there will be allegations of lost economic value (the owners' private loss on their investment). Such allegations will become a political argument against taking further actions curbing emissions. (These arguments will almost surely be put forward even though the public benefits of shutting down the coal fired plants may be enormous—as I have noted—and even though a standard argument in economics is that bygones-are-bygones. Mistaken investments in the past should not continue to justify distorted power generation. Elsewhere, however, the "politics" of stranded assets has played an important role—that is to say; private owners of large, sunk investments have (successfully) argued for preferential treatment for them to recoup their private investments, despite the attendant social costs.)

68. I should also respond to an expected argument from Defendants that, even if the U.S. were to lower its GHG emissions, other countries would increase their production of goods that create GHGs. This might be referred to as a "substitution" argument. There are two rejoinders to this:

    a. First, I turn to standard economic theory. That is, that in any given equilibrium the lowest-cost providers are providing any given resources. Thus, if the U.S. is providing GHG-dependent products today, it is because the marginal cost of the U.S. providing such products is below the next-cheapest alternative. If the U.S. were to cease producing, say, 100 "units" of GHGs, the next-cheapest alternative would increase its production by less than 100 "units" (because if it made economic sense for the next-cheapest alternative to produce more than 100 "units" they would already be doing so). As such, any substitution will be less than perfect and reductions in

U.S. emissions will be offset less than one-to-one by alternative supplies (i.e., there will be a net reduction).

b. Second, specific to GHG emissions, recent technical studies have shown that U.S. emissions will not be perfectly offset.[91] This is consistent with the general theory I mentioned above. While climate change is a global problem, the U.S. is a significant contributor to GHG emissions, and so actions by the U.S., both directly, and by the leadership which such actions provide, has a significant impact on these global outcomes. Indeed, the U.S. stands out as the sole country announcing that it is not committed to the reduction of carbon emissions, having announced that it will leave the Paris Agreement. Despite the U.S.'s actions, other countries remain committed. Thus, if the U.S. were to recommit itself to climate action, there is no significant risk of other countries polluting more, so as to offset the benefits of U.S. reductions in carbon emissions.

69. The government has recognized since the 1980s that the U.S. will need to take a leadership role in climate change. For example, a government memorandum from 1989 discusses the desire for the U.S. to have a leadership role in addressing climate change. The memorandum also makes clear that when it comes to addressing climate change the U.S. "simply cannot wait -- the costs of inaction will be too high."[92]

C. DEFENDANTS' USE OF DISCOUNTING IN DECISION-MAKING UNDERESTIMATES THE COSTS OF CLIMATE CHANGE ON YOUTH PLAINTIFFS AND FUTURE GENERATIONS AND THE BENEFITS OF MITIGATION, WITH DELETERIOUS CONSEQUENCES

70. In running the government, Defendants must repeatedly make decisions about projects and policies. They must evaluate alternative choices with which they are confronted. In this section, I explain that the way Defendants do this systematically undermines the

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[91] See, e.g., P. Erickson and M. Lazarus, "Would constraining US fossil fuel production affect global CO2 emissions? A case study of US leasing policy," *Climatic Change*, 2018, https://doi.org/10.1007/s10584-018-2152-z.

[92] Memorandum from Frederick M. Bernthal to Richard T. McCormack, Department of State, February 9, 1989, attachment "Environment, Health and Natural Resources Issues," and responses to "Question #1."

interests of Youth Plaintiffs in a way which cannot be justified. Indeed, economic science provides sound alternative methodologies for the evaluation of policies and projects which systemically lead to better outcomes for society in general, and would not systematically discriminate against Youth Plaintiffs in the way that existing policies do.

71. While there are a number of longstanding and well-established perspectives in economics which recognize that delaying the kinds of precautionary actions suggested above is deleterious to societal welfare, government practices and procedures underlying important decision-making systematically undervalue the costs to be borne by future generations (including Youth Plaintiffs and Affected Children).

72. The issue devolves around how governments should value benefits and costs that arise at some future date relative to those that occur today. Typically, less value is given to future effects than to current effects. The question is, how much less. Since the most catastrophic effects of climate change may not be felt for years (see paragraph 27 and footnote 19, above), saying that what happens in the future does not matter much biases public decision making against taking actions to protect Youth Plaintiffs.

73. The standard methodology for making such assessments is called cost-benefit analysis. In a cost-benefit analysis, using a discount rate is commonplace; however, that discount rate must be appropriate. As I have noted, issues around discounting are especially important in the context of climate change because the full benefits may not accrue for many years after society incurs costs to limit the emissions of GHGs.[93]

74. Formal intertemporal analysis on which so much of modern economics is based originated with the path breaking work of Frank Ramsey, who argued that there was no ethically defensible justification for discounting the well-being (utility) of future

[93] There is also a problem with how discounting is often applied when we consider future costs compared to future benefits. Standard economic theory says that risky future benefits (e.g., uncertainty regarding an investment's return) are discounted to account for that risk. That is, risky benefits are worth less than riskless benefits. When we consider costs, however, analysts often *reduce* risky costs: uncertainty regarding future costs should decrease the value of a project (i.e., increase its costs), not increase the value of a project.

generations.[94] In the almost one century since his work, no one has developed a persuasive argument to the contrary.[95]

75. There is an argument that future consumption should be discounted, since future incomes are assumed to be higher, and standard arguments of diminishing marginal utility imply that if that is the case, the value of consumption will be lower. But the high discount rates used by Defendants can only be justified by the assumption of high future increases in standards of living. Since 2008, there is overwhelming evidence that the pace of productivity has declined markedly, implying that we cannot count on past rates of increases prevailing in the future. There is one school of thought (studied and advocated by Prof. Robert Gordon at Northwestern) that argues even the current pace of

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[94] Clearly, if one thought that the world would end, say in 50 years, as a consequence of a nuclear war, unrelated to climate change, one would not need to take into account events beyond the 50-year extension. We rule out such possibilities, or assume that they are of sufficiently low probability as not to affect our analysis.

For mathematical tractability, many analyses assume a small, positive pure intergenerational discount rate. While ethically indefensible for our purposes, the results are not much different from those obtained with a zero discount rate.

[95] In the middle of the twentieth century, two teams of researchers, each with a prominent Nobel Prize winner, formulated "guides" to cost benefit analysis. See Dasgupta, Sen, and Marglin, prepared for UNIDO (the United Nations Industrial Development Organization) (P. Dasgupta, S.A. Marglin, A. Sen, *Guidelines for project evaluation*, United Nations Industrial Development Organization, Vienna (1972) (United Nations publication sales no.: E.72.II.B.11)) and Little and Mirrlees, prepared for OECD Development Center (I.M.D. Little and J.A. Mirrlees, *Manual of Industrial Project Analysis in Developing Countries vols. 1 and 2*, OECD, Paris (1968, 1969). Amartya Sen received the Nobel prize in 1998, Partha Dasgupta was knighted in 2002, Ian Little was the Deputy Director of the Economic Section at the U.K. Treasury and a distinguished Oxford development economist, and Sir James Mirrlees received the Nobel Prize in 1996.

In the 1970s, discounting became important as the country thought through how to respond to the oil price shocks: what were the requisite changes to its energy system? Though this was done in an era before the costs of carbon emissions were widely understood, the principles are still relevant. See J.E. Stiglitz, "The Rate of Discount for Cost-Benefit Analysis and the Theory of the Second Best," *Discounting for Time and Risk in Energy Policy*, R. Lind (ed.), Baltimore: The Johns Hopkins University Press, 1982, pp. 151-204.

There have been various guidelines published on this topic for internal government use, see, for example: OMB Circular No. A-94, "Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits" (Mar. 27, 1972) and OMB Circular No. A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs", Oct. 1992.

productivity—far lower even than in the recent past—may decline still more.[96] Whether one agrees with Gordon's assessment or not, this recent discussion has brought out four key points:

a. There is considerable uncertainty about the pace of increase in living standards.

b. The pace of increase in living standards is endogenous—it depends on what actions we take.

c. If there is significant climate change, and if we continue on our current path, there is a significant risk of a decrease in standards of living.

d. The marginal value of consumption is likely to be high in those states of nature where climate change is greater, and where the adverse effects of climate change are large. That is to say, the value of additional consumption—the ability to build or consume more—and therefore its price will be higher when the effects of climate change are greater. Thus, in those places where the effects of climate change are most pronounced—where damage is the greatest and remediation need and costs are the highest—the *social cost* of such remediation will also be at its highest, exacerbating the damages to Youth Plaintiffs (both because when damages are high, the cost of remediation is also high, and because levels of consumption—what is left over after paying for remediation costs, and taking into account the damage done by climate change—are low).

76. It would be foolhardy—and wrong—for public policy to proceed as if there were no risk, either of a decrease in living standards, and especially of a lowering of those standards as a result of a failure to appropriately curtail emissions.

77. Standard economics over the past half century has emphasized the importance of risk aversion, and that risk affects our actions. Common usage of discounting in public finance fails to take account of risk appropriately. When individuals are risk averse, they

[96] See, R.J. Gordon, *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War*, Princeton University Press, 2016. See also, R.J. Gordon, "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds," *NBER Working Paper*, No. 18315, August 2012, http://www.nber.org/papers/w18315.pdf.

are willing to buy insurance against a risk—to pay a considerable risk premium. This is also true for the business sector and society in general. This is especially important when we assess the appropriate response to the threat of climate change. The planet Earth cannot buy insurance from another planet against the risk of climate change here, but we can take precautionary actions. At the very least, this implies that the discount rate used for assessing climate change actions should be markedly different from that used for conventional short-term projects. As Chairman of the Council of Economic Advisers, I headed a review committee for the Office of Management and Budget (OMB) reviewing the guidelines for discounting, and that was the conclusion we reached in the late 1990s—that one must account for changes in relative price over time, and when our environment becomes more valuable in the future (i.e., as the value of preserving it becomes higher) that must be reflected in the economic analysis.[97] This was consistent with the position taken in the 2nd assessment of the IPCC, and in a paper I co-authored with the late Nobel laureate Kenneth Arrow and others.[98]

78. More than half a century ago, President Johnson sent a message to Congress that we faced two paths: the cheaper option, in the short-term, of carrying down the path of pollution, or the more expensive option (at the time), of restoring the country and its natural heritage to the people.[99]

> We are able to see the magnitude of the choice before us, and its consequences for every child born on our continent from this day forward. Economists estimate that this generation has already suffered losses from pollution that run into billions of dollars each year. But the ultimate cost of

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97 Our report was issued in 1996: "Economic Analysis of Federal Regulations Under Executive Order 12866," The White House, January 11, 1996, https://obamawhitehouse.archives.gov/omb/inforeg_riaguide/.

98 K. Arrow, W.R. Cline, K-G. Maler, M. Munasinghe, J. E. Stiglitz, and R. Squitieri, "Intertemporal Equity and Discounting," in *Global Climate Change: Economic and Policy Issues*, M. Munasinghe (ed.), World Bank Environment Paper 12, Washington, D.C. 1995, pp. 1-32. Reprinted in an abbreviated format as "Intertemporal Equity, Discounting, and Economic Efficiency," *Climate Change 1995: Economic and Social Dimensions of Climate Change*, J. Bruce, H. Lee, and E. Haites (eds.), Cambridge: Cambridge University Press, 1996, pp. 125-144.

99 "Preserving Our Natural Heritage," Message from the President of the United States, transmitting "Programs for Controlling Pollution and Preserving our Natural and Historical Heritage," February 23, 1966.

> pollution is incalculable. We see that we can corrupt and destroy our lands, our rivers, our forests, and the atmosphere itself all in the name of progress and necessity. Such a course leads to a barren America, bereft of its beauty, and shorn of its sustenance. We see that there is another course more expensive today, more demanding. Down this course lies a natural America restored to her people. The promise is clear rivers, tall forests, and clean air – a sane environment for man.

79. For the last 50 years, Defendants have shirked from the "more demanding" course of restoring "America … to her people." Defendants' policies that discount the future of Youth Plaintiffs and Affected Children at inappropriately high rates continue to steer America on the path of incalculable losses and away from that more demanding and sane course. The costs of fixing the damage today are much higher than they would have been in 1966 when President Johnson sent his message; but, the costs today are much lower than what they will be after another 50 years of fossil fuel pollution and inaction.

VI. CONCLUSION

80. The choice between incurring manageable costs now and the incalculable, perhaps even irreparable, burden Youth Plaintiffs and Affected Children will face if Defendants fail to rapidly transition to a non-fossil fuel economy is clear. While the full costs of the climate damages that would result from maintaining a fossil fuel-based economy may be incalculable, there is already ample evidence concerning the lower bound of such costs, and with these minimum estimates, it is already clear that the cost of transitioning to a low/no carbon economy are far less than the benefits of such a transition. No rational calculus could come to an alternative conclusion. Defendants must act with all deliberate speed and immediately cease the subsidization of fossil fuels and any new fossil fuel projects, and implement policies to rapidly transition the U.S. economy away from fossil fuels.

81. This urgent action is not only feasible, the relief requested will benefit the economy. More importantly, this action is necessary if Defendants are to prevent the extreme cost and damages Youth Plaintiffs and Affected Children are facing and will face to an even greater extent if Defendants continue on a path that does not account for what is scientifically necessary to protect the climate system they depend on for their future well-being and their personal and economic security.

Joseph E. Stiglitz, Ph.D.
April 13, 2018

INSIGHT | April 26, 2016

Life's a Beach

(https://www.youtube.com/watch?v=Zv8Yb4W-oC4)

Insight Video Preview (https://www.youtube.com/watch?v=Zv8Yb4W-oC4)

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- Insight Report (http://www.freddiemac.com/research/pdf/feb_2016_public_outlook.pdf)
- Forecast Table (http://www.freddiemac.com/research/docs/March_2016_Public.xls)

So you've always dreamed of living at the beach, but you're discouraged by the high price of beachfront property? Not to worry. We've found just the place for you. Three bedrooms, two baths, just under 2,000 square feet. Zillow®'s estimate (http://www.zillow.com/homes/for_sale/Grayland-WA/91561228_zpid/18370_rid/any_days/globalrelevanceex_sort/46.777081,-124.000368,46.696845,-124.115038_rect/12_zm/%5d) of the value of the home is $105,398, but the listed price was recently reduced to $54,900. Oh, one more thing. According to the information on Zillow, the property is "Located very close to 'Wash Away Beach,' home...will have to be moved off the property soon due to the land eroding away."

Washaway Beach is located on Cape Shoalwater in Washington State. Underwater sand bars near the entrance to Willapa Bay create a circular current that has been eroding (http://www.ecy.wa.gov/programs/sea/coast/erosion/washaway.html) the beach front at an average rate of 100 feet per year for the last century. The original location of the town of North Cove—homes, cannery, lighthouse, Coast Guard station, cemetery, school and post office—is now a mile off shore. State Highway 105 had to be moved inland and is threatened again in its new location.

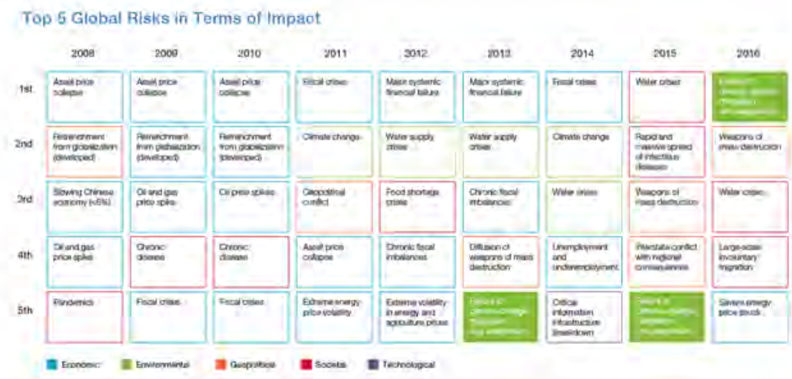
None of this has scared away buyers. In the six years leading up to 2007, 65 parcels changed hands. The lure of living at the seashore apparently outweighs the knowledge that it's only for a short time. Pricing reflects the unusual nature of the area. Beachfront property may sell for $500, but it might not survive the winter. A quarter-mile inland, property with a longer "life expectancy" (http://www.seattletimes.com/seattle-news/hungry-sea-devours-dreams/) may sell for $100,000.

Washaway Beach represents a unique and isolated natural hazard. However, the current trend of climate change—with the associated rising seas, changing weather patterns, and increasing temperatures—presents a more serious challenge to millions of people. Great uncertainty surrounds the pace and magnitude of climate change, but sea levels already are rising measurably, threatening coastal cities around the globe. Worldwide, it's estimated that a hundred million people live within three feet of mean high tide and another hundred million or so live within six feet of it.[1]

In the United States, South Florida is one of the more-vulnerable areas. Daily high-water levels in the Miami area have been increasing almost an inch a year, much faster than the average rate of global sea-level rise.[2] The city of Miami Beach already has spent around $100 million to combat recurrent flooding. Other cities on the Eastern seaboard of the U.S. also are experiencing a 10-fold increase in the frequency of flooding (http://www.nytimes.com/2016/02/23/science/sea-level-rise-global-warming-climate-change.html?_r=0). These floods may produce only a foot or two of standing saltwater, but they kill lawns and trees, block streets, clog storm drains, and threaten freshwater resources.

Insurance is an essential component of real estate transactions, and flood insurance currently makes it possible to obtain loans for homes in areas of identified flood risk. However, some of the varied impacts of climate change—rising sea levels, changing rainfall and flooding patterns, increasing temperatures—may not be insurable. As a result, some important features of housing finance may have to change. The potential impact of these systemic changes on the financial system is difficult to visualize today.

To clarify our thinking about this challenge, we focus on the risk of flooding. In the next section, we discuss the current system in the United States for dealing with flood risk. Finally, we pose some of the questions that will have to be addressed if climate change raises sea levels significantly.



Source: World Economic Forum. (2016) The Global Risks Report 2016. p11

(http://www.freddiemac.com/research/images/201604-is-global-risks-1600px.png)

How do we handle flood risk today?

Lenders require borrowers to take out and maintain insurance against risks that might compromise the value of the home that collateralizes a mortgage. For example, title insurance protects the borrower and the lender against the risk of a defect in the title that might prevent the borrower from selling the property or the bank from foreclosing in the event of a default. And homeowners insurance protects against a variety of risks such as fire and hail damage. However, most homeowners policies *do not* cover flood damage.

When a prospective home buyer applies for a mortgage, the lender consults the Flood Insurance Rate Maps (FIRMs) maintained (https://www.floodsmart.gov/floodsmart/pages/flooding_flood_risks/understanding_flood_maps.jsp) by the Federal Emergency Management Agency (FEMA). If the home is in a high-risk area—as defined by FEMA—the borrower must obtain a flood insurance policy. In addition to maintaining the FIRMs, FEMA also administers the National Flood Insurance Program (NFIP), which offers policies through a network of over 80 private insurance companies. FEMA sets national rates that do not vary across insurance companies or agents. Private, non-NFIP insurance also is available. In fact, NFIP policies are available only in communities that participate in NFIP. FEMA scores participating communities according to their floodplain management activities. Flood insurance premiums can be reduced fby as much as 45 percent in communities that adopt management standards that exceed the NFIP minimum.

Do you live in a high-risk area?

FEMA provides access to its Flood Insurance Rate Maps (FIRMs) on its website. You can check the risk of your home by going to this (https://msc.fema.gov/portal) site, and typing in your address. As an example, here (http://arcg.is/1QclgJf) is the map that covers Freddie Mac's headquarters on Jones Branch Drive in McLean, VA. The gray shaded areas indicate Special Flood Hazard Areas (SFHAs) along the creeks in the area. Fortunately, our headquarters do not lie within an SFHA.

On the other hand, this map (http://arcg.is/1QcmK6n) shows one panel of the FIRM for Miami Beach. The entire area is an SFHA.

Where is the flood risk?

To produce a flood risk map for a community, FEMA conducts a Flood Insurance Study. These studies include statistical data on river flow, storm tides, hydrologic/hydraulic analyses, and rainfall and topographic surveys. The study divides the community into areas defined by the level of flood risk. An important risk measure is the ***base flood*** which is defined as the flood having a one percent chance of being equaled or exceeded in any given year. The base flood often is called the ***100-year flood***; however, this term can be confusing. So-called 100-year floods can occur two years in a row, and the probability of a 100-year flood occurring during the term of a 30-year mortgage is 26 percent. In addition, the magnitude (https://www.floodsmart.gov/floodsmart/pages/flooding_flood_risks/understanding_flood_maps.jsp) of a 100-year flood can change over time as weather patterns change or there are changes to the terrain.

FEMA identifies the ***base flood elevation*** (BFE), as the elevation that would be reached by the base flood. Areas at elevations lower than the base flood elevation are defined by FEMA as Special Flood Hazard Areas (SFHAs). FEMA further divides the SFHAs into eight different flood insurance rate zones based on the magnitude of the flood hazard (http://www.fema.gov/media-library/assets/documents/7984). FEMA also identifies a lower-risk zone—the 500-year flood zone—defined as the area with a 0.2 percent probability in any given year that a flood exceeds the BFE.

Under federal law, flood insurance is mandatory for all federal or federally-related financial assistance for the acquisition and/or construction of buildings in SFHAs. In addition, the GSEs require flood insurance before they will purchase a loan for a property in an SFHA. Typically, a lender will require flood insurance on a house in an SFHA even if the loan will be held in its portfolio. In addition, lenders often require flood insurance (https://www.floodsmart.gov/floodsmart/pages/faqs/why-does-my-mortgage-lender-require-me-to-buy-flood-insurance.jsp) for houses outside of SFHAs which nonetheless are exposed to some level of flood risk. [3] Approximately 20 percent of flood insurance claims come from outside of SFHAs.

Coastal risk

In coastal areas, FEMA takes wave effects into account in determining the BFE and subdivides the SFHA zones further. For example, ***Zone A*** is defined as an area with shallow flooding only due to rising water, where potential for breaking waves and erosion is low, while ***Coastal Zone A*** (http://www.fema.gov/pdf/rebuild/mat/coastal_a_zones.pdf) is defined as an area with potential for breaking waves and erosion during a base flood. In addition, the Coastal Barrier Resources Act (CBRA) of 1982 defines a Coastal Barrier Resources System (CBRS)—ocean front and land around the Great Lakes and other protected areas—that serves as a buffer between coastal storms and inland areas. Properties within the CBRS (https://www.floodsmart.gov/floodsmart/pages/faqs/what-is-the-coastal-barrier-resources-system.jsp) are eligible for federally-regulated flood insurance only if the properties were built prior to 1982 and the community participates in the National Flood Insurance Program (NFIP) administered by FEMA.

The impact of rising sea levels—and some potential responses

The impact of rising sea levels depends on the pace and the magnitude of the change—two factors about which there is great uncertainty. For instance, a recent study (https://www.washingtonpost.com/news/energy-environment/wp/2016/03/30/antarctic-loss-could-double-expected-sea-level-rise-by-2100-scientists-say/) which updates the estimates on the amount of ice melting in Antarctica concluded that the increase in sea level may be twice the level that was previously estimated.

An additional source of uncertainty in the forecasts is the willingness and ability of the world's nations to change the trajectory of climate change. At the Paris climate conference in December 2015, 195 countries adopted a global action plan (https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf) to hold climate change to well below 2° Centigrade above pre-industrial levels. The success of this and future agreements hold the potential to mitigate some of the projected impacts of climate change.

Estimates of the impact

One measure of the impact of climate change is the estimated increase in the areas identified by FEMA as SFHAs, that is, areas where flood insurance is required. A 2013 study (http://www.aecom.ca/vgn-ext-templating/v/index.jsp?vgnextoid=e0642ed99724e310VgnVCM100000089e1bacRCRD) prepared for FEMA by AECOM and Deloitte Consulting LLP estimated that the area of the SFHAs will increase by 45 percent nationally on average by the end of this century. In coastal areas, SFHAs will increase by 55 percent, assuming no change in the shoreline. Under the more-likely assumption that shorelines recede, there will be no change in SFHAs; new SFHAs will simply replace the SFHAs that become submerged.

Any growth in SFHAs represents an increased burden on taxpayers. According to GAO estimates, the premiums (http://www.gao.gov/assets/670/667413.pdf) set by FEMA on NFIP flood insurance policies do not cover the risk. GAO gauged the subsidy for the years 2002 through 2013 at somewhere between $16 billion and $25 billion. Depending on assumptions about climate change and the amount of shoreline erosion, the AECOM study projects an increase between 20 and 90 percent in expected losses.

The climate risk assessment published by the Risky Business Project—an organization co-chaired by Michael Bloomberg, Henry Paulson, and Thomas Steyer—estimates that three-to-four percent of the US population will live in coastal SFHAs by 2100 and 11 percent of the US population will live in riverine (that is, inland) SFHAs. In addition, between $66 billion and $160 billion worth of real estate is expected to be below sea level by 2050. By the end of the century, the range is $238 billion to $507 billion.

The loss estimates above refer to insured properties with a high risk of flooding. However other areas will become permanently submerged, generating even larger losses. The Risky Business Project (http://riskybusiness.org/site/assets/uploads/2015/09/RiskyBusiness_Report_WEB_09_08_14.pdf) estimates the cost of all structures likely to be destroyed by the end of the century due to shoreline movement at two to four percent of the cumulative insurance premiums paid through 2100. In Florida alone, this study estimates a 1-in-20 chance that more than $346 billion in current property will be underwater by 2100.

Potential responses

Even with significant and coordinated global action like that outlined at the Paris climate conference, some of the projected (http://www.fema.gov/media-library-data/1424368115734-86cfbaeb456f7c1d57a05d3e8e08a4bd/FINAL_ResilienceClimateChange_JobAid_19FEB15_508_Complete_.pdf) impacts of climate change appear to be unavoidable. Governments and private organizations are working on plans (http://www.corpsclimate.us/docs/USACEAdaptationPolicy3June2011.pdf) to mitigate impacts where possible and to adapt to changes that are inevitable. Many are taking notes from the experience of the Netherlands, which has prospered for centuries despite lying below sea level.

However, the dikes and sea walls used by the Dutch may not solve the problems of South Florida. Florida sits on a substrate of porous limestone that holds Florida's supply of fresh water. As the sea level rises, it infiltrates the limestone underground and contaminates (http://www.marketplace.org/2015/02/10/sustainability/water-high-price-cheap/rising-seas-threaten-south-floridas-drinking-water) the freshwater supply. A sea wall might stop storm water surges on the surface, but it can't prevent the underground incursion of salt water.

While technical solutions may stave off some of the worst effects of climate change, rising sea levels and spreading flood plains nonetheless appear likely to destroy billions of dollars in property and to displace millions of people. The economic losses and social disruption may happen gradually, but they are likely to be greater in total than those experienced in the housing crisis and Great Recession. That recent experience illustrated the difficulty of allocating losses between homeowners, lenders, servicers, insurers, investors, and taxpayers in general. The delays in resolving these differences at times exacerbated the losses. Similar challenges will face the nation in dealing with the impact of climate change.

Some thorny issues to ponder:

- The government-supported NFIP currently incorporates a subsidy for homeowners. Suggestions to raise premiums to reduce or eliminate the subsidy so far have met with resistance from homeowners in SFHAs. However, taxpayers may balk at covering escalating losses as sea levels rise in light of the predictability of the losses. Taxpayers may feel that the affected homeowners ignored decades-long warnings of the risks they were bearing.
- A large share of homeowners' wealth is locked up in their equity in their homes. If those homes become uninsurable and unmarketable, the values of the homes will plummet, perhaps to zero. Unlike the recent experience, homeowners will have no expectation that the values of their homes will ever recover.
- In the housing crisis, a significant share of borrowers continued to make their mortgage payments even though the values of their homes were less than the balances of their mortgages. It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater. As a result, lenders, servicers and mortgage insurers are likely to suffer large losses.
- Some homeowners outside the impacted areas will nonetheless suffer losses as businesses are forced to relocate, taking employment opportunities with them. Companies that sell services to these relocating businesses also will suffer losses.
- Additionally, the effects on homeowners not in the impacted areas, but are nearby, will be complicated by the fact that there may be increased demand for their homes.
- Non-economic losses may be substantial as some communities disappear or unravel. Social unrest may increase in the affected areas.

One challenge for housing economists is predicting the time path of house prices in areas likely to be impacted by climate change. Consider an expensive beachfront house that is highly likely to be submerged eventually, although "eventually" is difficult to pin down and may be a long way off. Will the value of the house decline gradually as the expected life of the house becomes shorter? Or, alternatively, will the value of the house—and all the houses around it—plunge the first time a lender refuses to make a mortgage on a nearby house or an insurer refuses to issue a homeowner's policy? Or will the trigger be one or two homeowners who decide to sell defensively?

As the market shakes out in the affected areas, perhaps we'll be left with a host of Washaway Beaches. Some residents will cash out early and suffer minimal losses. Others will not be so lucky. And newcomers may appear, finally able to live out their dreams of living at the seashore, if only for a short time.

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1 Elizabeth Kolbert, "The Siege of Miami," The New Yorker, Dec. 21 & 28, pp. 42-50.

2 Elizabeth Kolbert, "The Siege of Miami," The New Yorker, Dec. 21 & 28, pp. 42-50.

3 The requirement to obtain flood insurance applies only to purchases with mortgages and not to cash purchases. The GSE requirement for flood insurance in SFHAs is a legal obligation of the GSEs and not simply a GSE policy. More broadly, federal regulators must require their regulated lenders to insure that borrowers obtain flood insurance for mortgages on properties within SFHAs.

Underwater

Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate

Introduction

Along nearly 13,000 miles of coastline of the contiguous United States, hundreds of thousands of buildings lie in the path of rising seas: schools, hospitals, churches, factories, homes, and businesses. Long before these properties and infrastructure are permanently underwater, millions of Americans living in coastal communities will face more frequent flooding, as the tides inch higher and reach farther inland. As sea levels rise, persistent high-tide flooding of homes, yards, roads, and business districts will begin to render properties effectively unlivable, and neighborhoods—even whole communities—financially unattractive and potentially unviable.

Yet property values in most coastal real estate markets do not currently reflect this risk. And most homeowners, communities, and investors are not aware of the financial losses they may soon face.

> ***By the end of the 21st century, nearly 2.5 million properties will be at risk of chronic flooding.***

BILLIONS OF DOLLARS OF PROPERTY AT RISK IN THE COMING DECADES

In the coming decades, the consequences of rising seas will strain many coastal real estate markets—abruptly or gradually, but some eventually to the point of collapse—with potential reverberations throughout the national economy. And with the inevitability of ever-higher seas, these are not devaluations from which damaged real estate markets will recover.

This analysis estimates the number of homes and commercial properties throughout the coastal United States that will be put at risk from chronic, disruptive flooding—defined as flooding that occurs 26 times per year or more (Dahl et al. 2017; Spanger-Siegfried et al. 2017)—in the coming decades. It brings together data on coastal regions that are projected to experience this type of flooding, and data on existing properties provided by Zillow*, the online real estate company. Our findings indicate that sea level rise, driven primarily by climate change and even absent heavy rains or storms, puts more than 300,000 of today's homes and commercial properties in the contiguous United States at risk of chronic, disruptive flooding within the next 30 years. The cumulative current value of the properties that will be at risk by 2045 is roughly $136 billion. In those 30 years—encompassing the terms of a typical mortgage taken out today—what will the properties be worth if they are flooding on a chronic basis? And how will the broader coastal real estate market fare in the long term? Our analysis finds that by the end of the 21st century nearly 2.5 million residential and commercial properties, collectively valued at $1.07 trillion today, will be at risk of chronic flooding.

Many experts in risk assessment, credit ratings, real estate markets, insurance markets, and flood policy (dozens of whom were consulted for this report), recognize that the risk of sea level rise to coastal real estate is significant and growing—and that for the most part, financial markets do not currently account for these risks.

RISKS BELOW THE RADAR

In many cases, the risks are masked by short-sighted government policies, market incentives, and public and private investments that prop up business-as-usual choices and fail to account for sea level rise (McNamara et al. 2015). Even in places such as Miami-Dade County, which is already experiencing disruptive tidal flooding, the real estate market is only just beginning to adjust (Tampa Bay Times 2017; Corum 2016; Urbina 2016; Spanger-Siegfried, Fitzpatrick, and Dahl 2014). This disconnect can be attributed to a lack of information about risks; subsidized, myopic development choices; and the continued attraction of seaside property and vibrant coastal economies (Keenan, Hill, and Gumber 2018). Other smaller, less in-demand locations, such as in coastal Louisiana and the eastern shore of Maryland, are already facing a chronic flooding reckoning (Spanger-Siegfried et al. 2017).

Properties will not be the only things to flood. Roads, bridges, power plants, airports, ports, public buildings, military bases, and other critical infrastructure along the coast also face the risk of chronic inundation. The direct costs of replacing, repairing, strengthening, or relocating infrastructure are not captured in our analysis, nor do we account for the indirect costs of flooded infrastructure, including disruptions to commerce and daily life (Neumann, Price, and Chinowsky 2015; NCA 2014; Ayyub and Kearney 2012). Taken together, these costs of chronic flooding of our coastal built environment—both property and infrastructure—could have staggering economic impacts.

* *Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.*

Homes and businesses in hundreds of US communities will face an unprecedented challenge as sea levels rise. Many of those communities, such as the barrier island town of Hampton Beach, New Hampshire, pictured here, developed over time for greatest-possible proximity to the ocean—but today the ocean is on the move, and the cost of that proximity is becoming evident. Although constructing seawalls and installing storm water pumps, for example, can serve to buy time in some places, most defensive measures are expensive to build, are not currently designed to fend off rising seas, and cannot prevent losses uniformly or indefinitely.

A NARROWING WINDOW OF OPPORTUNITY TO MAKE BETTER CHOICES

Even when these risks are understood, there are seldom easy solutions. As chronic flooding increases in coastal communities, a tricky cycle begins: investments in adaptation measures could be made to potentially forestall the flooding of properties and the subsequent decline in the tax base. But for communities to maintain credit-worthiness and access to the capital needed for these investments, they would increasingly need to show that they have already made smart decisions and investments to adapt and build resilience (Moody's Investors Services 2017; Walsh 2017; S&P 2016). Falling behind in this cycle, or lacking the means to invest in the first place, could have grave fiscal consequences.

There are many stakeholders in the coastal real estate market, from individual homeowners and business owners, to lenders, taxpayers, developers, insurers, and investors. Whether a property market crashes, or property values steadily decline in response to worsening flooding, these stakeholders are poised to sustain large collective losses. Many coastal residents, whether they own homes or not, will be affected as shrinking property tax bases prevent cities and towns from fully funding schools, emergency services, and infrastructure repairs, or as property tax rates rise for all residents to compensate for those properties devalued by flood risks.

As a nation, we have a narrowing window of opportunity to make better choices and ameliorate risks. The actual physical risks from sea level rise are growing and risk perceptions in the marketplace can shift abruptly, both of which leave communities vulnerable to economic hardships that many will not be able to cope with on their own. This creates a national imperative to prepare individuals and brace our communities and economies for an irreversible decline in the value of many coastal homes and commercial properties, even as we create pathways to new beginnings in safer locations. Given the scale of this challenge, action from the local to the national level will be required, engaging many sectors of the economy. The federal government has a unique and critical leadership role to help provide the tools, funding, resources, and policies that can guide more resilient choices and equitable outcomes along our imperiled coasts.

There will be no simple solution. But continued inaction is unacceptable; we must use the remaining response time wisely to meet this serious threat and protect coastal communities as effectively as we can.

FIGURE 1 What is Chronic Inundation?

With higher sea levels come higher high tides, which can reach onto normally dry land. As sea level rises further, this occasional flooding can become chronic, as even less extreme tides begin to cause flooding. The top panel shows the current reach of high tide (C) and the current extended reach of extreme tides, which defines a current chronic inundation zone where flooding occurs at least 26 times per year (D). The bottom panel shows how sea level rise expands the reach of not just extreme tides but also more typical tides such that some more land is permanently inundated and a portion of the community becomes chronically flooded.

Findings

In this analysis, we identified residential and commercial properties at risk of chronic inundation as sea levels rise, defined as experiencing at least 26 floods per year (Figure 1) (Dahl et al. 2017; Spanger-Siegfried et al. 2017). Using data provided by Zillow (Zillow 2017)*, we determined these properties' current collective value and contribution to community tax bases. We looked at outcomes for the entire coastline of the contiguous United States at multiple points in time through the end of the century, based on localized projections of three different sea level rise scenarios developed for the 2014 National Climate Assessment (Huber and White 2015; Walsh et al. 2014; Parris et al. 2012). In addition, we examined basic demographics of at-risk communities, including the number of people currently housed in these properties and at risk of being displaced, as well as factors such as race, age, and income that could make some populations more vulnerable than others to the physical and financial risks of flooding (Cleetus, Bueno, and Dahl 2015; US Census Bureau 2010; Cutter, Boruff, and Shirley 2003). For more information see Appendix: About this Analysis, p. 22.

Given the importance of individual properties to those who own or live in them, and the broader importance of the coastal real estate market to many market actors invested therein, the following results are based on the high sea level rise scenario, a scenario that results in 6.6 feet of global sea level rise by 2100 and should be used to inform decision-making where there is a low tolerance for risk (Parris et al. 2012).[1] Our results through the end of the century are generated based on today's existing property numbers, property values, and related data (Zillow 2017), and today's demographic statistics (US Census Bureau 2015; US Census Bureau 2010). Aside from rising sea levels and their direct threat to property, our results do not reflect what the future will bring in terms of additional coastal development, adaptation measures, the impact of major storms, population growth, other changes in property values, or other relevant factors. As a result, our findings may under- or overestimate the future number of properties, people, and value that will be affected over time (Hardy and Hauer 2018; Hauer 2017; Lentz et al. 2016).

* *Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.*

THE COAST-WIDE PICTURE

With this high sea level rise scenario, we found that within the next 15 years roughly 147,000 existing homes and 7,000 commercial properties—currently worth $63 billion—are at risk of being inundated an average of 26 times per year, or more. About 280,000 people are estimated to live in these homes today; in this time frame many will need to either adapt to regular floods or relocate.

By 2045—near the end of the lifetime of a 30-year home mortgage issued today—sea levels are projected to have risen such that nearly 311,000 of today's residential properties, currently home to more than half a million people, would be at risk of flooding chronically, representing a doubling of at-risk homes in the 15 years between 2030 and 2045. Not only are the mortgage loans on these homes at growing risk of default if the value of the properties drops, but each successful sale of one of these homes represents the potential transfer of a major latent financial liability. Eventually, the final unlucky homeowners will hold deeds to significantly devalued properties (Conti 2018). Our calculations show that in about 120 communities along US coasts, the properties that would be at-risk in 2045 currently represent a full 20 percent or more of the local property tax base, a crucial source of funding for schools, fire departments, law enforcement, infrastructure, and other public services. For about 30 communities, properties accounting for more than half of the local property tax base today would be at risk by 2045.

By the end of the century, as many as 2.4 million of today's residential properties and 107,000 commercial properties, worth $1.07 trillion today—roughly equivalent to the entire gross domestic product of Florida—would be at risk of chronic flooding (BEA 2018). Those properties are estimated to currently house about 4.7 million people, the equivalent of the entire population of Louisiana.

Together with previous studies of property at risk from rising seas, our findings illustrate a clear, rapidly growing risk to both coastal communities and the nation as a whole, given the deep financial stakes that both the private sector and the US taxpayer have in our coasts (Figure 2, p. 6) (Center for the Blue Economy 2018; Bretz 2017).

In Florida, the number of today's homes that are at risk from sea level rise balloons to more than 1 million by 2100.

COMMON THEMES AND STATE-LEVEL FINDINGS

As sea levels rise, each of the 23 coastal states in the contiguous US faces the loss of residential and commercial properties and frequent flooding of populated areas, posing new challenges for all communities and adding particular stressors for communities of color and low-income and working-class communities. The following is a selection of common themes that arise across many states. While our discussion of states and locations highlights areas of high risk, this does not mean that other locales face only minimal risk.

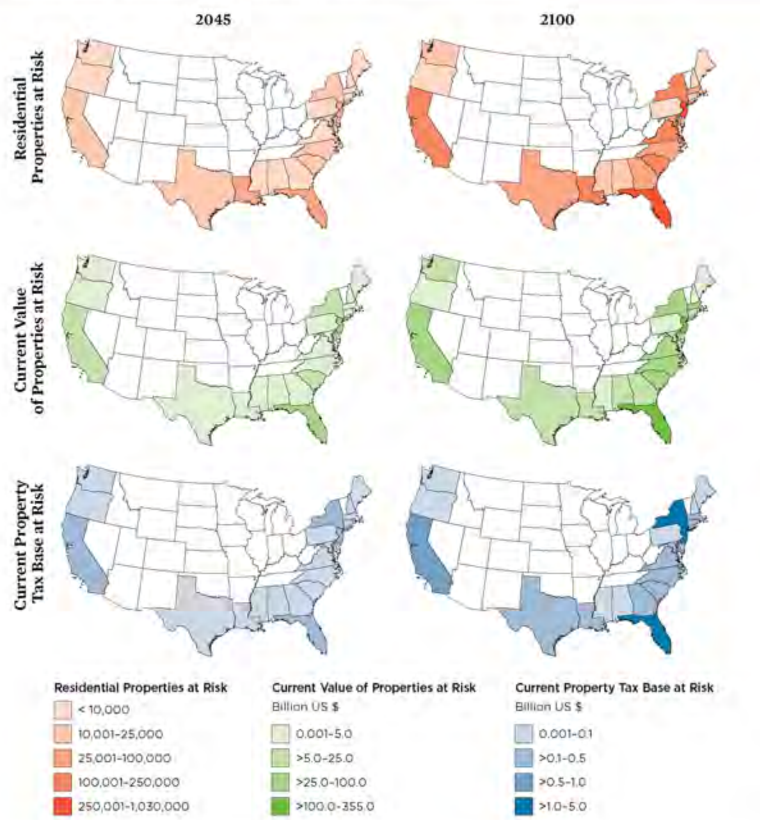
MOST TO LOSE? FLORIDA AND NEW JERSEY

On the east coast of the United States, generations of people have made homes and set up shop close to the water, making this coast some of the most developed land in the country. Often this development has taken place within fragile environments such as barrier islands and filled wetlands; some of the gravest consequences of this overdevelopment will be along the New Jersey and Florida coasts.

Within the next 30 years, roughly 64,000 homes in Florida and 62,000 in New Jersey will be at risk of chronic flooding. Along the Florida coast, Miami Beach alone, with its iconic high rises located within steps of the beach, accounts for more than 12,000 of those homes.[2] Of New Jersey's beach towns, 10 are projected to have at least 1,500 at-risk homes by 2045. Ocean City tops the list with more than 7,200 at-risk homes.

Development in at-risk areas such as the coast of Florida has continued despite the increasingly apparent risks of sea level rise. Indeed, with the allure of its weather and beaches, Florida's housing market has remained strong, even as sunny-day flooding has become a familiar and disruptive reality. Measures to reduce tidal flood risks are hampered in Florida by factors including the porous limestone bedrock underlying much of the state's coastal regions and the large quantity of housing built on extremely low-lying barrier islands (such as Miami Beach, pictured here) and filled land.

FIGURE 2. Residential Properties at Risk in 2045 and 2100

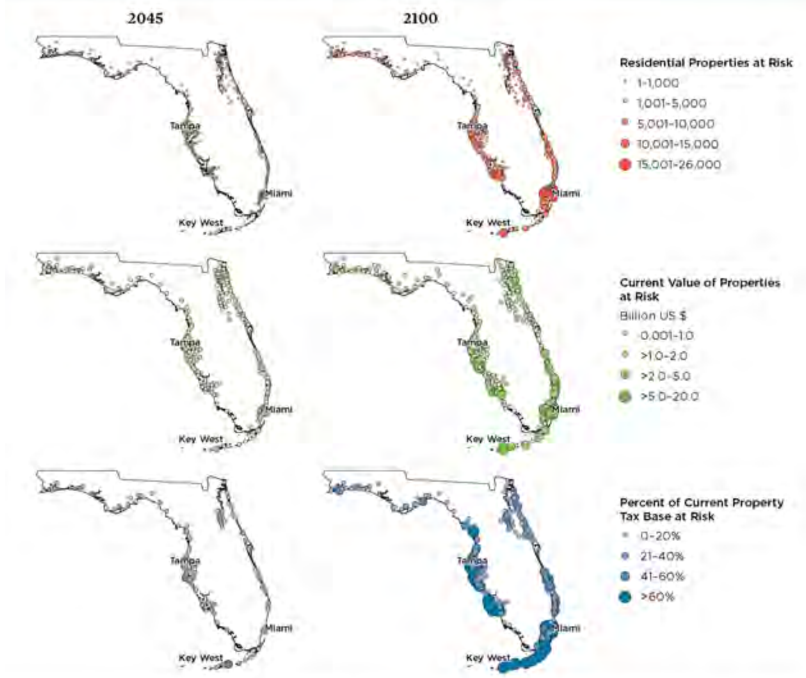


In the contiguous US, more than 310,000 existing homes are projected to be at risk of chronic inundation by 2045, a number that grows to nearly 2.4 million by the end of the century. Within the 30-year time frame represented in the 2045 maps shown here, the states with the most existing homes at risk are (in order) Florida, New Jersey, Louisiana, and California. Florida, New Jersey, and California also all rank in the top three in terms of current value of properties that would be at risk in 2045, and the current contribution of those properties to the local tax base. Note that in California, we have used assessed home values in place of market values, which makes our property value estimates for California conservative (see Appendix: About this Analysis on p. 22 for more details). Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

In Florida, the number of today's homes that are at risk from sea level rise balloons to more than 1 million by 2100, reflecting the scale of existing development in Florida's low-lying inland regions. By the end of the century, Florida alone would account for more than 40 percent of the nation's at-risk homes. In New Jersey, in the same time frame, more than 250,000 homes would be at risk.

Even as the reality of sea level rise has become clearer, development in flood-prone locations has burgeoned. Fifteen to 20 percent of the at-risk homes in 2045 and 2100 in both Florida and New Jersey were built after the year 2000. Roughly 2,600 of the coastal New Jersey homes at risk by 2045 were built or rebuilt after Hurricane Sandy devastated the region in 2012.

FIGURE 3. Acute Exposure in Florida



Florida leads the nation in the number of homes—along with property value and tax base (based on current values for each)—at risk of chronic inundation through the end of the century. At the ZIP code level, shown here with symbols located at the center of each ZIP code area, the Miami area, the Florida Keys, and Tampa-St. Petersburg stand out as being the most highly exposed within the next 30 years. By the end of the century, nearly 100 ZIP code areas in Florida could see properties chronically flooded that today represent 40 percent or more of their property tax base. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

FIGURE 4. Communities at Risk: Snapshots from California and New York

The San Francisco Bay area, in California, and Long Island, in New York, are both densely populated areas that face significant exposure to chronic inundation by 2045. Within the nine Bay Area counties, roughly 13,000 homes that currently house 33,000 people are at risk of chronic inundation in the next 30 years. On Long Island, roughly 40,000 people currently live in about 15,000 existing homes at risk in this time frame. Housing at risk is shown at the ZIP code level, with symbols located at the center of each ZIP code area. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

HOUSING RISK HOTSPOTS: CALIFORNIA AND NEW YORK

Along the southern shore of Long Island, New York, and around the San Francisco Bay, proximity to major metropolitan areas has spurred development for decades (Figure 4). In both regions, some suburban communities may find themselves facing considerably more risk than the nearby urban centers of Manhattan and San Francisco. By 2045, the three counties that make up most of Long Island—Suffolk, Nassau, and Queens—could encompass nearly 15,000 homes at risk of chronic inundation. Today, there are roughly 40,000 people living in those homes, which are collectively valued at $7.7 billion. In contrast, Manhattan has no at-risk homes in this time frame. Similarly, while San Francisco itself has just 270 at-risk homes in 2045, in the nine counties surrounding the San Francisco Bay roughly 13,000 properties—home to more than 33,000 people and valued at $8.6 billion today—are at risk.[3,4]

Within each of these regions, some communities are more exposed to chronic inundation than others. On Long Island, for example, Hempstead, Babylon, and Queens are projected to have more than 2,500 homes at risk by 2045, whereas there are only a few homes at risk in other towns. In the Bay Area, San Rafael, San Mateo, and San Jose are each projected to have more than 2,000 at-risk homes by 2045. Future impacts could also vary substantially within a metropolitan region, as some towns may invest in protective infrastructure, while others may choose not to, or may not be able to.

POVERTY, RACIAL INEQUITIES, AND TIDES CREATE HOTSPOTS OF RISK: LOUISIANA, MARYLAND, NORTH CAROLINA, AND NEW JERSEY

Communities with fewer resources to start with, or that are otherwise disadvantaged, will likely be most heavily affected by chronic flooding and its accompanying financial losses (Deas et al. 2017; Mearns and Norton 2010; Fothergill and Peek 2004). We used two metrics to identify communities that may have fewer resources to cope with chronic flooding: poverty rate and the percentage of the community composed of traditionally underserved groups—African Americans, Hispanic Americans, and tribal communities (US Census Bureau 2010).

In communities where the poverty level is above the national average, the erosion of the property tax base could have severe consequences for local residents.

Nearly 175 communities nationwide can expect significant chronic flooding by 2045, with 10 percent or more of their housing stock at risk. Of those, nearly 40 percent—or 67 communities—currently have poverty levels above the national average. The largest share of these is in Louisiana, where there are 25 communities with above-average poverty rates and with 10 percent or more of the homes at risk by 2045.[5] In several Terrebonne Parish communities such as Houma and Bayou Cane, between one in five and one in three residents lives in poverty. These and many other Louisiana regions are also home to large African American and tribal populations as well as other communities of color, where decades of systematic bias have limited personal and community-level financial resources (DHS 2018). In Terrebonne Parish communities, where up to one-third of the residents are living in poverty and half or more are African American, the projected chronic flooding of hundreds of homes and erosion of up to one-quarter of the property tax base could have severe consequences for local residents.

Louisiana is not the only state where poverty and exposure to chronic inundation intersect to create a hotspot of heightened risk. North Carolina, New Jersey, and Maryland also have significant numbers of highly exposed communities with above-average rates of poverty. Within the next 30 years, about a dozen communities along Maryland's eastern shore are projected to have one-third or more of their property tax base at risk. People living in these doubly vulnerable communities stand to lose the most, yet have fewer resources to adapt to flooding or relocate to safer areas.

GENERATIONAL WEALTH AT STAKE: NEW JERSEY, MARYLAND, AND TEXAS

Elderly homeowners tend to live on fixed incomes, own their homes outright, and/or have a relatively large share of personal wealth tied up in their property (Kaul and Goodman 2017; Butrica and Mudrazija 2016). When their property—or even just their neighborhood—is chronically flooded and the value of their home drops, they stand to lose a larger share of their personal wealth, without means of recouping it through future income. People living on fixed incomes can also be hurt financially as taxes rise on non-inundated properties to compensate for municipal budget shortfalls or when services they depend on (such as public transportation) are cut as those budgets shrink.

Of the roughly 400 US communities with at least 50 homes at risk of chronic inundation in 2030, about 60 percent (roughly 240 communities) currently have large populations of elderly people—far above the national average of 14.5 percent of the total population. In towns such as Beach Haven and Tuckerton, New Jersey; Madison, Maryland; and Croatan, North Carolina; each of which has high elderly populations, more than 20 percent of homes, value, and tax base are at risk within the next 15 years. Similarly, in several communities along the Texas coast, including the Bolivar Peninsula, Rockport, and Fulton, where hundreds of properties are at risk of chronic inundation by 2030, between one in five and one in three residents is currently over the age of 65.

FIGURE 5. Communities at Risk: Snapshots from Louisiana and Maryland

Chronic inundation is poised to add new challenges to communities already struggling with high rates of poverty. Of the nearly 120 Louisiana communities with at least one home at risk of chronic inundation by 2045, 60 percent currently have poverty rates above the national average of 12.7 percent. In Maryland, 30 of the roughly 105 communities that contain at-risk properties in 2045 (shown at the ZIP code level, with symbols located at the center of each ZIP code area) have above average poverty rates. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

BLUE COLLAR AMERICA AT RISK: MASSACHUSETTS, DELAWARE, PENNSYLVANIA, MARYLAND, VIRGINIA, MISSISSIPPI, OREGON, AND WASHINGTON

Hundreds of blue collar towns dot the US coastline. To assess the impact of chronic inundation on low- to moderate-income homeowners, we assessed the number of properties that are at risk of chronic inundation in each state and are valued below that state's median home value, as defined by the Zillow Home Value Index (Zillow 2018; Zillow Research 2014).

In eight states—Massachusetts, Delaware, Pennsylvania, Maryland, Virginia, Mississippi, Oregon, and Washington—60 percent or more of the homes at risk of chronic inundation within the next 30 years are valued below the state median.[6] In Delaware and Oregon, nearly all (90 percent or more) of the chronic inundation risk is borne by residents of these lower-value properties. In Oregon, these properties are clustered around Coos Bay and Astoria, two working-class towns. Likewise, in Massachusetts, in 2045, there are large clusters of at-risk homes in Revere, Saugus, and Winthrop—all working-class suburbs of Boston.

[***Of the roughly 14,000 commercial properties at risk on US coasts within the next 30 years, more than one-third are in Florida and New Jersey.***]

BUSINESS AS USUAL? FLORIDA AND NEW JERSEY

Our nation's coasts are defined not just by homes and neighborhoods, but by commercial districts. From corner cafés to high-rise office buildings, these properties and the businesses they house are critical components of the coastal economy. The low-lying and highly developed coastlines of Florida and New Jersey make the commercial sector in both states particularly exposed to chronic flooding as sea levels rise. Of the

For many Americans, to own a home on the coast is to claim a prized lifestyle and aesthetic—a "little slice of heaven." And in areas where they could afford to, many working-class communities have taken root there over the years. Unlike wealthier areas with larger homes and lots, smaller, lower-value homes cluster closely together in blue collar towns of Massachusetts, Delaware, Mississippi, New Jersey, and Oregon, to name a few. Many such clusters are in low-lying areas that rising tides will soon reach. For these residents, the loss of these properties could mean the loss of a large share of their personal wealth, as well as the loss of ways of life that have been shared over generations.

roughly 14,000 commercial properties at risk on US coasts within the next 30 years, more than one-third are in Florida and New Jersey. Those same two states are home to 45 percent of the commercial properties, coastwide, that would be at risk by end of the century.

The kinds of properties at risk are quite different in each state. In New Jersey, nearly all (96 percent) of the roughly 2,600 commercial properties that would be at risk in 2045, as well as the 11,000 at risk in 2100, are retail establishments: hotels, restaurants, gas stations, convenience stores, and pharmacies. In contrast, in Florida, 30 percent of the 2,300 commercial properties at risk in 2045 and 50 percent of the 38,000 at risk in 2100 are commercial office buildings, which include medical and financial offices, as well as more general offices and mixed-use buildings.

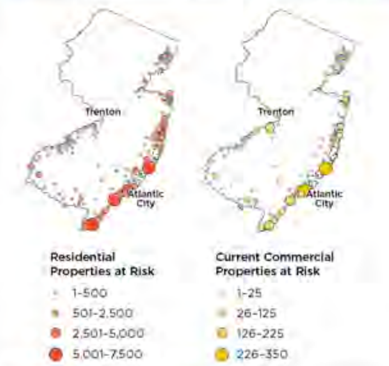
TOURISM REVENUE AT STAKE IN VACATION STATES: NEW JERSEY, NORTH CAROLINA, SOUTH CAROLINA, AND TEXAS

For many people, the coast is synonymous with beach vacations. Homes in coastal vacation destinations may be second homes or primary residences, rental properties, or beloved family homes passed down from generation to generation. The property taxes paid on these homes is often an important source of steady revenue in locations where tourism revenues are highly seasonal and weather-dependent. When a home in a beach town is at risk of chronic flooding, not only is the homeowner affected, but so is a larger network of people, from the vacationer who rents it for a week every summer to the year-round residents who benefit from the revenues generated by tourism. If a significant number of homes in the area are regularly flooded, the popularity of the town as a vacation destination could decline (Flavelle 2017a).

Tens of thousands of homes (if not more) in well-known coastal vacation destinations are projected to be at risk of chronic inundation in the next 30 years. Along the Texas coast, roughly 3,200 residential properties in Galveston and another 1,500 in Brazosport would be at risk, homes that currently represent 17 and 10 percent of the local property tax base, respectively. In South Carolina, nearly 1,500 homes on Kiawah Island would be at risk, and more than 2,700 on Hilton Head. On Kiawah Island, those homes represent nearly one-quarter of the local property tax base today. In North Carolina, the Outer Banks communities of Nags Head and Hatteras together would have nearly 2,000 at-risk homes in this timeframe. On the Jersey Shore, Ocean City alone would have more than 7,200 at risk homes by 2045, which today represents nearly 40 percent of the town's homes and nearly one-third of the local property tax base.

In many seaside communities, such as Galveston and Nags Head, homes are physically elevated. However, even if living spaces stay dry, if the access roads, surrounding land, and key infrastructure are flooded, home values and tourism would be adversely affected.

FIGURE 6. Communities at Risk: Snapshot of New Jersey



New Jersey leads the nation in the number of commercial properties at risk of chronic inundation in 2045 (right) and is second only to Florida in the number of residential properties at risk in that time frame (left). Results are shown at the ZIP code level, with symbols located at the center of each ZIP code area. Properties along the highly developed and much beloved Jersey Shore are particularly at risk. Nearly all of the commercial properties at risk in New Jersey are retail establishments including, but not limited to, shops, hotels and restaurants. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

A LOW SEA LEVEL RISE SCENARIO: RISKS TO REAL ESTATE DRASTICALLY REDUCED

The difference in impacts to real estate between high and low sea level rise scenarios is stark. A rapid decrease in carbon emissions coupled with slow melting of land-based ice could lead to substantially slower rates of sea level rise. With this low sea level rise scenario, by the year 2060, our analysis finds that the number of homes at risk of chronic inundation would be reduced by nearly 80 percent, from 625,000 with the high scenario to 138,000 with the low scenario. And by the end of the century, only 340,000 homes would be at risk with the low scenario, compared to 2.4 million with the high scenario.

If the global community adheres to the primary goal of the Paris Agreement of capping warming below 2°C

A rapid decrease in global carbon emissions coupled with slow melting of land-based ice could reduce the number of homes at risk of chronic inundation by 2060 by nearly 80 percent.

(UNFCCC 2018), and with limited loss of land-based ice, the United States could avoid losing residential properties that are currently valued at $780 billion, contribute $10 billion annually in property tax revenue, and house 4.1 million people.

Unfortunately, the low, or best-case, scenario is not the track we are on, given current emissions and the vulnerability of the Antarctic ice sheet to warming temperatures, as indicated by the latest research. (Mengel et al. 2018; DeConto and Pollard 2016). The low emissions scenario is one we should work toward but not count on—and decisionmakers must plan for the likely need to manage greater risks.

FIGURE 7. The Potential Economic Reverberations of Chronically Inundated Properties

With chronic inundation, homeowners and owners of commercial properties are directly at risk of significant financial losses as the value of their properties declines. Such losses have ramifications for the local community, which could see its property tax base eroded and its ability to fund local services compromised. There will also be implications for the wider economy, including for banks with outstanding mortgage loans on properties at risk of inundation, coastal property developers, investors and insurers, business owners whose places of business may face flooding, and US taxpayers, broadly, who may face increased taxes to pay for measures to cope with flooding and to reduce flood risk.

Implications

The declining value and increasingly unlivable condition of coastal homes will be damaging, even devastating, to individual homeowners. It will also have more widespread consequences, including for affected communities, lenders, investors, and taxpayers. Unlike housing market crashes of the past, where property values eventually rebounded in most markets, properties chronically inundated by rising seas will only go further underwater, raising the urgent need for more proactive long-term solutions.

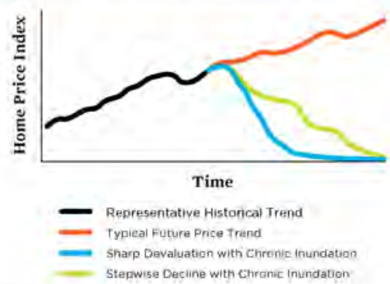
RISKS TO HOMEOWNERS AND BUSINESS OWNERS

With chronic inundation, average homeowners will risk being unable to capitalize on their greatest asset as their homes become undesirable on the real estate market and eventually unsellable. Flood insurance for chronically inundated coastal properties could become increasingly expensive—or not available at all (FEMA 2018; Dixon et al. 2017; Lieberman 2017; GAO 2017). A rash of coastal foreclosures and abandoned homes could ensue, causing neighborhood blight and millions of dollars in lost wealth, even as new real estate wealth is potentially created further inland. In some neighborhoods, even if many individual homes remain out of the chronic inundation zone, the large numbers of homes at risk could cause the neighborhood to collectively experience significant property value declines (Dixon et al. 2017).

Renters, too, could find themselves looking for new homes or putting up with flood-damaged properties—and perhaps facing a scarce local rental market and rising rents. In Miami, for example, developers are increasingly considering buying land in lower-income neighborhoods located farther inland and at higher elevations (Bolstad 2017). But without regulation and policy around these market-driven reactions to sea level rise, this practice can perpetuate racial and social inequities, as lower-income communities see their property values rise to unaffordable levels, creating climate gentrification (Keenan, Hill, and Gumber 2018; Beeler 2017).

Business owners are similarly at risk: flooded streets mean loss of traffic and in-person sales; flooded properties can mean loss of inventory and expensive clean-up; and flooded roads and parking lots can prevent workers from reaching and doing their jobs. Moreover, many business owners invest in the communities that host them, a revenue source that could dry up if those businesses are harmed by chronic flooding. Some commercial property owners will also see the value of their investments erode and may find it increasingly hard to secure long-term leases for properties that are at risk of inundation.

FIGURE 8: Loss in Home Value with Chronic Inundation



These curves depict illustrative trends in home prices with and without chronic inundation. The black line represents a typical historical trend. Going forward, home values in healthy real estate markets would typically trend upward over time (orange line). However, with chronic inundation some coastal real estate markets could face sharp devaluations if their risk is high or they do not have the resources to adapt (blue line); other communities with a longer time horizon to respond or the ability to invest in adaptation measures could face a slower, stepwise decline in property values (green line).

RISKS TO THE LOCAL TAX BASE: A VICIOUS CYCLE BEGINS

Falling property values mean reduced local tax revenue from those properties. In communities where a small share of homes is initially affected, local leaders may opt to raise the tax rate across all properties to mitigate the budget shortfall. However, when many homes are affected, the property tax base will be eroded more quickly, reducing municipal budgets (LILP/MCFE 2018).

Local tax revenues help fund the maintenance and new construction of infrastructure—including critical adaptation measures that could help protect homes, businesses, and infrastructure itself from chronic flooding. Access to additional capital for such projects depends on a municipality's credit rating; its credit rating depends on its financial health and degree of risk exposure, both of which are compromised as chronic flooding worsens. Ironically, communities may find it harder to raise funds for increasing their resilience to floods—through the bond market, for instance—if their credit rating is lowered because of flood risks. Turning again to the relatively wealthy city of Miami, in 2017 the city's residents voted in favor of a $400 million "Miami Forever" bond, which included $192 million for measures to help protect the city from sea level rise–induced flooding (Smiley 2017). But many smaller municipalities will not be able to drum up similar resources or act quickly enough while they are still credit-worthy, highlighting the need for marshaling a national response to help ensure that there is equitable, timely access to adaptation measures for all communities.

RISKS TO THE WIDER ECONOMY: LENDERS, TAXPAYERS, DEVELOPERS, AND INVESTORS

Mortgages on homes that could be chronically flooded during the term of the loan are inherently riskier. As chronic inundation worsens, homeowners will begin to find themselves with mortgages that exceed the value of their homes, and with homes that grow unlivable or difficult to insure. With no obvious option for reversing that trend, some might choose to abandon their homes and allow banks to foreclose on their mortgages. Lenders who provide mortgages, however, rely on

[Mortgages on homes that could be chronically flooded are inherently riskier, potentially with neither homeowner nor lender realizing it.]

the surety that the value of the property will be maintained, or even appreciate, so that their financial position is secure even in the event of foreclosure. That may cease to be the case for many coastal properties, many of which today carry these risky mortgages with neither homeowner nor lender realizing it (Federal Reserve 2018). Mortgage-backed securities and

Paul Zoeller/The Post And Courier via AP

Some communities and individuals are better positioned to absorb economic blows than others. And while wealthier homeowners, business owners, and communities may risk losing more value cumulatively, people who are less well-off risk losing a greater percentage of their wealth. Chronic flooding will place tremendous strain on low-income homeowners and renters, pressuring them, for example, to weigh costly flood-proofing investments against losing their homes. This mounting flood risk may spell deep losses for many, and without policies in place to help, will spell ruin for some.

bonds (essentially, investment vehicles created by bundling individual mortgages) tied into these riskier coastal real estate mortgages will thus also be at risk of losing value.

Real estate developers and investors risk sinking millions into properties that will shrink in value as chronic flooding increases. Insurers covering residential and commercial properties risk unsustainable payouts.

When enough major market actors become aware of and begin to act on these risks, it could potentially trigger a regional housing market crisis, or even a more widespread economic crisis.

Our Challenge–and Our Choices

The development along our nation's coasts today is the result of choices made over centuries. We've made our living from the sea; we've bought and built homes with ocean views; we've visited and vacationed in seaside towns, leaving behind money and taking away memories; we've toiled and built lives in coastal cities and small towns. Investors and developers have found ways to profit from this timeless pull to the seaside. Hundreds of years of history, personal and shared, painful and triumphant, are held in the homes, businesses, schools, roads, and treasured places that line our coasts. And much of it is at risk from sea level rise.

Despite long-available scientific information on observed and projected sea level, and the actual experience of flooding in some coastal communities, most coastal housing markets are a long way from reflecting the growing flood risks.

Imperfect information about localized risks and flawed policies have created a strong bias toward business-as-usual choices, greatly impeding science-based decisionmaking (Wing et al. 2018; Schwartz 2018). In the absence of adequate resources, or the wherewithal to invest in protective measures, many communities struggle to make more resilient choices. There are also significant questions about the accountability of local zoning regulators, developers, credit rating agencies, insurers, banks that proffer mortgages, and others who are effectively worsening the problem by ignoring or minimizing it (Allen 2017). In the near term, these policy and market incentives are serving to artificially prop up coastal real estate values (Becketti 2016).

But some experts and coastal residents are beginning to raise questions about the future of coastal real estate markets (Bernstein, Gustafson and Lewis 2018; Keenan, Hill, and Gumber 2018). Some real estate investors are also taking note (Coffee 2018; McConkey 2017). Zillow and Freddie Mac, two influential giants in the real estate sector, have both released reports in the last two years examining the impact of future sea level rise on coastal real estate (Rao 2017; Becketti 2016). Freddie Mac finds that sea level rise could "destroy billions of dollars in property and displace millions of people," with the resulting social and economic impacts "greater in total than those experienced in the housing crisis and Great Recession."

The prospect of these future losses compels action today. We must reorient policy and market forces toward solutions that work for people, ecosystems, coastal heritage, and the economy: by employing the best available science and information; by aligning existing policy and market incentives with the realities of sea level rise; and by investing in bold, transformative changes that limit harms and foster new frontiers of opportunity on safer ground.

KNOWING OUR RISK

To begin with, many homeowners and prospective home buyers are simply not sufficiently aware of the risks of sea level rise to their properties, whether present-day or future risks, and whether confined to major storms or chronic tidal flooding. This information is inadequately reflected in the Federal Emergency Management Agency's (FEMA) flood risk maps, for example, which only account for present-day flood risks (Schwartz 2018; Wing et al. 2018; Joyce 2017; Cleetus 2013). Although some individual states and localities have standards requiring real estate agents and home sellers to disclose flood risks at the time of a home sale, there are no uniform robust national requirements (Lightbody 2017).[7] Lenders and investors, especially those at a distance from the specific location, are also either largely unaware of growing tidal flood risks to properties or not adequately accounting for it in their business decisions (Farzad 2018; Allen 2017).

To address this gap in awareness, federal, state, and local policymakers, as well as members of the private sector, have important, complementary roles to play. These actions must be supplemented with resources and options for adaptation measures because greater awareness of flood risks will also bring challenges, especially to communities whose risks are revealed to be high. Actions should include the following:

1. The federal government must play a lead role in communicating risks to the public and incorporating those risks into its own policies and actions. Recent authoritative reports from the US Global Change Research Program and the National Oceanic and Atmospheric Administration (NOAA), together with online tools from federal government agencies such as the Environmental Protection Agency and NOAA, can serve a critical purpose in helping communities, policymakers, investors, and the broader public understand the risks of sea level rise (Sweet et al. 2018; EPA 2017; NOAA 2017a; USGCRP 2017). FEMA flood risk

maps—which help set flood insurance rates, guide local land-use policies, and inform infrastructure design standards—must be updated coast-wide to reflect sea level rise projections (TMAC 2016). This will help communicate the threat and encourage communities to take protective steps. Congress needs to increase funding beyond current levels and provide an explicit directive to FEMA to make this possible (ASFPM 2013).

2. State and local policymakers must help disseminate flood risk information to communities, and set local zoning and building regulations in line with these risks.

3. Flood-risk disclosure in the marketplace is vital to help individuals and businesses understand the risks to their investments and drive more resilient outcomes. National standards for flood-risk disclosure, including floods from sea level rise—for all real estate transactions—would go a long way toward making risks clear and transparent in coastal real estate markets. Mortgage underwriters and home appraisers can also play important roles in assessing and disclosing information about these risks to lenders and buyers.

Widespread adoption of industry standards and best practices for disclosing flood and other climate-related risks is needed. Financial institutions have begun taking steps to internalize climate risks, albeit slowly (Bonanno and Teras 2018). In the wake of the 2015 Paris Agreement, the Financial Stability Board—an international body that monitors and makes recommendations about the global financial system—launched the Taskforce on Climate-Related Financial Disclosures. The taskforce has released a set of recommendations on governance, strategy, risk management, and metrics and targets for financial-sector companies to support more accurate pricing of climate-related risks and thereby more informed investment decisions (TCFD 2017). These recommendations and the taskforce's five-year climate disclosure implementation pathway have the support of more than 250 major corporations, including banks, insurers, and investors.

Credit rating bodies also must start reflecting risks to coastal property, while rewarding proactive adaptation measures to limit those risks. For example, the credit rating agencies Moody's and Standard & Poor's have begun to evaluate and communicate how to account for climate risks in their credit ratings of municipal bonds (Bonanno and Teras 2018; Moody's Investors Services 2017; Walsh 2017; S&P 2016).

The historic attractiveness and market value of coastal property have long driven coastal development, like this pulse of new home construction in Richmond, California, some 20 years ago. Though the risks of sea level rise have been evident for some time in cities like Miami, Florida; Charleston, South Carolina; Norfolk, Virginia; and Annapolis, Maryland, in many such places a brisk pace of new home construction continues.

REALIGNING POLICIES AND MARKET INCENTIVES TO REFLECT GROWING FLOOD RISKS

Well-intentioned but short-sighted federal, state, and local policies can mask risk and create incentives that reinforce the status quo, or even expose *more* people and property to risk. The market's bias toward short-term decisionmaking and profits can also perpetuate risky investment choices. Identifying and reorienting the principal policies and market drivers of risky coastal development is a necessary and powerful way to move the nation toward greater resilience.

Here we identify several existing federal and state policies that play a de facto role in how communities—and financial markets—perceive and respond to coastal risks. Each of these policies can be improved to better incentivize and enhance resilience:

1. Federal disaster aid, when not accompanied by explicit incentives to reduce residents' and businesses' exposure to risks, has led states and municipalities to rebuild in a business-as-usual way and underinvest in risk-reduction measures (Kousky and Shabnam 2017; Moore 2017). Post-disaster investments should instead be made with a view to reducing future risks through a range of protective measures, including home buyouts and investments in flood-proofing measures as appropriate, and a requirement for adequate insurance coverage. For now, communities and financial sector actors rely on the assumption that federal aid will continue in its current form. Credit rating agencies have cited this assumption of continued federal aid for rebuilding as a reason to avoid downgrading the credit rating of municipalities that are exposed to risks of sea level rise.

BOX 1

Can't We Just Keep the Water Out?

As homeowners become more aware of the threat that chronic flooding poses to what is likely their most significant financial asset, interest in adaptation options—in particular, defensive measures that allow life to go on as usual—is likely to spike. And while adaptation is essential, there is cause for caution in embracing defensive measures as the sole or even primary solution.

Most community-level defensive measures are designed to help minimize wave action, reduce erosion, and protect against storm surge (NRC 2014). But keeping out normal, but higher, high tides is a different challenge. To defend large areas against chronic inundation, impervious seawalls (for example) would need to extend along large stretches of shoreline and avoid channeling incoming seas toward other exposed areas (NRC 2014). Or levees would need to be constructed, potentially requiring the use of large tracts of land and encouraging new development behind them (GAO 2016; Kousky 2014). As sea level rises, however, hard structures can aggravate coastal erosion, with natural habitat and beach loss, even as the walls fail to protect against infiltration of saltwater from below ground (Boda 2018; Vitousek et al. 2017; Moser et al. 2014; NRC 2014; Mazi, Koussis, and Destouni 2013; Barlow and Reichard 2010).

A seawall is constructed in New Jersey by the US Army Corps of Engineers. The hard defensive structures that are widely deployed today were typically built to dampen storm surge and limit erosion, not hold back normal but higher tides.

Such measures also come with an expiration date: either the defensive infrastructure reaches retirement age, or sea level rise catches up and necessitates further upgrades, at additional cost, lest it be overwhelmed.

Defensive measures can require investment—both initially and for ongoing maintenance and operation—on a scale that many communities will be unable to muster with diminished tax bases, particularly if they had fewer resources to start with. Individual property-level measures such as elevating buildings and installing doorway flood gates also require funding, and do not address the inundation of the roadways, commercial districts, septic systems, schools, etc. that those households and businesses rely on. Investing in defensive measures may help forestall chronic flooding in many locations, but for some home- and business owners there will be no practical or affordable way to keep the tide out of their property; for some communities, it will be similarly impractical or unaffordable to defend whole flooded areas. Options such as retreat and relocation will need to be part of the conversation.

2. Existing federal, state, and local policies could be effectively deployed for investments in measures that will both reduce risks ahead of time and help rebuild in a more resilient way (Kousky 2014). We should recognize coastal flood risk for the predictable, slow-moving disaster it is, rather than respond only episodically, i.e., in the aftermath of major storms. One way this can be done is by ramping up investments in FEMA's pre-disaster hazard mitigation grant program and the flood mitigation assistance program, and the community development block grant program administered by the US Department of Housing and Urban Development (HUD). A recent analysis by the National Institute of Building Sciences of almost a quarter century's worth of data found that for these types of flood risk mitigation programs, every $1 invested can save the nation $6 in future disaster costs (MMC 2017).

> ***Reforming short-sighted policy and market drivers of risky coastal development is a necessary and powerful way to move the nation toward greater resilience.***

3. The taxpayer-backed National Flood Insurance Program—while a vital program—has long been recognized as subsidizing some homeowners in flood-prone areas and inaccurately portraying flood risks because, in too many cases, insurance premiums and the flood risk maps that underlie them do not reflect true risks (Schwartz 2018; Joyce 2017; Kousky and Michel-Kerjan 2015). The most egregious examples are so-called repetitive loss properties that have received repeated payouts from the program despite being in places that are clearly too risky to insure (Moore 2017).[8] With sea level rise, the maps used by the National Flood Insurance Program are increasingly out of sync with the actual risks to coastal properties. Commonsense reforms to the program can ensure that it more effectively communicates flood risks, protects communities, and promotes better floodplain management.

4. A robust federal flood risk management standard should be restored and mandate that all federal investments take

BOX 2

Insights from Market Experts on the Financial Risks of Sea Level Rise: Excerpts from the Matrix of Voices

To better understand the financial implications of the risks of sea level rise to coastal property markets and the wider economy, we gathered perspectives from market experts—including representatives from credit rating agencies, insurers, real estate investors, bond investment advisors, and mortgage and real estate industry experts—and municipal officials. Taken together, a picture emerges that highlights the likely impact of sea level rise on coastal property values, the property tax base, and the many inextricably connected market sectors, and reinforces the need for broad-based action to limit harmful consequences for people and the economy.

The **six main insights** that emerged from the experts consulted were (see the full Matrix of Voices at *www.ucsusa.org/underwater* for more details):

1. **The financial risks of sea level rise are real and significant—and they are largely unaccounted for in the current market.**

   "Sea level rise is an extremely serious issue with direct implications for municipal credit ratings, which will in turn affect the value of their bonds. Also, if the tax base contracts substantially, that will affect the ability of municipalities to pay back bond investors."
   —*Andrew Teras, vice president and senior analyst, Breckinridge Capital Advisors*

   "The impacts to coastal real estate markets, coastal businesses, and property tax bases will be geographically concentrated in the near term, but will become more widespread over time. Many of today's financial decisions do not consider sea level rise, but as the evidence evolves, market signals (insurance rates, community credit scores) may increasingly reflect a heightened risk."
   —*Roger Grenier, senior vice president, global resilience practice leader, AIR Worldwide, Consulting and Client Services*

   "As risks increase, insurers will pull out of markets and limit coverages, increase deductibles, or raise rates. When significant volumes of property value decline and mortgage delinquencies increase, there are major ramifications for our entire financial system, as we experienced in the 2008 financial collapse caused by the mortgage-market meltdown."
   —*Cynthia L. McHale, director, Ceres*

   "There is no risk, it's a guaranteed total loss. The only uncertainty is the timeline."
   —*Mayor Philip Stoddard, South Miami*

2. **Some initial steps are underway to try to incorporate these risks, but there are barriers to doing so.**

   "The challenge to incorporating climate risks like sea level rise into market-based decisions today is that there is no uniform way to communicate future risk conditions, nor consensus on the timeframe to consider in communication, or which model results/scenarios should form the basis of any outreach."
   —*Carolyn Kousky, PhD, director for policy research and engagement, Wharton Risk Management and Decision Processes Center, University of Pennsylvania*

   "As an investment manager, one of the biggest challenges is the disconnect between time horizons for our clients' investments in bonds—usually three to five years—and the time frame for significant tipping points when, say, 50 to 70 percent of the tax base is at risk of flooding."
   —*Andrew Teras, vice president and senior analyst, Breckinridge Capital Advisors*

into account future flood risks in order to help protect vital federally funded infrastructure, ensure wise use of taxpayer dollars, and also set a valuable guidepost for communities. State and local building and zoning regulations that are solely focused on near-term economic outcomes, and thereby allow questionable coastal development, are essentially building new exposure to risk when they could and should be reducing such exposure (IBHS 2018). Additional important opportunities include more protective building standards and coastal zone management regulations to help encourage flood-resilience measures in floodplains, including the protection of wetlands and barrier islands and other natural flood-risk reduction methods.

5. Increased funding for voluntary home buyout programs administered by FEMA and the HUD can also help homeowners move to safer locations. Communities in high-risk areas may also increasingly need relocation grants and technical assistance, and, correspondingly,

"Our first infrastructure challenge is going to be loss of septic tank function. Installing municipal sewer systems after a neighborhood is built-out is very expensive. We are looking at the costs and cringing. Nobody is going to help, not the feds, not the state, not the county. So, cost is the biggest barrier."
– *Mayor Philip Stoddard, South Miami*

3. **Some federal and local policies, in their current form—particularly those related to disaster risk response, flood insurance, and zoning regulations—unintentionally serve to mask the risks to coastal communities.**

"Flood insurance creates risky behavior when it is extended to new development. Zoning regulations should be considering the 100-year outlook for the land, including the future cost of providing access and infrastructure to the land, incenting construction in areas without sea level rise risk, and 'charging' areas with [sea level risk] to cover the future public costs of mitigating those risks."
– *Douglas M. Poutasse, executive vice president, head of strategy and research, Bentall Kennedy (US) LP*

"The existing government-backed system effectively creates a program of subsidized insurance coverage for Americans to live at the coast... In addition, current spending is heavily weighted towards post-disaster mitigation, instead of investing in communities before disasters occur... Finally, the economic incentives of the real estate industry, construction industry, and local chambers of commerce are often not aligned with risk-informed policies and practices."
– *Roger Grenier, senior vice president, global resilience practice leader, AIR Worldwide, Consulting and Client Services*

4. **A coastal property market correction is inevitable, but the form and severity it will take in specific locations, and its timing, are still uncertain.**

"If policymakers confront the National Flood Insurance Program's moral hazards and reduce the scope of coverage it provides, or increase premiums in line with the underlying risk, development or redevelopment of coastal lands might be constrained as they become uninsurable."
– *Kurt Forsgren, managing director, infrastructure sector lead, S&P Global Ratings*

"Once the properties enter the 'decline' phase, the behavior of owners changes. They invest less new capital in maintaining and improving their properties, because the shortened time frame to receive a return on additional investment necessitates a higher rate of return. This becomes a self-reinforcing mechanism, as properties with lower reinvestment become less attractive to tenants and occupants."
– *Douglas M. Poutasse, executive vice president and head of strategy and research, Bentall Kennedy (US) LP*

5. **Some communities will be hit harder than others, especially if policy interventions are not made ahead of a steep downward adjustment in property values.**

"The concern I always have is that, ultimately, only some portions of the vast US coastline will be protected, i.e., major urban areas. Many, many other portions of the coast, along with their respective people and livelihoods, will remain in harms' way."
– *Cynthia L. McHale, director, Ceres*

6. **Standards and guidelines for risk disclosure are an important first step for market actors to be able to account for these risks in their business models.**

"S&P Global Ratings see the uniform and transparent disclosure by governments of the potential effects of gradual environmental change and extreme weather events as both an important input into our assessment of management's ability to respond to the risks, and one of the largest challenges to the market. Uniform risk disclosure is necessary for markets to price this risk accurately."
– *Kurt Forsgren, managing director, infrastructure sector lead, S&P Global Ratings*

communities that receive an influx of new residents may need financial resources. And as sea levels rise, federal, state, and local policies and resources should specifically target and address the needs of disadvantaged communities.

6. Banks, insurers, real estate investors, developers, and other major financial actors in coastal areas should establish guidelines and standards to incorporate the risks of sea level rise in their business models, thus better serving the long-term economic interests of their clients. A blinkered focus on near-term profits and market factors can obscure significant risks just beyond the horizon.

If there are changes in the perception of risk to coastal properties or if there is a growing political or social pressure to make changes, the marketplace or policymakers could make rapid changes to align incentives with risks. Potential examples of these types of shifts include changes in insurance premiums or criteria for insurability, changes in lending terms, and changes in credit ratings for communities. These types of tipping points could trigger very quick shifts in property values and the broader economic health of a coastal community.

Unfortunately, a rapid realignment of taxpayer and private-sector investments reflecting true risk could jeopardize the well-being of communities unless deliberate steps are taken to provide options for them ahead of time. The withdrawal of private-sector investment dollars, and even public dollars when places are deemed too costly to support, could bring disruptive local impacts and market speculation with inequitable outcomes, particularly for those communities with fewer resources. Rather than a wholesale rapid withdrawal of funding for these areas, a judicious scaling back of new investment in line with flood risks would be far preferable from a societal perspective, together with a redirection of those investments toward options to help communities cope and build resilience.

PLANNING FOR A RESILIENT FUTURE FOR ALL

As a nation, we must use wisely the diminishing response time that communities have to reduce their exposure to this threat, from the individual scale to the economy as a whole. For communities facing chronic flooding of properties in the near term, it is imperative to act quickly to phase out policies that perpetuate and increase risk, while considering options for retreat from the highest-risk places. For cities and towns where the effects of chronic inundation will become apparent by mid-century, a slightly longer time horizon might allow for more creative solutions and comprehensive policies and planning. Targeted resources must be made available for disadvantaged communities for whom any of these adaptive responses could pose steep challenges. Given the wide-scale nature of the risks to our nation, we need a holistic, timely response strategy.

[Decisionmakers still have choices that can help limit threats to coastal cities and towns, and ultimately, to the national economy.]

Decisionmakers still have choices that can help limit—even if they cannot eliminate—threats to coastal cities and towns, and ultimately, to the national economy. Three main strategies exist for adapting to sea level rise on any coast: defend, accommodate, and retreat. Decisions about which combination of strategies to employ, and when and where, require expertise, stakeholder engagement, and ultimately the resources to implement the chosen options. Many cities and towns can expect adaptation to be costly, and that some financial losses will be inevitable. Homeowners and communities cannot be expected to absorb all of these potentially crippling costs on their own, especially those with fewer resources. A range of relevant actors—chiefly, the federal government—can implement policies that will help support adaptation and limit the extent of financial loss, ensuring that these taxpayer-funded resources are wisely and equitably deployed. The private sector also has an important role in driving innovative risk-reduction measures and creating new loci of economic opportunities in areas further inland.

Sea level rise is challenging us to reimagine our coasts in many ways. Hundreds of communities will face losses. Retreat may be necessary from some of the highest-risk places. But there are opportunities to be had too—especially if we plan and invest wisely. Inland communities may be revitalized by the influx of new residents and new businesses. New communities can emerge, new infrastructure be built, and new economic opportunities created. All of this will only be possible with visionary leadership from policymakers, the private sector, and communities themselves.

Critically, the United States must also work with other nations to slow the pace and limit the magnitude of sea level rise through aggressive reductions in heat-trapping emissions, in order to allow as many communities and homes as possible—both at home and abroad—to avoid chronic inundation in the years ahead.

RESEARCH AGENDA FOR MEETING THIS CHALLENGE

Developing a coherent, just, and forward-thinking approach to the challenges we face will require further research on several fronts.

First, the many stakeholder groups within the coastal real estate sector—from individual homeowners to insurers—need to examine their tidal flooding tolerance and explore thresholds beyond which a pull-back (physically or financially) from affected areas is required. Within the private sector, for example, a careful examination of the risks could trigger decisions—such as not granting loans, raising insurance premiums, or downgrading credit—which will in turn drive big, sometimes painful, changes that begin to align market outcomes with those risks. Local-scale, community-specific modeling under different climate projections is a key piece of this research that can be built out.

This Hampton Beach, New Hampshire, home captures both our desire to be close to the ocean and the risks of sea level rise. Homeowners and communities have a narrowing window of time to take action. They require support from local, state, and national elected officials to manage what lies ahead.

Second, communities will need more complete information on whether and how they can be made more resilient in place: for example, through what measures, at what cost, for how long? Third, further research is needed around successful models for retreat that could lead to positive outcomes for coastal and inland communities, particularly considering lessons learned following buyouts and individual homeowner retreat after Hurricane Sandy (Binder and Greer 2016). Critical areas in which we need to build our understanding are the necessary governance structures that will best support coastal retreat, legal implications of historically dry land going underwater, and the relationship between market downturns and climate-induced migration (Flavelle 2018; Kousky 2014). Additionally, as communities increasingly face the challenge of frequent, disruptive flooding, they will need to marshal resources to rise to that challenge—which inherently puts communities with fewer resources at a disadvantage (ERG 2013). We will therefore need to deepen our understanding of how policies can be made equitable and how best to enact them (Deas et al. 2017).

Conclusion

The cliff's edge of a real estate market deflation due to flooding and sea level rise is already visible for many communities if they choose to look. The trajectory of our current actions—continued building in vulnerable places and ever-increasing global warming emissions—is propelling us closer to that edge. There are thresholds for properties at risk of chronic flooding from sea level rise beyond which regular life becomes unmanageable and financial loss becomes a better bet than struggling to live with floodwater. There are thresholds for communities beyond which economic and financial viability, and crucial public services, are threatened. When enough of those households and communities falter, entire real estate markets may face a tipping point. Whether we react to this threat by implementing science-based, coordinated, and equitable solutions—or walk, eyes open, toward a crisis—is up to us right now.

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The opinions expressed herein do not necessarily reflect those of the organizations that funded the work or the individuals who provided advice to the authors, reviewed the report, or provided quotes. The Union of Concerned Scientists bears sole responsibility for the report's contents.

DISCLOSURE

Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions presented in this report are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.

DISCLAIMER

This research is intended to help individuals and communities appreciate when sea level rise may place existing coastal properties (aggregated by community) at risk of tidal flooding. It captures the current value and tax base contribution of those properties (also aggregated by community) and is not intended to predict changes in those values, nor in the value of any specific property. The projections herein are made to the best of our scientific knowledge and comport with our scientific and peer review standards. They are limited by a range of factors, including but not limited to the quality of property-level data, the resolution of coastal elevation models, the potential installment of defensive measures not captured by those models, and uncertainty around the future pace of sea level rise. More information on caveats and limitations can be found at www.ucsusa.org/underwater. Neither the authors nor the Union of Concerned Scientists are responsible or liable for financial or reputational implications or damages to homeowners, insurers, investors, mortgage holders, municipalities, or other any entities. The content of this analysis should not be relied on to make business, real estate or other real world decisions without independent consultation with professional experts with relevant experience. The views expressed by individuals in the quoted text of this report do not represent an endorsement of the analysis or its results.

ENDNOTES

1. Complete results for the intermediate and low scenarios are available here at *www.ucsusa.org/underwater*. The high scenario used throughout this report is not now thought to be extreme, given recent observations and analysis of land-based ice melt (e.g., Kopp et al. 2017, Schroeder et al. 2017; DeConto and Pollard 2016). In addition, in 2017 the National Oceanic and Atmospheric Administration released new sea level rise scenarios that are comparable to these three and include an "extreme" scenario of a roughly eight-foot increase by 2100 (Sweet et al. 2017).
2. In southeast Florida, individual units in high-rise buildings (which have been constructed at a rapid pace on low-elevation land in recent years) account for many at-risk homes. In this analysis, ground-floor chronic flooding risk is applied to the entire building since the unit's access, functionality, and value are all impacted (see the full methodology at *www.ucsusa.org/underwater*.)
3. The shore line of the San Francisco Bay contains a vast network of locally controlled defensive structures such as seawalls and levees. This analysis explicitly accounts for only those structures identified by the Federal Emergency Management Agency as reducing flood risk—namely, those surrounding Foster City and the Oakland International Airport. As such, the statistics reported here likely do not reflect the varying levels of protection that other coastal defense structures could potentially provide to Bay Area communities.
4. California home values reflect assessed rather than market values, unlike all other coastal states in this analysis. See the full methodology at *www.ucsusa.org/underwater* for details.
5. Many Louisiana communities have locally controlled levees or other flood-control structures that were not explicitly included in this analysis. Federally controlled leveed areas as defined by the US Army Corps of Engineers were excluded from the analysis. See the full methodology at *www.ucsusa.org/underwater* for details.
6. If properties of all values were equally at risk, 50 percent of the at-risk homes would be valued below the state median.
7. In general, real estate agents and home sellers are required to disclose all material facts that could affect the price or desirability of a property. But in practice, unless they are shown to have actual knowledge of flood risks, there is no easy way to require agents and sellers to disclose projected sea level rise–related flood risk under current laws.
8. A recent study from the Natural Resources Defense Council, using data from FEMA, found that from 1978 through 2015 the agency paid $5.5 billion to repair or rebuild 30,000 severe repetitive loss properties that have been flooded an average five times or more. Texas, New Jersey, New York, and Florida ranked the highest in terms of both numbers of these properties and damage costs.

APPENDIX: ABOUT THIS ANALYSIS

Our basic methodology

This analysis intersects two existing datasets: 1) zones of chronic inundation along the US coastline, previously published by Dahl et al. 2017 and Spanger-Siegfried et al. 2017; and 2) the Zillow Transaction and Assessment Database (ZTRAX), which contains property data gathered by county assessors' offices and has been collated by the online real estate company Zillow. The chronic inundation zones are defined for a suite of future years and sea level rise projections, as described as follows. The overarching goal of the analysis is to evaluate the risks of chronic, disruptive flooding to the coastal real estate sector.

What is chronic inundation?

Building on prior research, this analysis defines a chronic inundation zone as any area where tidal flooding occurs 26 times per year (on average, twice a month) (Dahl et al. 2017). This frequency is based on previously published thresholds (e.g., Sweet and Park 2014), consultation with technical experts at universities and federal agencies, and perspective gained from local community experts. The flood tolerance of individual homeowners or homebuyers, however, will be highly subjective. Similarly, the willingness of private sector actors to bear financial exposure in flooded locations may change far earlier than the threshold used here. When it comes to real estate markets, it may take considerably less flooding to drive big choices and changes.

What sea level rise scenarios did we use and why?

We used three scenarios developed for the 2014 National Climate Assessment and localized for this analysis (Huber and White 2015; Walsh et al. 2014; Parris et al. 2012). We refer to our projections as the high, intermediate, and low scenarios (Figure A-1). The high scenario assumes rapid ice sheet loss and projects a global average sea level rise of 6.6 feet (2.0 m) above 1992 levels by the end of this century. The intermediate scenario assumes a moderate rate of ice sheet loss that increases over time for a rise of 4.0 feet (1.2 m) by the end of this century. The low scenario assumes curtailed warming and sea level rise that is driven primarily by ocean warming with very little contribution of ice loss, and projects a rise of 1.6 feet (0.5 m) by the end of this century. Because the total 21st-century warming in this scenario is in line with the Paris Agreement's goal of holding warming to less than 3.6°F (2°C) above preindustrial temperature levels, we use this scenario as a proxy for sea level rise under the Paris Agreement (Rasmussen et al. 2018).

We have made projections for at-risk properties under all three scenarios, but in this report, we lead with results of the high scenario. The high scenario is considered most applicable in situations with a low tolerance for risk. This makes it most suitable for estimating the scale of risk to residential properties, which typically represent a homeowner's greatest single asset. The full suite of results is available online at *www.ucsusa.org/underwater*.

How were incomplete or inaccurate data in the ZTRAX dataset handled?

Within the ZTRAX dataset, issues such as missing values are common. We applied three broad corrections to the ZTRAX data. First, we removed properties that were duplicated in the database. Second, we re-geocoded each property using an external service (geocod.io) to ensure its positional accuracy. Finally, for properties missing a market value or a property tax value, we calculated the missing value based on the reported assessed value and county-specific information about the ratio between assessed and market values and/or effective tax rates. Missing market and property tax values were calculated only for residential properties. It is important to note that for California, where there is no simple ratio between assessed value, market value, and property tax value, we used assessed value in place of market value.

How were population and demographic statistics derived?

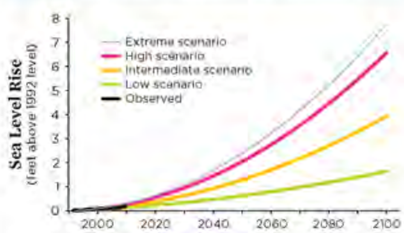
Estimates of the number of residents living in homes at risk of chronic inundation were derived using the housing unit method (Smith 1986) and 2010 census data on occupancy rate and number of people per household (US Census Bureau 2010). Population totals as well as racial demographics were also taken from the 2010 census. Community-level poverty rates were derived from the 2011–2015 American Community Survey.

What are the key caveats, assumptions, and limitations?

1. Our determination of the extent of chronic inundation is dependent upon the quality of the underlying elevation data, which were provided by the National Oceanic and Atmospheric Administration (Marcy et al. 2011; NOAA 2017b). These data vary in horizontal resolution and accuracy, and communities are encouraged to work with the highest resolution elevation data available to do more detailed mapping.
2. Even the highest-resolution elevation data used here do not fully capture many local coastal defenses, such as sea walls. Though most defenses are constructed to manage storm surge and erosion, not to keep out higher tides, areas with such structures in place may not experience as much flooding as suggested by our analysis.
3. Tidal dynamics vary greatly depending on local coastal morphology. Features such as bays, inlets, barrier islands, and wetlands can attenuate or amplify the tide relative to its level at the open ocean–facing tide gauges that were used to determine chronic inundation water levels.
4. This analysis makes no assumptions about adaptation measures that communities may implement in the future, such as building flood control structures or restoring wetlands. Several factors could affect whether and how communities implement adaption measures, including geography, resources, and the range of options available to any given community.
5. Population, demographics, number of properties, and associated property data are assumed to be constant at present-day levels. Studies incorporating future population growth into sea level rise studies tend to show greater population impacts, which suggests that our results may be conservative (Hauer, Evans, and Mishra 2016).

For more details on this analysis, see *www.ucsusa.org/underwater*.

FIGURE A-1. Projected 21st Century Sea Level Rise



How much the sea level rises this century depends on our past and future emissions of heat-trapping gases as well as how Earth responds to those emissions. We based our projections for sea level rise—our low, intermediate, and high scenarios—on the intermediate-low, intermediate-high, and highest scenarios from the Third National Climate Assessment (Parris et al. 2012). The Fourth National Climate Assessment includes an "extreme" sea level rise scenario predicated on our growing understanding of the sensitivity of Antarctic ice to warming temperatures (Sweet et al. 2017).

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Underwater

Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate

In the coming decades, many coastal real estate markets will be strained by tidal flooding, with potential reverberations throughout the national economy.

As sea levels rise, more and more American homes and businesses will experience frequent, disruptive flooding that makes everyday life impossible. More than 300,000 of today's coastal homes are at risk of this untenable flooding within the term of a 30-year mortgage.

Yet property values in most coastal real estate markets do not currently reflect this risk. And with short-sighted investments and policies at all levels of government concealing this growing problem, homeowners, businesses, communities, and investors are not aware of the financial losses they may soon face.

In the coming decades, many coastal real estate markets will be strained by flooding, some to the point of collapse, with potential reverberations throughout the national economy. Individual homeowners and businessowners, banks, lenders, investors, developers, insurers, and taxpayers are poised to sustain large collective losses. Shrinking property tax bases could spell decline for many coastal cities and towns.

We have scant time remaining to brace our communities, and our local and national economies, for this challenge. While there are no easy solutions, knowing our risk—and using that knowledge to create bold new policies and market incentives—will help protect coastal communities. Whether we react to this threat by implementing science-based, coordinated, and equitable solutions—or walk, eyes open, toward a crisis—is up to us right now.

Union of Concerned Scientists

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Risk & Insurance

2017 Most Dangerous Emerging Risks

Coastal Mortgage Value Collapse

As seas rise, so does the risk that buyers will become leery of taking on mortgages along our coasts.

April 7, 2017

Rising seas encroach on our cities and towns at rates exponentially greater than before.

So-called King Tides, urged on by climate change and brought about by the close alignment of the sun, the moon and the earth are already producing flooding in Miami 10 days a year.

Debate the cause if you want to expend more hot air denying science. But it's a fact that resale values of coastal homes in Miami, Atlantic City and Norfolk, Va. are already starting to erode.

These bellwether locations signify a growing and alarming threat; that continually rising seas will damage coastal residential and commercial property values to the point that property owners will flee those markets in droves, thus precipitating a mortgage value collapse that could equal or exceed the mortgage crisis that rocked the global economy in 2008.

"Insurance deals with extreme weather and billions of dollars of losses, but what we are talking about is uninsured loss of fair market value that is trillions of dollars in losses and I am not talking about in 2100, I'm talking about the next mortgage cycle," said Albert Slap, president of Coastal Risk Consulting, a Florida firm that provides lot by lot modeling of flood risk.

Models created by Coastal Risk Consulting show flooding rates of Miami properties are going to rise substantially between now and 2050, within that 30–year mortgage cycle he refers to.

“The results of our modeling and that of NOAA and many others shows that the increase in flooding on people’s properties, due to astronomy and physics, not weather, is alarming and significant and in all likelihood is not backstopped by insurance,” Slap said.

Adding to the threat is that real estate agents and homeowners aren’t incentivized or required to reveal how frequently properties flood, or how exposed they are to flooding.

“Forty percent of Americans live on the coast, which means you have trillions of dollars at risk for climate change that hasn’t been modeled for default increases,” Slap said.

The Pew Charitable Trusts, as part of its testimony to Congress as the National Flood Insurance Program undergoes review, is asking that all homeowners be required to report on that risk.

Many coastal homes are backstopped by the NFIP, which is still billions in debt from its losses in the Katrina-Wilma-Rita hurricane cycle of 2005.

Private sector insurers are eyeing ways to write more flood business. But if the NFIP suffers further losses, and private sector insurers retreat, what then?

“If you look at it systematically, if a broad number of insurance companies decide that they need to triple homeowners insurance rates, or they need to pull out of a local market, that would create a lot of problems in terms of the value of the properties that are in that locale,” said Cynthia McHale, president of insurance for Ceres, a nonprofit that advocates for sustainable business practices.

In November, Sean Becketti, the chief economist for the economic and housing research group at Freddie Mac, the federally backed housing lender, co-authored a paper that documented this very risk.

The paper referenced the fact that daily high-water levels in Miami are increasing at a rate of an inch per year, much faster than the rate of global sea-level rise. Other cities along the Eastern seaboard are experiencing a 10-fold increase in the frequency of flooding, according to Freddie Mac.

“A large share of homeowners’ wealth is locked up in the equity in their homes,” Becketti wrote.

“If those homes become uninsurable and unmarketable, the values of the homes will plummet, perhaps to zero.”

“Forty percent of Americans live on the coast, which means you have trillions of dollars at risk for climate change that hasn’t been modeled for default increases.” —Albert Slap, president, Coastal Risk Consulting

In the housing crisis of 2008, according to Becketti, a significant percentage of borrowers continued to make their even though the value of their homes was less than their mortgages.

“It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater,” Becketti said.

“As a result, lenders, servicers and mortgage insurers are likely to suffer large losses,” he said.

Insurers would suffer, according to Ceres’ McHale, and not just as backers of insurance policies.

“Insurance companies themselves are major commercial and residential mortgage holders,” she said.

“They assume that the property is going to hold its value and act as collateral if needed. If it doesn’t hold its value, where is the collateral?”

“Not only will their mortgages be metaphorically underwater, they are going to be literally underwater,” said Slap.

“And there is no coming back from it.”

“The New York Times” published a piece in November that detailed the case of Roy and Carol Baker of Sarasota, Fla. The Bakers tried for months to sell their home in Siesta Key, according to the story, but buyers kept backing out when they discovered the annual flood insurance premium was about $7,000.

“This experience will become more common, economists say, as the federal government shifts away from subsidizing flood insurance rates to get premiums closer to reflecting the true market cost of the risk,” reporter Ian Urbina wrote in his piece.

The Climate Race

What Becketti, Slap and others say is true, said Helen Thompson, a director, commercial marketing at Esri, the mapping and analytics company that works with insurers and property owners.

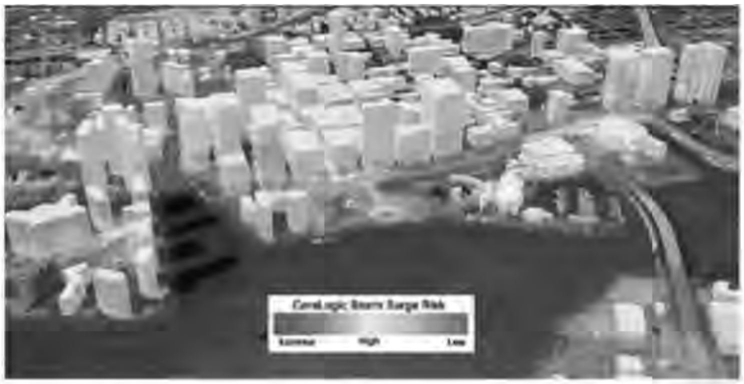
But she said there is a solution, the public and private sector working together to address the problem: That and about $4 trillion.

“The challenge for a lot of people is to understand the scope and the scale of this issue, and in some ways, like the mortgage bubble before, if you are ignorant of the problem, you can’t fix it,” she said.

“I think taking action means crafting a discussion of the problem and moderated expressions of what those solutions are, based on science and analysis and not hyperbole,” she said.

It’s well documented how dire the nation’s infrastructure needs are.

Thompson compares the current dilemma posed by climate change and sea rise in the U.S. and elsewhere to the cholera epidemic that ravaged London in the mid-19th century. What’s needed now, she said, is something akin to the massive public works projects that were undertaken to provide Londoners with cleaner drinking water.



"They realized the social and political cost of this," Thompson said.

"We need to change our thinking to say this is not just about handing debt to our children, it's about maintaining the same level of opportunity and quality of life for our children," she said.

Thompson points to China, which she says is investing in climate change-resistant ports and additional infrastructure internationally to remain economically competitive.

"It's in their best interests as a global manufacturing hub to mitigate the cost and the impact of climate change because of how much collateral damage it will do to their economies," Thompson said.

She said the U.S. needs to go down the same path, and step on it.

"I call it the 'climate race,' like the space race," she said.

"The infrastructure needs to be created to deal with this, and the United States is massively lagging."

Slap envisions another solution, a "climate ready" mortgage program, similar to the federal government's energy efficient mortgage program, which gives property owners federally guaranteed loans to make energy efficiency upgrades.

Such a program would provide loans for sewage backflow preventers, changing the grade on a driveway, or elevating a home on a platform.

Thompson said the massive infrastructure projects she envisions could include moving the vital container operations at the Port of Miami inland and constructing a berm to defend against sea water.

Office building owners in Lower Manhattan, which was so damaged by Superstorm Sandy, are increasingly investing in flood prevention barricades and moving critical building components like HVAC and plumbing components to higher floors.

Americans just got a chilling reminder of the dangers presented by changing weather patterns and crumbling infrastructure. Fears that the Oroville Dam on California's Feather River would buckle under heavy rainfall got everyone's attention.

"People are looking at that and saying, 'We didn't realize what this change in weather patterns means in the long term,' " Thompson said, and they are relating the Oroville event to infrastructure in their own towns and the risks they present.

As the NFIP undergoes its annual review in Congress, Slap said administrators would do well to exclude King Tide events.

"If you were to go to NFIP and ask them if they cover King Tide flooding, they would say, 'If it meets our definition of flood then we must cover it.' This is a red flag, because what you are saying is the government and the taxpayers are covering sea level rise and that is not something we can afford," Slap said.

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As the seas have been rising, home values have been sinking.

Scientists from the non-profit First Street Foundation find $7.4 billion has been lost in home value across 5 coastal states from 2005 to 2017 due to sea level rise flooding. These findings have been integrated into Flood iQ, a sea level rise flooding prediction tool from First Street Foundation, so individuals can find property-specific value loss and aggregated total city loss.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant, recently released an academic publication in the journal Population Research and Policy Review proving $465 million was lost in Miami-Dade County real-estate market value from 2005 to 2016 due to sea level rise flooding. This peer-reviewed analysis was expanded to cover all of Florida, South Carolina, North Carolina, Virginia and Georgia by analyzing over 5.5 million real estate transactions in these states and extrapolating the results to 12.2 million properties, to find a total home value loss of $7.4 billion since 2005. Lists of the top 250 most impacted cities and ZIP codes have been released.

Previous academic studies have forecasted the negative impact sea level rise will have on the value of coastal properties in the future but "Estimating Recent Local Impacts of Sea-Level Rise on Current Real-Estate Losses: A Housing Market Case Study in Miami-Dade, Florida" is the first to show that depreciation has already taken place. By identifying the predictors of home value, such as square footage or proximity to amenities, while controlling for economic trends like the 2008 housing recession, the scientists were able to isolate the impact frequent tidal flooding, caused by sea level rise, has had on home value.

"It is one thing to project what the future impacts of sea level rise could be, but it is quite another to know that the market has already responded negatively to this threat," said McAlpine.

"We need to act now," said Porter. "The ability to pay for solutions to sea level rise is directly related to our ability to finance them. We do not want to see the beginning of a domino effect, where lost property value lowers the tax base and cripples our ability to finance solutions."

This is the first academic paper to demonstrate that sea level rise is directly to blame for a decrease in coastal home value and the first to identify the role nearby flooding plays in that decrease. Proximity to road flooding was proven to have as much of an impact on home value as direct, property-level, flooding--indicating that all members of a community should be concerned by any amount of flooding in the streets.

"Flooding does not have to be a way of life for coastal communities. Cities can take measures to mitigate the impact and protect property values," said Matthew Eby, Executive Director at First Street Foundation. "But without action, the rate of home value loss will only accelerate."

• • •

First Street Foundation, is a 501(c)(3) tech nonprofit that educates policymakers and the public about the risks, causes, and solutions to sea level rise.

Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

For questions please reach out to pr@firststreet.org


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A five state analysis of home value loss due to sea level rise and flooding
Total properties that lost value: 616,626
Georgia 11,360
Virginia 47,035
North Carolina 81,908
South Carolina 92,775
Florida 384,548
$
7.4 B Total property value loss
Florida -$5.42 B
South Carolina -$1.11 B
North Carolina -$582 M
Virginia -$280 M
Georgia -$15 M

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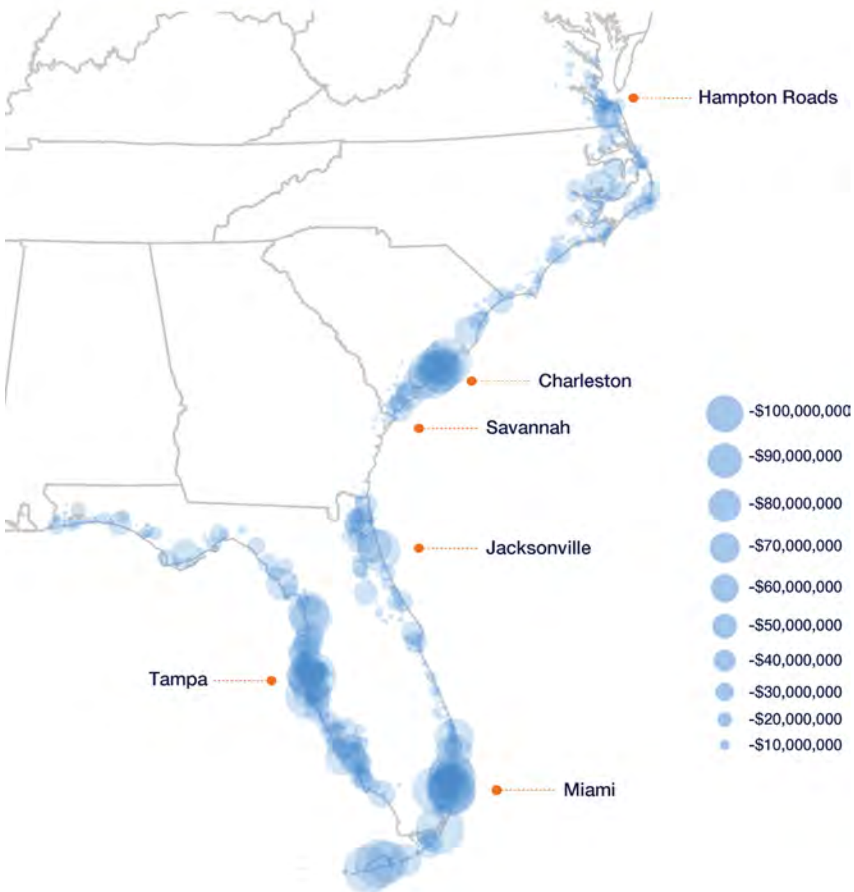
Total property value lost from 2005 - 2017 (by zip code)



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Top 20 cities by total property value lost from 2005 - 2017

Rank	City Name	Total Property Value Lost
1	Miami Beach, FL	-$337,167,466
2	Hollywood, FL	-$304,568,101
3	Charleston, SC	-$266,217,606
4	Saint Petersburg, FL	-$243,968,610
5	Fort Lauderdale, FL	-$193,885,367
6	Key Largo, FL	-$159,615,296
7	Mount Pleasant, SC	-$149,072,672
8	Jacksonville, FL	-$146,483,838
9	Key West, FL	-$133,015,501
10	Miami, FL	-$125,275,830
11	Kiawah Island, SC	-$90,490,822
12	Doral, FL	-$85,517,020
13	Saint Augustine, FL	-$79,809,123
14	Tampa, FL	-$76,084,992
15	Holmes Beach, FL	-$75,212,310
16	Chesapeake, VA	-$71,009,779
17	Homosassa, FL	-$66,584,367
18	Palm Beach, FL	-$62,445,556
19	Sanibel, FL	-$55,567,578
20	Norfolk, VA	-$55,515,241

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Top 20 zip codes by total property value lost from 2005 - 2017

Rank	ZIP Code	State	Total Property Value Lost
1	33019	Florida	-$256,107,024
2	33040	Florida	-$194,923,568
3	29455	South Carolina	-$178,870,640
4	33037	Florida	-$176,269,824
5	33703	Florida	-$152,503,280
6	33140	Florida	-$147,746,416
7	33141	Florida	-$135,996,864
8	33042	Florida	-$106,351,368
9	29466	South Carolina	-$98,784,464
10	29401	South Carolina	-$97,694,512
11	33178	Florida	-$94,402,840
12	34217	Florida	-$88,288,480
13	33301	Florida	-$82,690,952
14	33138	Florida	-$78,050,480
15	32080	Florida	-$77,920,312
16	33139	Florida	-$77,767,328
17	33043	Florida	-$77,283,352
18	34448	Florida	-$76,522,504
19	34429	Florida	-$74,219,792
20	29412	South Carolina	-$72,215,928

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Sea Level Rise Sinks Mississippi Home Values by More Than $263 Million

For Immediate Release: December 3, 2018

Scientists from First Street Foundation and Columbia University analyzed recent housing market trends in Mississippi and found home values lost $263.8 million from 2005 to 2017 due to sea level rise flooding. Bay St. Louis showed the greatest property value loss, totaling $95.4 million. There, the average impacted home would be worth 49% more if tidal flooding were not a risk. Pass Christian had the second highest loss at $26.8 million, followed by Kiln at $24.9 million. Homeowners can use FloodiQ.com to look up their personal home value loss as well as the total loss for their city.

The Mississippi analysis expands on the Foundation's previous research on other states which has been widely covered by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor.

The research is based on peer reviewed methodology, established by Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant. Their original analysis of the Miami-Dade County real estate market, published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 15 housing market-specific models to cover Florida, Georgia, South Carolina, North Carolina, Virginia, as well as New York, New Jersey, Connecticut, Mississippi and Alabama. By analyzing approximately 10 million real estate transactions, and applying the results to 20 million properties, the researchers have found a $14.6 billion loss in home values across those ten states.

The Mississippi findings come from a study that also analyzed home values in Alabama. That state lost $157 million in home values due to sea level rise flooding. The Alabama results have also been integrated into First Street's Flood iQ tool.

McAlpine and Porter's research is the first to quantify the observed negative impact of sea level rise on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value. While some of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding.

"In Bay St. Louis the average impacted home would be worth 49% more if tidal flooding were not a risk, and in Kiln 41% more," said McAlpine. "These are the hardest hit neighborhoods in Mississippi because homes and roads are at low elevations and sea level rise is increasing the frequency of flooding along the Jourdan River."

The research is also the first to find that in addition to direct property-lot flooding, nearby road flooding also has a major impact on home value.

"As we have expanded our study, the results have been incredibly consistent," said Porter. "Americans across 10 states have already lost $14.6 billion from increased flooding caused by sea level rise, and all signs are pointing to this being an accelerating trend."

"What has made this research truly striking for people is its integration with Flood iQ," said Matthew Eby, Executive Director of First Street Foundation."People can look up their personal addresses and learn just how much value they have lost due to sea level rise flooding. It's powerful, and in some cases, devastating."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

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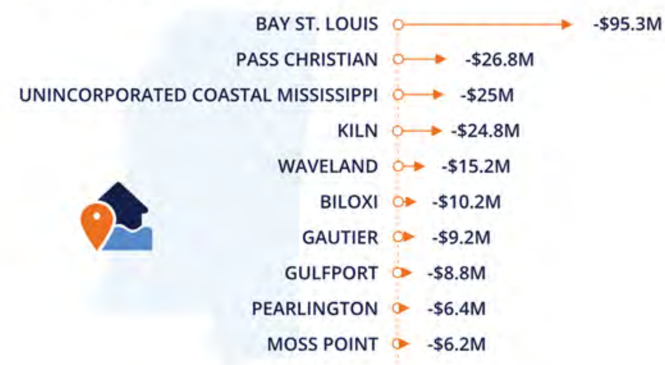
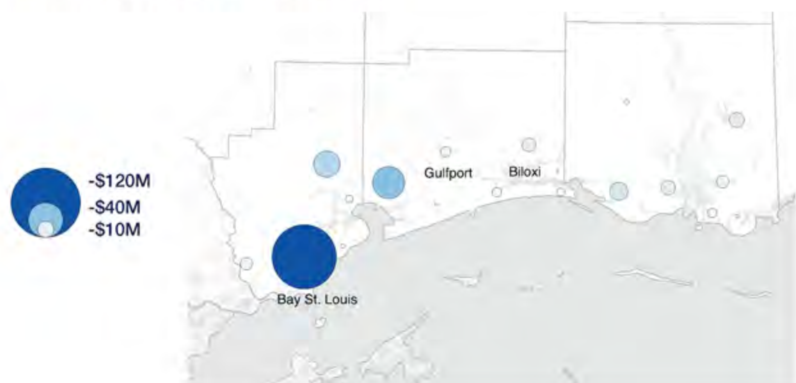
Top Ten Impacted Mississippi Cities



Mississippi Property Loss by Zip Code



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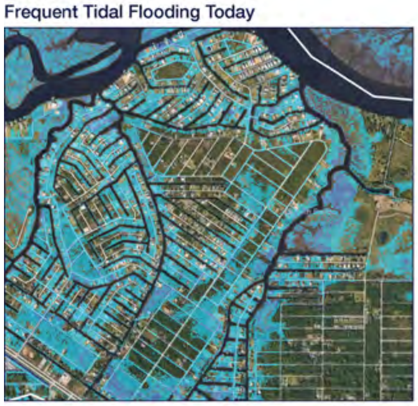
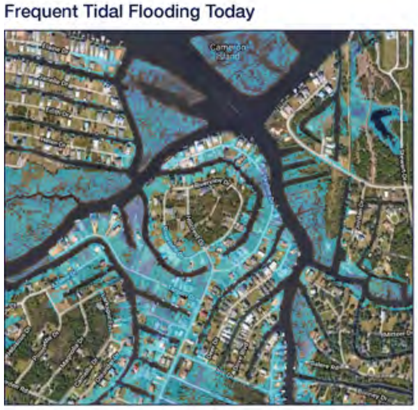
Bay St. Louis Tidal Flooding Today and in 15 Years

A:
Shoreline Park
Frequent Tidal Flooding Today

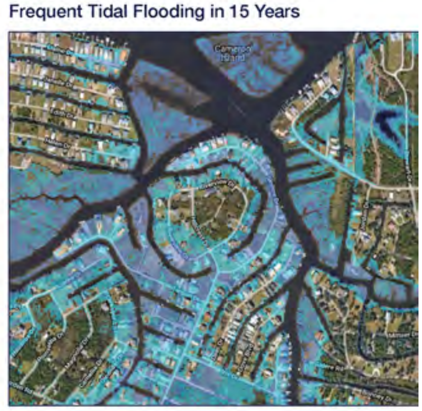


A:
Shoreline Park
Frequent Tidal Flooding in 15 Years

B:
Shoreline Park
Frequent Tidal Flooding Today



B:
Shoreline Park
Frequent Tidal Flooding in 15 Years



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Rising Seas Swallow $403 Million in New England Home Values
For Immediate Release: January 22, 2019

Data scientists from First Street Foundation and Columbia University have expanded their peer-reviewed housing market research to include 2.5 million coastal properties in Massachusetts, Maine, New Hampshire, and Rhode Island and found that increased tidal flooding caused by sea level rise has eroded $403.1 million in relative home values between 2005 and 2017. Coastal homes in Massachusetts were hit hardest, losing $273.4 million in relative appreciation. Homes in Maine saw $69.9 million in unrealized value, followed by Rhode Island at $44.7 million, and New Hampshire at $15.2 million. One of the region's hardest hit homes, a triplex located on Marginal Street in Boston, currently valued at $373,725, would be worth more than double at $799,054 if not for increased tidal flooding due to sea level rise.

Homeowners can learn how much relative value their personal property missed out on over the 12 year study period and how much value it is projected to lose over the next 15 years at FloodiQ.com. The interactive visualization tool also shows current inundation estimates for frequent and annual tidal floods as well as from hurricane storm surge, and how those levels are projected to increase over the next 15 years.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant first established their peer-reviewed methodology with an analysis of the Miami-Dade County real estate market. That study published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 16 housing market-specific models. By analyzing approximately 11 million real estate transactions, and applying the results to 22.5 million properties, the researchers have found a $15 billion loss in home values across 14 states. The Foundation's previous research was reported by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor

"Each time we analyze a new state we see the same phenomenon," said Porter. "Increased tidal flooding leads to a loss in home value appreciation. As sea level rise accelerates, we expect the corresponding loss in relative home value to accelerate as well."

McAlpine and Porter's research is the first to quantify the observed negative impact of increasingly frequent flooding, driven by sea level rise, on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value,

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such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding caused by sea level rise has had on home value. While most of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding. The research is also the first to find that in addition to direct property-lot flooding nearby road flooding also has a major impact on home value.

"It's not just property lot flooding that leads to home value loss, persistent flooding of nearby roads has a significant impact as well," said McAlpine. "Road flooding affects commutes and school bus access, and because it's on display for everyone to see, it can give an area a negative reputation. In New England, winter flooding can create sheets of ice on roadways, adding another, dangerous, consequence to street flooding."

FloodiQ.com is the first publicly available database that gives coastal residents, homeowners, and prospective homebuyers access to comprehensive flood risk and property value loss information.

"This levels the playing field for average Americans looking to invest in real-estate by giving them access to the same information as institutional investors and the wealthy," said Matthew Eby, Executive Director of First Street Foundation. "Knowing the direct impact of previous flood events on the value of your home and understanding how the risks of flooding will increase as sea levels rise is something the public deserves to know."

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

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Massachusetts: Top 5 Hardest Hit Cities

Massachusetts: Top 3 Hardest Hit Homes

City: Boston
Street: Marginal St
Tax Assessed Value: $373,725
Should be Worth: $799,054
Relative Value Loss: -$425,329

City: Salisbury
Street: Central Ave
Tax Assessed Value: $227,900
Should be Worth: $421,822
Relative Value Loss: -$193,922

City: Salisbury
Street: Cable Ave
Tax Assessed Value: $349,000
Should be Worth: $582,422
Relative Value Loss: -$233,422

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Tidal Flooding will Increase with Sea Level Rise

Highest Annual Tidal Flooding: Today

Highest Annual Tidal Flooding: In 15 Years

City: Boston
Street: Marginal St

Depth of Flooding (feet)
<1 1-2 2-3 3+

City: Salisbury
Street: Central Ave

Depth of Flooding (feet)
<1 1-2 2-3 3+

City: Salisbury
Street: Cable Ave

Depth of Flooding (feet)
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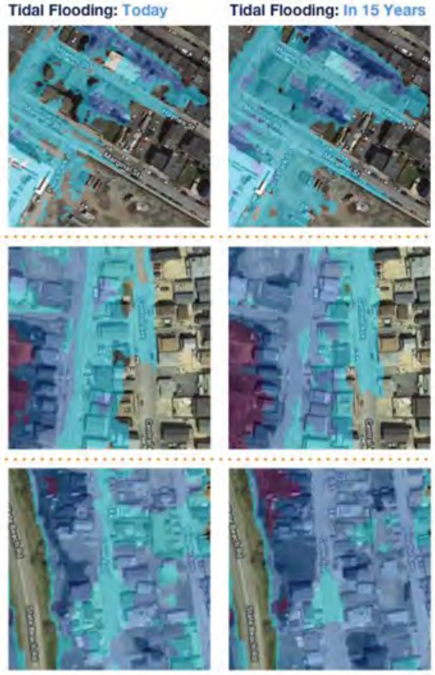

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Rhode Island: Top 5 Hardest Hit Cities

Rhode Island: Top 3 Hardest Hit Homes

City: Warren
Street: Child St
Tax Assessed Value: $179,300
Should be Worth: $294,148
Relative Value Loss: -$114,848

City: Warren
Street: Metacom St
Tax Assessed Value: $130,700
Should be Worth: $213,373
Relative Value Loss: -$82,673

City: Warren
Street: Market St
Tax Assessed Value: $131,500
Should be Worth: $205,699
Relative Value Loss: -$74,199

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Tidal Flooding will Increase with Sea Level Rise

Highest Annual Tidal Flooding: Today | **Highest Annual Tidal Flooding:** In 15 Years

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Depth of Flooding (feet)
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Depth of Flooding (feet)
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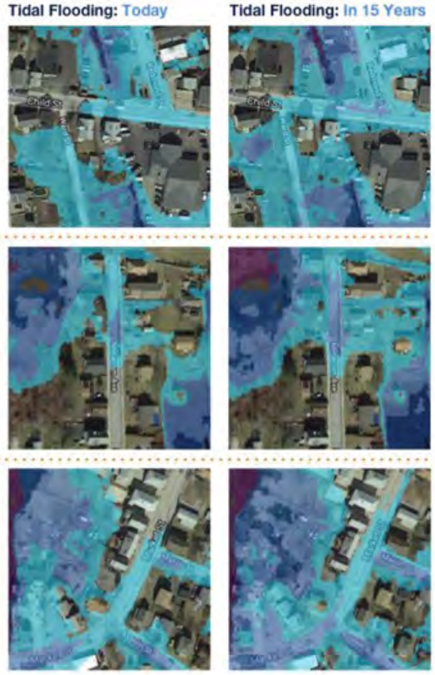

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Maine: Top 5 Hardest Hit Cities

Maine: Top 3 Hardest Hit Homes

City: Scarborough
Street: E Grand Ave
Tax Assessed Value: $117,100
Should be Worth: $248,556
Relative Value Loss: -$131,456

City: Bath
Street: Varney Mill Rd
Taxed Assess Value: $92,900
Should be Worth: $150,674
Relative Value Loss: -$57,774

City: Bath
Street: Washington St
Taxed Assessed Value: $93,800
Should be Worth: $145,898
Relative Value Loss: -$52,098

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Tidal Flooding will Increase with Sea Level Rise

Highest Annual Tidal Flooding: Today

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Street: E Grand Ave

Depth of Flooding (feet)
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Street: Varney Mill Rd

Depth of Flooding (feet)
<1 1 - 2 2 - 3 3+

City: Bath
Street: Washington St

Depth of Flooding (feet)
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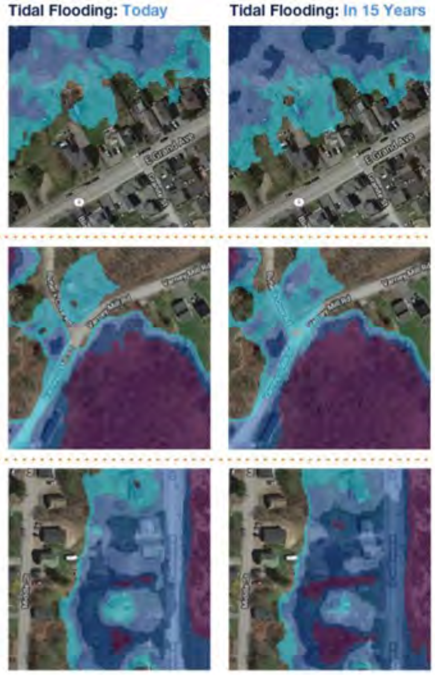

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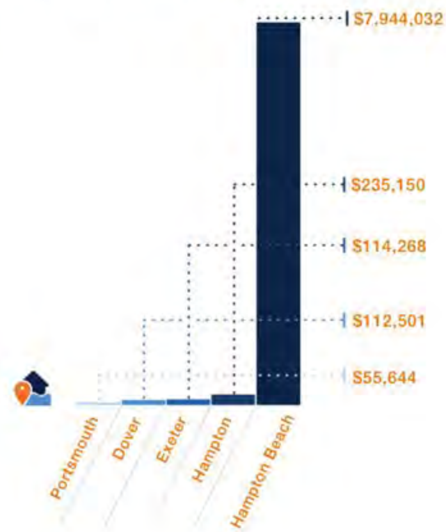
New Hampshire: Top 5 Hardest Hit Cities



New Hampshire: Top 3 Hardest Hit Homes

City: Hampton Beach
Street: Page Ln
Tax Assessed Value: $516,800
Should be Worth: $841,066
Relative Value Loss: -$324,266

City: Hampton Beach
Street: Perkins Ave
Tax Assessed Value: $560,700
Should be Worth: $840,406
Relative Value Loss: -$279,706

City: Hampton Beach
Street: Wall St
Tax Assessed Value: $236,800
Should be Worth: $425,731
Relative Value Loss: -$188,931

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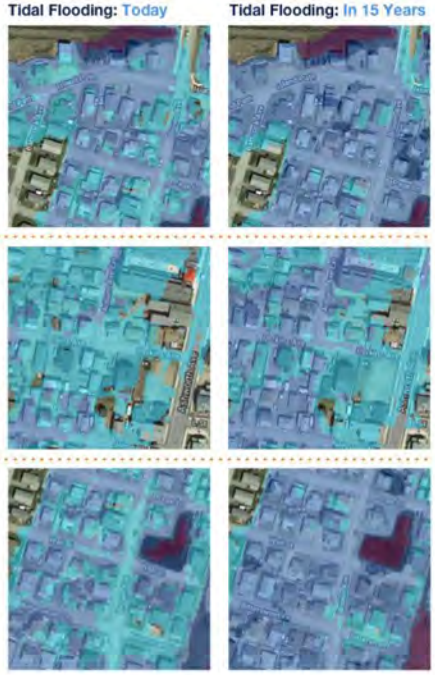
Tidal Flooding will Increase with Sea Level Rise

	Highest Annual Tidal Flooding: Today	**Highest Annual Tidal Flooding:** In 15 Years
City: Hampton Beach **Street:** Page Ln **Depth of Flooding (feet)** <1 1 - 2 2 - 3 3+		
City: Hampton Beach **Street:** Perkins Ave **Depth of Flooding (feet)** <1 1 - 2 2 - 3 3+		
City: Hampton Beach **Street:** Wall St **Depth of Flooding (feet)** <1 1 - 2 2 - 3 3+		



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August 23rd, 2018

As the seas have been rising, Tri-State home values have been sinking.

Scientists from the non-profit First Street Foundation analyzed recent housing market trends in New York, New Jersey, and Connecticut and found $6.7 billion has been lost in home value from 2005 to 2017 due to sea level rise flooding.

This builds on their previous research that found $7.4 billion in home value had been lost across 5 southeastern coastal states, bringing the total loss in the 8 states to $14.1 billion. These findings have been integrated into Flood iQ, a flood risk tool from First Street Foundation, which enables individuals to find their property-specific value loss and aggregated loss for their city.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant, recently released an academic publication in the journal *Population Research and Policy Review* showing $465 million was lost in Miami-Dade County's real-estate market from 2005 to 2016 due to sea level rise flooding. The peer-reviewed analysis has now been expanded to cover all of New York, New Jersey, Connecticut, Florida, Georgia, South Carolina, North Carolina, and Virginia by analyzing over 9.2 million real estate transactions, and extrapolating the results to 20 million properties. The expanded analysis has found a total home value loss of $14.1 billion across these eight coastal states since 2005.

Previous peer-reviewed academic studies have forecasted the negative impact sea level rise will have on the future value of coastal properties, but McAlpine and Porter's research is the first to demonstrate value loss has already occured. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value.

"This is the first market indicator that rising seas and related flooding have depressed home values," said McAlpine. "This is not just a Florida issue, but an issue the entire coastal United States needs to address."

"As we have expanded our study, the results have been incredibly consistent," said Porter. "Americans across 8 states have already lost $14.1 billion from increased flooding caused by sea level rise, and all signs are pointing to this being an accelerating trend."

The research is the first to find that in addition to direct, property-lot flooding, nearby road flooding also has a major impact on home value. This suggests that all residents in neighborhoods with flooding should be concerned by any flooding in their streets.

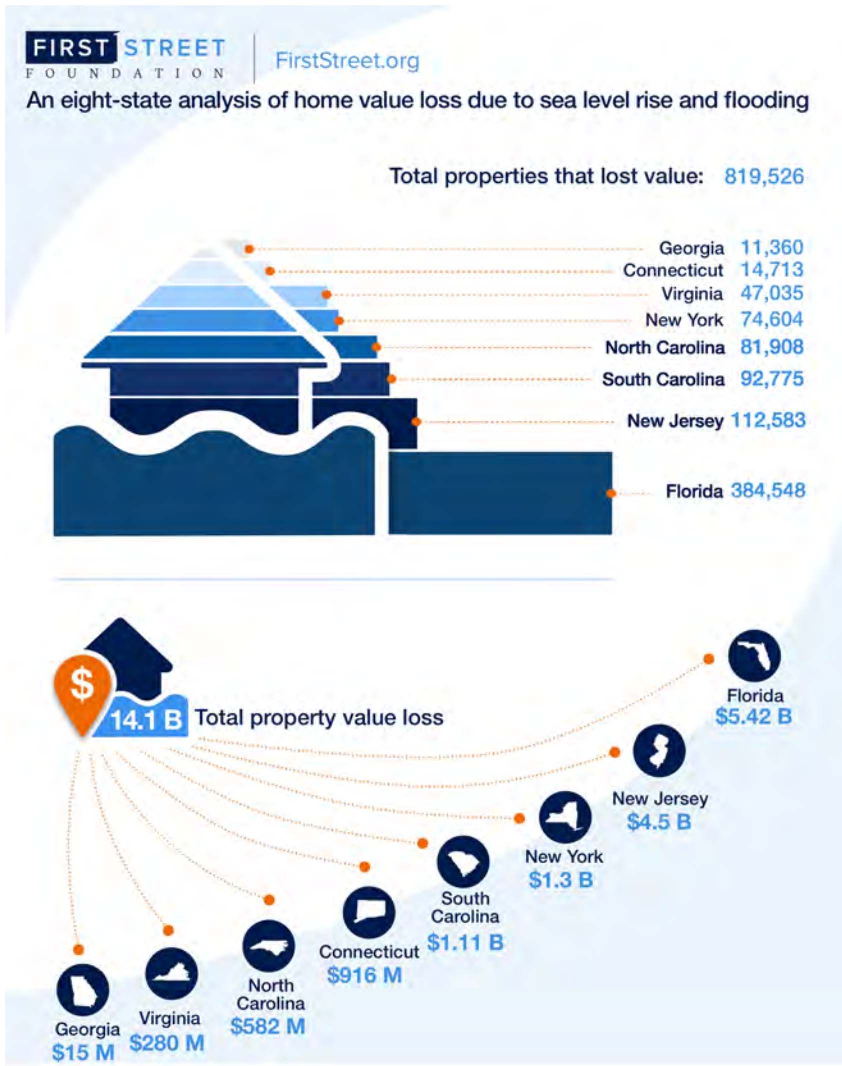
"We all knew that flooding issues were getting worse from sea level rise, but the home value loss associated with it is truly staggering," said Matthew Eby, Executive Director at First Street Foundation. "The time to act is now."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that educates policymakers and the public about the risks, causes, and solutions to sea level rise.

Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

For questions please reach out to pr@firststreet.org.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An eight-state analysis of home value loss due to sea level rise and flooding
Total properties that lost value: 819,526
Georgia 11,360
Connecticut 14,713
Virginia 47,035
New York 74,604
North Carolina 81,908
South Carolina 92,775
New Jersey 112,583
Florida 384,548
$
14.1 B Total property value loss
Florida $5.42 B
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South Carolina $1.11 B
Connecticut $916 M
North Carolina $582 M
Virginia $280 M
Georgia $15 M


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Total property value lost from 2005 - 2017 (by zip code)
New York
Charleston
Savannah
Jacksonville
Tampa
Miami
$600,000,000
$500,000,000
$400,000,000
$300,000,000
$200,000,000
$100,000,000

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Top 20 cities by total property value lost from 2005 - 2017

Rank	City Name	Total Property Value Lost
1	Ocean City, NJ	$530,439,399
2	Miami Beach, FL	$337,167,466
3	Hollywood, FL	$304,568,101
4	Charleston, SC	$266,217,606
5	Saint Petersburg, FL	$243,968,610
6	North Beach Haven, NJ	$216,899,215
7	Sea Isle City, NJ	$208,644,351
8	Fort Lauderdale, FL	$193,885,367
9	New York City, NY	$185,052,918
10	Atlantic City, NJ	$174,748,706
11	Avalon, NJ	$165,956,129
12	Key Largo, FL	$159,615,296
13	Brigantine, NJ	$158,874,047
14	Mount Pleasant, SC	$149,072,672
15	Jacksonville, FL	$146,483,838
16	North Wildwood, NJ	$138,435,750
17	Key West, FL	$133,015,501
18	Freeport, NY	$131,021,192
19	Milford City, CT	$126,947,753
20	Mystic Island, NJ	$125,508,045

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Top 20 zip codes by total property value lost from 2005 - 2017

Rank	ZIP Code	State	Total Property Value Lost
1	08008	New Jersey	$541,193,136
2	08226	New Jersey	$531,806,217
3	08260	New Jersey	$314,508,114
4	33019	Florida	$256,107,024
5	08243	New Jersey	$207,078,907
6	33040	Florida	$194,923,568
7	08087	New Jersey	$188,439,710
8	29455	South Carolina	$178,870,640
9	33037	Florida	$176,269,824
10	08401	New Jersey	$174,857,998
11	08202	New Jersey	$172,525,022
12	08742	New Jersey	$169,124,952
13	08203	New Jersey	$158,766,736
14	33703	Florida	$152,503,280
15	33140	Florida	$147,746,416
16	08751	New Jersey	$137,627,358
17	33141	Florida	$135,996,864
18	11520	New York	$131,216,057
19	06460	Connecticut	$127,332,216
20	08735	New Jersey	$124,707,036

FIRST STREET FOUNDATION

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Sea Level Rise Sinks Alabama Home Values by More Than $157 Million

For Immediate Release: December 3, 2018

Scientists from First Street Foundation and Columbia University analyzed recent housing market trends in Alabama and found home values lost $157.9 million from 2005 to 2017 due to sea level rise flooding. The unincorporated area of Mobile Bay saw the greatest loss at $46.7 million, followed by Gulf Shores at $26.1 million, and Mobile at $25.9 million. Homeowners can use FloodiQ.com to look up their personal home value loss as well as the total loss for their city.

The Alabama analysis expands on the Foundation's previous research across other states which has been widely covered by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor.

The research is based on peer reviewed methodology, established by Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant. Their original analysis of the Miami-Dade County real estate market, published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 15 housing market-specific models to cover Florida, Georgia, South Carolina, North Carolina, Virginia, as well as New York, New Jersey, Connecticut, Mississippi and Alabama. By analyzing approximately 10 million real estate transactions, and applying the results to 20 million properties, the researchers have found a $14.6 billion loss in home values across ten states.

The Alabama findings come from a study that also analyzed home values in Mississippi. That state lost more than $263 million in value due to sea level rise flooding. The Mississippi results have also been integrated into First Street's Flood iQ tool.

McAlpine and Porter's research is the first to quantify the observed negative impact of sea level rise on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value. While some of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding.

"People like living by the water," said McAlpine. "In Alabama many of the homes experiencing tidal flooding are beach homes built on stilts, so there is an expectation of flooding to some degree. Still, we are seeing value loss due to the increasing frequency and severity of flooding as people look to buy at higher elevations."

"All signs point to this being an accelerating trend," said Porter. "As we have expanded our study, the results have been incredibly consistent. Americans across 10 states have lost $14.6 billion from increased flooding caused by sea level rise."

The research is also the first to find that in addition to direct property-lot flooding nearby road flooding also has a major impact on home value.

"What has made this research truly striking for people is its integration with Flood iQ," said Matthew Eby, Executive Director of First Street Foundation." People can look up their personal addresses and learn just how much value they have lost due to sea level rise flooding. It's powerful, and in some cases, devastating."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

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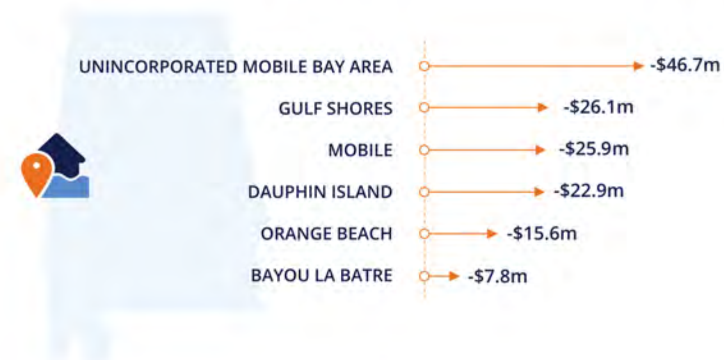
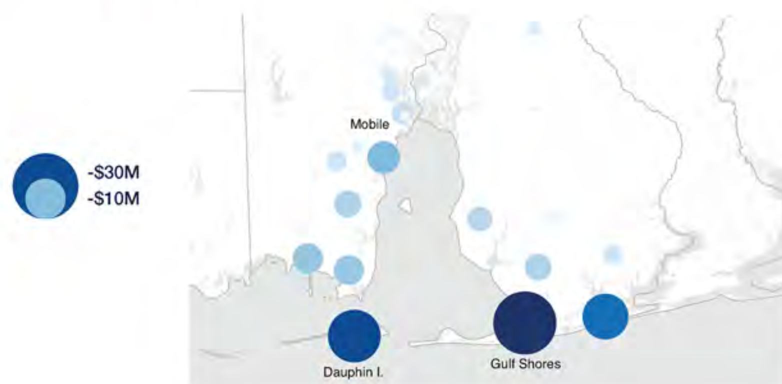
Alabama Cities With Loss Above $5 Million



Alabama Property Loss by Zip Code



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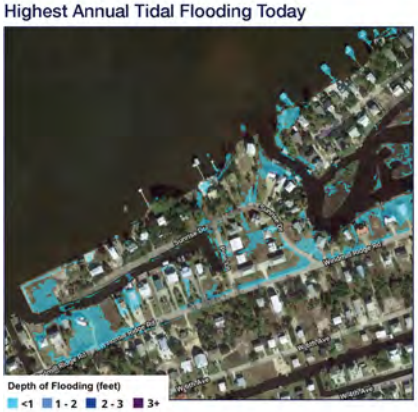
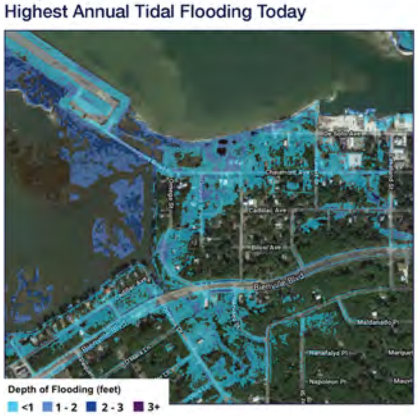
Alabama Flooding Will Get Worse with Sea Level Rise

A:
Gulf Shores
Highest Annual Tidal Flooding Today

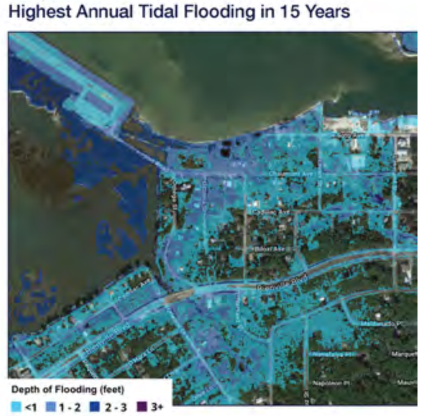


A:
Gulf Shores
Highest Annual Tidal Flooding in 15 Years

B:
Dauphin Island
Highest Annual Tidal Flooding Today



B:
Dauphin Island
Highest Annual Tidal Flooding in 15 Years



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MOODY'S
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Print

Announcement: Moody's: Climate change is forecast to heighten US exposure to economic loss placing short- and long-term credit pressure on US states and local governments

28 Nov 2017

New York, November 28, 2017 -- The growing effects of climate change, including climbing global temperatures, and rising sea levels, are forecast to have an increasing economic impact on US state and local issuers. This will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies, Moody's Investors Service says in a new report.

The report differentiates between climate trends, which are a longer-term shift in the climate over several decades, versus climate shock, defined as extreme weather events like natural disasters, floods, and droughts which are exacerbated by climate trends. Our credit analysis considers the effects of climate change when we believe a meaningful credit impact is highly likely to occur and not be mitigated by issuer actions, even if this is a number of years in the future.

Climate shocks or extreme weather events have sharp, immediate and observable impacts on an issuer's infrastructure, economy and revenue base, and environment. As such, we factor these impacts into our analysis of an issuer's economy, fiscal position and capital infrastructure, as well as management's ability to marshal resources and implement strategies to drive recovery.

Extreme weather patterns exacerbated by changing climate trends include higher rates of coastal storm damage, more frequent droughts, and severe heat waves. These events can also cause economic challenges like smaller crop yields, infrastructure damage, higher energy demands, and escalated recovery costs.

"While we anticipate states and municipalities will adopt mitigation strategies for these events, costs to employ them could also become an ongoing credit challenge," Michael Wertz, a Moody's Vice President says. "Our analysis of economic strength and diversity, access to liquidity and levers to raise additional revenue are also key to our assessment of climate risks as is evaluating asset management and governance."

One example of climate shock driving rating change was when Hurricane Katrina struck the City of New Orleans (A3 stable). In addition to widespread infrastructure damage, the city's revenue declined significantly and a large percentage of its population permanently left New Orleans.

"US issuer resilience to extreme climate events is enhanced by a variety of local, state and federal tools to improve immediate response and long-term recovery from climate shocks," Wertz says.

For issuers, the availability of state and federal resources is an important element that broadens the response capabilities of local governments and their ability to mitigate credit impacts. As well, all municipalities can benefit from the deployment of broader state and federal aid, particularly disaster aid from the Federal Emergency Management Agency (FEMA) to help with economic recovery.

Moody's analysts weigh the impact of climate risks with states and municipalities' preparedness and planning for these changes when we are analyzing credit ratings. Analysts for municipal issuers with higher exposure to climate risks will also focus on current and future mitigation steps and how these steps will impact the issuer's overall profile when assigning ratings.

The report "Environmental Risks -- Evaluating the impact of climate change on US state and local issuers," is available to Moody's subscribers at http://www.moodys.com/researchdocumentcontentpage.aspx?docid=PBM_1071049

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EUROSYSTÈME

The green swan

Central banking and financial stability in the age of climate change

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Abstract

Climate change poses new challenges to central banks, regulators and supervisors. This book reviews ways of addressing these new risks within central banks' financial stability mandate. However, integrating climate-related risk analysis into financial stability monitoring is particularly challenging because of the radical uncertainty associated with a physical, social and economic phenomenon that is constantly changing and involves complex dynamics and chain reactions. Traditional backward-looking risk assessments and existing climate-economic models cannot anticipate accurately enough the form that climate-related risks will take. These include what we call "green swan" risks: potentially extremely financially disruptive events that could be behind the next systemic financial crisis. Central banks have a role to play in avoiding such an outcome, including by seeking to improve their understanding of climate-related risks through the development of forward-looking scenario-based analysis. But central banks alone cannot mitigate climate change. This complex collective action problem requires coordinating actions among many players including governments, the private sector, civil society and the international community. Central banks can therefore have an additional role to play in helping coordinate the measures to fight climate change. Those include climate mitigation policies such as carbon pricing, the integration of sustainability into financial practices and accounting frameworks, the search for appropriate policy mixes, and the development of new financial mechanisms at the international level. All these actions will be complex to coordinate and could have significant redistributive consequences that should be adequately handled, yet they are essential to preserve long-term financial (and price) stability in the age of climate change.

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Contents

Foreword by Agustín Carstens

A growing body of research by academics, central banks and international institutions including the BIS focuses on climate-related risks. These studies show that physical risks related to climate change can severely damage our economies, for example through the large cost of repairing infrastructure and coping with uninsured losses. There are also transition risks related to potentially disorderly mitigation strategies. Both physical and transition risks, in turn, can increase systemic financial risk. Thus their potential consequences have implications for central banks' financial stability mandate. All these considerations prompted central banks to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS), which the BIS has been part of since its inception.

This book helps to trace the links between the effects of climate change, or global warming, and the stability of our financial sectors. It includes a comprehensive survey of how climate change has been progressively integrated into macroeconomic models and how these have evolved to better assess financial stability risks stemming from climate change (eg stress testing models using global warming scenarios). But the book also recognises the limitations of our models, which may not be able to accurately predict the economic and financial impact of climate change because of the complexity of the links and the intrinsic non-linearity of the related phenomena. Nevertheless, despite the high level of uncertainty, the best scientific advice today suggests that action to mitigate and adapt to climate change is needed.

Naturally, the first-best solution to address climate change and reduce greenhouse gas emissions is Pigovian carbon taxation. This policy suggests that fundamental responsibility for addressing issues related to climate change lies with governments. But such an ambitious new tax policy requires consensus-building and is difficult to implement. Nor can central banks resolve this complex collective action problem by themselves. An effective response requires raising stakeholders' awareness and facilitating coordination among them. Central banks' financial stability mandate can contribute to this and should guide their appropriate involvement. For instance, central banks can coordinate their own actions with a broad set of measures to be implemented by other players (governments, the private sector, civil society and the international community). This is urgent since climate-related risks continue to build, and negative outcomes such as what this book calls "green swan" events could materialise.

Contributing to this coordinating role is not incompatible with central banks doing their share within their current mandates. In this sense there are many practical actions central banks can undertake (and, in some cases, are already undertaking). They include enhanced monitoring of climate-related risks through adequate stress tests; developing new methodologies to improve the assessment of climate-related risks; including environmental, social and governance (ESG) criteria in their pension funds; helping to develop and assess the proper taxonomy to define the carbon footprint of assets more precisely (eg "green" versus "brown" assets); working closely with the financial sector on disclosure of carbon-intensive exposure to assess potential financial stability risks; studying more precisely how prudential regulation could deal with risks to financial stability arising from climate change; and examining the adequate room to invest surplus FX reserves into green bonds.

The BIS has been collaborating with the central bank community on all these aspects. In addition, in September 2019 it launched its green bond BIS Investment Pool Fund, a new vehicle that facilitates central banks' investments in green bonds. And with this book it hopes to steer the debate and discussions further while recognising that all these actions will require more research and be challenging, but nevertheless essential to preserving long-term financial and price stability in the age of accelerated climate change.

Agustín Carstens
BIS General Manager

Foreword by François Villeroy de Galhau

In the speech he delivered when receiving the Nobel Prize in Literature in 1957, the French writer Albert Camus said: "Each generation doubtless feels called upon to reform the world. Mine knows that it will not reform it, but its task is perhaps even greater. It consists in preventing the world from destroying itself". Despite a different context, these inspiring words are definitely relevant today as mankind is facing a great threat: climate change.

Climate change poses unprecedented challenges to human societies, and our community of central banks and supervisors cannot consider itself immune to the risks ahead of us. The increase in the frequency and intensity of extreme weather events could trigger non-linear and irreversible financial losses. In turn, the immediate and system-wide transition required to fight climate change could have far-reaching effects potentially affecting every single agent in the economy and every single asset price. Climate-related risks could therefore threaten central banks' mandates of price and financial stability, but also our socio-economic systems at large. If I refer to our experience at the Banque de France and to the impressive success of the Network for Greening the Financial System (NGFS) we launched in December 2017, I would tend to affirm that our community is now moving in the right direction.

But despite this growing awareness, the stark reality is that we are all losing the fight against climate change. In such times, the role our community should play in this battle is questioned. It is then important to clearly state that we cannot be the only game in town, even if we should address climate-related risks within the remit of our mandates, which may include considering options relating to the way we conduct monetary policy. On monetary policy, I have two strong beliefs, and we will have the opportunity to discuss them against the backdrop of the ECB strategic review led by Christine Lagarde. First, we need to integrate climate change in all our economic and forecasting models; second we need, instead of opening a somewhat emotional debate on the merits of a green quantitative easing, which faces limitations, to do an overhaul of our collateral assessment framework to reflect climate-related risks.

In order to navigate these troubled waters, more holistic perspectives become essential to coordinate central banks', regulators' and supervisors' actions with those of other players, starting with governments. This is precisely what this book does. If central banks are to preserve financial and price stability in the age of climate change, it is in their interest to help mobilize all the forces needed to win this battle. This book is an ambitious, carefully thought-out and therefore necessary contribution toward this end.

François Villeroy de Galhau
Governor of the Banque de France

Scientific knowledge is as much an understanding of the diversity of situations for which a theory or its models are relevant as an understanding of its limits.

Elinor Ostrom (1990)

Executive Summary

This book reviews some of the main challenges that climate change poses to central banks, regulators and supervisors, and potential ways of addressing them. It begins with the growing realisation that climate change is a source of financial (and price) instability: it is likely to generate physical risks related to climate damages, and transition risks related to potentially disordered mitigation strategies. Climate change therefore falls under the remit of central banks, regulators and supervisors, who are responsible for monitoring and maintaining financial stability. Their desire to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development prompted them to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS).

However, integrating climate-related risk analysis into financial stability monitoring and prudential supervision is particularly challenging because of the distinctive features of climate change impacts and mitigation strategies. These comprise physical and transition risks that interact with complex, far-reaching, nonlinear, chain reaction effects. Exceeding climate tipping points could lead to catastrophic and irreversible impacts that would make quantifying financial damages impossible. Avoiding this requires immediate and ambitious action towards a structural transformation of our economies, involving technological innovations that can be scaled but also major changes in regulations and social norms.

Climate change could therefore lead to "green swan" events (see Box A) and be the cause of the next systemic financial crisis. Climate-related physical and transition risks involve interacting, nonlinear and fundamentally unpredictable environmental, social, economic and geopolitical dynamics that are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere.

In this context of deep uncertainty, traditional backward-looking risk assessment models that merely extrapolate historical trends prevent full appreciation of the future systemic risk posed by climate change. An "epistemological break" (Bachelard (1938)) is beginning to take place in the financial community, with the development of forward-looking approaches grounded in scenario-based analyses. These new approaches have already begun to be included in the financial industry's risk framework agenda, and reflections on climate-related prudential regulation are also taking place in several jurisdictions.

While these developments are critical and should be pursued, this book presents two additional messages. First, scenario-based analysis is only a partial solution to apprehend the risks posed by climate change for financial stability. The deep uncertainties involved and the necessary structural transformation of our global socioeconomic system are such that no single model or scenario can provide a full picture of the potential macroeconomic, sectoral and firm-level impacts caused by climate change. Even more fundamentally, climate-related risks will remain largely unhedgeable as long as system-wide action is not undertaken.

Second, it follows from these limitations that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, if they sit still and wait for other government agencies to jump into action, they could be exposed to the real risk of not being able to deliver on their mandates of financial and price stability. Green swan events may force central banks to intervene as "climate rescuers of last resort" and buy large sets of devalued assets, to save the financial system once more. However, the biophysical foundations of such a crisis and its potentially irreversible impacts would quickly show the limits of this "wait and see" strategy. On the other hand, central banks cannot (and should not) simply replace governments and private actors to make up for their insufficient action, despite growing social pressures to do so. Their goodwill could even create some moral hazard. In short, central banks, regulators and supervisors can only do so much (and many of them are already taking action within their mandates), and their action can only be seen as enhancing other climate change mitigation policies.

To overcome this deadlock, a second epistemological break is needed: central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. We believe that they can best contribute to this task in a role that we dub the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the risk, time horizon and system resilience approaches (see Box B).

Contributing to this coordinating role is not incompatible with central banks, regulators and supervisors doing their own part within their current mandates. They can promote the integration of climate-related risks into prudential regulation and financial stability monitoring, including by relying on new modelling approaches and analytical tools that can better account for the uncertainty and complexity at stake. In addition, central banks can promote a longer-term view to help break the "tragedy of the horizon", by integrating sustainability criteria into their own portfolios and by exploring their integration in the conduct of financial stability policies, when deemed compatible with existing mandates.

But more importantly, central banks need to coordinate their own actions with a broad set of measures to be implemented by other players (ie governments, the private sector, civil society and the international community). This coordination task is urgent since climate-related risks continue to build up and negative outcomes could become irreversible. There is an array of actions to be consistently implemented. The most obvious ones are the need for carbon pricing and for systematic disclosure of climate-related risks by the private sector.

Taking a transdisciplinary approach, this book calls for additional actions that no doubt will be difficult to take, yet will also be essential to preserve long-term financial (and price) stability in the age of climate change. These include: exploring new policy mixes (fiscal-monetary-prudential) that can better address the climate imperatives ahead and that should ultimately lead to societal debates regarding their desirability; considering climate stability as a global public good to be supported through measures and reforms in the international monetary and financial system; and integrating sustainability into accounting frameworks at the corporate and national level.

Moreover, climate change has important distributional effects both between and within countries. Risks and adaptation costs fall disproportionately on poor countries and low-income households in rich countries. Without a clear indication of how the costs and benefits of climate change mitigation strategies will be distributed fairly and with compensatory transfers, sociopolitical backlashes will increase. Thus, the needed broad social acceptance for combating climate change depends on studying, understanding and addressing its distributional consequences.

Financial and climate stability could be considered as two interconnected public goods, and this consideration can be extend to other human-caused environmental degradation such as the loss of biodiversity. These, in turn, require other deep transformations in the governance of our complex adaptive socioeconomic and financial systems. In the light of these immense challenges, a central contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all capabilities to combat climate change.

Box A: From black to green swans

The "green swan" concept used in this book finds its inspiration in the now famous concept of the "black swan" developed by Nassim Nicholas Taleb (2007). Black swan events have three characteristics: (i) they are unexpected and rare, thereby lying outside the realm of regular expectations; (ii) their impacts are wide-ranging or extreme; (iii) they can only be explained after the fact. Black swan events can take many shapes, from a terrorist attack to a disruptive technology or a natural catastrophe. These events typically fit fat tailed probability distributions, ie they exhibit a large skewness relative to that of normal distribution (but also relative to exponential distribution). As such, they cannot be predicted by relying on backward-looking probabilistic approaches assuming normal distributions (eg value-at-risk models).

The existence of black swans calls for alternative epistemologies of risk, grounded in the acknowledgment of uncertainty. For instance, relying on mathematician Benoit Mandelbrot (1924–2010), Taleb considers that fractals (mathematically precise patterns that can be found in complex systems, where small variations in exponent can cause large deviation) can provide more relevant statistical attributes of financial markets than both traditional rational expectations models and the standard framework of Gaussian-centred distributions (Taleb (2010)). The use of counterfactual reasoning is another avenue that can help hedge, at least partially, against black swan events. Counterfactuals are thoughts about alternatives to past events, "thoughts of what might have been" (Epstude and Roese (2008)). Such an epistemological position can provide some form of hedging against extreme risks (turning black swans into "grey" ones) but not make them disappear. From a systems perspective, fat tails in financial markets suggest a need for regulation in their operations (Bryan et al (2017), p 53).

Green swans, or "climate black swans", present many features of typical black swans. Climate-related risks typically fit fat-tailed distributions: both physical and transition risks are characterised by deep uncertainty and nonlinearity, their chances of occurrence are not reflected in past data, and the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). In this context, traditional approaches to risk management consisting in extrapolating historical data and on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. That is, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management, as discussed in this book.

However, green swans are different from black swans in three regards. First, although the impacts of climate change are highly uncertain, "there is a high degree of certainty that some combination of physical and transition risks will materialize in the future" (NGFS (2019a), p 4). That is, there is certainty about the need for ambitious actions despite prevailing uncertainty regarding the timing and nature of impacts of climate change. Second, climate catastrophes are even more serious than most systemic financial crises: they could pose an existential threat to humanity, as increasingly emphasized by climate scientists (eg Ripple et al (2019)). Third, the complexity related to climate change is of a higher order than for black swans: the complex chain reactions and cascade effects associated with both physical and transition risks could generate fundamentally unpredictable environmental, geopolitical, social and economic dynamics, as explored in Chapter 3.

Box B: The five Cs – contribute to coordination to combat climate change: the risk, time horizon and system resilience approaches

Responsibilities / Paradigmatic approach to climate change	Measures to be considered[1] by central banks, regulators and supervisors	Measures to be implemented by other players[2] (government, private sector, civil society)
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	Voluntary disclosure of climate-related risks by the private sector (Task Force on Climate-related Financial Disclosures) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating environmental, social and governance (ESG) considerations into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		
Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – Green monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures which are deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

1. INTRODUCTION – "PLANET EARTH IS FACING A CLIMATE EMERGENCY"

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to "tell it like it is." On the basis of this obligation [...] we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of global socioeconomic and financial systems. Our current production and consumption patterns cause unsustainable emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2): their accumulated concentration in the atmosphere above critical thresholds is increasingly recognised as being beyond our ecosystem's absorptive and recycling capabilities. The continued increase in temperatures has already started affecting ecosystems and socioeconomic systems across the world (IPCC (2018), Mora et al (2018)) but, alarmingly, climate science indicates that the worst impacts are yet to come. These include sea level rise, increases in weather extremes, droughts and floods, and soil erosion. Associated impacts could include a massive extinction of wildlife, as well as sharp increases in human migration, conflicts, poverty and inequality (Human Rights Council (2019), IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Ripple et al (2019)).

Scientists today recommend reducing GHG emissions, starting immediately (Lenton et al (2019), Ripple et al (2019)). In this regard, the 2015 United Nations Climate Change Conference (COP21) and resulting Paris Agreement among 196 countries to reduce GHG emissions on a global scale was a major political achievement. Under the Paris Agreement (UNFCCC (2015)) signatories agree to reduce greenhouse gas emissions "as soon as possible" and to do their best to keep global warming "to well below 2 degrees" Celsius (2°C), with the aim of limiting the increase to 1.5°C. Yet global emissions have kept rising since then (Figueres et al (2018)),[1] and nothing indicates that this trend is reverting.[2] Countries' already planned production of coal, oil and gas is inconsistent with limiting warming to 1.5°C or 2°C, thus creating a "production gap", a discrepancy between government plans and coherent decarbonisation pathways (SEI et al (2019)).

Changing our production and consumption patterns and our lifestyles to transition to a low-carbon economy is a tough collective action problem. There is still considerable uncertainty on the effects of climate change and on the most urgent priorities. There will be winners and losers from climate change mitigation, exacerbating free rider problems. And, perhaps even more problematically, there are large time lags before climate damages become apparent and irreversible (especially to climate change sceptics): the most damaging effects will be felt beyond the traditional time horizons of policymakers and other economic and financial decision-makers. This is what Mark Carney (2015) referred to as "the tragedy of the horizon": while the physical impacts of climate change will be felt over a long-term horizon, with massive costs and possible civilisational impacts on future generations, the time horizon in which financial, economic and political players plan and act is much shorter. For instance, the time horizon of rating

[1] Ominously, David Wallace-Wells recently observed in *The Uninhabitable Earth* (2019), "We have done as much damage to the fate of the planet and its ability to sustain human life and civilization since Al Gore published his first book on the climate than in all the centuries – all the milleniums – that came before."

[2] The Agreement itself is legally binding, but no enforcement mechanisms exist and the GHG reduction targets set by each country through their Nationally Determined Contributions (NDCs) are only voluntary.

agencies to assess credit risks, and of central banks to conduct stress tests, is typically around three to five years.

Our framing of the problem is that climate change represents a green swan (see Box A): it is a new type of systemic risk that involves interacting, nonlinear, fundamentally unpredictable, environmental, social, economic and geopolitical dynamics, which are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere. Climate-related risks are not simply black swans, ie tail risk events. With the complex chain reactions between degraded ecological conditions and unpredictable social, economic and political responses, with the risk of triggering tipping points,[3] climate change represents a colossal and potentially irreversible risk of staggering complexity.

Carbon pricing and beyond

Climate change is widely considered by economists as an externality that, as such, should be dealt with through publicly imposed Pigovian carbon taxes[4] in order to internalise the climate externalities. Indeed, according to basic welfare economics, a good policy to combat climate change requires such a "price" to act as an incentive to reduce GHG emissions. A carbon tax, for example, creates an incentive for economic agents to lower emissions by switching to more efficient production processes and consumption patterns. The amount of this tax needs to reflect what we already know about the medium- to long-term additional costs of climate change. From a mainstream economist's perspective, a carbon tax that reflects the social cost of carbon (SCC) would make explicit the "shadow cost" of carbon emissions and would be sufficient to induce economic actors to reduce emissions in a perfect Walrasian world.

By this analytical framing, central banks, regulators and supervisors have little to do in the process of decarbonising the economic system. Indeed, the needed transition would mostly be driven by non-financial firms and households, whose decentralised decisions would be geared towards low-carbon technologies thanks to carbon pricing. From a financial perspective, using a carbon tax to correctly price the negative externality would be sufficient to reallocate financial institutions' assets from carbon-intensive towards greener capital. At most, central banks and supervisors should carefully scrutinise financial market imperfections, in order to ensure financial stability along the transition towards a low-carbon economy.

Yet the view that carbon pricing is the sole answer to climate change, and its corollary in terms of monetary and prudential policies (ie that central banks, regulators and supervisors should not really be concerned by climate change) suffers from three significant limitations, which contribute to overlooking potential "green swan" events.

First, even though conceptually carbon pricing has been recognised as the first best option for decades, in practice it has not been implemented at a level sufficient to drive capital reallocation from "brown" (or carbon-intensive) to "green" (or low-carbon) assets. The reality is that governments have failed to act and will continue to do so unless much broader pressure from civil society and business induces significant policy change. Given the current deficiency in global policy responses, it only becomes more likely that the physical impacts of climate change will affect the socioeconomic system in a rapidly warming world. Given that rising temperatures will unleash complex dynamics with tipping points, the impact of

3 A tipping point in the climate system is a threshold that, when exceeded, can lead to large changes in the state of the system. Climate tipping points are of particular interest in reference to concerns about global warming in the modern era. Possible tipping point behaviour has been identified for the global mean surface temperature by studying self-reinforcing feedbacks and the past behaviour of Earth's climate system. Self-reinforcing feedbacks in the carbon cycle and planetary reflectivity could trigger a cascading set of tipping points that lead the world into a hothouse climate state (source: Wikipedia).

4 From Arthur C Pigou (1877–1959), who proposed the concept and the solution to externality problems by taxation, an idea that is key to modern welfare economics and to the economic analysis of environmental impacts. Other economic instruments aimed at pricing carbon exist, such as emission trading schemes (ETS), also known as cap-and-trade systems. Unlike a tax, where the price is determined ex ante, the price of CO_2 in a cap-and-trade mechanism is determined ex post, as a result of the supply and demand of quotas to emit CO_2.

global warming will affect our economies in a disorderly yet cumulative manner that, in turn, could trigger unforeseeable negative financial dynamics.

These so-called physical risks will have financial consequences that are naturally of concern to central bankers and supervisors. They can threaten financial stability by causing irreversible losses, as capital is affected by climate change and as financial agents may be unable to protect themselves from such climate shocks. These risks can also threaten price stability by triggering supply shocks on various commodities, which could in turn generate inflationary or even stagflationary effects (Villeroy de Galhau (2019a)). It should also be noted that traditional policy instruments may be less effective at smoothing these shocks, to the extent that these are more or less permanent biophysical shocks, rather than transitory economic shocks (Cœuré (2018)).

Second, climate change is not merely another market failure but presumably "the greatest market failure the world has ever seen", as leading climate economist Lord Nicholas Stern puts it (Stern (2007)). Given the size of the challenge ahead, carbon prices may need to skyrocket in a very short time span towards much higher levels than currently prevail. Moreover, taking climate-related risks and uncertainty seriously (eg by including the possibility of tipping points leading to catastrophic and irreversible events) should lead to even sharper increases in the SCC (Ackerman et al (2009), Cai and Lontzek (2019), Daniel et al (2019), Weitzman (2009)). With this in mind, the transition may trigger a broad range of unintended consequences. For example, it is increasingly evident that mitigation measures such as carbon price adjustments could have dramatic distributional consequences, both within and across countries.

More to the point of actions by central bankers and supervisors, newly enforced and more stringent environmental regulations could produce or reinforce financial failures in credit markets (Campiglio (2016)) or abrupt reallocations of assets from brown to green activities motivated by market repricing of risks and/or attempts to limit reputational risks and litigations. All this could result in a "climate Minsky moment" (Carney (2018)), a severe financial tightening of financial conditions for companies that rely on carbon-intensive activities (so-called "stranded assets"; see Box 1), be it directly or indirectly through their value chains. These risks are categorised as transition risks; as with physical risks, they are of concern to central bankers and supervisors. Here, the "paradox is that success is failure" (Carney (2016)): extremely rapid and ambitious measures may be the most desirable from the point of view of climate mitigation, but not necessarily from the perspective of financial stability over a short-term horizon. Addressing this tension requires a broad range of measures, as extensively discussed in this book.

Third, the climate change market failure is of such magnitude that it would be prudent to approach it as more than just a market failure. It is a subject that combines, among other things, uncertainty, risk, potentially deep transformations in our lifestyles, prioritising long-term ethical choices over short-term economic considerations, and international coordination for the common good. With this in mind, recent and growing transdisciplinary work suggests that our collective inability to reverse expected climate catastrophes originates in interlocked, complex institutional arrangements, which could be described as a socio-technical system: "a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks" (Geels et al (2004), p 3).

Given this institutional or sociotechnical inertia, higher carbon prices alone may not suffice to drive individual behaviours and firms' replacement of physical capital towards low-carbon alternatives, as economics textbooks suggest. For instance, proactive fiscal policy may be an essential first step to build adequate infrastructure (eg railroads), before carbon pricing can really lead agents to modify their behaviour (eg by switching from car to train). Tackling climate change may therefore require finding complex policy mixes combining monetary, prudential and fiscal instruments (Krogstrup and Oman (2019)) as well as many other societal innovations, as discussed in the last chapter. Going further, the fight against climate change is taking place at the same time when the post-World War II global institutional framework is under growing criticism. This means that the unprecedented level of international coordination required to address the difficult (international) political economy of climate change is seriously compromised.

Therefore, to guarantee a successful low-carbon transition, new technologies, new institutional arrangements and new cultural frameworks should emerge (Beddoe et al (2009)) towards a comprehensive reshaping of current productive structures and consumption patterns. The analogy one may use to envision the change ahead is that of engaging in a multidimensional combat against climate change (Stiglitz (2019)). Even for the sceptics who prefer a "wait and see" approach, a pure self-interested risk management strategy recommends buying the proper insurance of ambitious climate policies (Weitzman (2009)) as a kind of precautionary principle[5] (Aglietta and Espagne (2016)), "pari Pascalien"[6] or "enlightened doomsaying"[7] (Dupuy (2012)), ie as a hedging strategy against the possibility of green swan events.

For all these reasons, even if a significant increase in carbon pricing globally remains an essential step to fight climate change, other (second-, third- or fourth-best from a textbook perspective) options must be explored, including with regard to the financial system.

Revisiting financial stability in the age of climate change

The reflections on the relationship between climate change and the financial system are still in their early stages: despite rare warnings on the significant risks that climate change could pose to the financial system (Carbon Tracker (2013)), the subject was mostly seen as a fringe topic until a few years ago (Chenet (2019a)). But the situation has changed radically in recent times, as climate change's potentially disruptive impacts on the financial system have started to become more apparent, and the role of the financial system in mitigating climate change has been recognised.

This growing awareness of the financial risks posed by climate change can be related to three main developments. First, the Paris Agreement's (UNFCCC (2015)) Article 2.1(c) explicitly recognised the need to "mak[e] finance flows compatible with a pathway toward low greenhouse gas emissions and climate-resilient development", thereby paving the way to a radical reorientation of capital allocation. Second, as mentioned above, the Governor of the Bank of England, Mark Carney (2015), suggested the possibility of a systemic financial crisis caused by climate-related events. Third, in December 2017 the Central Banks and Supervisors Network for Greening the Financial System[8] (NGFS) was created by a group of central banks and supervisors willing to contribute to the development of environment and climate risk management in the financial sector, and to mobilise mainstream finance to support the transition toward a sustainable economy.

The NGFS quickly acknowledged that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).[9] The NGFS also acknowledged that these risks are tied to complex layers of interactions between the macroeconomic, financial and climate systems (NGFS (2019b)). As this book

5 The precautionary principle is used to justify discretionary measures by policymakers in situations where there are plausible risks of harming the public through certain decisions, but extensive scientific knowledge on the matter is lacking.

6 The French philosopher, mathematician and physicist Blaise Pascal (1623–62) used a game theory argument to justify faith as a "hedge": rational people should believe in God as a "pari" or bet. They would incur small losses of pleasure (by accepting to live a life without excessive pleasures), which would be more than offset by infinite gains (eternity in heaven) if God existed. In the same way, accepting some small inconveniences (adjusting one's lifestyle to climate imperatives) is compensated by a more sustainable earth ecosystem, if indeed global warming exists (from the climate change sceptic's perspective).

7 The concept of "enlightened doomsaying" (catastrophisme éclairé) put forward by the French philosopher of science Jean-Pierre Dupuy (2012) involves imagining oneself in a catastrophic future to raise awareness and trigger immediate action so that this future does not take place.

8 As of 12 December 2019, the NGFS is composed of 54 members and 12 observers. For more information, see www.ngfs.net.

9 As acknowledged by the NGFS (2019a), the legal mandates of central banks and financial supervisors vary throughout the world, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions.

will extensively discuss, assessing climate-related risks involves dealing with multiple forces that interact with one another, causing dynamic, nonlinear and disruptive dynamics that can affect the solvency of financial and non-financial firms, as well as households' and sovereigns' creditworthiness.

In the worst case scenario, central banks may have to confront a situation where they are called upon by their local constituencies to intervene as climate rescuers of last resort For example, a new financial crisis caused by green swan events severely affecting the financial health of the banking and insurance sectors could force central banks to intervene and buy a large set of carbon-intensive assets and/or assets stricken by physical impacts.

But there is a key difference between green swan and black swan events: since the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, the biophysical causes of the crisis will be difficult, if not impossible, to undo at a later stage. Similarly, in the case of a crisis triggered by a rapid transition to a low-carbon economy, there would be little ground for central banks to rescue the holders of assets in carbon-intensive companies. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. Intervening as climate rescuers of last resort could therefore affect central bank's credibility and crudely expose the limited substitutability between financial and natural capital.

Given the severity of these risks, the uncertainty involved and the awareness of the interventions of central banks following the 2007–08 Great Financial Crisis, the sociopolitical pressure is already mounting to make central banks (perhaps again) the "only game in town" and to substitute for other if not all government interventions, this time to fight climate change. For instance, it has been suggested that central banks could engage in "green quantitative easing"[10] in order to solve the complex socioeconomic problems related to a low-carbon transition.

Relying too much on central banks would be misguided for many reasons (Villeroy de Galhau (2019a), Weidmann (2019)). First, it may distort markets further and create disincentives: the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are needed to transition to a global low-carbon economy. That includes fiscal, regulatory and standard-setting authorities in the real and financial world whose actions should reinforce each other. Second, and perhaps most importantly, it risks overburdening central banks' existing mandates. True, mandates can evolve, but these changes and institutional arrangements are very complex issues because they require building new sociopolitical equilibria, reputation and credibility. Although central banks' mandates have evolved from time to time, these changes have taken place along with broader sociopolitical adjustments, not to replace them.

Outline

These considerations suggest that central banks may inevitably be led into uncharted waters in the age of climate change. Whereas they cannot and should not replace policymakers, they also cannot sit still, since this could place them in the untenable situation of climate rescuer of last resort discussed above. This book sets out from this analytical premise and asks the following question: what, then, should be the role of central banks, regulators and supervisors in preserving financial stability[11] in the age of climate change? It is organised as follows.

Chapter 2 provides an overview of how climate-related risks are threatening socioeconomic activities, thereby affecting the future ability of central banks and supervisors to fulfil their mandates of monetary and financial stability. Following the old adage "that which is measured can be managed" (Carney (2015)), the obvious task in terms of financial regulation and supervision is therefore to ensure

[10] See De Grawe (2019) and the current debate about green quantitative easing in the United States and Europe.

[11] The question of price stability is also touched upon, although less extensively than financial stability.

that climate-related risks become integrated into financial stability monitoring and prudential supervision. However, such a task presents a significant challenge: traditional approaches to risk management consisting in extrapolating historical data based on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. Indeed, both physical and transition risks are characterised by deep uncertainty, nonlinearity and fat-tailed distributions. As such, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management. In fact, such a break has started to take place in the financial community, with the development of forward-looking, scenario-based risk management methodologies.

Chapter 3 assesses the methodological strengths and limitations of these methodologies. While their use by financial institutions and supervisors will become critical, it should be kept in mind that scenario-based analysis will not suffice to preserve financial stability in the age of climate change: the deep uncertainty at stake and the need for a structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers (although new modelling and analytical approaches will be critical to embrace the uncertain and non-equilibrium patterns involved). In particular, forward-looking approaches remain highly sensitive to a broad set of uncertain parameters involving: (i) the choice of a scenario regarding how technologies, policies, behaviours, macroeconomic variables and climate patterns will interact in the future; (ii) the translation of such scenarios into granular sector- and firm-level metrics in an evolving environment where all firms will be affected in unpredictable ways; and (iii) the task of matching the identification of a climate-related risk with the adequate mitigation action.

Chapter 4 therefore argues that the integration of climate-related risks into prudential regulation and (to the extent possible) into the relevant aspects of monetary policy will not suffice to shield the financial system against green swan events. In order to deal with this challenge, a second epistemological break is needed: there is an additional role for central banks to be more proactive in calling for broader changes. This needs not threaten existing mandates. On the contrary, calling for broader action by all players can only contribute to preserving existing mandates on price and financial stability. As such, and grounded in the transdisciplinary approach that is required to address climate change, this book makes four propositions (beyond the obvious need for carbon pricing) that are deemed essential to preserve financial stability in the age of climate change, related to: long-termism and sustainable finance; coordination between green fiscal policy, prudential regulation and monetary policy; international monetary and financial coordination and reforms; and integration of natural capital into national and corporate systems of accounting. Some potential obstacles related to each proposition are discussed.

Chapter 5 concludes by discussing how financial (and price) stability and climate stability can be considered as two public goods, the maintenance of which will increasingly depend on each other. Moreover, the need to ensure some form of long-term sustainability increasingly applies to prevent other human-caused environmental degradations such as biodiversity loss, and could require deep transformations in the governance of our socio-ecological systems. All this calls for new quantitative and qualitative approaches aimed at building system resilience (OECD (2019a), Schoon and van der Leeuw (2015)). At a time when policymakers are facing well known political economy challenges and when the private sector needs more incentives to transition to a low-carbon economy, an important contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all efforts to combat climate change.

2. CLIMATE CHANGE IS A THREAT TO FINANCIAL AND PRICE STABILITY

Climate change is the Tragedy of the Horizon. We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

Mark Carney (2015)

2.1 Climate change as a severe threat to ecosystems, societies and economies

At 415 parts per million (ppm),[12] Earth's concentration of CO_2 as of 11 May 2019 was higher than ever in human history, and far above the 270–280 ppm that had prevailed for millennia up to the Industrial Revolution (Graph 1, left-hand panel), guaranteeing stable climate conditions in which human societies were able to develop agriculture (Feynman and Ruzmaikin (2007)) and become more complex (Chaisson (2014)). The past decades, in particular, have shown a sharp increase in levels of atmospheric CO_2, from approximately 315 ppm in 1959 to 370 ppm in 1970 and 400 ppm in 2016 (right-hand panel).[12]

Evolution of atmospheric CO_2 concentration — Graph 1

Atmospheric CO_2 concentration over the past 12 millennia, measured in parts per million (left-hand panel); and annual total CO_2 emissions by world region since 1751 (right-hand panel).

Sources: Bereiter et al. (2015), NOAA, www.esrl.noaa.gov/gmd/ccgg/trends/data.html; Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov; and Global Carbon Project (2018). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

These increasing levels of atmospheric CO_2 concentration, caused by human activity (IPCC (2018)), primarily the burning of fossil fuels (Hansen et al (2013)) but also deforestation and intensive agriculture (Ripple et al (2017)), prevent the Earth's natural cooling cycle from working and cause global warming. Global warming has already increased by close to 1.1°C since the mid-19th century. Temperatures are currently rising at 0.2°C per decade, and average yearly temperatures are increasingly

[12] Based on the daily record of global atmospheric carbon dioxide concentration measured at Mauna Loa Observatory in Hawaii, and reported by the Scripps Institution of Oceanography at UC San Diego. See https://scripps.ucsd.edu/programs/keelingcurve/.

among the hottest ever recorded (IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Millar et al (2017), Ripple et al (2017)).

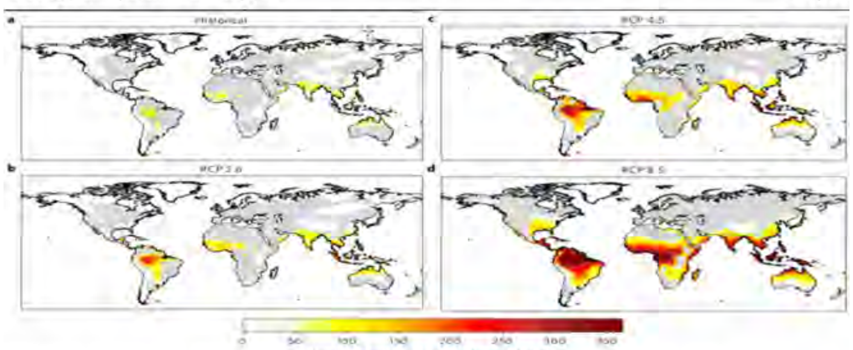
Current trends are on track to lead to systemic disruptions to ecosystems, societies and economies (Steffen et al (2018)). The continued increase in temperatures will lead to multiple impacts (IPCC (2018)) such as rising sea levels, greater intensity and incidence of storms, more droughts and floods, and rapid changes in landscapes. For instance, mean sea levels rose 15 centimetres in the 20th century, and the rate of rising is increasing. The impacts on ecosystems will be significant, potentially leading to species loss or even a massive extinction of wildlife (Ripple et al (2017)). Soil erosion could also accelerate, thereby decreasing food security and biodiversity (IPCC (2019)). Marine biodiversity, marine ecosystems and their ecological functions are also threatened (Masson-Delmotte and Moufouma-Okia (2019)).

The effects of climate change may be catastrophic and irreversible for human populations, potentially leading to "untold suffering", according to more than 11,000 scientists (Ripple et al (2019)). Sea levels could rise by several metres with critical impacts for small islands, low-lying coastal areas, river deltas and many ecological systems on which human activity depends. For instance, increased saltwater intrusion could lead to major agricultural losses, and flooding could damage existing infrastructure (Masson-Delmotte and Moufouma-Okia (2019)). A two-metre sea level rise triggered by the potential melting of ice sheets could displace nearly 200 million people by 2100 (Bamber et al (2019)). Even more worrisome, past periods in the Earth's history indicate that even warming of between 1.5°C and 2°C could be sufficient to trigger long-term melting of ice in Greenland and Antarctica and a sea level rise of more than 6 metres (Fischer et al (2018)).

Humans may have to abandon many areas in which they currently manage to sustain a living, and entire regions in South America, Central America, Africa, India, southern Asia and Australia could become uninhabitable due to a mix of high temperatures and humidity levels (Im et al (2017), Mora et al (2018); see Graph 2). About 500 million people live in areas already affected by desertification, especially in southern and East Asia, the Middle East and sub-Saharan Africa, which will only be under greater socioeconomic pressure due to climate change (IPCC (2019)).

Average temperature changes

Graph 2



Number of days per year above a deadly threshold by the end of the century in a business as usual scenario.
Source: Mora et al (2017).

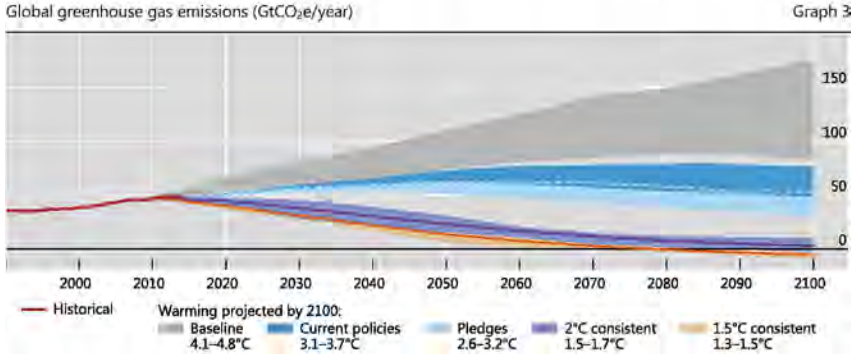
Climate change is not just a future risk: it has actually already started to transform human and non-human life on Earth,[13] although the worst impacts are yet to come. Crop yields and food supply are already affected by climate change in many places across the globe (Ray et al (2019)). Parts of India are undergoing chronic severe water crises (Subramanian (2019)). Heatwaves are becoming more frequent in most land regions, and marine heatwaves are increasing in both frequency and duration (Masson-Delmotte and Moufouma-Okia (2019)). Extreme weather events have increased significantly over the past 40 years (Stott (2016)). Large-scale losses of coral reefs have started to occur (Hughes et al (2018)). Even keeping global warming below 1.5°C could result in the destruction of 70–90% of reef-building corals (IPCC (2018)), on which 25% of all marine life depends (Gergis (2019)).

In turn, avoiding the worst impacts of climate change amounts to a massive, unprecedented, challenge for humanity. The planet is producing close to 40 gigatonnes (Gt) of CO_2 per year, and it is on track to double by 2050. We should reduce emissions to almost zero by then (Graph 3) in order to comply with the UN Paris Agreement of 2015 (UNFCCC (2015)), which set the goal of keeping global warming well below 2°C and as close as possible to 1.5°C above pre-industrial levels (defined as the climate conditions experienced during 1850–1900).

Nevertheless, the special report of the IPCC on the 1.5°C goal (IPCC (2018)) shows that the gap between current trends and emission reduction targets set by countries through their nationally determined contributions (NDCs) – which were already insufficient to limit global warming to 2°C – is widening and leading to somewhere between 3°C and 4°C of warming, which is consistent with a "Hothouse Earth" pathway (Steffen et al (2018)).

2100 warming projections: emissions and expected warming based on pledges and current policies

Global greenhouse gas emissions ($GtCO_2e$/year) Graph 3



Source: Climate Action Tracker.

The impacts on economic output could be significant if no action is taken to reduce carbon emissions. Some climate-economic models indicate that up to a quarter of global GDP could be lost (Burke et al (2015a)), with a particularly strong impact in Asia, although these predictions should be taken cautiously given the deep uncertainty involved (as discussed in Chapter 3). In any case, both the demand side and the supply side are affected (examples in Table 1).

[13] A list of observed impacts, with links to relevant studies, can be found at: impact.gocarbonneutral.org/.

Climate change-related shocks and their effects on... Table 1

	Type of shock	From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risk
	Consumption	Changes in consumption patterns, eg more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in extreme cases. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Sources: NGFS (2019b), adapted from Batten (2018).

Demand-side shocks are those that affect aggregate demand, such as private (household) or public (government) consumption demand and investment, business investment and international trade. Climate damages could dampen consumption, and business investments could be reduced due to uncertainty about future demand and growth prospects (Hallegatte (2009)). Climate change is also likely to disrupt trade flows (Gassebner et al (2010)) and reduce household wealth. Even less exposed economies can have extensive interactions with global markets and be affected by extreme climate shocks.

Supply-side shocks could affect the economy's productive capacity, acting through the components of potential supply: labour, physical capital and technology. For instance, higher temperatures tend to reduce the productivity of workers and agricultural crops (IPCC (2019)). Moreover, climate change can trigger massive population movements (Opitz Stapleton et al (2017)), with long-lasting effects on labour market dynamics and wage growth. Supply-side shocks can also lead to a diversion of resources form investment in productive capital and innovation to climate change adaptation (Batten (2018)). Damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)). Even if the relevant capital stocks might survive, efficiency might be reduced and some areas might have to be abandoned (Batten (2018)).

These economic shocks can have major impacts on the price and financial instability, as respectively explored next.

2.2 The redistributive effects of climate change

Climate change has important distributional effects both between and within countries. The geographical distribution of potential physical risks triggered by rising temperatures (Graph 2) clearly shows that they primarily affect poor and middle-income countries. Moreover, transition risks might also disproportionately impact the natural endowments, traditional carbon-intensive industries and consumption habits of poor countries and low-income households. The cost of mitigation and adaptation might also be prohibitive for both groups.

The degree of awareness about the risks posed by climate change is also unevenly shared within societies, following – and sometimes reinforced by – inequalities of wealth and income. In some cases, denial has been a convenient demagogic response to these issues, compounded by accusations of intrusion into national sovereignty. Another popular political stance has been to dismiss the challenges posed by climate change as merely a concern of the wealthy and well protected. The debate with climate change sceptics is a legitimate and necessary step towards improving the analytics on these issues while creating the sociopolitical conditions to start implementing policies to mitigate risks. There is a relatively old and large literature calling for fairness and social justice when designing adaptation and mitigation policies (eg Adger et al (2006), Cohen et al (2013)). All this will require a better understanding of the redistributive effects of climate change, of the policies to adapt our economies and of the associated costs of mitigation. Without a clear map for how the costs and benefits of climate change mitigation strategies will be distributed, it is almost certain – as we have been observing in many recent cases – that political backlashes will increase against a lower-carbon society. Thus, the sociopolitical viability of combating climate change depends on addressing its distributional consequences.

Indeed, the enormous challenges described above mean that the policies to combat climate change will be quite invasive and are likely to have significant collateral effects on our societies and our production and consumption processes, with associated distributional effects. Zachmann et al (2018) conduct a study of the distributional consequences of mitigation policies and point out that the intensity of these effects depends on the choice of the policy instrument used, the targeted sector, the design of the intervention and the country's degree of development and socioeconomic conditions. They study the impact of climate policies on households of different income levels (low to high) and assess policies addressing climate change as regressive, proportionate or progressive. They take into account households' budget and wealth constraints (eg their inability to quickly shift to lower carbon consumption baskets as well as investment in lower-carbon houses and durable goods). They conclude that the regressive distributional effects of many climate policies requires compensating lower-income households for their negative income effects as well as being gradual and progressive in the introduction of such policies.

Dennig et al (2015) also study regional and distributional effects of climate change policies. They use a variant of the Regional Integrated model of Climate and the Economy (RICE) – a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE) – and introduce economic inequalities in the model's regions. Their study confirm that climate change impacts are not evenly distributed within regions and that poorer people are more vulnerable, suggesting that this must be taken into account when setting the social cost of carbon. However, improving the poverty and inequality modelling in climate research requires more efforts as the current approaches are limited as argued by Rao et al (2017) because current models do not capture well household heterogeneity and proper representation of poor and vulnerable societal segments.

Finally, there is an extensive literature and numerous studies pointing to the distributional impact of climate change on poor countries and the need to scale up international mechanisms to finance their transition and reduce their vulnerability to climate change-related events with well known implications for massive migration. This has been a significant part of the discussions of the UN Conference of the Parties (COP) since its inception. For example, the Adaptation Fund was established at the COP 7 in 2001 but only set up under the Kyoto Protocol of the United Nations Framework Convention on Climate Change

(UNFCCC) and officially launched in 2007. The mechanism has revolved around the need for rich countries to contribute to the adaptation cost by developing countries. At COP 2015 in 2009, this resulted in the pledge by advanced economies to mobilise $100 billion in aid by 2020. So far, the practical implementation has remained limited.

2.3 Climate change as source of monetary instability

Although this book focuses on financial stability, it should be noted that climate-related shocks are likely to affect monetary policy through supply-side and demand-side shocks, and thereby affect central banks' price stability mandate. Regarding supply-side shocks (McKibbin et al (2017)), pressures on the supply of agricultural products and energy are particularly prone to sharp price adjustments and increased volatility. The frequency and severity of such events might increase, and impact supply through more or less complex channels. There are still relatively few studies analysing the impact of climate-related shocks on inflation, but some studies indicate that food prices tend to increase in the short term following natural disasters and weather extremes (Parker (2018), Heinen et al (2018), Debelle (2019)).

In addition to these short-term pressures on prices, supply shocks can also reduce economies' productive capacity. For instance, climate change could have long-standing impacts on agricultural yields, lead to frequent resource shortages or to a loss in hours worked due to heat waves. These effects, in turn, can reduce the stock of physical and human capital, potentially resulting in reduced output (Batten (2018), McKibbin et al (2017)). But climate change can also translate into demand shocks, for instance by reducing household wealth and consumption (Batten (2018)). Climate mitigation policies could also affect investment in some sectors, with various indirect impacts further discussed in the next chapter.

In sum, the impacts of climate change on inflation are unclear partly because climate supply and demand shocks may pull inflation and output in opposite directions, and generate a trade-off for central banks between stabilising inflation and stabilising output fluctuations (Debelle (2019)). Moreover, if climate-related risks end up affecting productivity and growth, this may have implications for the long-run level of the real interest rate, a key consideration in monetary policy (Brainard (2019)).

Traditionally, monetary policy responses are determined by looking at their impact on prices and expectations. If there is a presumption that the impact is temporary, the response can be to wait and see or "look through" the shock as it does not affect prices and expectations on a permanent basis. However, if the shock has more lasting effects, there could be motives to consider a policy reaction to adjust aggregate demand conditions. In the case of climate-related risks, the irreversibility of certain climate patterns and impacts poses at least three new challenges for monetary policy (Olovsson (2018)):

(i) While the use of cyclical instruments aims to stimulate or subdue activity in the economy over relatively short periods, climate change is expected to maintain its trajectory for long periods of time (Cœuré (2018)). This situation can lead to stagflationary supply shocks that monetary policy may be unable to fully reverse (Villeroy de Galhau (2019a)).

(ii) Climate change is a global problem that demands a global solution, whereas monetary policy seems, currently, to be difficult to coordinate between countries (Pereira da Silva (2019a)). As such, the case for a single country or even a monetary zone to react to inflationary climate-related shocks could be irrelevant.

(iii) Even if central banks were able to re-establish price stability after a climate-related inflationary shock, the question remains whether they would be able to take pre-emptive measures to hedge ex ante against fat-tail climate risks, ie green swan events (Cœuré (2018)).

It should nevertheless be admitted that studies on the impact of climate change on monetary stability are still at an early stage, and that much more research is needed. Far more evidence has been collected on the potential financial impacts of climate change, as discussed in the rest of this book.

2.4 Climate change as a source of financial instability

Even though a growing number of stakeholders has recognised the socioeconomic risks posed by climate change over the past decades, much of the financial sector seemed to remain unconcerned until a few years ago. The situation has changed radically over the past few years, as the potentially disruptive impacts of climate change on the financial system started to become more apparent (Carney (2015)). As further detailed in Chapter 4, some central banks, regulators and supervisors are already taking steps towards integrating climate-related risks into supervisory practices, and more could follow in the near future. The NGFS, created in December 2017, quickly recognised that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).

There are two main channels[14] through which climate change can affect financial stability:

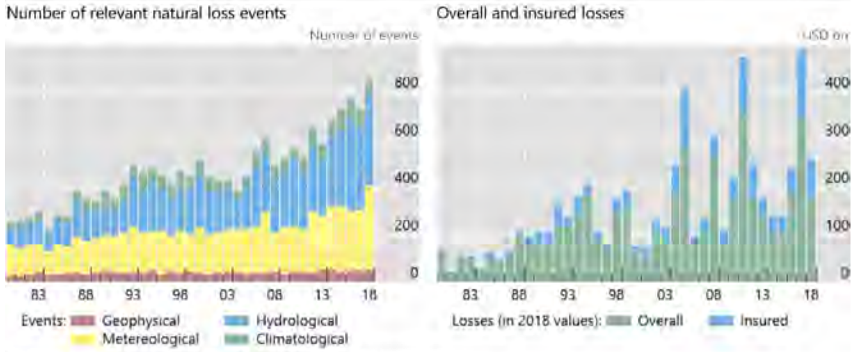
Physical risks are "those risks that arise from the interaction of climate-related hazards [...] with the vulnerability of exposure to human and natural systems" (Batten et al (2016)). They represent the economic costs and financial losses due to increasing frequency and severity of climate-related weather events (eg storms, floods or heat waves) and the effects of long-term changes in climate patterns (eg ocean acidification, rising sea levels or changes in precipitation). The losses incurred by firms across different financial portfolios (eg loans, equities, bonds) can make them more fragile.

The destruction of capital and the decline in profitability of exposed firms could induce a reallocation of household financial wealth. For instance, rising sea levels could lead to abrupt repricing of real estate (Bunten and Kahn (2014)) in some exposed regions, causing large negative wealth effects that may weigh on demand and prices through second-round effects. Climate-related physical risks can also affect the expectation of future losses, which in turn may affect current risk preferences. For instance, homes exposed to sea level rise already sell at a discount relative to observationally equivalent unexposed properties equidistant from the beach (Bernstein et al (2019)).

As natural catastrophes increase worldwide (Graph 4), non-insured losses (which represent 70% of weather-related losses (IAIS (2018)) can threaten the solvency of households, businesses and governments, and therefore financial institutions. Insured losses, on their end, may place insurers and reinsurers in a situation of fragility as claims for damages keep increasing (Finansinspektionen (2016)). More broadly, damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)).

[14] A third type of risk, liability risk, is sometimes mentioned. This refers to "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible" (Carney (2015), p 6). However, such costs and losses are often considered to be part of either physical or transition risk.

Increase in the number of extreme weather events and their insurance,[15] 1980–2018 Graph 4



Includes copyrighted material of Munich Re and its licensors.

Source: MunichRe (2018).

Moreover, the fat-tailed probability distributions of many climate parameters are such that the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). This could place financial institutions in situations in which they might not have sufficient capital to absorb climate-related losses. In turn, the exposure of financial institutions to physical risks can trigger contagion and asset devaluations propagating throughout the financial system.

Transition risks are associated with the uncertain financial impacts that could result from a rapid low-carbon transition, including policy changes, reputational impacts, technological breakthroughs or limitations, and shifts in market preferences and social norms. In particular, a rapid and ambitious transition to lower emissions pathways means that a large fraction of proven reserves of fossil fuel cannot be extracted (McGlade and Elkins (2015)), becoming "stranded assets", with potentially systemic consequences for the financial system (see Box 1). For instance, an archetypal fire sale might result if these stranded assets suddenly lose value, "potentially triggering a financial crisis" (Pereira da Silva (2019a)). As Mark Carney puts it: "too rapid a movement towards a low-carbon economy could materially damage financial stability. A wholesale reassessment of prospects, as climate-related risks are re-evaluated, could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment" (Carney (2016), p 2).

Moreover, the value added of many other economic sectors dependent on fossil fuel companies will probably be impacted indirectly by transition risks (Cahen-Fourot et al (2019a,b)). For instance, the automobile industry may be strongly impacted as technologies, prices and individual preferences evolve. Assessing how the entire value chain of many sectors could be affected by shocks in the supply of fossil fuels is particularly challenging, as will be further discussed in the next chapter.

Physical and transition risks are usually assessed separately, given the complexity involved in each case (as discussed in the next chapter). However, they should be understood as part of the same framework and as being interconnected (Graph 5). A strong and immediate action to mitigate climate change would increase transition risks and limit physical risks, but those would remain existent (we are already

[15] This figure does not allow them to be extrapolated into the future, and they should be interpreted carefully. For instance, some natural catastrophes, such as typhoons, could become less frequent but more intense.

experiencing some of the first physical risks of climate change). In contrast, delayed and weak action to mitigate climate change would lead to higher and potentially catastrophic physical risks, without necessarily entirely eliminating transition risks (eg some climate policies are already in place and more could come). Delayed actions followed by strong actions in an attempt to catch up would probably lead to high both physical and transition risks (not represented in Graph 5).

Framework for physical and transition risks — Graph 5

Scenario	Rapid Transition	Two-degree	Business-as-intended	Business-as-usual
Corrective transition response	Very strong	Strong	Substantial	Limited
Change in temperature, 2100 vs pre-industrial era	1.5°C	2°C	3°C	4°C

Source: adapted from Oliver Wyman (2019); authors' elaboration.

Box 1: Introduction to stranded assets

Limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). These are referred to as stranded assets. For instance, a study (McGlade and Elkins (2015)) found that in order to have at least a 50% chance of keeping global warming below 2°C, over 80% of current coal reserves, half of gas reserves and a third of oil reserves should remain unused from 2010 to 2050. As the risk related to stranded assets is not reflected in the value of the companies that extract, distribute and rely on these fossil fuels, these assets may suffer from unanticipated and sudden writedowns, devaluations or conversion to liabilities.

Estimates of the current value and scope of stranded assets vary greatly from one study to another. For instance, Mercure et al (2018) estimate that the discounted loss in global wealth resulting from stranded fossil fuel assets may range from $1 trillion to $4 trillion. Carbon Tracker (2018)[16] approximates the amount at $1.6 trillion, far below the International Renewable Energy Agency's (IRENA) (2017) estimate of $18 trillion, but the scope and definitions used by each of them differ. Therefore, as discussed more extensively in Chapter 3, it is critical to understand the models used by each of these studies to fully appreciate their respective outcomes and potential limitations.

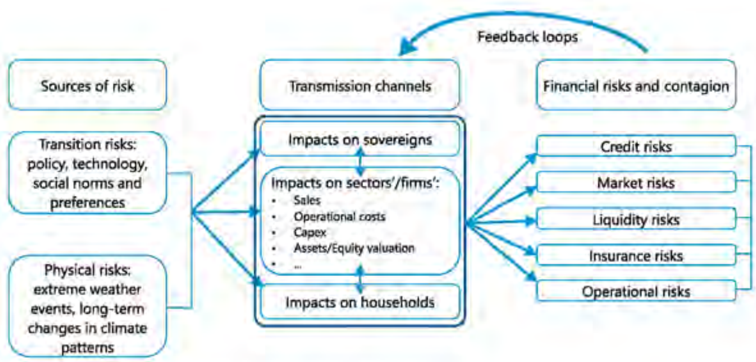
Physical and transition risks can materialise in terms of financial risk in five main ways (DG Treasury et al (2017)), with many second-round effects and spillover effects among them (Graph 6):

- ***Credit risk***: climate-related risks can induce, through direct or indirect exposure, a deterioration in borrowers' ability to repay their debts, thereby leading to higher probabilities of default (PD) and a higher loss-given-default (LGD). Moreover, the potential depreciation of assets used for collateral can also contribute to increasing credit risks.

[16] In a scenario with an increase in temperatures of 1.75°C.

- ***Market risk**:* Under an abrupt transition scenario (eg with significant stranded assets), financial assets could be subject to a change in investors' perception of profitability. This loss in market value can potentially lead to fire sales, which could trigger a financial crisis. The concept of climate value-at-risk (VaR) captures this risk and will be further discussed in the next chapter.
- ***Liquidity risk**:* although it is covered less in the literature, liquidity risk could also affect banks and non-bank financial institutions. For instance, banks whose balance sheet would be hit by credit and market risks could be unable to refinance themselves in the short term, potentially leading to tensions on the interbank lending market.
- ***Operational risk**:* this risk seems less significant, but financial institutions can also be affected through their direct exposure to climate-related risks. For instance, a bank whose offices or data centres are impacted by physical risks could see its operational procedures affected, and affect other institutions across its value chain.
- ***Insurance risk**:* for the insurance and reinsurance sectors, higher than expected insurance claim payouts could result from physical risks, and potential underpricing of new insurance products covering green technologies could result from transition risks (Cleary et al (2019)).

Channels and spillovers for materialisation of physical and transition risks Graph 6



Sources: adapted from DG Treasury et al (2017); authors' elaboration.

2.5 The forward-looking nature of climate-related risks – towards a new epistemology of risk

The potentially systemic risks posed by climate change explain why it is in the interest of central banks, regulators and financial supervisors to ensure that climate-related risks are appropriately understood by all players (NGFS (2019a)). It is therefore not surprising that the first recommendation made by the NGFS in its first comprehensive report called for "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS (2019a), p 4). This integration helps ensure that financial institutions and the financial system as a whole are resilient to climate-related risks (NGFS (2019a)).

Moreover, a systematic integration of climate-related risks by financial institutions could act as a form of shadow pricing on carbon, and therefore help shift financial flows towards green assets. That is, if investors integrate climate-related risks into their risk assessment, then polluting assets will become more costly. This would trigger more investment in green assets, helping propel the transition to a low carbon economy (Pereira da Silva (2019a)) and break the tragedy of the horizon by better integrating long-term risks (Aufauvre and Bourgey (2019)). A better understanding of climate-related risks is therefore a key component of Article 2.1.c of the Paris Agreement, which aims to "mak[e] finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC (2015)).

However, integrating climate-related risks into financial stability monitoring and prudential supervision presents a significant challenge: traditional approaches to risk management are based on historical data and assumptions that shocks are normally distributed (Dépoues et al (2019)). The fundamental financial concept of value-at-risk (VaR) captures losses that can be expected with a 95–99% level of confidence and over a relatively short-term horizon. Capital requirements are also typically calculated (through estimated PD, exposure at default and estimated LGD) on a one-year horizon and based on credit ratings that largely rely on historical track records of counterparties.

The problem is that extrapolating historical trends can only lead to mispricing of climate-related risks, as these risks have barely started to materialise: physical risks will become worse as global warming goes on, and transition risks are currently low given the lack of ambitious policies on a global scale. Moreover, climate-related risks typically fit fat-tailed distributions and concentrate precisely in the 1% not considered by VaR. Finally, climate change is characterised by deep uncertainty: assessing the physical risks of climate change is subject to uncertainties related to climate patterns themselves, their potentially far-reaching impacts on all agents in the economy, and complex transmission channels (NGFS (2019a,b)), especially in the context of globalised value chains; transition risks are also subject to deep or radical uncertainty with regard to issues such as the policies that will be implemented (eg carbon pricing versus command-and-control regulations), their timing, the unpredictable emergence of new low-carbon technologies or changes in preferences and lifestyles that could take place. All these issues are further discussed in Chapter 3.

As a result, the standard approach to modelling financial risk consisting in extrapolating historical values (eg PD, market prices) is no longer valid in a world that is fundamentally reshaped by climate change (Weitzman (2011), Kunreuther et al (2013)). In other words, green swan events cannot be captured by traditional risk management.

The current situation can be characterised as an "epistemological obstacle" (Bachelard (1938)). The latter refers to how scientific methods and "intellectual habits that were useful and healthy" under certain circumstances, can progressively become problematic and hamper scientific research. Epistemological obstacles do not refer to the difficulty or complexity inherent to the object studied (eg measuring climate-related risks) but to the difficulty related to the need of redefining the problem. For instance, as a result of the incompatibility between probabilistic and backward-looking risk management approaches and the uncertain and forward-looking nature of climate-related risks, "investors, at this stage, face a difficult task to assess these risks – there is for instance no equivalent of credit ratings for climate-related financial risks" (Pereira da Silva (2019a)).

As scientific knowledge does not progress continuously and linearly but rather through a series of discontinuous jumps with changes in the meaning of concepts, nothing less than an epistemological break (Bachelard, 1938) or a "paradigm shift" (Kuhn (1962)) is needed today to overcome this obstacle and more adequately approach climate-relate risks (Pereira da Silva (2019a)).

In fact, precisely an epistemological break may be taking place in the financial sector: recently emerged methodologies aim to assess climate-related risks while relying on the fundamental hypothesis that, given the lack of historical financial data related to climate change and the deep uncertainty involved, new approaches based on the analysis of prospective scenarios are needed.[17] Unlike probabilistic approaches to financial risk management, they seek to set up plausible hypotheses for the future. This can help financial institutions integrate climate-related risks into their strategic and operational procedures (eg for the purpose of asset allocation, credit rating or insurance underwriting) and financial supervisors assess the vulnerability of specific institutions or the financial system as a whole.

A consensus is emerging among central banks, supervisors and practitioners involved in climate-related risks about the need to use such forward-looking, scenario-based methodologies (Batten et al (2016), DG Treasury et al (2017), TCFD (2017), NGFS (2019a), Regelink et al (2017)). As shown by the Task Force on Climate-related Financial Disclosures[18] (TCFD; Graph 7), managing climate-related risks through a forward-looking approach can lead financial institutions to test the resilience of corporations in their portfolios to potential materialisations of physical and transition risks, their impact on key performance indicators and the adaptive capacities of these firms.

Testing the resilience of corporations to potential materialisations of physical and transition risks

Graph 7

What scenarios (and narratives) are appropriate, given the exposures? Consider input parameters, assumptions, and analytical choices. What reference scenario(s) should be used?

Evaluate the potential effects on the organisation's strategic and financial position under each of the defined scenarios. Identify key sensitivities.

Use the results to identify applicable, realistic decisions to manage the identified risks and opportunities. What adjustments to strategic/financial plans would be needed?

Source: Adapted from TCFD (2017).

These methodologies may already be facilitating a more systematic integration of climate-related risks in the financial sector: some insurance companies are reassessing their cost of insuring physical risk; some rating agencies are increasingly re-evaluating credit risks in the light of growing climate-related risks; and some asset managers are becoming more selective and inclined to start picking green assets and/or ditching brown assets in their portfolio allocation (Bernardini et al (2019), Pereira da Silva (2019a)).

Hence, it is critical for central banks, regulators and supervisors to assess the extent to which these forward-looking, scenario-based methodologies can ensure that the financial system is resilient to climate-related risks and green swan events. The next chapter undertakes a critical assessment of these methodologies.

[17] It is noteworthy that these methodologies have been produced by a variety of players including consulting firms, non-profit organisations, academics, international organisations and financial institutions themselves.

[18] See www.fsb-tcfd.org/. The TCFD was set up in 2015 by the Financial Stability Board (FSB), to develop voluntary, consistent climate-related financial risk disclosures for use by companies, banks and investors in providing information to stakeholders.

3. MEASURING CLIMATE-RELATED RISKS WITH SCENARIO-BASED APPROACHES: METHODOLOGICAL INSIGHTS AND CHALLENGES

Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way future strategies, designs or plans are developed.

Maier et al (2016)

This chapter reviews some of the methodological challenges that financial institutions and supervisors face when conducting forward-looking, scenario-based analysis aimed at identifying and managing climate-related risks. It focuses on the main conceptual issues; a detailed discussion of the technical features of each existing methodology is beyond the scope of this book (for more exhaustive reviews see, for instance, Hubert et al (2018), UNEP-FI (2018a,b, 2019)). Also, our discussion is focused mostly on methodologies aimed at measuring transition risks,[19] although some challenges related to physical risks are mentioned.

Our key conclusion is that, despite their promising potential, forward-looking analyses cannot fully overcome the limitations of the probabilistic approaches discussed in the previous chapter and provide sufficient hedging against "green swan" events. That is, although the generalised use of forward-looking, scenario-based methodologies can help financial and economic agents to better grapple with the long-term risks posed by climate change, they will not suffice to "break the tragedy of the horizon" and induce a significant shift in capital allocation towards low-carbon activities. Two main limitations exist.

First, the materialisation of physical and transition risks depends on multiple nonlinear dynamics (natural, technological, societal, regulatory and cultural, among others) that interact with each other in complex ways and are subject to deep uncertainty. Climate-economic models are inherently incapable of representing all these interactions, and they therefore overlook many social and political forces that will strongly influence the way the world evolves. With this in mind, the outcomes of a scenario-based analysis should be assessed very cautiously and cannot suffice to guide decision-making. The broad range of results concerning the monetary value of stranded assets – one of the most prominent transition risks – are symptomatic of the complexity and uncertainty at stake (see Box 2 below).

In particular, the complex and multiple interactions between climate and socioeconomic systems are such that the task of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of scenarios describing how technologies, policies, behaviours, macroeconomic and even geopolitical dynamics and climate patterns may interact in the future (Chapter 3.2), especially given the intrinsic limitations of most equilibrium climate-economic models (Chapter 3.1);

(ii) The translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in largely unpredictable ways (Chapter 3.3).

[19] This choice is notably informed by the fact that physical risks arising from a global warming beyond 2°C can be so systemic that aiming to measure them quickly becomes impossible. Transition risks can therefore be seen as those that must arise if we decide to remain within safer climate boundaries. In practice, physical and transition risks are interconnected, as discussed in Chapter 2.3. However, current climate-related risk methodologies generally fail to analyse physical and transition risks jointly, in spite of recent efforts in this direction.

Second, and more fundamentally, climate-related risks will remain largely uninsurable or unhedgeable as long as system-wide action is not taken (Chapter 3.4). In contrast to specific areas where scenario analysis can help financial institutions avoid undesirable outcomes (eg avoiding a dam collapse for a hydropower project), climate-related scenario analysis cannot by itself enable a financial institution or the financial system as a whole to avoid and withstand "green swan" events. For instance, a financial institution willing to hedge itself against an extreme transition risk (eg a sudden and sharp increase in carbon pricing) in the current context of weak climate policies may simply be unable to find adequate climate-risk-free assets if these are not viable in the current environment ("green" assets and technologies are still nascent and also present significant risks).

The first limitation can be partially resolved through better data (Caldecott (2019), NGFS (2019a)) and through the development of new models, in particular non-equilibrium models that can better account for nonlinearity, uncertainty, political economy considerations and the role of money and finance (Mercure et al (2019), Monasterolo et al (2019)). However, the second limitation is a reminder that only a structural transformation of our global socioeconomic system can really shield the financial system against "green swan" events. This calls for alternative epistemological positions that can fully embrace uncertainty and the need for structural transformations, including through more qualitative and politically grounded approaches (Aglietta and Espagne (2016), Chenet et al (2019a, 2019b), Ryan-Collins (2019)).

This does not mean that the development of forward-looking methodologies is not useful. On the contrary, non-financial and financial firms alike will increasingly need to rely on them to explore their potential vulnerabilities. But for central banks, regulators and supervisors concerned about the resilience of the system as a whole, the development of forward-looking, scenario-based methodologies should be assessed with a more critical stance. Much like a carbon price and other policies, they are a critical step that can become fully operational only if a system-wide transition takes place, as further discussed in Chapter 4.

Box 2: Methodological uncertainty surrounding the monetary value of stranded assets

As discussed in Chapter 2, limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). The case has often been made that risks related to stranded assets are not reflected in the value of the companies that extract, distribute and rely on these fossil fuels. This could lead to a significant and sudden drop in their value if ambitious climate policies are adopted.

However, estimating precisely the current value of fossil fuel assets that may be stranded in the future is an exercise replete with uncertainty. As such, the diverging estimates obtained (eg between $1 trillion and $4 trillion according to Mercure et al (2018); around $1.6 trillion as estimated by Carbon Tracker (2018);[20] and up to $18 trillion according to IRENA (2017)) should be carefully assessed as they are based on different geographical scopes, assumptions and valuation methods, among others. For instance, some estimates (eg IRENA (2017)) cover the stranded value of fossil fuel assets (eg the discounted cash flows of future revenues that will be lost) whereas others (eg IEA (2014)) focus on the stranded capital, ie the losses related to the capital invested in a project subject to stranding.

One source of uncertainty has to do with today's valuation of fossil fuel reserves. Some methodologies assume that these reserves significantly contribute to the current valuation of fossil fuel companies. In contrast, IHS Markit (2015) argues that oil and gas companies' market valuations are mostly driven by commercially proved reserves that will be monetised over the next 10 to 15 years, and not so much by the resources that would be likely to be stranded over a longer-term horizon. If this is true, the market mispricing of fossil fuel assets may not be as large as often expected. Some studies also suggest that investors are already reacting to climate-related risks: based on the

[20] In a scenario with an increase in temperatures of 1.75°C.

performance of high-emissions industries in the S&P 500 index before and after the Paris Agreement, Ilhan et al (2018) suggest that investors are actually already incorporating information about climate-related risks when assessing risk profiles. Other studies also find that the risk premium of fossil fuel firms has increased following the Paris Agreement (de Greiff et al (2018)) and that this rise in risk premium is due to increased awareness of transition risks (Delis et al (2018)). In short, the extent to which stranded assets are already valued remains unclear.

Estimating the impacts of stranding fossil assets with geographical granularity is essential to appreciate which companies can be hit, yet it also requires making uncertain choices with regard to which resources will actually be stranded (McGlade and Ekins (2015)). In this respect, Mercure et al (2018) conduct a precise geographical analysis of stranded assets based on the costs of extraction of fossil fuels around the world, assuming that resources in locations with higher extraction costs will be stranded first. They find that Saudi Arabia could keep selling oil in a low-carbon scenario given its competitive prices, whereas Canadian and US unconventional oils could be stranded much faster, with potential significant impacts on their GDPs. In practice, the most vulnerable countries (Canada and the United States in this case) would probably be tempted to subsidise their fossil fuel production to avoid such negative impacts.

Financial institutions can also be impacted indirectly through complex cascades of stranded assets (Cahen-Fourot et al (2019a,b)). For instance, in addition to the direct risk borne by investors exposed to stranded assets, financial assets can also suffer from the economic impacts of the transition triggered by a fall in corporate profits in different sectors that rely on stranded assets and (Caldecott (2017), Dietz et al (2016)). For jurisdictions where fossil fuel companies are state-owned (and therefore not valued by markets), the main financial impacts may only be indirect, eg through loss of revenues that could affect sovereign risk and/or GDP growth.

When mixing geographical with indirect impacts, it appears that stranding assets could have significant geopolitical repercussions and potentially deeply transform existing global value chains, but such considerations remain largely out of the scope of current assessments. For instance, the scenario developed by Mercure et al (2018) asks the question of how OPEC members would recycle their oil-related surpluses. Similarly, if all coal resources were to be stranded, the immediate impacts would fall significantly on China, which consumed 50% of the world's coal in 2018 (BP (2019)); yet this could also have system-wide impacts on global value chains, including potential sharp price increases in advanced economies.

Finally, estimating the value of stranded assets while relying on climate-economic models can lead to paradoxical assumptions. In particular, and as discussed in Chapter 3.2, some climate-economic models rely so much on negative emissions technologies and on carbon capture and storage (CCS) to meet the 1.5°C or 2°C targets that fossil fuels may no longer need to be stranded that rapidly. Under certain scenarios, these technologies can increase the remaining carbon budget to reach a 2°C world by up to 290% (Carbon Brief (2018)). This poses the question of the technological assumptions supporting each assessment of stranded assets and for transition risks in general, as discussed in this chapter.

3.1 Climate-economic models versus deep uncertainty – an overview

The very first step in conducting a scenario analysis is to determine a narrative of how climate and socioeconomic factors will interact, so that they can be translated into a sectoral and firm-level scenario. For instance, to embed a climate-related shock into existing stress test methodologies (see Borio et al (2014)), the first step is to assess how such a shock would impact the economy (eg through variables such as GDP or interest rates), which in turn translates into impacts to the financial system. In the case of transition risks, some critical elements of the narrative of a scenario refer to:

– What climate target is sought: as of today, most transition scenarios rely on limiting global warming to 2°C above pre-industrial temperatures by 2100, but more scenarios based on a 1.5°C limit may emerge as this latter target is increasingly understood as the more "acceptable" upper limit (eg IPCC (2018));

- When mitigation measures start (eg immediately and relatively smoothly, or with delay and more abruptly) and over which time horizon they take place;
- What kind of "shock" is applied: for instance a policy shock (such as a carbon tax, but other regulations can also be used) or a technological shock (eg a technological breakthrough leading to declining cost of renewable energy, or on the contrary a situation where substitution between carbon-intensive and low-carbon technologies is limited).

These initial inputs can then be translated into macroeconomic and/or sectoral outputs. In order to do this, most methodologies rely on climate-economic models such as Integrated Assessment Models (IAMs). For instance, Oliver Wyman's (2019) and Carbon Delta's (2019)[21] respective transition scenarios apply data from IAMs such as REMIND[22], GCAM[23] and IMAGE[24], and Battiston (2019) relies on IAMs to conduct system-wide climate stress tests.

IAMs cover a great range of methodological approaches and sectoral and regional disaggregation, but at their core they generally combine a climate science module linking greenhouse gas (GHG) emissions to temperature increases, and an economic module linking increases in temperatures to economic and policy outcomes. Some key variables serve to link the climate and economic modules, such as: the accumulation of GHGs in the atmosphere; the evolution of mean temperatures; a measure of well-being (GDP); a damage function linking increases in global temperatures to losses in GDP; and a cost function generated by the policies aimed at reducing GHG emissions (eg a carbon tax).

Although IAMs are used by the UN Intergovernmental Panel on Climate Change (IPCC)[25] to explore some of the relationships between society and the natural world, their limitations with regard to economic modelling are increasingly recognised. In particular, critical assumptions about the damage functions (impacts of climate change on the economy) and discount rates (how to adjust for climate-related risk) have been subject to numerous debates (Ackerman et al (2009), Pindyck (2013), Stern (2016)), as further discussed below. Other oft-mentioned limitations include: the absence of an endogenous evolution of the structures of production[26] (Acemoğlu et al (2012, 2015), Pottier et al (2014)); the choice of general equilibrium models with unrealistic assumptions on well-functioning capital markets and rational expectations (Keen (2019)); the emphasis on relatively smooth transitions to a low-carbon economy and the quick return to steady state following a climate shock (Campiglio et al (2018)); and the suppression of the critical role of financial markets (Espagne (2018); Mercure et al (2019)).

[21] See www.carbon-delta.com/climate-value-at-risk/.

[22] REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows for the analysis of technology options and policy proposals for climate mitigation. The REMIND model was developed by the Potsdam Institute for Climate Impact Research (PIK). www.pik-potsdam.de/research/transformation-pathways/models/remind/remind.

[23] The Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. The Joint Global Change Research Institute (JGCRI) is the home and primary development institution for GCAM. jgcri.github.io/gcam-doc/v4.2/.

[24] IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The IMAGE modelling framework has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency. models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

[25] The IPCC is composed of three working groups. Working Group I assesses scientific aspects of the climate system and climate change; Working Group II assesses the vulnerabilities of socioeconomic and natural systems to climate change, as well as their consequences and adaptation options; Working Group III assesses the options for limiting greenhouse gas emissions and mitigating climate change.

[26] It should be noted that some IAMs feature endogenous technological change (IPCC (2014, p 423)).

For all these reasons, it is increasingly recognised that "today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change" (NGFS (2019a, p 4), Weyant (2017)). This does not mean that IAMs and climate-economic models in general are not useful for specific purposes and under specific conditions (Espagne (2018)). In particular, a new wave of models embracing uncertainty and complexity seems better able to account for heterogeneity and nonlinearities, as well as for cascade effects, policy path dependency and interactions between macroeconomic and financial dynamics (see Dafermos et al (2017), Espagne (2017), Mercure et al (2019), Monasterolo et al (2019)). The central bank community could gain from exploring these new modelling approaches, as discussed in Chapter 3.5.

Nevertheless, the deep uncertainty related to physical and transition risks means that both the neoclassical approach of most IAMs and alternative approaches such as demand-led and non-equilibrium models will remain unable to capture many forces triggered by climate change. A corollary is that the outcomes of such models should be interpreted cautiously by both financial practitioners and financial regulators and supervisors. Some of the key sources of uncertainty with respect to climate-related physical and transition risks are outlined below and further detailed in Annexes 1 and 2.

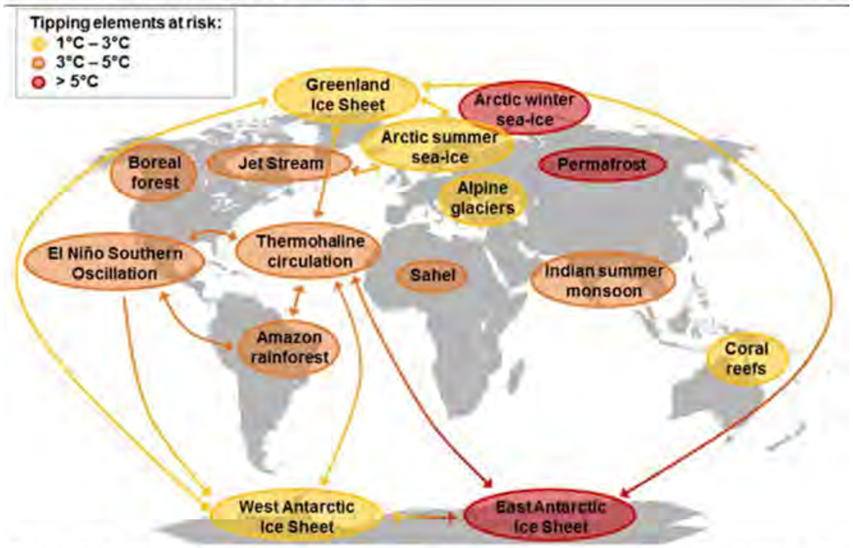
With regard to physical risks (see Annex 1), some of the main sources of modelling uncertainty relate to the following features:

– Deep uncertainty exists with regard to the biogeochemical processes potentially triggered by climate change. Climate scientists have shown not only that tipping points exist but remain difficult to estimate with precision, but also that they could generate tipping cascades on other biogeochemical processes, as shown in Graph 8 below. Evidence is now mounting that tipping points in the Earth system such as the loss of the Amazon forest or the West Antarctic ice sheet could occur more rapidly than was thought (Lenton et al (2019));

– The impacts of such biogeochemical processes on socioeconomic systems can be highly nonlinear, meaning that small changes in one part of the system can lead to large changes elsewhere in the system (Smith (2014)) and to chaotic dynamics that become impossible to model with high levels of confidence. For instance, it seems that climate change will mostly impact developing economies, which could increase global inequality (Diffenbaugh and Burke (2019)) and generate mass migrations and conflicts (Abel et al (2019), Bamber et al (2019), Kelley et al (2015)). These could have major implications for development across the world (Human Rights Council (2019)) but their probability of occurrence and degrees of impact remain largely impossible to appropriately integrate into existing models. However, advanced economies are not exempt from significant impacts either. For instance, Dantec and Roux (2019) assess how climate change may affect different French territories and demand multiple adaptation strategies in areas such as urban planning, water management or agricultural practices;

– In the light of these considerations, it has been argued that the damage functions used by IAMs are unable to account for the tail risks related to climate change (Calel et al (2015)), and in some cases lead studies to suggest "optimal" warming scenarios that would actually correspond to catastrophic conditions for the future of human and non-human life on Earth: for instance, while DICE (Dynamic Integrated Climate-Economy) modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)). Similarly, the social cost of carbon (which adds up in monetary terms all the costs and benefits of adding one additional tonne of CO_2), and the choice of a rate of discount of future damages can provide "almost any result one desires" (Pindyck (2013, p 5)) and lead to outcomes and policy recommendations that are "grossly misleading" (Stern (2016)). Climate modellers typically embrace uncertainty by showing the great range of outcomes that can result from a specific event or pattern (eg a specific CO_2 atmospheric concentration can translate into different increases in global temperature and different sea level rises, with respective confidence intervals), but this dimension tends be lost in climate-economic models based on benefit-cost analysis (Giampietro et al (2013), Martin and Pindyck (2015)).

Global map of potential tipping cascades — Graph 8



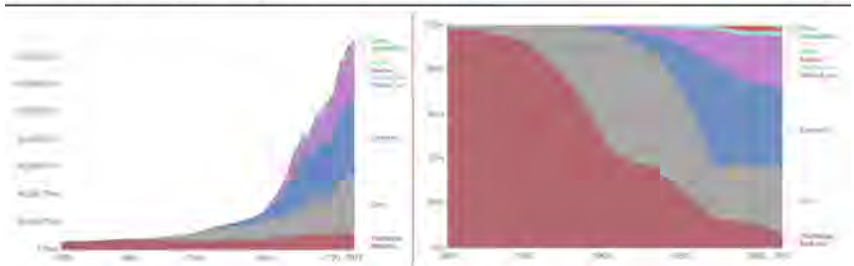
The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements that could generate cascades, based on expert elicitation.

Source: Adapted from Steffen et al (2018).

With regard to transition risks (see Annex 2), one of the main sources of modelling uncertainty relates to the general use of economy-wide carbon prices as a proxy for climate policy in IAMs. This assumption tends to overlook many social and political forces that can influence the way the world evolves, as recognised by the IPCC itself (IPCC (2014, p 422)). As the history of energy and social systems shows (Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)), the evolution of primary energy uses is deeply influenced by structural factors and requires deep transformations of existing socioeconomic systems (Graph 9, left-hand panel). Past transformations have responded to a variety of stimuli including relative prices but also many other considerations such as geopolitical (eg choice of nuclear energy by certain countries to guarantee energy independence) and institutional ones (eg proactive policies supporting urban sprawl and its related automobile dependency). Attempts to reverse these inertias through pricing mechanisms alone could be insufficient.

Moreover, all major energy transitions in the past (Graph 9, right-hand panel) have taken the form of energy additions in absolute terms (Graph 9, left-hand panel). That is, they were energy additions more than energy transitions. For instance, biomass (in green) has decreased in relative terms but not in absolute terms. This highlights the sobering reality that achieving a low-carbon transition in a smooth manner represents an unprecedented challenge with system-wide implications. With this in mind, estimating the social cost of carbon with confidence is all the more difficult "due to considerable uncertainties [...] and [results that] depend on a large number of normative and empirical assumptions that are not known with any certainty" (IPCC (2007, p 173)).

Evolution of energy systems, in absolute and relative terms — Graph 9



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

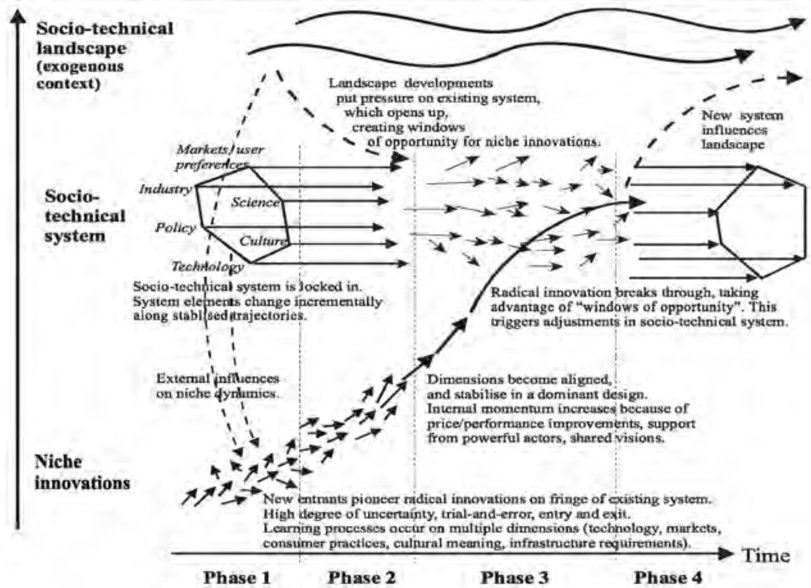
Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

To account for this complexity, transdisciplinary approaches around concepts such as socio-technical systems and transitions (Geels et al (2017)) seem more appropriate to embrace the multiple dimensions involved in any climate change mitigation transition (Box 3). These approaches are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011, pp 356–7)). In particular, socio-technical transition scholars provide a framework for more sophisticated qualitative and quantitative approaches to three parameters that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

In short, the physical and transition risks of climate change are subject to multiple forces (natural, technological, societal, regulatory and cultural, among others) that interact with each other and are subject to uncertainty, irreversibility, nonlinearity and fat-tailed distributions. Moreover, physical and transition risks will increasingly interact with each other, potentially generating new cascade effects that are not yet accounted for (Annex 3).

In the rest of this chapter, we discuss how to go beyond the limitations of climate-economic models as discussed above to better assess climate-related risks, especially with regard to: (i) the choice of scenarios regarding how technologies, policies, behaviours, and macroeconomic – and even geopolitical – dynamics will interact in the future (Chapter 3.2); (ii) the translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in unpredictable ways (Chapter 3.3); and (iii) the matching of climate-related risk assessments with appropriate financial decision-making (Chapter 3.4). One key finding is that alternative approaches are needed to fully embrace the uncertainty and the need for structural transformation at stake (Chapter 3.5).

Phases of transformations of existing socio-technical systems — Graph 10



Source: Adapted from Geels et al (2017).

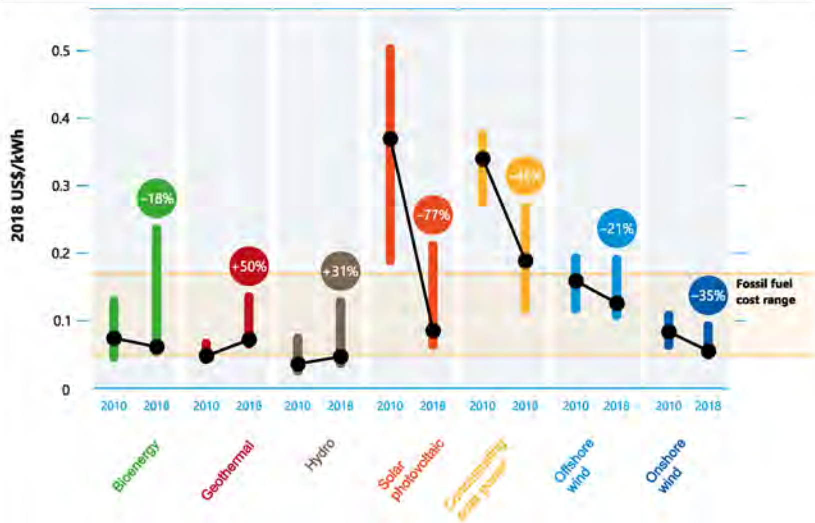
Box 3: A multi-layered perspective on socio-technical transition

Multi-layered perspectives on socio-technical transition can provide a framework for more sophisticated qualitative and quantitative approaches to the interactions between three layers that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

First, technological niches and innovations will, unsurprisingly, be a key parameter of a successful transition. Yet their representation in existing models fails to reflect the unpredictable and disruptive nature of technological innovations. As an example, the sharp increase of usage and cost variation in many renewable energy technologies over the past few years (Graph 3.A) has outpaced most predictions, and this seems to have responded more to massive investments in R&D and targeted subsidies to solar energy than to any ambitious carbon pricing mechanism (Zenghelis (2019)). In contrast, the intermittency of renewable energy remains a considerable problem that tends to be overlooked (Moriarty and Honnery (2016), Smil (2017a)). Moreover, other sectors may be impossible to decarbonise in the medium term regardless of carbon pricing, as we can observe (so far) not only with aviation or cement, but also with parts of the energy sector. In short, the type of technological solution that will prevail in a low-carbon world is largely unpredictable. A case in point is the transportation sector: the most promising technological alternatives have varied greatly over short time horizons (Graph 3.B) and with new technologies such as hydrogen fuel (Morris et al (2019), Li (2019), Xin (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

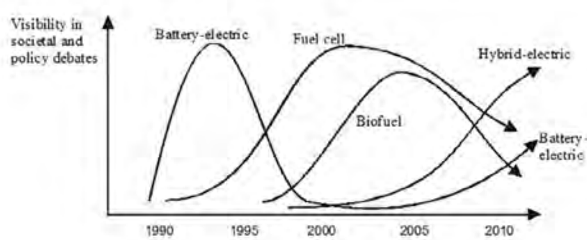
Graph 3.A



Source: UNEP (2019).

Changes in visibility of transportation technologies through time

Graph 3.B



Source: Geels et al (2017).

Second, the successful implementation of technologies does not depend only on their relative prices but also on the so-called socio-technical regimes in which they operate, ie the rules and norms guiding the use of particular technologies. For instance, once car-based transportation systems are set up in a city or country, they largely become self-sustaining "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017, p 465)). Although pricing mechanisms can surely contribute to overcoming this institutional inertia, other regulations may be needed such as rules on the weight of new cars (to avoid rebound effects[27]) and proactive support to the development of public transportation to limit the number of personal vehicles. More broadly, some solutions may depend not on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)), along with positive impacts for the national rail operator (Henley (2019)), are responses to a "Greta Thunberg effect" rather than a technological breakthrough.

Third, technological, behavioural and regulatory changes do not take place in a vacuum but in specific socio-technical landscapes, ie in contexts comprising "both slow-changing trends (eg demographics, ideology, spatial structures, geopolitics) and exogenous shocks (eg wars, economic crises, major accidents, political upheavals)" (Geels et al (2017, p 465)). In other words, assessing specific transition paths requires integrating many real-world considerations into the scope of the analysis, which is particularly difficult for modellers whose objective is precisely to simplify the representation of the world for reasons of tractability. Some features of the current "socio-technical landscape" that will prove essential to consider for the transition (further developed in Annex 2) include:

- A rather weakened multilateral order that is an important barrier to address the multiple trade-offs that a global low-carbon transition will generate. For instance, stranding fossil fuels may require the United States and Canada to immediately stop extracting unconventional oil, with potentially significant impacts on the output of their national economies (Mercure et al (2018)). Similarly, as China consumed half of the world's coal in 2018 (BP (2019)) and Asia has accounted for 90% of new coal plants over the past two decades (IEA (2019)), stranding such assets could have major impacts on global value chains, for example with sharp increases in the price of imports for advanced economies, sharp decreases in corporate profits in Asia, and potential relocations of certain economic activities. These could have significant implications for global imbalances. With this in mind, aiming to strand these assets rapidly and in a fair manner would probably require unprecedented international cooperation, including significant compensation mechanisms for countries that do not exploit fossil fuel reserves. However, past experiences such as the Yasuni-ITT initiative in Ecuador show the difficulty of reaching agreements on compensation for not polluting (Martin and Scholz (2014), Warnars (2010)). Finally, a low-carbon transition could trigger new geopolitical tensions and potential conflicts, including conflicts related to the quest for resources needed for renewable energy (IRENA (2019), Pitron (2018)). Hence, existing models still have a long way to go to account for the international political economy of climate change and for the principle of "common but differentiated responsibilities" enshrined in international climate negotiations (UNFCCC (2015)).

- Significant transformations of market economies have taken place over the past decades, including a decrease in growth rates in advanced economies but also at the global level (despite rapid growth in emerging and developing economies). Discussions are under way about the causes of this slowdown (eg a new "secular stagnation", whether structural and possibly related to a long-term decline in productivity (Gordon (2012)), or a more conjunctural slowdown in aggregate demand that can be addressed by new macroeconomic policies). Other transformations include a shift in corporate governance towards maximisation of shareholder value and short-termism (Mazzucato (2015)) and increased inequalities within nations (Piketty (2014)) despite a relative decrease in inequalities among nations (Milanovic (2016)). These features pose significant questions such as the social acceptability of a low-carbon transition. For

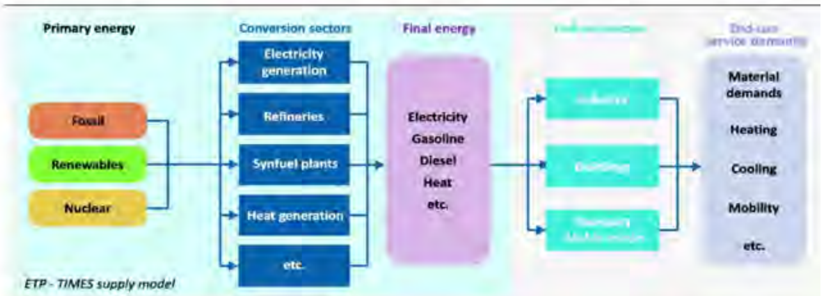
[27] In energy economics, rebound effects occur when initial energy efficiency gains are cancelled out by behavioural or systemic responses, for instance if a consumer uses the financial gains from increased housing energy efficiency to set higher temperatures or to increase energy use elsewhere. As a concrete example, increases in cars' energy efficiency over the past few years have been offset by the fact that households are buying larger cars and that the number of passengers per car is decreasing (IEA (2019)).

instance, given that such a transition requires "intensive public discussion" (Stern (2008, p 33)), it is unclear whether mechanisms such as revenue-neutral carbon taxes will be sufficient. Some argue that if inequalities were lower in the first place, it could become easier to reach consensus on difficult topics such as the burden-sharing efforts to mitigate and adapt to climate change (Chancel (2017), Otto et al (2019)). That is, without suggesting an optimal specific path, climate change needs to be considered as being embedded in a myriad of real-world socioeconomic challenges, not as an ad hoc challenge that should simply not interfere with other challenges.

3.2 Climate-related uncertainties and the choice of scenarios

Forward-looking approaches that are built around an IAM inevitably inherit all the limitations of the climate-economic models mentioned in the previous chapter. Here we focus mostly on technological uncertainties, given the difficulty of accounting for the other sources of uncertainty discussed above (eg international political economy uncertainties associated with the transition). It should also be noted that some methodology providers do not rely on IAMs but rather on "technologically-based" models. For instance, the ET Risk Project,[28] developed by a consortium of stakeholders, uses scenarios provided by the International Energy Agency (IEA) and adapts these based on bottom-up market analyses. The IEA produces scenarios on the development of energy technologies and the investments needed to upscale them under different climate pathways and policy tracks (regulations, carbon pricing, etc).[29] For instance, the IEA's 2017 *Energy Technology Perspectives* (ETP) report (Graph 11) seeks to offer a "technology-rich, bottom-up analysis of the global energy system" (IEA (2017)).

Structure of the ETP model — Graph 11



Source: IEA (2017).

[28] http://et-risk.eu/.

[29] These include a "Current Policies Scenario" akin to a "business as usual" setup, a "New Policies Scenario" focused on the Nationally Determined Contributions (NDCs) set by each country following the Paris Agreement (UNFCCC (2015)), and a more ambitious "Sustainable Development Scenario".

Whether they rely on IAMs or "technology-based" models, it is critical to assess which choices inform the selected technological pathway (eg development of carbon capture and storage (CCS) technologies, nuclear energy, price of renewable energy, gains obtained from energy efficiency, etc) as these strongly determine which sectors and companies could benefit from it. However, the representation of clean technology diffusion rates in energy-systems models is inherently subject to much uncertainty (Barreto and Kemp (2008)). Some scenarios rely on the rapid development of existing technologies to respond to increasing demand for energy (eg IEA (2017)), while others focus on the potential reduction in energy demand to be achieved through energy efficiency and modification of existing behaviours (eg Negawatt (2018)). Other technology-based scenarios include BP's Rapid transition scenario, IRENA's REmap scenario, Greenpeace's Advanced Energy Revolution scenario (for a comprehensive review of scenarios, see Colin et al (2019), The Shift Project and IFPEN (2019)) or, with a different approach, the Science-Based Targets Initiative.[30]

An important source of technological uncertainty has to do with the role allocated to negative emissions and to CCS technologies.[31] Their relative importance varies widely across models: in a subset of 2°C scenarios, between 400 and 1,600 gigatonnes of carbon dioxide ($GtCO_2$) can be compensated through negative emissions and CCS, corresponding to 10–40 years of current emissions (Carbon Brief (2018)). This increases the size of the remaining carbon budget by between 72 and 290%, compared to scenarios where negative emissions and CCS do not occur. In practice, however, significant uncertainty exists with regard to CCS technologies due to technological constraints, potentially high costs and environmental and health risks (IPCC (2014)).

As a result, a scenario with a large role for negative emissions and CCS will naturally reduce the amount of assets that are stranded (eg the GCAM model in the graph below, for a 2°C scenario), whereas a scenario with less room for negative emissions will require a more massive development of renewables (as in the MESSAGE, REMIND and WITCH models) or considerable improvements in energy efficiency (as in IMAGE). This means that the financial impacts of a specific financial portfolio will be entirely different depending on which scenario is chosen.

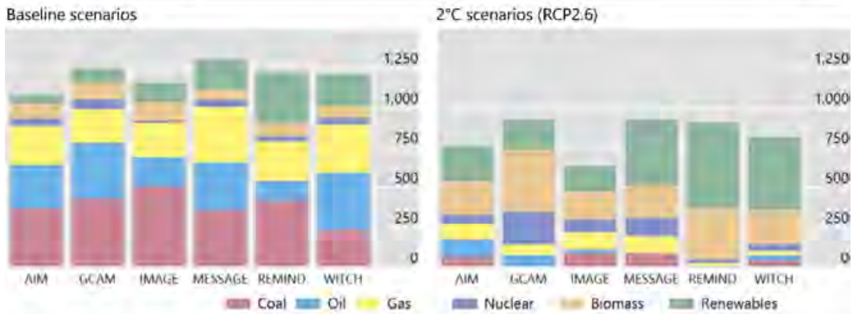
[30] The Science-Based Targets Initiative (sciencebasedtargets.org/) differs from the other listed scenarios. Instead of a comprehensive approach, it aims to provide companies with pathways to align their emissions to climate targets on a sectoral basis, based on current scientific knowledge.

[31] CCS is technically not a "negative emissions" technology since it does not remove CO_2 from the atmosphere, but stores new emissions instead. That is, it avoids new emissions but does not capture past emissions. CCS is usually included in the category of BECCS (bioenergy with carbon capture and storage).

The 2100 primary energy mix

Exajoules of primary energy

Graph 12



The 2100 primary energy mix according to six IAMs, for SSP2 ("middle of the road") RCP2.6 scenarios. The energy mix in a "baseline" scenario is shown on the left, and scenarios that limit global warning to 2°C are shown on the right. Fossil fuel categories include CCS and non-CCS use.

Sources: Carbon Brief (2018); IIASA SSP Database.

Partially as a result of these sources of technological uncertainty, the volume of investments needed (a critical element to assess the risk and opportunities related to a low-carbon transition) can vary significantly. The survey of six models estimating the additional annual average energy-related investments needed to limit global warming to 1.5°C (over the period 2016 to 2050, compared to the baseline) finds significant variations, with values ranging from $150 billion ($2010) to $1,700 billion ($2010). Total investments (ie not just additional ones) in low-carbon energy also vary greatly, from $0.8 trillion ($2010) to $2.9 trillion ($2010; IPCC (2018, p 153)). Estimated needed investments vary even over shorter time horizons. For instance, global investments needed in sustainable infrastructure for the period 2015–30 range from less than $20 trillion to close to $100 trillion (Bhattacharya et al (2016, p 27)).

These estimates depend significantly on initial assumptions and methodological choices. For instance, in MESSAGE (the energy core of IIASA's[32] IAM framework), emissions-reduction investments occur in the models' regions and at the time they are cheapest to implement (assuming full temporal and spatial flexibility), based on the cost assumptions of 10 representative generation technologies (Zhou et al (2019)). In contrast, the New Climate Economy project estimates the investments needed in infrastructure by using existing technologies and investment patterns, assuming an exogenous growth rate of 3% and no productivity gains (Bhattacharya et al (2016)). Other assumptions are also critical, eg supply side investments could be lowered by up to 50% according to some studies if strong policies to limit energy demand growth are implemented (Grubler et al (2018), in IPCC (2018)).

Therefore, scenarios "should be considered illustrative and exploratory, rather than definitive [...]. It is important to remember that scenarios represent plausible future pathways under uncertainty. Scenarios are not associated with probabilities, nor do they represent a collectively exhaustive set of potential outcomes or actual forecasts" (Trucost ESG Analysis (2019, p 39)). Their "results are subject to a

[32] The International Institute for Applied Systems Analysis (IIASA)'s model is composed of five different models: the two most important that represent the energy system (MESSAGE) and land-use competition (GLOBIOM), and three that represent the macroeconomic system (MACRO), the climate system (MAGICC) and air pollution and GHG emissions (GAINS). The MESSAGE framework divides the world into 11 regions. For an overview, see: https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html.

high degree of uncertainty" (Zhou et al (2019, p 3)) and cannot be allocated probabilities of occurrence, ie they should be assessed with extreme caution by finance supervisors engaged in financial stability monitoring.

3.3 Translating a climate-economic scenario into sector- and firm-level risk assessments

To incorporate climate-related risks into financial institutions' risk management procedures and financial stability monitoring, the main challenge to determining a reasonable scenario consists in translating it into granular metrics at the sector (see Box 4 below) and firm level. A firm-level assessment is critical as it can distinguish how firms with a similar exposure to climate scenarios have different adaptive capacities, making them more or less vulnerable. Indeed, the climate vulnerability of a firm does not depend only on its exposure to climate-related risks (which can be relatively similar for different firms in the same sector) but also on its sensitivity and its adaptive capacity to a specific scenario (eg its ability to develop new low-carbon technologies in response to climate-related risks, or to pass through additional costs to its suppliers or customers). For instance, two oil and gas companies may fall under the same industry classification but be exposed to transition risks in very different ways, depending on factors such as the likelihood of owning stranded assets (as discussed above) or their degree of diversification into renewable energy.

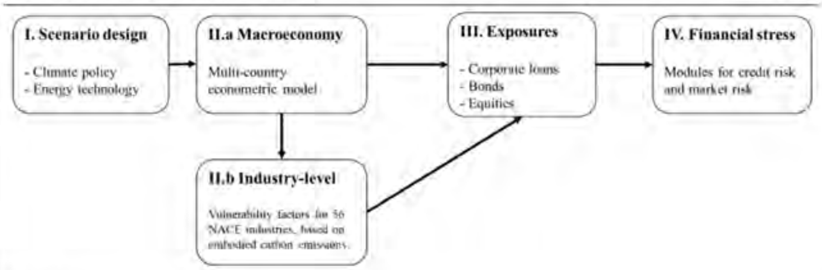
Box 4: The Netherlands Bank's climate stress test

The Netherlands Bank's methodology (Vermeulen et al (2018, 2019)) first defines climate scenarios and shocks (mostly via carbon taxes and technological development paths) based on literature and validated by experts (block I in figure below). The policy shock consists in the abrupt implementation of a $100 carbon tax, and the technology shock in the rapid development of renewable energy, which leaves fossil fuel dependent technologies obsolete, resulting in capital stock write-offs. These shocks can be assessed separately or jointly (double shock); they can also lead to a negative confidence shock affecting the behaviour of consumers, producers and investors. These scenarios are translated into macroeconomic impacts on GDP, consumer prices, stock prices and interest rates through NiGEM (block II.a in Graph 4.A), a multi-country macroeconomic model. The central bank then estimates the vulnerability of each sector to transition risks, based on the embodied CO_2 emissions of 56 NACE industries[33] (ie including the emissions related to their value chain) weighted by their contribution to GDP (block II.b in the graph). The impact of the transition on each NACE industry is then connected to the national financial sector portfolios of corporate loans, bonds and equities (block III in the figure below). In the last step (block IV in Graph 4.A), the central bank calculates losses for financial institutions with the aid of traditional top-down approaches to stress testing. The results of the climate stress test indicate losses of up to 11% of assets for insurers and up to 3% for banks, potentially leading to a reduction of about 4 percentage points in Dutch banks' CET1 ratio[34].

[33] NACE is the industry standard classification system used in the European Union.

[34] Common Equity Tier 1 (CET1) is a component of Tier 1 capital that consists mostly of common stock held by a bank or other financial institution. It is the highest quality of regulatory capital, as it absorbs losses immediately when they occur. See: https://www.bis.org/fsi/fsisummaries/defcap_b3.pdf.

Overview of the stress test framework Graph 4.A



Source: Vermeulen et al (2019).

Climate change mitigation and adaptation also brings opportunities related to the development of low-carbon technologies and climate-friendly policies (see Graph 13), which are captured by several climate-related risk assessment methodologies (eg Mercer, Oliver Wyman and Carbon Delta). UNEP-FI (2019) estimates that profits generated by a 30,000-company universe in the transition to a 2°C world could amount to $2.1 trillion, although this number should be taken cautiously given the many sources of uncertainty discussed above. It is therefore important to assess how climate-related risks and opportunities will impact specific key performance indicators (KPIs) of a firm, such as its sales, operational and maintenance costs, capital expenditures, R&D expenditures, and potential impairment of fixed assets.

Climate-related risks, opportunities and financial impact Graph 13

Source: TCFD (2017).

One of the main difficulties at this stage is determining how a firm is exposed to climate-related risks throughout its value chain. A firm can be exposed to these risks through: (i) direct, so-called "scope 1" emissions (particularly important in sectors such as mining, aviation or the chemical industry); (ii) indirect, so-called "scope 2" emissions resulting from purchased energy (eg real estate or energy-intensive industries); and (iii) other indirect emissions related to its entire upstream and downstream value chain, so-called "scope 3" emissions.[35] A case in point for scope 3 is the automotive industry, where the main exposure lies not so much with the sector's own emissions (scope 1) or its energy sources (scope 2), but with carbon combustion by end users (scope 3). For buildings, scope 3 emissions are twice as high as direct emissions (Hertwich and Wood (2018)). This is not to say that the emissions related to scopes 1, 2 and 3 are sufficient to assess the exposure of a firm. For instance, a firm with high emissions today could become decarbonised and seize many opportunities under specific transition paths. Still, focusing on scopes 1, 2 and 3 means that a comprehensive risk assessment should look at potential vulnerabilities throughout the entire value chain.

The assessment of a firm's exposure to its scope 1, 2 and 3 emissions and its translation into risk metrics can be conducted in quantitative or qualitative manners. The PACTA stress test model,[36] based on International Energy Agency (IEA) technological pathways up to 2050 compatible with a specific climate scenario (eg a 2°C or 1.75°C rise in temperatures) and on proprietary databases including existing investment plans at the firm level, determines how each firm within specific sectors may become aligned or misaligned with the scenario. This insight then informs a delayed stress test tool that calculates shocks based on alternative cash flows, discounted in a valuation or credit risk model. The assessment of the risk materiality by sector is a key dimension of this methodology, which involves technological, market and policy considerations.

Another methodology, developed by Carbon Delta (2019), proceeds by breaking down each country's emission reduction pledge (as indicated by its Nationally Determined Contribution, or NDC) into sector-level targets, and then assigning emission reduction quantities to a firm's production facilities based on its emission profile within each sector, using a proprietary asset location database. The costs relative to the transition are then obtained by multiplying the required GHG reduction amount by the price per tonne of carbon dioxide (tCO_2) obtained via IAMs for the scenario under analysis (eg for a 3°C, 2°C and 1.5°C rise in temperatures). In order to estimate the revenues that each firm could obtain from a low-carbon transition, Carbon Delta (2019) uses a database covering millions of low-carbon patents granted by authorities worldwide, and a qualitative assessment of each low-carbon patent portfolio as a proxy for firms' adaptive capacity.

Other approaches rely more extensively on qualitative judgments regarding the adaptive capacity of firms in each sector. For instance, Oliver Wyman (2019) resorts to experts' judgments to forecast how specific companies in the portfolio may adapt to climate-related risks, although it also includes quantitative tools to estimate impacts of scenarios on prices, volumes, cost, impairment and capital expenditure of counterparties. Carbone 4's (2016) bottom-up assessment considers firms' adaptive capacities to a low-carbon transition, relying on a mix of qualitative and quantitative indicators such as the investments made in R&D and the CO_2 reduction objectives of the firm related to its scope 1, 2 and 3 emissions. Allianz Global Investor integrates technological, regulatory and physical considerations qualitatively into its asset allocation procedures (IIGCC (2018)).

[35] The GHG Protocol Corporate Standard classifies a company's GHG emissions into three "scopes". "Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions." Source: ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf.

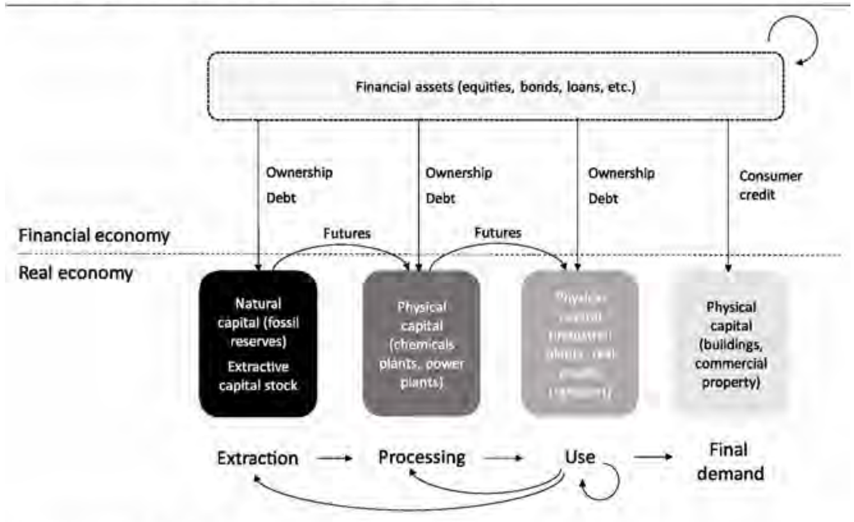
[36] www.transitionmonitor.com/.

Other approaches have also emerged to better account for the indirect exposures to climate-related risks, without necessarily relying on scopes 1, 2 and 3. For instance, Battiston et al (2017) classify economic activities into six sectors (fossil-fuel, utility, energy intensive, transportation, housing, and finance) and twenty subsectors based on their relative vulnerability to climate transition risks (as a function of their emissions). They further map out the exposure of financial institutions (through equity and debt) to these different sectors, which enables them to capture potential knock-on effects within financial networks. When applying a sectoral shock (eg a carbon tax), the firms in sectors that have not adapted their business model to the energy transition face increased costs and reduced revenues, whereas the firms that have invested in alternative technologies are able to increase their profits. This methodology can be applied to the financial system as a whole or to specific financial institutions (Battiston et al (2017)), and to different asset classes such as equity, corporate and sovereign bonds (Battiston and Monasterolo (2019)), while capturing second-round effects related to the holding of financial assets.

Another way of estimating indirect exposures is to look at production networks, as suggested by Cahen-Fourot et al (2019a,b). Using input-output tables for 10 European economies and based on the monetary value of productive capital stocks (Cahen-Fourot et al (2019b)), the authors seek to provide a systemic perspective on how the reduction in production in one sector can cascade to physical stocks supporting the rest of the economic activity through chains of intermediate exchange. That is, as physical inputs stop flowing from one sector to another, more sectors along value chains are also impacted. For instance, the mining and quarrying sector (including the extraction of fossil fuels), although it accounts for a relatively low share of value added, tends to provide crucial inputs for many other downstream economic activities such as construction, electricity and gas, coke and refined petroleum products or land transport; in turn, these sectors are critical for the correct functioning of public administration, machinery and equipment and real estate activities; and so on. In short, stranding an asset in one specific sector can trigger a "cascade of stranded assets" affecting many other sectors of the economy.

While these two approaches bring critical insights into the interconnectedness among sectors and potential transmission channels of transition shocks and could greatly benefit from being combined (see Graph 14), applying them to future scenarios is not without its challenges. Indeed, relying on existing sectoral classifications and interconnections cannot be assumed to serve as a good proxy for future interconnectedness, given the need to change the very productive structures of the economy. In this sense, they are probably more tailored to the conduct of a climate stress test with a relatively short-term horizon (assuming a static portfolio) than as a tool to be used by financial institutions in a dynamic environment.

Natural, physical and financial assets at risk of stranding | Graph 14



Source: Campiglio et al (2017).

Regardless of the approach chosen, some critical sources of uncertainty to keep in mind when conducting forward-looking risk assessments concern the ability to predict:

- *The development and diffusion of new technologies*: As new technologies that do not yet exist or are not yet widespread appear and scale up, they may reshape existing market structures in unpredictable ways. For instance, wholesale online distribution would have been unpredictable a few decades ago. With this in mind, it is difficult to predict how a specific firm will perform in a new environment that will be determined not only by its own strategy but also by multiple elements in its value chain;
- *Each firm's market power:* In response to climate regulations, some firms may be able to offset an increase in operating costs through their customers (by increasing final prices) or suppliers (by decreasing purchasing prices), while others may not have this market power. For instance, after the introduction of the EU Emissions Trading Scheme (ETS) in 2005, some electricity generators were able to pass through more than 100% of the cost increase to consumers (UNEP-FI (2019)). Determining each firm's market position and power and its related pass-through capacity in a dynamic environment remains a considerable task. Some methodologies (eg Oliver Wyman) aim to assess firms' ability to withstand a decrease in demand due to possible product substitutions and cost pass-through (based among other things on the estimated price elasticity of demand); others examine the adaptive capacity of firms based on the potential development of low-carbon and emissions abatement technologies (eg Carbone 4; ET Risk).

– *The exposure to liability risks that have not yet arisen:* Existing methodologies focus on physical and transition risks, but liability risks[37] may become increasingly important in the future. A case in point is PG&E (Baker and Roston (2019), Gold (2019)), the owner of California's largest electric utility, which filed for bankruptcy in early 2019 after wildfire victims sued the company for failing to adjust its grid to the risks posed by increasingly drier climate conditions. Several legal actions against energy and oil and gas companies (eg Drugmand (2019)) are also under way, often brought by cities or civil society organisations seeking compensation for climate-related disasters or the non-compliance of their business plans with the Paris Agreement (Mark (2018)). These examples show how in the future, firms may be exposed not only to the physical and transition risks of climate change, but also to legal risks. However, assessing liability risks is a major challenge not only because of their inherent uncertainty (eg predicting which lawsuits will be triggered by future uncertain events) but also because of variations in the legal framework of each jurisdiction. For instance, in some jurisdictions the government acts as reinsurer "of last resort" in the case of natural disasters; in this case the risks end up being borne by the government rather than the firm or insurer.

Overall, the outcomes provided by each methodology are therefore highly sensitive to the ways in which they account for specific scenarios and how they translate them into static or dynamic corporate metrics that take into account the scope 1, 2 and 3 emissions. Although the lack of data is commonly and rightly invoked as a barrier to the development of climate-related risk assessment, it is also important to emphasise that bridging the data gap will not fully "resolve" the sources of uncertainty discussed above.

3.4 From climate-related risk identification to a comprehensive assessment of financial risk

Once a scenario has been translated into specific metrics at the firm or sector level, there remains the challenging task of integrating such an analysis into a financial institution's internal risk management procedures/a supervisor's practices. In this respect, some methodologies provide a scorecard or climate risk rating and estimates of the carbon impact of a portfolio (eg Carbone 4). Other methodologies aim to calculate the specific impact on asset pricing or credit risks, for instance through the concept of climate value-at-risk (climate VaR), which compares a climate disaster scenario to a baseline scenario. For instance, Carbon Delta estimates future cash flows generated by each firm and discounts them to measure current values that can inform credit risk models (eg a Merton model).

Regardless of the method chosen, at least three main methodological challenges should be kept in mind when conducting such an exercise.

First, it is possible for investors to see the long-term risks posed by climate change, while remaining exposed to fossil fuels in the short term (Christophers (2019)), especially if they believe that hard regulations will not be put in place anytime soon. The identification of the risk is one thing; mitigation is entirely another. For instance, Lenton et al (2019) find that the emergency to act is not only a factor of the risk at stake but also the urgency (defined as reaction time to an alert divided by the intervention time left to avoid a bad outcome). In other words, even identifying all the risks (if even possible) would not necessarily suffice to "break the tragedy of the horizon". Accordingly, new approaches to risk such as MinMax rules (Battiston (2019)), where the economic agent takes a decision based on the goal of minimising losses (or future regrets) in a worst case scenario, may be needed. Other approaches to risk management such as real option analyses, adaptation pathways or robust decision analysis are also already used for specific projects such as infrastructure and large industrial projects (Dépoues et al (2019)).

[37] As described by Carney (2015): "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible". It should be noted that in some approaches (eg TCFD (2017)), "legal" risks (which share similar features with liability risks) are captured under physical and/or transition risks.

However, there are no indications that financial institutions would naturally choose this approach (except in specific cases such as project finance), and it is unclear how regulators could promote its use by financial institutions. In other words, the question of how to adjust risk modelling approaches to allow for longer time horizons remains a challenging one (Cleary (2019, p 28)).

Second, it is possible for financial institutions to hedge individually against climate change, without reducing the exposure of the system as a whole as long as system-wide action is not taken. For instance, Kling et al (2018) find that climate-vulnerable countries exhibit a higher cost of debt on average. This means that as markets hedge against climate-related risks by increasing risk premiums, the risk is transferred to other players such as climate-vulnerable sovereigns, which also happen to be poorer countries on average. Carney (2015) had also noted that insurers' rational responses to physical risks can paradoxically trigger new risks: for instance, storm patterns in the Caribbean have left many households unable to get private cover, prompting "mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned" (Carney (2015, p 6)). Another risk may have to do with the development of financial products in response to climate-related risks, such as weather derivatives: these may help individual institutions hedge against specific climate-related risks, but they can also amplify systemic risk (NGFS (2019b, p 14)). In short, reckoning climate-related risks can lead financial institutions to take rational actions that, while hedging them individually from a specific shock, do not hedge against the systemic risks posed by climate change. For central banks, regulators and supervisors, this poses difficult questions, such as the adequate prudential regulation that should be deployed in response.

Third, in order to fully appreciate the potential systemic dimension of "green swan" events or "climate Minsky moments", more work is still needed on how a climate-related asset price shock (eg stranded assets) could trigger other losses within a dynamic financial network, including contagion effects towards non-climate-related sectors. The 2007–08 Great Financial Crisis has shown how a shock in one sector, subprime mortgages, can result in multiple shocks in different regions and sectors with little direct exposure to subprimes (for instance, affecting German Landesbanken and southern Europe's banking systems and sovereign credit risks). In this respect, abrupt shifts in market sentiment related to climate change could affect all players, including those who were hedged against specific climate-related risks (Reynolds (2015)).

These challenges go a long way towards explaining the "cognitive dissonance" (Lepetit (2019)) between the increased acceptance of the materiality of climate-related risks by financial institutions, and the relative weakness of their actions in response. In short, accounting for the multiple transmission channels of climate-related risks across firms, sectors and financial contracts while reflecting a structural change of economic structures remains a task filled with uncertainty. As a result, the question of how much asset values are affected and how much credit ratings should be impacted today in the face of future uncertain events remains unclear for deeper reasons than purely methodological ones. Despite these limitations, scenario-based analysis will remain critical for financial and non-financial firms aiming to increase their chances of adapting to future risks. That is, these methodological obstacles should not be a pretext for inaction, since climate-related risks remain real.

3.5 From climate-related risk to fully embracing climate uncertainty – towards a second "epistemological break"

The previous analyses have highlighted that regardless of the approach taken, the essential step of measuring climate-related risks presents significant methodological challenges related to: (i) the inability of macroeconomic and climate scenarios to holistically capture a large range of climate, social and economic factors; (ii) their translation into corporate metrics within a dynamic economic environment; and (iii) the difficulty of matching the identification of a climate-related risk with the adequate mitigation action. Climate-economic models and forward-looking risk analysis are important and can still be improved, but they will not suffice to provide all the information required to hedge against "green swan" events.

As a result of these limitations, two main avenues of action have been proposed. We argue that they should be pursued in parallel rather than in an exclusive manner. First, central banks and supervisors could explore different approaches that can better account for the uncertain and nonlinear features of climate-related risks. Three particular research avenues (see Box 5 below) consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels. Nevertheless, the descriptive and normative power of these alternative approaches remain limited by the sources of deep and radical uncertainty related to climate change discussed above. That is, the catalytic power of scenario-based analysis, even when grounded in approaches such as non-equilibrium models, will not be sufficient to guide decision-making towards a low-carbon transition.

As a result of this, the second avenue from the perspective of maintaining system stability consists in "going beyond models" and in developing more holistic approaches that can better embrace the deep or radical uncertainty of climate change as well as the need for system-wide action (Aglietta and Espagne (2016), Barmes (2019), Chenet et al (2019a), Ryan-Collins (2019), Svartzman et al (2019)). The concept of "risk" refers to something that has a calculable probability, whereas uncertainty refers to the possibility of outcomes that do not lend themselves to probability measurement (Knight (2009) [1921], Keynes (1936)), such as "green swan" events. The question of decision-making under deep or radical uncertainty is making a comeback following the 2007–08 Great Financial Crisis (Webb et al (2017)). According to former governor of the Bank of England Mervyn King, embracing radical uncertainty requires people to overcome the belief that "uncertainty can be confined to the mathematical manipulation of known probabilities" (King (2017, p 87)) with alternative and often qualitative strategies aimed at strengthening the resilience and robustness of the system (see also Kay and King (2020)).

As such, a second "epistemological break" is needed to approach the role of central banks, regulators and supervisors in the face of deep or radical uncertainty. This demands a move from an epistemological position of risk management to one that seeks to build the resilience of complex adaptive systems that will be impacted in one way or another by climate change. What should then be the role of central banks, regulators and supervisors in this approach? In the next chapter, we argue that the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within an institutional environment involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a more systematic integration of sustainability considerations into financial and economic decision-making.

Box 5: New approaches for forward-looking risk management: non-equilibrium models, sensitivity analysis and case studies

In order to better account for the specific features of climate-related risks (deep uncertainty, nonlinearity, multiple and complex transmission channels within and among transition and physical risks, etc), three complementary research avenues seem particularly promising. They consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels.

Non-equilibrium models:

Mercure et al (2019) find that "equilibrium" and "non-equilibrium" models tend to yield opposite conclusions regarding the economic impacts of climate policies. Equilibrium models (such as DSGE) remain the most widely used for climate policy, yet their central assumption that prices coordinate the actions of all agents (under constrained optimisation) so as to equilibrate markets for production factors fails to represent transition patterns (including some discussed above) in a consistent manner.

In this context, non-equilibrium models may be better positioned to address three critical features of the transition:

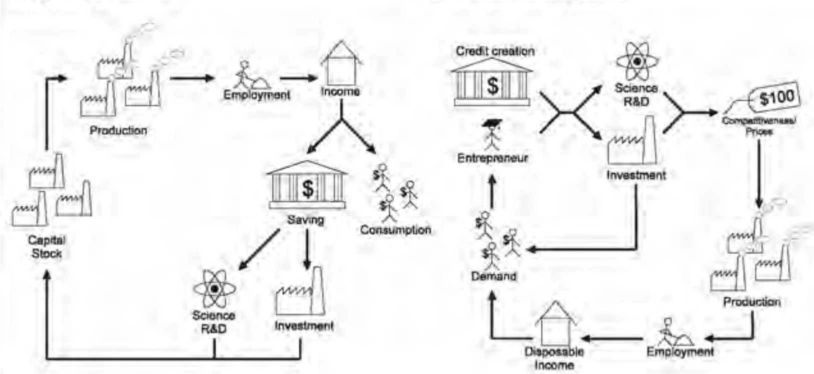
1. Path dependency: in non-equilibrium models, the state of the economy depends on its state in previous time steps. This approach seems particularly aligned with the purpose of scenario analysis, consisting as it does in describing the economy under different possible and diverging circumstances that are dependent on past and present decisions. For instance, it is easier to represent how socio-technical inertia shapes current behaviours, beyond and despite pricing mechanisms.

2. Role of money and finance: the need to better account for the dynamics of the financial sector has been widely discussed after the 2007–08 Great Financial Crisis, yet the discussion has only slightly permeated the field of climate economics so far (Mercure et al (2019)). A more central role is often attributed to finance in non-equilibrium models, particularly in the post-Keynesian school of thought through stock-flow consistent models: money is created by banks in response to demand for loans, and therefore investments are not constrained by existing savings (Graph 5.A). This may better represent the behavioural dynamics of financial institutions than DSGE (Dafermos et al (2017)), especially when merged with agent-based models (Monasterolo et al (2019)). For instance, financial institutions can expand lending and investments in times of economic optimism and restrict them when the perceived risk of default is too high, including because of climate-related issues.

3. Role of energy: standard economic theory, based on the cost share of energy in GDP, implies that a decrease in energy use reduces GDP but only to a limited extent. For instance, as energy costs typically represent less than 10% of GDP, a 10% reduction in energy use would lead to a loss in GDP of less than 1% (Batten (2018, p 28)). However, a growing literature suggests that the role of energy in production should not be treated as a third input independently from labour and capital (as in three-factor Cobb-Douglas production functions) but through a different "epistemological perspective" (Keen et al (2019)): energy is an input to labour and capital, without which production becomes impossible (Ayres (2016)). In this view, an improvement in energy efficiency may paradoxically lead (all other things being equal) to a sharp decrease in GDP. Given the critical role of energy for the transition, non-equilibrium models that can account for the peculiar role of energy in economics (Ayres (2016), Keen et al (2019), The Shift Project and IFPEN (2019)) may be critical for future scenario-based analysis.

Alternative models Graph 5.A

Supply-led / Equilibrium Demand-led / Non-equilibrium



Source: Mercure et al (2019).

Sensitivity analysis:

Conducting relatively simple scenario-based risk assessments, also called sensitivity analyses, may be another approach to capture some features of climate-related risks, especially transition risks. Sensitivity analyses "represent a fast and easy method for assessing the sensitivity of a portfolio to a given risk" (DG Treasury et al (2017, p 67)) and they do not need to rely on complex scenarios. The methodological difficulties related to scenario-based models "argue in favor of sensitivity analyses that measure the impact of a shock without necessarily incorporating it into a comprehensive scenario" (DG Treasury et al (2017, p 6)).

An example of such sensitivity analysis is ICBC (2016): the bank subjected firms in two sectors of its portfolio, thermal power and cement, to a selection of heavy, medium and light environmental stresses (tighter atmospheric pollution emissions limits for thermal power; tighter atmospheric pollutant emissions and discharges for cement). The test was carried out assuming that all other things remain equal, ie without factoring in the macroeconomic effects of such measures (eg carbon leakage to neighbouring countries). It estimated:

- The impacts of these regulatory shocks on the firms' costs, prices and quantity sold under each scenario;
- How credit ratings would be impacted;
- The possible changes in the firm credit rating and probability of default, and derived the change in the non-performing loan (NPL) ratio.

The recent climate stress test conducted by the UK's Prudential Regulation Authority (PRA (2019a)) takes a similar approach. The PRA translated three broad categories of climate scenarios (sudden and disorderly transition; progressive and orderly transition; no transition) into impacts on the asset side of insurance companies' balance sheets by applying a negative shock to the value of some companies they have in their investment portfolios. For instance, as part of the sudden and disorderly scenario (see Scenario A in Table 5.A), general insurance companies are required to simulate the impact of a valuation shock on their power generation firms (–65% for the coal sector, –35% for oil, –20% for gas, and +10% for renewable energy). Different shocks are applied to several sectors, such as fuel extraction (see below) but also transport, utilities, agriculture and real estate.

The PRA recognises that "the development of hypothetical values affecting investments are based on the interpretation of available literature by the PRA and discussions with specialists in the field" (PRA (2019a, p 50)), including several of the methodologies mentioned above. That is, the valuation shocks correspond to a coherent narrative aimed at signalling potential risks to financial institutions, rather than an attempt at precise modelling of the valuation shock.

Sensitivity analysis — Table 5.A

Sector	% of investment portfolio in following sectors	Assumptions	Transition risk			Physical risk		
			Scenario			Scenario		
			A	B	C	A	B	C
Fuel extraction	Gas/coal/oil (incl crude)	Change in equity value for sections of the investment portfolio comprising material exposure to the energy sector as below						
		Coal	−45%	−40%				
		Oil	−42%	−38%				
		Gas	−25%	−15%				
							−5%	−20%
Power generation		Coal	−65%	−55%				
		Oil	−35%	−30%				
		Gas	−20%	−15%				
		Renewables (incl nuclear)	+10%	+20%				
							−5%	−20%

Source: PRA (2019a).

Case studies:

A third avenue for forward-looking analyses in the presence of climate uncertainty consists in assessing the potential impacts of a climate-related transition or physical shock on one specific sector or region. This can provide a level of analysis that stands in between scenario analysis (which lacks granularity and suffers from many sources of uncertainty) and sensitivity analysis (which lacks a systemic view).

Along these lines, Huxham et al (2019) assess the transition risks for the South African economy in a scenario consistent with temperature rises well below 2°C above pre-industrial levels, by examining potential impacts of a reduction in demand and price of energy sources such as coal (which provides 91% of South African electricity and significantly contributes to the country's export revenues). For instance, infrastructure that supports carbon-intensive activities such as power plants and port infrastructure may have to be replaced or retired early, companies (assessed on an individual basis) and investors could be hurt and could lay off workers, leading to reduced demand for certain products. Governments could face lower tax revenues while also having to deal with increasing expenditures related to industries and workers in transition.

One advantage of such studies is that they can explore the vulnerability of firms and sovereigns to potential economic policies within a limited perimeter, which enables greater transparency regarding the assumptions made and greater detail in the narratives chosen. For instance, the South African case study considers the impact of government policies shifting fiscal incentives from climate-vulnerable sectors to low-carbon activities, and the support from international development finance institutions in this process.

4. POLICY RESPONSES – CENTRAL BANKS AS COORDINATING AGENTS IN THE AGE OF CLIMATE UNCERTAINTY

Rien n'est plus puissant qu'une idée dont l'heure est venue ("There is nothing more powerful than an idea whose time has come").

Attributed to Victor Hugo

Acknowledging the limitations of risk-based approaches and embracing the deep uncertainty at stake suggests that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, they cannot resort to simply measuring risks (hoping that this will catalyse sufficient action from all players) and wait for other government agencies to jump into action: this could expose central banks to the real risk that they will not be able to deliver on their mandates of financial and price stability. In the worst case scenario, central banks may have to intervene as climate rescuers of last resort or as some sort of collective insurer for climate damages. For example, a new financial crisis caused by such "green swan" events severely affecting the financial health of the banking and insurance sectors could put central banks under pressure to buy their large set of assets devalued by physical or transition impacts.

But there is a key difference from an ordinary financial crisis, because the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, meaning that the biophysical causes of the crisis will be difficult if not impossible to undo at a later stage. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. A potential intervention as climate rescuer of last resort would then expose in a painful manner the limited substitutability between financial and natural capital, and therefore affect the credibility of central banks.

On the other hand, central banks cannot succumb to the growing social demand arguing that, given the severity of climate-related risks and the role played by central banks following the 2007–08 Great Financial Crisis, central banks could now substitute for many (if not all) government interventions. For instance, pressures have grown to have central banks engage in different versions of "green quantitative easing" in order to "solve" the complex socioeconomic problems related to a low-carbon transition. However, the proactive use of central bank balance sheets is highly politically controversial and would at the very least require rethinking the role of central banks with a historical perspective. Goodhart (2010) argues that central banks have had changing functional roles throughout history, alternating between price stability, financial stability and support of the State's financing in times of crisis. Central bankers in advanced economies have grounded their actions around the first role (price stability) over the past decades, and increasingly around the second role (financial stability) since the 2007–08 Great Financial Crisis. Proposals concerning "green quantitative easing" could be seen as an attempt to define a third role through a more explicit and active support of green fiscal policy.

Without denying the reality of evolutionary perspectives on central banking (eg Aglietta et al (2016), Goodhart (2010), Johnson (2016), Monnet (2014)) and the fact that climate change could perhaps be the catalyst of new evolutions, the focus on central banks as the main agents of the transition is risky for many reasons, including potential market distortions and the risk of overburdening central banks' existing mandates (Villeroy de Galhau (2019a), Weidmann (2019)). More fundamentally, mandates can evolve but these changes in mandates and institutional arrangements are also very complex issues because they require new sociopolitical equilibria, reputation and credibility. Central bankers are not elected officials and they should not replace or bypass the necessary debates in civil society (Volz (2017)). From a much more pragmatic perspective, mitigating climate change requires a combination of fiscal, industrial and land planning policies (to name just a few) on which central banks have no experience.

To overcome this deadlock, we advocate a third position: without aiming to replace policymakers and other institutions, central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. The risks posed by climate change offer central banks a special perspective that private players and policymakers cannot necessarily adopt given their respective interests and time horizons. In that context, central banks have an advantage in terms of proposing new policies associated with new actions, in order to contribute to the societal debates that are needed. We believe that they can best contribute to this task in a role that we call the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the "risk", "time horizon" and "system resilience" approaches (see Table 3).

Embracing deep or radical uncertainty therefore calls for a second "epistemological break" to shift from a management of risks approach to one that seeks to assure the resilience of complex adaptive systems in the face of such uncertainty (Fath et al (2015), Schoon and van der Leeuw (2015)).[38] In this view, the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within a much broader evolution involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a better integration of sustainability into financial and economic decision-making.

Importantly, central banks can engage in this debate not by stepping out of their role but precisely with the objective of preserving it. In other words, even though some of the actions required do not fall within the remit of central banks and supervisors, they are of direct interest to them insofar as they can enable them to fulfil their mandates in an era of climate-related uncertainty.

This chapter explores some potential actions that are needed precisely to preserve the mandate and credibility of central banks, regulators and supervisors in the long term. The purpose here is not to provide an optimal policy mix, but rather to contribute to the emerging field of climate and financial stability from the perspective of deep or radical uncertainty. We suggest two broad ranges of measures. First, as detailed in Chapter 4.1, we recall that central banks, supervisors and regulators have a role to play through prudential regulation related to their financial stability mandate. However, while assessing and supervising climate-related risks is essential, it should be part of a much broader political response aimed at eliminating the economy's dependence on carbon-intensive activities, where central banks cannot and should not become the only players to step forward.

We then suggest and critically discuss four non-exhaustive propositions[39] that could contribute to guaranteeing system resilience and therefore financial stability in the face of climate uncertainty: (i) Beyond climate-related risk management, central banks can themselves and through their relationship with their financial sectors proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance in order to "break the tragedy of the horizon" (Chapter 4.2); (ii) Better coordination of fiscal, monetary and prudential and carbon regulations is essential to successfully support an environmental transition, especially at the zero lower bound (Chapter 4.3); (iii) Increased international cooperation on environmental issues among monetary and financial authorities will be essential (Chapter 4.4); (iv) More systematic integration of climate and sustainability dimensions within corporate

[38] This system resilience view holds that: (i) new analytical frameworks are needed to represent the interactions between humans and their natural environment; (ii) these interactions need transdisciplinary approaches (rather than multidisciplinary ones where each discipline continues to adhere to its own views when approaching another discipline requiring a different paradigm); and (iii) open systems are generally not in equilibrium, ie their behaviour is adaptive and dependent upon multiple evolving interactions.

[39] In particular, "command and control" policies are not discussed (given that their implementation tends to depend on specific national and subnational factors), although they also probably have a critical role to play in the transition.

and national accounting frameworks can also help private and public players manage environmental risks (Chapter 4.5). Some potential obstacles related to each proposition are also discussed.

We do not touch on carbon pricing not because we think it is not important. On the contrary, we take it as given that higher and more extensive carbon pricing is an essential part of the policy mix going forward, and that it will become both more politically accepted and more economically efficient if the other measures outlined here are implemented.

The five Cs – contribute to coordination to combat climate change:
The "risk", "time horizon" and "system resilience" approaches

Table 3

Responsibilities / **Paradigmatic approach to climate change**	**Measures to be considered[1] by central banks, regulators and supervisors**	**Measures to be implemented by other players[2] (government, private sector, civil society)**
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	– Voluntary disclosure of climate-related risks by the private sector (TCFD) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating ESG into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		

Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – "Green" monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

4.1 Integrating climate-related risks into prudential supervision – insights and challenges

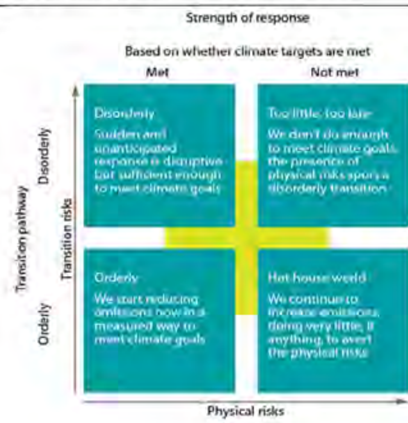
While acknowledging the methodological challenges associated with measuring climate-related risks and the need for alternative approaches (Chapter 3.5), central banks and supervisors should keep pushing for climate-related risks to be integrated into both financial stability monitoring and micro-supervision (NGFS (2019a, p 4)).

The first task, assessing the size of climate-related risks in the financial system, requires developing new analytical tools, for example by integrating climate scenarios into regular stress tests. In the same way that stress tests are conducted by regulatory authorities to assess the resilience of banking institutions in an adverse macro-financial scenario (Borio et al (2014)), proposals have been made over the past years to develop so-called "climate stress-tests" (eg ESRB (2016), Regelink et al (2017), Schoenmaker and Tilburg (2016), UNEP-FI (2019)). Some central banks, regulators and supervisors have already started to consider or develop climate risk scenario analyses for stress tests (Vermeulen et al (2018, 2019), EBA (2019), EIOPA (2019), PRA (2019a), Allen et al (2020)).

In practice, a stress test focusing on the physical risks of climate change (bottom-right scenario in Graph 15), which typically involves projections over several decades, seems particularly difficult to reconcile with the relatively short-term period considered under traditional stress tests (DG Treasury et al (2017, p 19)). In contrast, a climate stress test seems more adapted to manage abrupt transition risks (top-left scenario in Graph 15) that may occur over a relatively short-term horizon compatible with traditional stress tests.

In theory, if climate stress tests find that climate-related risks are material, systemic capital buffers could be applied to mitigate the exposure to climate-related risks (ESRB (2016)). In practice, the main use of these scenarios at this stage is to help financial institutions familiarise themselves with such exercises (Cleary (2019)) and to potentially create catalytic change as well as gaining experience through "learning by doing". A key task for supervisors is to establish a set of reference scenarios that could be used for climate stress tests, while identifying and disclosing the key sources of uncertainty attached to each scenario, as well as leaving flexibility for users to modify the assumptions and parameters of the scenario as deemed appropriate to their national and regional context.

Four representative high-level scenarios for climate stress tests — Graph 15



Source: NGFS (2019a).

The second task for central banks and supervisors consists in ensuring that climate-related risks are well incorporated into individual financial institutions' strategies and risk management procedures. In addition to initiatives based on the voluntary disclosure of climate-related risks such as the Task Force on Climate-related Financial Disclosures (TCFD), it is increasingly accepted that mandatory disclosure should be implemented to strengthen and systematise the integration of climate-related risks. Financial institutions should better understand climate-related risks and consider them in their risk management procedures and investment decisions, as well as in their longer-term strategies (NGFS (2019a)).

Discussions have emerged with regard to how the three pillars of the Basel Framework could integrate climate-related risks:[40]

[40] In the absence of a carbon price, it has also been suggested that the structure of capital of non-financial firms could be adjusted to reflect their exposure to climate-related risks (ESRB (2016), Bolton and Samama (2012)). If both financial institutions and non-financial firms need to align their capital requirements to their exposure to climate-related risks, the cost of capital could increase for non-financial firms and lead financial firms to assess risks differently. However, such an idea would necessitate much more careful analysis and would not necessarily fall under the remit of central banks and supervisors.

- *Pillar 1 on minimum capital requirements:* If being exposed to climate-related risks is seen as part of financial risks, then it might be appropriate to consider capital requirements to reflect such risks. In this respect, proposals have emerged in favour of either a "green supporting factor" (which would reduce capital requirements for banks with lower exposure to climate-related risks) or a "brown penalising factor", which would increase capital requirements for banks with higher exposure to exposed sectors (Thöma and Hilke (2018)). Although additional research is needed, it seems that discussions are evolving towards favouring a "brown penalising factor" as more appropriate. Exposure to "brown" assets can increase financial risks, but it is not obvious why being exposed to "green" sectors would necessarily reduce non-climate-related financial risks, and thereby justify lower capital requirements. In any case, regulations based on distinguishing "green" from "brown" assets require working on an agreed upon "taxonomy", defining which assets can be considered "green" (or "brown" if the goal is to penalise exposure to fossil fuels). China has already established a definition for green loans and the European Commission has tabled a legislative proposal to develop such a taxonomy (NGFS (2019a)). It is noteworthy that such a classification is not exempt from conflicting views over what is "green" (Husson-Traoré (2019)), and that classifications could differ significantly from one country or region to another.[41] Even more fundamentally, it should be recalled that the "greenness" or "brownness" of assets do not necessarily correspond to their vulnerability to climate-related risks. For instance, "green" assets are subject to both transition risks (eg because of the technological and regulatory[42] uncertainty related to the transition) and physical risks (eg a renewable power plant could be impacted by extreme weather events);
- *Pillar 2 on the supervision of institutions' risk management:* Regulators could prescribe additional capital on a case by case basis, *for instance* if a financial institution does not adequately monitor and manage climate-related risks. This would first require new expectations to be set in this regard. For instance, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA (2019b)). And Brazil's central bank requires commercial banks to incorporate environmental risks into their governance framework (FEBRABAN (2014));
- *Pillar 3 on disclosure requirements:* Supervisory authorities can contribute to improving the pricing of climate-related risks and to a more efficient allocation of capital by requiring more systematised disclosure of climate-related risks. As indicated in the NGFS first comprehensive report, "authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues" (NGFS (2019a, p 27)). For this to happen, guidance is needed to ensure a more systematic, consistent and transparent disclosure of climate-related risks. Some regulators and supervisors have already paved the way for such systematic disclosure. Article 173 of the French Law on Energy Transition for Green Growth (*loi relative à la transition énergétique pour la croissance verte,* 2015) requires financial and non-financial firms to disclose the climate-related risks they are exposed to and how they seek to manage them.[43] In doing so, Article 173 encourages financial sector firms to become increasingly aware of how climate change can affect

[41] For instance, "green coal" or nuclear energy are subject to diverging interpretations from one jurisdiction to another. Moreover, the fact that an activity is deemed "green" does not necessarily mean that it is less risky: as discussed in the previous chapter, the uncertainty regarding future technologies is such that some "green" sectors and technologies may not succeed in the transition. It is therefore important to keep in mind that taxonomies cannot replace or be conflated with a climate-related risk analysis, although the two topics are often discussed together.

[42] For instance, renewable energy capacity can be affected by a change in feed-in tariffs. "Feed-in tariff" refers to a policy instrument offering long-term contracts to renewable energy producers (households or businesses).

[43] Paragraph V of Article 173 requires banks to identify and disclose their climate-related risks and tasks the French government with providing guidance on the implementation of a scenario to conduct climate stress tests on a regular basis; paragraph VI requires institutional investors and asset managers to report on the integration of ESG (environmental, social and governance) criteria and climate-related risks into their investment decision processes (DG Treasury et al (2017)).

their risk management processes and supervising authorities to follow these developments closely (ACPR (2019)). And the European Commission has set up a Technical Expert Group (TEG) on sustainable finance that seeks, among other things, to provide guidance on how to improve corporate disclosure of climate-related risks (UNEP-FI (2019)).

Some developing and emerging economies have already started developing climate-related regulations (see D'Orazio and Popoyan (2019)), although no measures on capital requirements have yet been implemented. Different categories of intervention can be found across developing and emerging economies (Dikau and Ryan-Collins (2017)), such as credit guidance (Bezemer et al (2018)), which reflects the often broader mandate of central banks in these countries. For instance, commercial banks and non-bank financial institutions in Bangladesh are required to allocate 5% of their total loan portfolio to green sectors (Dikau and Ryan-Collins (2017)). Other countries such as China and Lebanon have established (or are in the process establishing) differentiated reserve requirements in proportion to local banks' lending to green sectors (D'Orazio and Popoyan (2019)).

The potential impacts of climate-related prudential regulation remain unclear. Most of the proposals discussed above remain subject to accurately assessing climate-related risks, as discussed in Chapter 3. More fundamentally, the role of prudential policy is to mitigate excessive financial risks on the level of individual financial institutions and the financial system as a whole, not to reconfigure the productive structures of the economy (ESRB (2016)); nevertheless, the latter is precisely what is needed to mitigate climate-related risks. The SME Supporting Factor introduced in the European Union in 2014 (reducing capital requirements for loans to small and medium-sized enterprises) does not seem to have generated major changes in bank lending to SMEs (EBA (2016), Mayordomo and Rodríguez-Moreno (2017)), although it demanded far less structural transformation than decarbonising our global economic system. Hence, adopting climate-related prudential regulations such as additional capital buffers may only very partially contribute to hedging financial institutions from "green swan" events.

Perhaps even more problematically, trade-offs could appear between short-term and long-term financial stability in the case of ambitious transition pathways. As stated by Bank of England Governor Mark Carney (Carney (2016)), the "paradox is that success is failure": extremely rapid and ambitious measures may be the most desirable from the point of view of climate change mitigation, but not from the perspective of financial stability over a short-term horizon. Minimising the occurrence of "green swan" events therefore requires a more holistic approach to climate-related risks, as discussed in the rest of this chapter.

4.2 Promoting sustainability as a tool to break the tragedy of the horizon – the role of values

Beyond approaches based strictly on risks, central banks and supervisors can help disseminate the adoption of so-called environmental, social and governance (ESG) standards in the financial sector, especially among pension funds and other asset managers.[44] The definition of ESG criteria and their integration into investment decisions can vary greatly from one institution to another, but it generally involves structuring a portfolio (of loans, bonds, equities, etc) in a way that aims to deliver a blend of financial, social and environmental benefits (Emerson and Freundlich (2012)). ESG-based asset allocation has grown steadily over the past years, and now funds that consider ESG in one form or another total \$30.7 trillion of assets under management.[45]

[44] As stated by the NGFS, central banks and supervisors "may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates" (NGFS (2019a, p 28)).

[45] Estimated by the Global Sustainable Investment Alliance (2019).

Some central banks have also started to lead by example by integrating sustainability factors into their own portfolio management. For instance, the Banque de France and Netherlands Central Bank have adopted a Responsible Investment Charter for the management of own funds as well as pension portfolios, and are in the process of integrating ESG criteria into their asset management. Moreover, central banks are increasingly looking at "green" financial instruments as an additional tool for their foreign exchange (FX) reserve management. In a context of a prolonged period of low returns on the traditional safe assets (eg negative yields on a significant portion of government fixed income instruments), the requirements of liquidity, return and sustainability/safety need to be gauged against the properties of these new instruments. The eligibility of green bonds as a reserve asset will depend on several evolving factors such as their outstanding amount (still relatively small) and their risk-return profile. Fender et al (2019) suggest that the results of an illustrative portfolio construction exercise show that including both green and conventional bonds can help generate diversification benefits and hence improve the risk-adjusted returns of traditional government bond portfolios.

This being said, one should not confuse ESG- or green-tilted portfolios with hedging climate-related risks. As a general matter, ESG and green filters consider the impact of a firm on its environment rather than the potential impacts of climate change on the risk profile of the firm (UNEP-FI (2019)). Moreover, the integration of ESG metrics with pure risk-return considerations is far from straightforward. Some studies find that ESG and socially responsible investment (SRI) can enhance financial performance and/or reduce volatility (eg Friede et al (2015)), while others find that divesting from controversial stocks reduces financial performance (eg Trinks and Scholtens (2017)). Revelli and Viviani's (2015) meta-analysis of 85 papers finds that the consideration of sustainability criteria in stock market portfolios "is neither a weakness nor a strength compared with conventional investments", and that results vary considerably depending on the thematic approach or the investment horizon among other factors.

The main benefit of promoting a sustainable finance approach, including through ESG, may actually not lie in the greater impetus for asset managers to reduce their exposure to climate-related risks, but rather in broadening the set of values driving the financial sector. The financial industry has in recent decades mostly focused on financial risks and returns, and has often been criticised for its increased short-termism. By accepting potentially lower financial returns in the short run to ameliorate longer-term social and environmental results, time can be valued in a manner that better corresponds to environmental systems' "own patterns of time sequences for interactions among parts, abilities to absorb inputs, or produce more resources" (Fullwiler (2015, p 14)). This can promote long-termism in the financial sector and thereby contribute to overcoming the "tragedy of the horizon" (and therefore indirectly reduce climate-related risks). As such, the recent rise in the sustainable finance movement may offer "an opportunity to build a more general theory of finance" (Fullwiler (2015)) that would seek to balance risk-return considerations with longer-term social and environmental outcomes.

An additional ambitious and controversial proposal is to apply climate-related considerations to central banks' collateral framework. The goal of this proposal is not that central banks should step out of their traditional role when implementing monetary policies, but rather to recognise that the current implementation of market neutrality, because of its implicit bias in favour of carbon-intensive industries (Matikainen et al (2017), Jourdan and Kalinowski (2019)) could end up affecting central banks' very own mandates in the medium to long term. Honohan (2019) argues that central banks' independence will be more threatened by staying away from greening their interventions than by carefully paying attention to their secondary mandates such as climate change. Thus, and subject to safeguarding the ability to implement monetary policy, a sustainable tilt in the collateral framework could actually contribute to reducing financial risk, ie it would favour market neutrality over a longer time horizon (van Lerven and Ryan-Collins (2017)).

In this spirit, several proposals and initiatives have started to emerge. For instance, Monnin (2018) relies on a specific climate-related risks methodology to measure how the European Central Bank's corporate sector purchase programme (CSPP, which stood at €176 billion as of November 2018) could have differed from the current model if assessment of climate-related risks had been conducted. The study finds that about 5% of the issuers within the ECB's CSPP portfolio would fall out of the investment grade category if climate-related risks were factored in. The author suggests that the ECB could integrate such procedures not only into its unconventional monetary policies but also into its collateral framework. Following a simpler approach for the management of its FX reserves, the Swedish central bank recently decided to reject issuers with a "large climate footprint" (Flodén (2019)), for instance by selling bonds issued by a Canadian province and two Australian states.

Although legal opinions have yet to be issued on this matter, it appears that in many cases central banks already do have a legal mandate for considering the type of assets to use as collateral when implementing monetary policy. For instance, in the case of the Eurosystem the primary responsibility of central banks is to maintain price stability, with a secondary responsibility to support economic growth. In turn, the definition of economic growth by the European Union includes the sustainable development of Europe (Schoenmaker (2019)). The mandates of several central banks other than the ECB also include broader socioeconomic goals than price stability (Dikau and Volz (2019)).

However, the potential impact of such actions is still under debate and needs a cautious approach. It is true that a reweighting of eligible collateral towards low-carbon assets is likely to reduce the credit spread of newly eligible companies (Mésonnier et al (2017)) and to provide a powerful signalling effect to other financial market participants (Braun (2018), Schoenmaker (2019)). Nevertheless, the main challenge in the short run with regard to climate change is not the cost of credit of green projects but their insufficient number in the first place. It is therefore not entirely obvious how large an effect the greening of central banks' collateral framework could have. In fact, the ECB has already bought almost one quarter of the eligible public sector green bonds and one fifth of the eligible corporate green bonds (Cœuré (2018)). This may have already encouraged more issuers to sell green debt (Stubbington and Arnold (2019)), yet central bank monetary operations are clearly insufficient and do not even seek to trigger structural changes in the "real economy". Even if central bank actions could lead to downgrading of the price of carbon-intensive assets that are not compatible with a low-carbon trajectory, only climate policy can ensure that they simply disappear.

Governments could play a much more critical role in supporting sustainable investments. In this respect, it is noteworthy that the European Commission's (2018) action plan on sustainable finance also seeks to mainstream sustainability into investment decisions, and promote "long termism" among financial institutions. Many measures could be taken in this regard. For instance, the French Economic, Social and Environmental Council (ESEC (2019)) recommends that household savings should be channelled towards long-term sustainable investments through fiscal incentives (see also Aussilloux and Espagne (2017)). And Lepetit et al (2019) further recommend offering a public guarantee on all household savings channelled to long-term SRI vehicles (and certified as such). Therefore, even if investments in a low-carbon economy were to provide lower returns and/or returns over a longer time horizon than current market expectations (Grandjean and Martini (2016)), those could then be partially offset by a lower risk for households.

4.3 Coordinating prudential regulation and monetary policy with fiscal policy – Green New Deal and beyond

In addition to promoting sustainable investments, direct government expenditures will also be an opportunity to develop new technologies in a timely fashion and to regulate their use in ways that guarantee lower-carbon production and consumption patterns (eg by avoiding rebound effects in the transportation sector, as discussed above). This is not a reason for central banks not to address climate change; rather, it is a simple observation of the fact that fiscal policies are key to climate change mitigation and that prudential and monetary tools can only complement these policies (Krogstrup and Oman (2019)). Indeed, the public sector is usually in a better position to fund investments in R&D for early-stage technologies with uncertain and long-term returns. In a series of case studies across different sectors (eg nanotech and biotech), Mazzucato (2015) has shown how government investment in high-risk projects has proved essential to create the conditions for private investments to follow.

Sustainable public infrastructure investments are also fundamental as they lock in carbon emissions for a long time (Arezki et al (2016), Krogstrup and Oman (2019)). They can provide alternative means of production and consumption, which would then enable economic agents to change their behaviour more effectively in response to a carbon price (Fay et al (2015), Krogstrup and Oman (2019)). Indeed, carbon prices alone may not suffice to shift individual behaviour and firms' replacement of physical capital towards low-carbon alternatives until infrastructures suited for alternative energies are in place. For instance, building an efficient public transit system may be a precondition to effective taxation of individual car use in urban areas.

It is noteworthy that under this approach, government action would not seek to manage climate-related risks optimally but rather to steer markets "in broadly the right direction" (Ryan-Collins (2019)). In turn, such a proactive shift in policymaking could lead market players to reassess the risks related to climate change. Public investments in the low-carbon transition could "become the next big technological and market opportunity, stimulating and leading private and public investment" (Mazzucato and Perez (2015)), and potentially create millions of jobs that could compensate for those that might be lost due to the changes in labour markets caused by technological progress (Pereira da Silva (2019a)).

In spite of a rapidly growing literature pointing towards better coordination between fiscal, monetary and prudential regulation, arguments regarding the optimal climate policy mix remain scarce. However, and as a general matter, fiscal tools are critical to accelerate the transition, whereas prudential and monetary tools can mostly support and complement them (Krogstrup and Oman (2019)). Public banks may also have an important role to play in providing a significant part of the long-term funding needed for the transition (Aglietta and Espagne (2016), Campiglio (2016), Marois and Güngen (2019)). In this regard, the European Investment Bank (EIB (2019)) announcement that it will cease financing fossil fuel energy projects by the end of 2021 could be a major landmark.

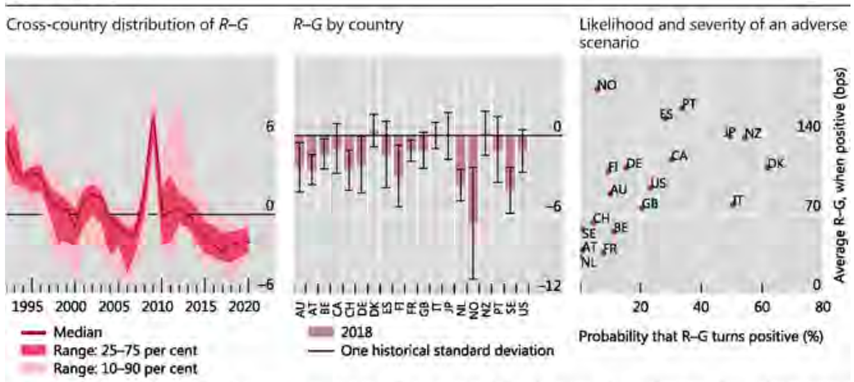
The key question that has arisen with regard to fiscal policy is that of how governments could fund such investments, and what kind of policy mix this could entail. Revisiting the nature of the interactions between fiscal and monetary policy (and prudential regulation) is precisely what has been suggested by some proponents of a Green New Deal in the United States (eg Kelton (2019), Macquarie (2019)), which partly relies on Modern Monetary Theory (MMT), also known as Neo-Chartalism. One key argument of MMT is that currency is a public monopoly for any government, as long as it issues debts in its own currency and maintains floating exchange rates. Following that reasoning, the sovereign could use money creation to achieve full employment (or a climate-related objective) by a straightforward financing of economic activity. The obvious risk of inflation can be addressed subsequently by raising taxes and issuing bonds as the policy goes to remove excess liquidity from the system. A government that by definition issues its own money cannot be forced to default on debt denominated in its own currency. The major underlying assumption is therefore that of "seigniorage without limits": governments can incur deficit spending "without" limits other than those imposed by biophysical scarcity, without automatically generating inflation (Wray (2012)). MMT scholars are generally considered to be outliers in the broader post-Keynesian school, and some of their claims related to the unlimited spending power of governments have been criticised by other post-Keynesian or closely related authors (Lavoie (2013), Palley (2019)). Some of them have suggested more traditional green countercyclical fiscal and monetary policy instead (Harris (2013), Jackson (2017)). Other commentators have pointed out (Summers (2019a), Krugman (since 2011, but more recently 2019)), that MMT poses significant problems. It would undermine the complex set of institutional and contractual arrangements that have maintained price and financial stability in our societies. Moreover, numerous experiments in the history of hyperinflation in advanced economies and mostly in developing countries show that, while outright default in a country's own central bank currency might be avoided, the value of domestic assets including money could be reduced to almost zero.

From a very different perspective, and without sharing the conceptual premises of MMT, several economists have recently argued that financing the low-carbon transition with public debt is both politically more feasible than through carbon taxation and economically more sustainable in the current low interest rate environment, which provides several countries with a larger than previously anticipated fiscal room for manoeuvre (Bernanke (2017), Borio and Song Shin (2019), DeLong and Summers (2012), Blanchard (2019), Summers (2019b)). McCulley and Pozsar (2013) suggest that what matters in times of crisis is not monetary stimulus per se but whether monetary policy helps the fiscal authority maintain stimulus. In this respect, the fact that central banks in advanced economies are globally setting interest rates near or even below zero at a time where massive investments are needed is probably the greatest contribution from central banks to governments' capability to play their role in combating climate change.

As zero or negative interest rates may remain in place for a long period (Turner (2019)), financing the transition to a low-carbon economy via government debt presents fewer risks and would not threaten the mandate of central banks, as long as private and public debt growth continues to be closely monitored and regulated (Adrian and Natalucci (2019)) and there is fiscal space. When it is measured by the cost of servicing debt (*R*) minus the output growth (*G*) rate or (*R* – *G*) to assess the sustainability of debt-to-GDP, there is room in many advanced economies. Over the last 25 years there has been a secular downward trend in government funding costs relative to nominal growth. Graph 16 shows that the difference between government effective funding costs and nominal growth became negative for the median advanced economy around 2013 (left-hand panel) and has since then gone deeper and deeper into negative territory. And, according to the most recent data available (2018), almost all advanced economies now pay an effective interest cost of debt that is below their nominal GDP growth rate. In particular, lower funding costs for the government mean that previously accumulated debts will be cheaper to refinance than previously expected. That is, lower government funding costs mean that the primary balance required to stabilise public debt as a ratio of GDP also falls, down to the point where governments could even run primary deficits while keeping public debt (as a share of GDP) constant.

Government interest burden and snapback risk

In percentage points | Graph 16



Using current government yields. AU = Australia; AT = Austria; BE = Belgium; CA = Canada; CH = Switzerland; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GB = United Kingdom; IT = Italy; JP = Japan; NL = Netherlands; NO = Norway; NZ = New Zealand; PT = Portugal; SE = Sweden; US = United States.

Sources: OECD, *Economic Outlook*; BIS calculations.

Combating climate change and financing the set of policies with public debt could perhaps be the way out of the existing conundrum for policymakers in advanced economies (Pereira da Silva (2019b)): low unemployment coexisting with low inflation for a prolonged period of time despite low interest rates. Reigniting growth through investment in low-carbon technologies is most probably more sustainable from a macroeconomic and environmental perspective than any of the previous consumption-led and household debt-based recoveries (Pereira da Silva (2016)). Some of the investments that could foster productivity in the long run include long overdue infrastructure spending, including in projects that are necessary to develop a low-carbon economy. For example, this type of fiscal stimulus may help create the necessary new science/technology/engineering/maths (STEM) jobs in new green industries, services and infrastructure. These jobs might be able to compensate for the jobs that are very likely to be significantly curtailed by technological progress in the new digital economy. Finally, where fiscal space is available, financing the transition to a lower-carbon economy with public debt could build greater social consensus for eventually accepting carbon taxation.

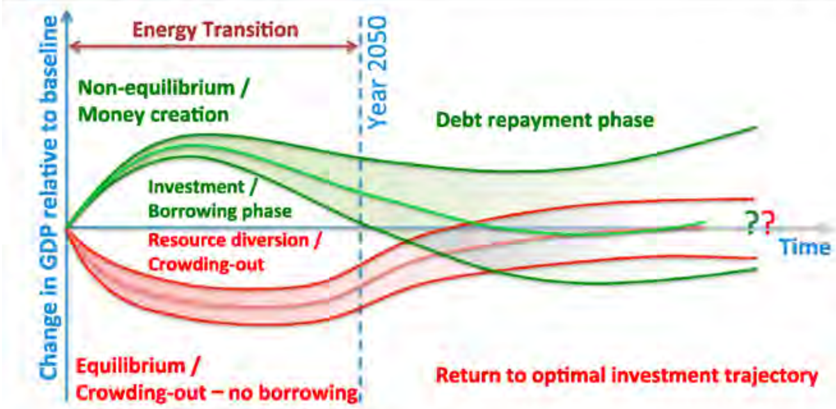
All this should not lead us to consider that there is a "silver bullet" and that the transition to a low-carbon economy can – under current financial circumstances – be easily funded through fiscal policy, as if we had a "free lunch". There could be a risk of a yield snapback. But there are other issues too. In particular, most of the literature calling for fiscal policy action assumes in a more or less explicit manner that it will have a positive impact on economic growth, employment and environmental outcomes, without paying attention to potential technical and institutional limitations and trade-offs between those goals. For instance, the strong reliance of a low-carbon economy on labour-intensive activities may strengthen the "Baumol's cost disease" effect and contribute to slowing down productivity and economic growth (Jackson (2017)). Moreover, the slowdown in productivity gains could be structural (Gordon (2012), Cette et al (2016)) and it is far from clear how the low-carbon transition will reverse it: most of the low-carbon investments needed in advanced economies aim to replace business-as-usual (more carbon-intensive) expected investments, without necessarily creating the conditions for a new boost in productivity. Some have gone further by casting doubt on whether it is even technically possible to decouple economic growth from environmental harm, including but not limited to CO_2 emissions (Jackson (2017), Hickel (2019), Macquarie (2019), OECD (2019b), Parrique et al (2019)).

These potential limitations, in turn, pose major questions for macroeconomic theory, such as estimating the size of the investment multiplier in a low-carbon transition. For instance, an improvement in energy efficiency could lead to a sharp decline in the supply side investments needed for the transition (Grubler et al (2018), in IPCC (2018)), and the latter could paradoxically lead (all other things being equal) to a decrease in GDP, especially if we rely on models where energy plays a critical and non-substitutable role in production (See Box 5 in Chapter 3.5). With this in mind, arguing that public investments will naturally crowd in private investments seems to rely on optimistic (or at least uncertain) assumptions regarding the nature of the transition. Moreover, a "crowding in" effect could paradoxically lead to undesirable (and still poorly accounted for) rebound effects (eg Gillingham et al (2016), Ruzzenenti et al (2019)): savings related to energy efficiency improvements can lead to an increase in the consumption of other fossil-intensive goods and services. In fact, assumptions about crowding out (in supply-led equilibrium models) or crowding in (in demand-led non-equilibrium models) may both (Graph 17) fail to discuss the specific technological, institutional and behavioural assumptions that specific transition paths entail.

These considerations suggest that the low-carbon transition consists in much more than just an investment plan, and that the socio-technical transition needed involves broader considerations than an optimal policy mix, including other ways of measuring system resilience and performance in the context of a low-carbon transition (Fath et al (2015), Ripple et al (2019), Svartzman et al (2019), UNEP (2019)). Without aiming for exhaustiveness, we discuss two of these broader considerations next: potential reforms of the international monetary and financial system in the light of climate considerations and the integration of sustainability into corporate and national accounting.

Impacts of the energy transition on GDP in non-equilibrium (demand-led) vs equilibrium (supply-led) models

Graph 17



Source: Mercure et al (2019).

4.4 Calling for international monetary and financial cooperation

Climate stability is a global public good, which raises difficult questions regarding international policy coordination and burden-sharing between countries at different stages of economic development. Unfair or poorly coordinated international action may simply incentivise some countries to free-ride (Krogstrup and Obstfeld (2018)). Achieving a smooth transition where all countries do their fair share means that a significant compensation mechanism must be agreed upon between developed and developing and emerging economies. As mentioned earlier, these economies need to see that their support for action combating climate change takes into account their stage of industrialisation.

Thus, climate change mitigation actions need to be built on international cooperation between advanced and developing countries (Villeroy de Galhau (2019b)) and recognition of the need for technology transfers and increases in official development assistance to developing countries. So far, developed countries have committed to jointly mobilise $100 billion per year by 2020 for climate action in developing countries (UNFCCC (2015)). But will this commitment be honoured, as current pledges are still far from this amount (OECD (2019c))? And will they suffice to trigger the massive investments needed in developing economies? If not, what are the implications and likely repercussions?

A sober assessment of international cooperation is that there has been uneven progress so far in mitigating climate change. On the one hand, collective action and stated commitments have flourished in multilateral conferences and internationally agreed commitments such as the Paris Agreement (UNFCCC (2015)). For instance, the recently created Coalition of Finance Ministers for Climate Action and the signing of the "Helsinki Principles"[46] could become a critical platform to articulate the need for fiscal policy and the use of public with prudential and monetary action and international coordination. The creation of the Network for Greening the Financial System (NGFS) is another success of such cooperation, possibly in the

[46] See www.cape4financeministry.org/coalition_of_finance_ministers.

very spirit of Bretton Woods (Villeroy de Galhau (2019c)). On the other hand, recent global debates have been dominated by a reaction against multilateralism (BIS (2017)). This mindset obviously does not help in combating climate change and delays collective action on the real problems. For instance, although coal, oil and gas are the central drivers of climate change, they are rarely the subject of ad hoc international climate policy and negotiations (SEI et al (2019)).

Inspiration for overcoming these limitations can be found in the literature on the commons and more precisely in Elinor Ostrom's (1990, 2010) principles for the governance of Common Pool Resources (CPRs). CPRs are "systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others" (Ostrom (2002)). In this sense, the remaining stock of carbon that can be used while still having a fair chance of remaining below 1.5°C or 2°C can be considered as a CPR: burning fossil fuels in one place decreases the carbon budget available to others. One of Ostrom's key insights was to show that the over-exploitation of CPRs is due not so much to the lack of property rights, as often believed (Hardin (1968)), as to the lack of an adequate governance regime regulating the use of CPRs.

Building on Ostrom's insights, which are increasingly being adopted in both the climate and economic communities,[47] central banks along with other stakeholders could implement a governance regime based on CPRs by: (i) further identifying the risks to these resources (eg over-exploitation of the carbon budget); (ii) finding actions that reduce climate-related risks at the global and local levels; and (iii) monitoring these arrangements through the design and enforcement of rules for system stability. This implies coordination, local participation, some sense of fairness in burden-sharing, incentives and penalties, among others.

Given the difficulty of managing global commons (Ostrom et al (1999)), one concrete way of moving towards such a global joint governance of climate and financial stability would be to set up a new international agency (Bolton et al (2018)) that would play a role on two levels with: (i) a financial support mechanism between countries in case of severe climate events; and (ii) supervision of the climate policies being put in place. The theoretical justification of such an agency lies in the fact that, similarly to the creation of an international institutional framework after World War II to face the major global challenges of the time (such as postwar reconstruction), there is now a need for ad hoc institutions to tackle the new global challenges posed by climate change. In a similar spirit, Rogoff (2019) calls for the creation of a World Carbon Bank, which would constitute a vehicle for advanced economies to coordinate aid and technical transfers to developing countries.

Rather than creating new ad hoc institutions, other proposals have focused on embedding climate concerns within existing international institutions such as the International Monetary Fund (IMF), as part of their responsibilities to manage the international monetary and financial system. In particular, proposals have been made to issue "green" Special Drawing Rights (SDRs) through the IMF to finance green funds (Aglietta and Coudert (2019), Bredenkamp and Pattillo (2010), Ferron and Morel (2014), Ocampo (2019)). For instance, Aglietta and Coudert (2019, p 9) suggest creating "Trust Funds in which unused SDRs could be invested to finance the guaranteed low-carbon investment program. A more ambitious method consists of SDR loans to national and international public development banks being pledged to finance the national intentions of carbon emission reductions under the Paris Agreement".[48] Scaling up these "commons-based" mechanisms may require a major overhaul of the global governance system; yet they could become essential to build a "green" and multilateral financial system capable of channelling savings from all parts of the world to finance the low-carbon transition (Aglietta and Coudert (2019), Aglietta and Espagne (2018)).

[47] The third part of the IPCC (2014) report was dedicated to Elinor Ostrom, who was also awarded the Nobel Memorial Prize in Economic Sciences in 2009.

[48] A prerequisite to such a system would be for the IMF to take on the role of a "green" international lender of last resort, by issuing SDRs in exchange for excess reserves held by central banks and governments.

4.5 Integrating sustainability into corporate and national accounting frameworks

Beyond mechanisms aimed at financing the low-carbon transition, the severity of climate and other environmental crises has led a flourishing stream of research to reconsider how to account for economic value in an age of increasing ecological degradation. In particular, accounting standards at the corporate and national levels have increasingly been criticised for their incapacity to value the role of natural capital in supporting economic activity (see Costanza et al (1997)).

The concept of natural capital refers to "the stock of natural ecosystems on Earth including air, land, soil, biodiversity and geological resources … (which) underpins our economy and society by producing value for people, both directly and indirectly" (Natural Capital Coalition[49]). In turn, this stock of natural ecosystems provides a flow of services, called ecosystem services. These consist of provisioning, regulating, cultural and supporting services (Graph 18). For instance, a forest is a component of natural capital; the associated timber (provisioning service), climate regulation (regulating service) and touristic activities (cultural service) are examples of the ecosystem services it provides; and the forest nutrient cycle is a supporting service that enables all of the above.

Ecosystem services – an overview Graph 18

Source: Millennium Ecosystem Assessment (2005).

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Natural capital and ecosystem services are essential to economic activity in many forms and their degradation (eg soil erosion due to climate change) can have a major impact on human and produced capital (UN Environment (2018)). Important efforts and new frameworks have emerged in the past few years to integrate natural capital into accounting standards at the corporate level and into national accounts, as respectively outlined below.

With regard to corporate accounting, some suggest that a key step in getting companies to achieve a better trade-off between their financial objectives and their environmental and social impact is to transform corporate accounting, ie how companies report their performance to investors (de Cambourg (2019), Rambaud and Richard (2015)). A first encouraging development is the more systematic reporting of carbon emissions by companies under the standardised greenhouse gas protocol.[50] Another

[49] See www.naturalcapitalcoalition.org.

[50] See ghgprotocol.org/.

encouraging development is the creation of the Task Force on Climate-related Financial Disclosures (TCFD), which (as discussed above) seeks to coordinate and standardise reporting of company exposures to climate-related risks so as to allow investors to better manage their exposures to these risks. A third encouraging development is the rise of the integrated reporting movement (see Eccles et al (2015), UN Environment (2018)), which seeks to expand standardised accounting statements to include both financial and non-financial performance in a single integrated annual report. A particularly important initiative in this respect is the creation of the Sustainability Accounting Standards Board (SASB),[51] which already proposes standards for the reporting of non-financial ESG metrics.

In order to systematise integrated reporting approaches, regulatory action will be needed to induce or compel companies to systematically report their environmental and social performance according to industry-specific reporting standards. Few examples exist but some exceptions can be found, eg in the case of Article 173 of the French Law on Energy Transition for Green Growth (discussed above) and the recent support from French public authorities for the development of environmental and social reporting (de Cambourg (2019)). More debate will also be needed to streamline the reporting requirements. For instance, a specific question concerns whether natural capital should remain confined to extra-financial considerations or lead to changes in existing accounting norms, such as in the CARE/TDL model (see Rambaud (2015)).

Nevertheless, there is still a long way to go, as the fiduciary duties of CEOs and asset managers must be redefined and firms' non-financial performance metrics put on par with accounting measures of financial performance. An internationally coordinated effort to encourage the adoption of these standards would significantly accelerate the transition towards integrated reporting and/or new ways of accounting for natural capital. Such efforts would benefit central banks and supervisors as standardised accounting measures can allow investors to make relative comparisons across companies' respective exposure to environmental and social risks.

With regard to the integration of natural capital into national accounts, one of the main arguments put forward has to do with the fact that GDP accounts for only a portion of a country's economic performance. It provides no indication of the wealth and resources that support this income. For example, when a country exploits its forests, wood resources are identified in national accounts but other forest-related services, such as the loss in carbon sequestration and air filtration, are completely ignored. Several steps have been made towards better integration of natural capital into national accounts. The Inclusive Wealth Report (UN Environment (2018)) evaluates the capacities and performance of the national economies around the world, based on the acknowledgment that existing statistical systems are geared to measure flows of income and largely miss the fact that these depend upon the health and resilience of capital assets like natural capital. The World Bank Group has also spearheaded a partnership to advance the accounting of natural wealth and ecosystem services.[52]

Better accounting systems for natural capital are necessary to internalise climate externalities, but it should be recognised that the concepts of natural capital and ecosystem services are difficult to define precisely. For instance, pricing and payment mechanisms for ecosystem services can hardly account for the inherent complexity of any given ecosystem (eg all the services provided by a forest) and often lead to trade-offs by valuing a subset of services only, sometimes to the detriment of others (Muradian and Rival (2012)). They can also fail to provide the desired incentives if they are not designed in ways that recognise the complexity of socio-ecological systems (Muradian et al (2013)) and the need to strengthen cooperation in governing the local and global commons (Ostrom (1990, 2010), Ostrom et al (1999)). Hence, rather than envisaging it as an easy solution, accounting for natural capital and its related ecosystem services should constitute but one among a diverse set of potential solutions (Muradian et al (2013)).

[51] See www.sasb.org/.

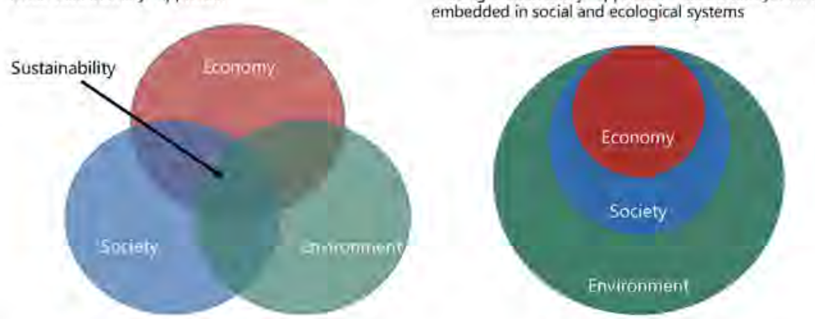
[52] See www.wavespartnership.org/.

Another significant limitation of the concept of natural capital has to do with the common assumption that it is substitutable for other forms of capital (Barker and Mayer (2017)). According to this assumption, what matters is that capital as a whole increase, not which components make up the increase. If, for example, an increase in manufactured capital (eg machines and roads) exceeds the depletion of natural capital, then the conclusion would be that society is better off. This view has been coined the "weak sustainability" approach. In contrast, proponents of an alternative "strong sustainability" argue that the existing stocks of natural capital and the flow of ecosystem services they provide must be maintained because their loss cannot be compensated by an increase in manufactured or human capital (Daly and Farley (2011)). For instance, the depletion of natural capital in a warming world cannot be compensated by higher income. In this view, the economy is embedded in social and biophysical systems (Graph 19, right-hand panel); it is not a separate entity as the traditional approach to sustainable development is framed (Graph 19, left-hand panel).

Two approaches to sustainability | Graph 19

"Weak sustainability" approach

"Strong sustainability" approach – economic system is embedded in social and ecological systems



Source: Authors' elaboration.

Instead of seeking to "internalise" external costs in order to correct market failures, proponents of the "strong sustainability" approach, including ecological economists, suggest "a more fundamental explanation" (OECD (2019b, p 13)) of the dependence of economic systems upon the maintenance of life support ecosystem services (such as climate regulation). Bringing the economic system back within Earth's "sustainability limits" therefore involves much more than marginal changes in the pricing and accounting systems, and could entail re-evaluating the notion of endless economic growth itself (Georgescu-Roegen (1971), Martinez-Alier (1987), Daly and Farley (2011), Jackson (2017), Spash (2017)). Rethinking macroeconomic and financial systems in the light of these considerations is still an underdeveloped area of research in most of the economic discipline, although great progress has been achieved in recent times towards mainstreaming this question (eg OECD (2019b)).

New approaches will be needed in the process of mainstreaming these questions (see Annex 4). In particular, the development of systems analysis has been identified as a promising area of research that should inform economic policies in the search for fair and resilient socio-ecological systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). In contrast to risk management, a system resilience approach "accepts that transitions to new phases are part of its nature and the system will not return to some previous equilibrium. New normals are normal" (OECD (2019a, p 3)). Greater focus on institutional and evolutionary approaches and on political economy considerations may also be needed

(Gowdy and Erickson (2005), Vatn (2007)), as overcoming the roadblocks to sustainability can be seen as requiring an evolutionary redesign of worldviews, institutions and technologies (Beddoe et al (2009)).

Notwithstanding these important limitations, the ways in which accounting norms incorporate (or not) environmental dimensions remains critical: accounting norms reflect broader worldviews of what is valued in a society (Jourdain (2019)), at both the microeconomic and macroeconomic level. From a financial stability perspective, it therefore remains critical to integrate biophysical indicators into existing accounting frameworks to ensure that policymakers and firm managers systematically include them in their risk management practices over different time horizons.

5. CONCLUSION – CENTRAL BANKING AND SYSTEM RESILIENCE

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of socioeconomic systems. The potential economic implications of physical and transition risks related to climate change have been debated for decades (not without methodological challenges), yet the financial implications of climate change have been largely ignored.

Over the past few years, central banks, regulators and supervisors have increasingly recognised that climate change is a source of major systemic financial risks. In the absence of well coordinated and ambitious climate policies, there has been a growing awareness of the materiality of physical and transition risks that would affect the stability of the financial sector. Pursuing the current trends could leave central banks in the position of "climate rescuers of last resort", which would become untenable given that there is little that monetary and financial flows can do against the irreversible impacts of climate change. In other words, a new global financial crisis triggered by climate change would render central banks and financial supervisors powerless.

Integrating climate-related risks into prudential regulation and identifying and measuring these risks is not an easy task. Traditional risk management relying on the extrapolation of historical data, despite its relevance for other questions related to financial stability, cannot be used to identify and manage climate-related risks given the deep uncertainty involved. Indeed, climate-related risks present many distinctive features. Physical risks are subject to nonlinearity and uncertainty not only because of climate patterns, but also because of socioeconomic patterns that are triggered by climate ones. Transition risks require including intertwined complex collective action problems and addressing well known political economy considerations at the global and local levels. Transdisciplinary approaches are needed to capture the multiple dimensions (eg geopolitical, cultural, technological and regulatory ones) that should be mobilised to guarantee the transition to a low-carbon socio-technical system.

These features call for an epistemological break (Bachelard (1938)) with regard to financial regulation, ie a redefinition of the problem at stake when it comes to identifying and addressing climate-related risks. Some of this break is already taking place, as financial institutions and supervisors increasingly rely on scenario-based analysis and forward-looking approaches rather than probabilistic ones to assess climate-related risks. This is perhaps compounding a new awareness that is beginning to produce a repricing of climate-related risks. That, in turn, can contribute to tilting preferences towards lower-carbon projects and might therefore act, to some extent, as a "shadow price" for carbon emissions.

While welcoming this development and strongly supporting the need to fill methodological, taxonomy and data gaps, the essential step of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of a scenario regarding how technologies, policies, behaviours, geopolitical dynamics, macroeconomic variables and climate patterns will interact in the future, especially given the limitations of climate-economic models.

(ii) The translation of such scenarios into granular corporate metrics in an evolving environment where all firms and value chains will be affected in unpredictable ways.

(iii) The task of matching the identification of a climate-related risk with the adequate mitigation action.

In short, the development and improvement of forward-looking risk assessment and climate-related regulation will be essential, but they will not suffice to preserve financial stability in the age of climate change: the deep uncertainty involved and the need for structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers. A corollary is that the integration of climate-related risks into prudential regulation and (to the extent possible) into monetary policy would not suffice to trigger a shift capable of hedging the whole system again against green swan events.

Because of these limitations, climate change risk management policy could drag central banks into uncharted waters: on the one hand, they cannot simply sit still until other branches of government jump into action; on the other, the precedent of unconventional monetary policies of the past decade (following the 2007–08 Great Financial Crisis), may put strong sociopolitical pressure on central banks to take on new roles like addressing climate change. Such calls are excessive and unfair to the extent that the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are necessary to achieve a global low-carbon transition. But these calls might be voiced regardless, precisely because of the procrastination that has been the dominant modus operandi of many governments for quite a while. The prime responsibility for ensuring a successful low-carbon transition rests with other branches of government, and insufficient action on their part puts central banks at risk of no longer being able to deliver on their mandates of financial (and price) stability.

To address this latter problem, a second epistemological break is needed. There is also a role for central banks to be more proactive in calling for broader change. In this spirit, and grounded in the transdisciplinary approach that is required to address climate change, this book calls for actions beyond central banks that are essential to guarantee financial (and price) stability.

Central banks can also play a role as advocates of broader socioeconomic changes without which their current policies and the maintenance of financial stability will have limited chances of success. Towards this objective, we have identified four (non-exhaustive) propositions beyond carbon pricing:

(i) Central banks can help proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance.

(ii) Central banks can call for an increased role for fiscal policy in support of the ecological transition, especially at the zero lower bound.

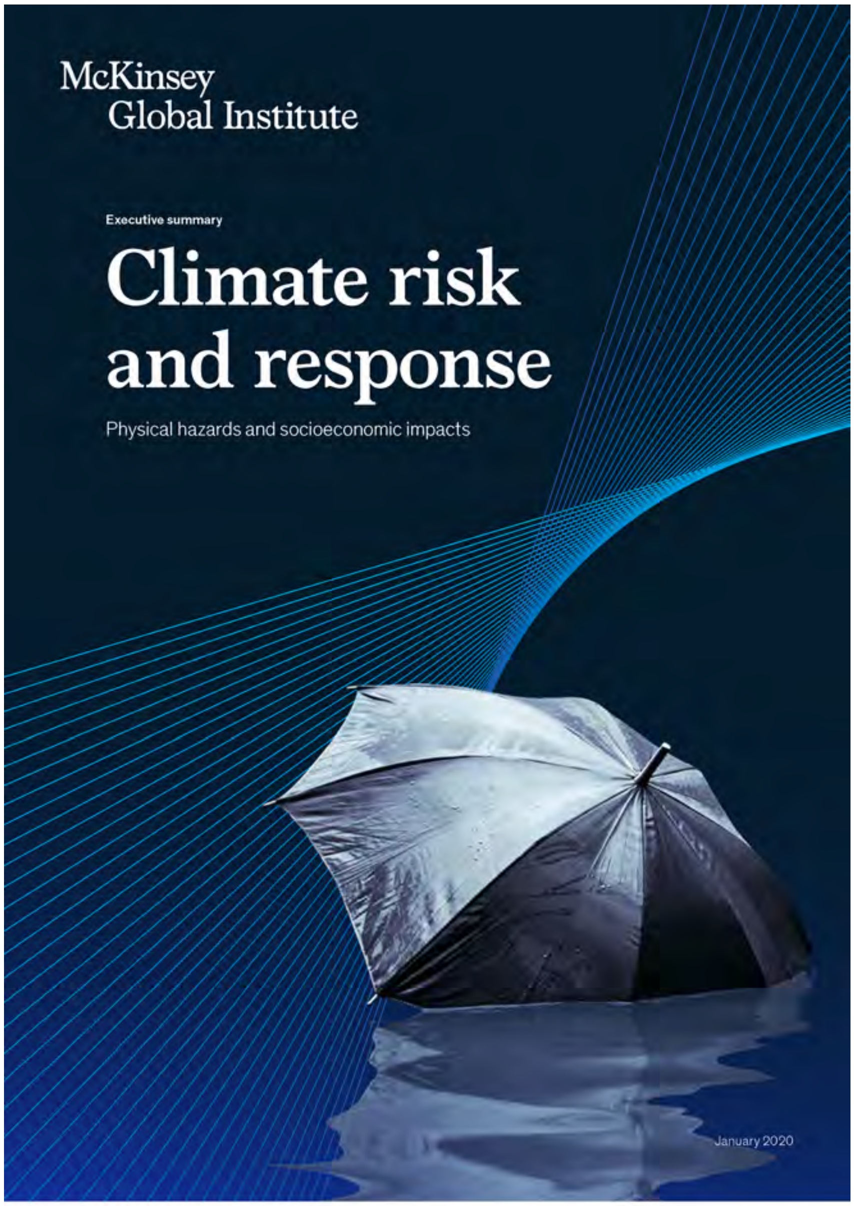
(iii) Central banks can increase cooperation on ecological issues among international monetary and financial authorities.

(iv) Central banks can support initiatives promoting greater integration of climate and sustainability dimensions within corporate and national accounting frameworks.

Financial and climate stability are two increasingly interdependent public goods. But, as we enter the Anthropocene (Annex 4), long-term sustainability extends to other human-caused environmental degradations such as biodiversity loss, which could pose new types of financial risks (Schellekens and van Toor (2019)). Alas, it may be even more difficult to address these ecological challenges. For instance, preserving biodiversity (often ranked second in terms of environmental challenges) is a much more complex problem from a financial stability perspective, among other things because it relies on multiple local indicators despite being a global problem (Chenet (2019b)).

The potential ramifications of these environmental risks for financial stability are far beyond the scope of this book. Yet, addressing them could become critical for central banks, regulators and supervisors insofar as the stability of the Earth system is a prerequisite for financial and price stability. In particular, the development of systems analysis has been identified as a promising area of research that should inform economic and financial policies in the search for fair and resilient complex adaptive systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). Future research based on institutional, evolutionary and political economy approaches may also prove fundamental to address financial stability in the age of climate- and environment-related risks.

Faced with these daunting challenges, a key contribution of central banks and supervisors may simply be to adequately frame the debate. In particular, they can play this role by: (i) providing a scientifically uncompromising picture of the risks ahead, assuming a limited substitutability between natural capital and other forms of capital; (ii) calling for bolder actions from public and private sectors aimed at preserving the resilience of Earth's complex socio-ecological systems; and (iii) contributing, to the extent possible and within the remit of the evolving mandates provided by society, to managing these risks.


McKinsey
Global Institute
Executive summary
Climate risk and response
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January 2020

McKinsey Global Institute

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Climate risk and response

Physical hazards and socioeconomic impacts

January 2020

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Preface

McKinsey has long focused on issues of environmental sustainability, dating to client studies in the early 1970s. We developed our global greenhouse gas abatement cost curve in 2007, updated it in 2009, and have since conducted national abatement studies in countries including Brazil, China, Germany, India, Russia, Sweden, the United Kingdom, and the United States. Recent publications include *Shaping climate-resilient development: A framework for decision-making* (jointly released with the Economics of Climate Adaptation Working Group in 2009), *Towards the Circular Economy* (joint publication with Ellen MacArthur Foundation in 2013), *An integrated perspective on the future of mobility* (2016), and *Decarbonization of industrial sectors: The next frontier* (2018). The McKinsey Global Institute has likewise published reports on sustainability topics including *Resource revolution: Meeting the world's energy, materials, food, and water needs* (2011) and *Beyond the supercycle: How technology is reshaping resources* (2017).

In this report, we look at the physical effects of our changing climate. We explore risks today and over the next three decades and examine cases to understand the mechanisms through which physical climate change leads to increased socioeconomic risk. We also estimate the probabilities and magnitude of potential impacts. Our aim is to help inform decision makers around the world so that they can better assess, adapt to, and mitigate the physical risks of climate change.

This report is the product of a yearlong, cross-disciplinary research effort at McKinsey & Company, led by MGI together with McKinsey's Sustainability Practice and McKinsey's Risk Practice. The research was led by Jonathan Woetzel, an MGI director based in Shanghai, and Mekala Krishnan, an MGI senior fellow in Boston, together with McKinsey senior partners Dickon Pinner in San Francisco and Hamid Samandari in New York, partner Hauke Engel in Frankfurt, and associate partner Brodie Boland in Washington, DC. The project team was led by Tilman Melzer, Andrey Mironenko, and Claudia Kampel and consisted of Vassily Carantino, Peter Cooper, Peter De Ford, Jessica Dharmasiri, Jakob Graabak, Ulrike Grassinger, Zealan Hoover, Sebastian Kahlert, Dhiraj Kumar, Hannah Murdoch, Karin Östgren, Jemima Peppel, Pauline Pfuderer, Carter Powis, Byron Ruby, Sarah Sargent, Erik Schilling, Anna Stanley, Marlies Vasmel, and Johanna von der Leyen. Brian Cooperman, Eduardo Doryan, Jose Maria Quiros, Vivien Singer, and Sulay Solis provided modeling, analytics, and data support. Michael Birshan, David Fine, Lutz Goedde, Cindy Levy, James Manyika, Scott Nyquist, Vivek Pandit, Daniel Pacthod, Matt Rogers, Sven Smit, and Thomas Vahlenkamp provided critical input and considerable expertise.

While McKinsey employs many scientists, including climate scientists, we are not a climate research institution. Woods Hole Research Center (WHRC) produced the scientific analyses of physical climate hazards in this report. WHRC has been focused on climate science research since 1985; its scientists are widely published in major scientific journals, testify to lawmakers around the world, and are regularly sourced in major media outlets. Methodological design and results were independently reviewed by senior scientists at the University of Oxford's Environmental Change Institute to ensure impartiality and test the scientific foundation for the new analyses in this report. Final design choices and interpretation of climate hazard results were made by WHRC. In addition, WHRC scientists produced maps and data visualization for the report.

We would like to thank our academic advisers, who challenged our thinking and added new insights: Dr. Richard N. Cooper, Maurits C. Boas Professor of International Economics at Harvard University; Dr. Cameron Hepburn, director of the Economics of Sustainability

Programme and professor of environmental economics at the Smith School of Enterprise and the Environment at Oxford University; and Hans-Helmut Kotz, Program Director, SAFE Policy Center, Goethe University Frankfurt, and Resident Fellow, Center for European Studies at Harvard University.

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As with all MGI research, this work is independent, reflects our own views, and has not been commissioned by any business, government, or other institution. We welcome your comments on the research at MGI@mckinsey.com.

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In brief

Climate risk and response: Physical hazards and socioeconomic impacts

After more than 10,000 years of relative stability—the full span of human civilization—the Earth's climate is changing. As average temperatures rise, acute hazards such as heat waves and floods grow in frequency and severity, and chronic hazards, such as drought and rising sea levels, intensify. Here we focus on understanding the nature and extent of physical risk from a changing climate over the next three decades, exploring physical risk as it is the basis of both transition and liability risks. We estimate inherent physical risk, absent adaptation and mitigation, to assess the magnitude of the challenge and highlight the case for action. Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. We link climate models with economic projections to examine nine cases that illustrate exposure to climate change extremes and proximity to physical thresholds. A separate geospatial assessment examines six indicators to assess potential socioeconomic impact in 105 countries. The research also provides decision makers with a new framework and methodology to estimate risks in their own specific context. Key findings:

Climate change is already having substantial physical impacts at a local level in regions across the world; the affected regions will continue to grow in number and size. Since the 1880s, the average global temperature has risen by about 1.1 degrees Celsius with significant regional variations. This brings higher probabilities of extreme temperatures and an intensification of hazards. A changing climate in the next decade, and probably beyond, means the number and size of regions affected by substantial physical impacts will continue to grow. This will have direct effects on five socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

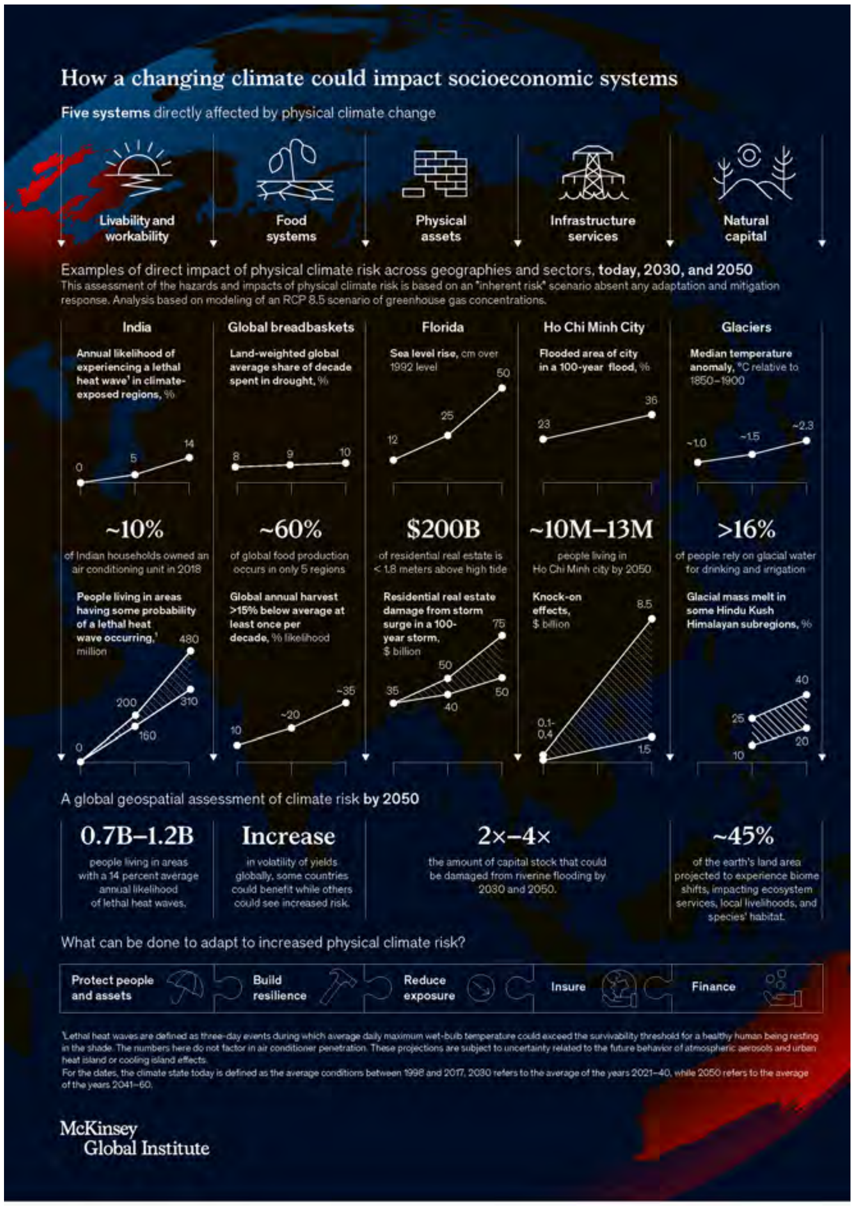
The socioeconomic impacts of climate change will likely be nonlinear as system thresholds are breached and have knock-on effects. Most of the past increase in direct impact from hazards has come from greater exposure to hazards versus increases in their mean and tail intensity. In the future, hazard intensification will likely assume a greater role. Societies and systems most at risk are close to physical and biological thresholds. For example, as heat and humidity increase in India, by 2030 under an RCP 8.5 scenario, between 160 million and 200 million people could live in regions with an average 5 percent annual probability of experiencing a heat wave that exceeds the survivability threshold for a healthy human being, absent an adaptation response. Ocean warming could reduce fish catches, affecting the livelihoods of 650 million to 800 million people who rely on fishing revenue. In Ho Chi Minh City, direct infrastructure damage from a 100-year flood could rise from about $200 million to $300 million today to $500 million to $1 billion by 2050, while knock-on costs could rise from $100 million to $400 million to between $1.5 billion and $8.5 billion.

The global socioeconomic impacts of climate change could be substantial as a changing climate affects human beings, as well as physical and natural capital. By 2030, all 105 countries examined could experience an increase in at least one of the six indicators of socioeconomic impact we identify. By 2050, under an RCP 8.5 scenario, the number of people living in areas with a non-zero chance of lethal heat waves would rise from zero today to between 700 million and 1.2 billion (not factoring in air conditioner penetration). The average share of annual outdoor working hours lost due to extreme heat and humidity in exposed regions globally would increase from 10 percent today to 15 to 20 percent by 2050. The land area experiencing a shift in climate classification compared with 1901–25 would increase from about 25 percent today to roughly 45 percent.

Financial markets could bring forward risk recognition in affected regions, with consequences for capital allocation and insurance. Greater understanding of climate risk could make long-duration borrowing unavailable, impact insurance cost and availability, and reduce terminal values. This could trigger capital reallocation and asset repricing. In Florida, for example, estimates based on past trends suggest that losses from flooding could devalue exposed homes by $30 billion to $80 billion, or about 15 to 35 percent, by 2050, all else being equal.

Countries and regions with lower per capita GDP levels are generally more at risk. Poorer regions often have climates that are closer to physical thresholds. They rely more on outdoor work and natural capital and have less financial means to adapt quickly. Climate change could also benefit some countries; for example, crop yields could improve in Canada.

Addressing physical climate risk will require more systematic risk management, accelerating adaptation, and decarbonization. Decision makers will need to translate climate science insights into potential physical and financial damages, through systematic risk management and robust modeling recognizing the limitations of past data. Adaptation can help manage risks, even though this could prove costly for affected regions and entail hard choices. Preparations for adaptation—whether seawalls, cooling shelters, or drought-resistant crops—will need collective attention, particularly about where to invest versus retreat. While adaptation is now urgent and there are many adaptation opportunities, climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.


How a changing climate could impact socioeconomic systems
Five systems directly affected by physical climate change
Livability and workability
Food systems
Physical assets
Infrastructure services
Natural capital
Examples of direct impact of physical climate risk across geographies and sectors, today, 2030, and 2050
This assessment of the hazards and impacts of physical climate risk is based on an "inherent risk" scenario absent any adaptation and mitigation response. Analysis based on modeling of an RCP 8.5 scenario of greenhouse gas concentrations.
India
Annual likelihood of experiencing a lethal heat wave[1] in climate-exposed regions, %
0
5
14
~10%
of Indian households owned an air conditioning unit in 2018
People living in areas having some probability of a lethal heat wave occurring,[1] million
0
200
160
480
310
Global breadbaskets
Land-weighted global average share of decade spent in drought, %
8
9
10
~60%
of global food production occurs in only 5 regions
Global annual harvest >15% below average at least once per decade, % likelihood
10
~20
~35
Florida
Sea level rise, cm over 1992 level
12
25
50
$200B
of residential real estate is < 1.8 meters above high tide
Residential real estate damage from storm surge in a 100-year storm, $ billion
35
50
40
75
50
Ho Chi Minh City
Flooded area of city in a 100-year flood, %
23
36
~10M–13M
people living in Ho Chi Minh city by 2050
Knock-on effects, $ billion
0.1-0.4
8.5
1.5
Glaciers
Median temperature anomaly, °C relative to 1850–1900
~1.0
~1.5
~2.3
>16%
of people rely on glacial water for drinking and irrigation
Glacial mass melt in some Hindu Kush Himalayan subregions, %
10
25
40
20
A global geospatial assessment of climate risk by 2050
0.7B–1.2B
people living in areas with a 14 percent average annual likelihood of lethal heat waves.
Increase
in volatility of yields globally, some countries could benefit while others could see increased risk.
2×–4×
the amount of capital stock that could be damaged from riverine flooding by 2030 and 2050.
~45%
of the earth's land area projected to experience biome shifts, impacting ecosystem services, local livelihoods, and species' habitat.
What can be done to adapt to increased physical climate risk?
Protect people and assets
Build resilience
Reduce exposure
Insure
Finance
[1]Lethal heat waves are defined as three-day events during which average daily maximum wet-bulb temperature could exceed the survivability threshold for a healthy human being resting in the shade. The numbers here do not factor in air conditioner penetration. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
For the dates, the climate state today is defined as the average conditions between 1998 and 2017, 2030 refers to the average of the years 2021–40, while 2050 refers to the average of the years 2041–60.
McKinsey Global Institute

Coping with rising temperatures in Singapore.
© Getty Images

Executive summary

McKinsey has a long history of research on topics related to the economics of climate change. Over the past decade, we have published a variety of research including a cost curve illustrating feasible approaches to abatement and reports on understanding the economics of adaptation and identifying the potential to improve resource productivity.[1] This research builds on that work and focuses on understanding the nature and implications of physical climate risk in the next three decades.

We draw on climate model forecasts to showcase how the climate has changed and could continue to change, how a changing climate creates new risks and uncertainties, and what steps can be taken to best manage them. Climate impact research makes extensive use of scenarios. Four "Representative Concentration Pathways" (RCPs) act as standardized inputs to climate models. They outline different atmospheric greenhouse gas concentration trajectories between 2005 and 2100. During their inception, RCPs were designed to collectively sample the range of then-probable future emission pathways, ranging from lower (RCP2.6) to higher (RCP 8.5) CO_2 concentrations. Each RCP was created by an independent modeling team and there is no consistent design of the socio-economic parameter assumptions used in the derivation of the RCPs. By 2100, the four RCPs lead to very different levels of warming, but the divergence is moderate out to 2050 and small to 2030. Since the research in this report is most concerned with understanding inherent physical risks, we have chosen to focus on the higher-emission scenario, i.e. RCP 8.5, because of the higher-emissions, lower-mitigation scenario it portrays, in order to assess physical risk in absence of further decarbonization (Exhibit E1).

We focus on physical risk—that is, the risks arising from the physical effects of climate change, including the potential effects on people, communities, natural and physical capital, and economic activity, and the implications for companies, governments, financial institutions, and individuals. Physical risk is the fundamental driver of other climate risk types—transition risk and liability risk.[2] We do not focus on transition risks, that is, impacts from decarbonization, or liability risks associated with climate change. While an understanding of decarbonization and the risk and opportunities it creates is a critical topic, this report contributes by exploring the nature and costs of ongoing climate change in the next one to three decades in the absence of decarbonization.

[1] See, for example, *Shaping climate-resilient development: A framework for decision-making*, Economics of Climate Adaptation, 2009; "Mapping the benefits of the circular economy," *McKinsey Quarterly*, June 2017; *Resource revolution: Meeting the world's energy, materials, food, and water needs*, McKinsey Global Institute, November 2011; and *Beyond the supercycle: How technology is reshaping resources*, McKinsey Global Institute, February 2017. For details of the abatement cost curves, see *Greenhouse gas abatement cost curves*, McKinsey.com.

[2] Transition risk can be defined as risks arising from transition to a low-carbon economy; liability risk as risks arising from those affected by climate change seeking compensation for losses. See *Climate change: What are the risks to financial stability?* Bank of England, KnowledgeBank.

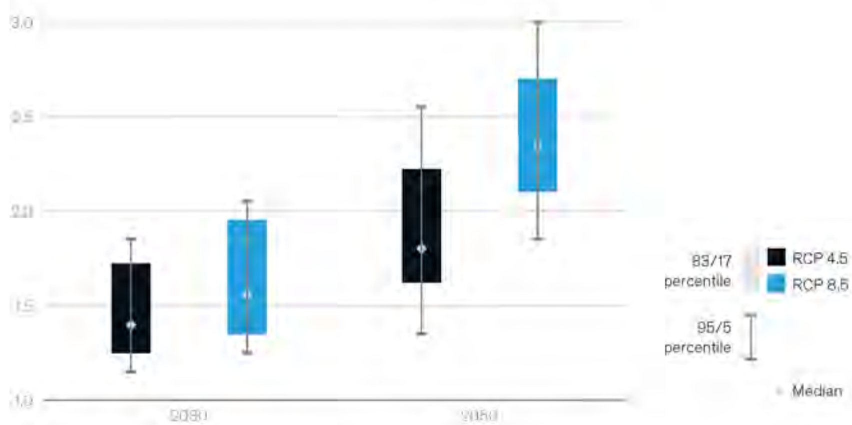
Our work offers both a call to action and a set of tools and methodologies to help assess the socioeconomic risks posed by climate change. We assess the socioeconomic risk from "acute" hazards, which are one-off events like floods or hurricanes, as well as from "chronic" hazards, which are long-term shifts in climate parameters like temperature.[1] We look at two periods: between now and 2030 and from 2030 to 2050. In doing so, we have relied on climate hazard data from climate scientists and focused on establishing socioeconomic impact, given potential changes in climate hazards (see Box E1, "Our research methodology"). We develop a methodology to measure the risk from the changing climate and the uncertainties associated with these estimates (see Box E2, "How our methodology addresses uncertainties"). At the end of this executive summary, we highlight questions for stakeholders seeking to respond to the challenge of heightened physical climate risk (see Box E3, "Questions for individual stakeholders to consider").

Exhibit E1

We make use of RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization.

Global average land and sea surface temperature anomaly relative to 1850–1900 average

°C



Note: For clarity of graph, outliers beyond 95th to 5th percentile are not shown. This chart shows two [illegible]

Source: Intergovernmental Panel on Climate Change; [illegible]

[1] By hazards, we mean climate-induced physical phenomena that have the potential to impact natural and socioeconomic systems.

Box E1

Our research methodology

In this report, we measure the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. While many scientists, including climate scientists, are employed at McKinsey & Company, we are not a climate modeling institution. Our focus in this report has been on translating the climate science data into an assessment of physical risk and its implications for stakeholders. Most of the climatological analysis performed for this report was done by Woods Hole Research Center (WHRC), and in other instances, we relied on publicly available climate science data, for example from institutions like the World Resources Institute. WHRC's work draws on the most widely used and thoroughly peer-reviewed ensemble of climate models to estimate the probabilities of relevant climate events occurring. Here, we highlight key methodological choices:

Case studies

In order to link physical climate risk to socioeconomic impact, we investigate nine specific cases that illustrate exposure to climate change extremes and proximity to physical thresholds. These cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of MGI research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We find these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds. As such, these cases represent leading-edge examples of climate change risk. They show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Global geospatial analysis

In a separate analysis, we use geospatial data to provide a perspective on climate change across 105 countries over the next 30 years. This geospatial analysis relies on the same five-systems framework of direct impacts that we used for the case studies. For each of these systems, we identify a measure, or measures, of the impact of climate change, using indicators where possible as identified in our cases.

Similar to the approach discussed above for our cases, our analyses are conducted at a grid-cell level, overlaying data on a hazard (for example, floods of different depths, with their associated likelihoods), with exposure to that hazard (for example, capital stock exposed to flooding), and a damage function that assesses resilience (for example, what share of capital stock is damaged when exposed to floods of different depth). We then combine these grid-cell values to country and global numbers. While the goal of this analysis is to measure direct impact, due to data availability issues, we have used five measures of socioeconomic impact and one measure of climate hazards themselves—drought. Our set of 105 countries represents 90 percent of the world's population and 90 percent of global GDP. While we seek to include a wide range of risks and as many countries as possible, there are some we could not cover due to data limitations (for example, the impact of forest fires and storm surges).

What this report does not do

Since the purpose of this report is to understand the physical risks and disruptive impacts of climate change, there are many areas which we do not address.

— We do not assess the efficacy of climate models but instead draw on best practice approaches from climate science literature and highlight key uncertainties.

— We do not examine in detail areas and sectors that are likely to benefit from climate change such as the potential for improved agricultural yields in parts of Canada, although we quantify some of these benefits through our geospatial analysis.

— As the consequences of physical risk are realized, there will likely be acts of adaptation, with a feedback effect on the physical risk. For each of our cases, we identify adaptation responses. We have not conducted a detailed bottom-up cost-benefit analysis of adaptation but have built on existing literature and expert interviews to understand the most important measures and their indicative cost, effectiveness, and implementation challenges, and to estimate the expected global adaptation spending required.

— We note the critical importance of decarbonization in a climate risk management approach but a detailed discussion of decarbonization is beyond the scope of this report.

— While we attempt to draw out qualitatively (and, to the extent possible, quantitatively) the knock-on effects from direct physical impacts of climate change, we recognize the limitations of this exercise given the complexity of socioeconomic systems. There are likely knock-on effects that could occur which our analysis has not taken into account. For this reason, we do not attempt to size the global GDP at risk from climate change (see Box 4 in Chapter 4 for a detailed discussion).

— We do not provide projections or deterministic forecasts, but rather assess risk. The climate is the statistical summary of weather patterns over time and is therefore probabilistic in nature. Following standard practice, our findings are therefore framed as "statistically expected values"—the statistically expected average impact across a range of probabilities of higher or lower climate outcomes.[1]

[1] We also report the value of "tail risks"—that is, low-probability, high-impact events like a 1-in-100-year storm—on both an annual and cumulative basis. Consider, for example, a flooding event that has a 1 percent annual likelihood of occurrence every year (often described as a "100-year flood"). In the course of the lifetime of home ownership—for example, over a 30-year period—the cumulative likelihood that the home will experience at least one 100-year flood is 26 percent.

Box E2

How our methodology addresses uncertainties

One of the main challenges in understanding the physical risk arising from climate change is the range of uncertainties involved. Risks arise as a result of an involved causal chain. Emissions influence both global climate and regional climate variations, which in turn influence the risk of specific climate hazards (such as droughts and sea-level rise), which then influence the risk of physical damage (such as crop shortages and infrastructure damages), which finally influence the risk of financial harm. Our analysis, like any such effort, relies on assumptions made along the causal chain: about emission paths and adaptation schemes; global and regional climate models; physical damage functions; and knock-on effects. The further one goes along the chain, the greater the intrinsic model uncertainty.

Taking a risk-management lens, we have developed a methodology to provide decision makers with an outlook over the next three decades on the inherent risk of climate change—that is, risk absent any adaptation and mitigation response. Separately, we outline how this risk could be reduced via an adaptation response in our case studies. Where feasible, we have attempted to size the costs of the potential adaptation responses. We believe this approach is appropriate to help stakeholders understand the potential magnitude of the impacts from climate change and the commensurate response required.

The key uncertainties include the emissions pathway and pace of warming, climate model accuracy and natural variability, the magnitude of direct and indirect socioeconomic impacts, and the socioeconomic response. Assessing these uncertainties, we find that our approach likely results in conservative estimates of inherent risk because of the skew in uncertainties of many hazard projections toward "worse" outcomes as well as challenges with modeling the many potential knock-on effects associated with direct physical risk.[1]

Emissions pathway and pace of warming

As noted above, we have chosen to focus on the RCP 8.5 scenario because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Under this scenario, science tells us that global average temperatures will reach just over 2 degrees Celsius above preindustrial levels by 2050. However, action to reduce emissions could mean that the projected outcomes—both hazards and impacts—based on this trajectory are delayed post 2050. For example, RCP 8.5 predicts global average warming of 2.3 degrees Celsius by 2050, compared with 1.8 degrees Celsius for RCP 4.5. Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080.

Climate model accuracy and natural variability

We have drawn on climate science that provides sufficiently robust results, especially over a 30-year period. To minimize the uncertainty associated with any particular climate model, the mean or median projection (depending on the specific variable being modeled) from an ensemble of climate models has been used, as is standard practice in the climate literature. We also note that climate model uncertainty on global temperature increases tends to skew toward worse outcomes; that is, differences across climate models tend to predict outcomes that are skewed toward warmer rather than cooler global temperatures. In addition, the climate models used here omit potentially important biotic feedbacks including greenhouse gas emissions from thawing permafrost, which will tend to increase warming.

[1] See Naomi Oreskes and Nicholas Stern, "Climate change will cost us even more than we think," *New York Times*, October 23, 2019.

To apply global climate models to regional analysis, we used techniques established in climate literature.[2] The remaining uncertainty related to physical change is variability resulting from mechanisms of natural rather than human origin. This natural climate variability, which arises primarily from multiyear patterns in ocean and/or atmosphere circulation (for example, the El Niño/La Niña oscillation), can temporarily affect global or regional temperature, precipitation, and other climatic variables. Natural variability introduces uncertainty surrounding how hazards could evolve because it can temporarily accelerate or delay the manifestation of statistical climate shifts.[3] This uncertainty will be particularly important over the next decade, during which overall climatic shifts relative to today may be smaller in magnitude than an acceleration or delay in warming due to natural variability.

Direct and indirect socioeconomic impacts

Our findings related to socioeconomic impact of a given physical climate effect involve uncertainty, and we have provided conservative estimates. For direct impacts, we have relied on publicly available vulnerability assessments, but they may not accurately represent the vulnerability of a specific asset or location. For indirect impacts, given the complexity of socioeconomic systems, we know that our results do not capture the full impact of climate change knock-on effects. In many cases, we have either discussed knock-on effects in a qualitative manner alone or relied on empirical estimations. This may underestimate the direct impacts of climate change's inherent risk in our cases, for example the knock-on effects of flooding in Ho Chi Minh City or the potential for financial devaluation in Florida real estate. This is not an issue in our 105-country geospatial analysis, as the impacts we are looking at there are direct and as such we have relied on publicly available vulnerability assessments as available at a regional or country level.

Socioeconomic response

The amount of risk that manifests also depends on the response to the risk. Adaptation measures such as hardening physical infrastructure, relocating people and assets, and ensuring backup capacity, among others, can help manage the impact of climate hazards and reduce risk. We follow an approach that first assesses the inherent risk and then considers a potential adaptation response. The inherent or ex ante level of risk is the risk without taking any steps to reduce its likelihood or severity. We have not conducted a detailed bottom-up cost-benefit analysis of adaptation measures but have built on existing literature and expert interviews to understand the most important measures and their indicative cost, effectiveness, and implementation challenges in each of our cases, and to estimate the expected global adaptation spending required. While we note the critical importance of decarbonization in an appropriate climate risk management approach, a detailed discussion of decarbonization is beyond the scope of this report.

How decision makers incorporate these uncertainties into their management choices will depend on their risk appetite and overall risk-management approach. Some may want to work with the outcome considered most likely (which is what we generally considered), while others may want to consider a worse- or even worst-case scenario. Given the complexities we have outlined above, we recognize that more research is needed in this critical field. However, we believe that despite the many uncertainties associated with estimates of impact from a changing climate, it is possible for the science and socioeconomic analysis to provide actionable insights for decision makers. For an in-depth discussion of the main uncertainties and how we have sought to resolve them, see Chapter 1.

[2] See technical appendix for details.
[3] Kyle L. Swanson, George Sugihara, and Anastasios A. Tsonis, "Long-term natural variability and 20th century climate change," *Proceedings of the National Academy of Sciences*, September 2009, Volume 106, Number 38.

We find that risk from climate change is already present and growing. The insights from our cases help highlight the nature of this risk, and therefore how stakeholders should think about assessing and managing it. Seven characteristics stand out. Physical climate risk is:

- **Increasing.** In each of our nine cases, the level of physical climate risk increases by 2030 and further by 2050. Across our cases, we find increases in socioeconomic impact of between roughly two and 20 times by 2050 versus today's levels. We also find physical climate risks are generally increasing across our global country analysis even as some countries find some benefits (such as increased agricultural yields in Canada, Russia, and parts of northern Europe).

- **Spatial.** Climate hazards manifest locally. The direct impacts of physical climate risk thus need to be understood in the context of a geographically defined area. There are variations between countries and also within countries.

- **Non-stationary.** As the Earth continues to warm, physical climate risk is ever-changing or non-stationary. Climate models and basic physics predict that further warming is "locked in" over the next decade due to inertia in the geophysical system, and that the temperature will likely continue to increase for decades to come due to socio-technological inertia in reducing emissions.[4] Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions. Furthermore, given the thermal inertia of the earth system, some amount of warming will also likely occur after net-zero emissions are reached.[5] Managing that risk will thus require not moving to a "new normal" but preparing for a world of constant change. Financial markets, companies, governments, or individuals have mostly not had to address being in an environment of constant change before, and decision making based on experience may no longer be reliable. For example, engineering parameters for infrastructure design in certain locations will need to be re-thought, and home owners may need to adjust assumptions about taking on long-term mortgages in certain geographies.

- **Nonlinear.** Socioeconomic impacts are likely to propagate in a nonlinear way as hazards reach thresholds beyond which the affected physiological, human-made, or ecological systems work less well or break down and stop working altogether. This is because such systems have evolved or been optimized over time for historical climates. Consider, for example, buildings designed to withstand floods of a certain depth, or crops grown in regions with a specific climate. While adaptation in theory can be carried out at a fairly rapid rate for some systems (for example, improving the floodproofing of a factory), the current rate of warming—which is at least an order of magnitude faster than any found in the past 65 million years of paleoclimate records—means that natural systems such as crops are unable to evolve fast enough to keep pace.[6] Impacts could be significant if system thresholds are breached even by small amounts. The occurrence of multiple risk factors (for example, exposure to multiple hazards, other vulnerabilities like the ability to finance adaptation investments, or high reliance on a sector that is exposed to climate hazard) in a single geography, something we see in several of our cases, is a further source of potential nonlinearity.

- **Systemic.** While the direct impact from climate change is local, it can have knock-on effects across regions and sectors, through interconnected socioeconomic and financial systems. For example, flooding in Florida could not only damage housing but also raise insurance costs, affect property values of exposed homes, and in turn reduce property tax revenues

[4] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1.
[5] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; H. Damon Matthews & Ken Caldeira, "Stabilizing climate requires near zero emissions". *Geophysical Research Letters* February 2008, Volume 35; Myles Allen et al, *"Warming caused by cumulative carbon emissions towards the trillionth ton."* Nature, April 2009, Volume 485.
[6] Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science*, August 2013, Volume 341, Number 6145; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," Proceedings of the National Academy of Sciences, March 2014, Volume 111, Number 9.

for communities. Like physical systems, many economic and financial systems have been designed in a manner that could make them vulnerable to a changing climate. For example, global production systems like supply chains or food production systems have optimized efficiency over resiliency, which makes them vulnerable to failure if critical production hubs are impacted by intensifying hazards. Insurance systems are designed so that property insurance is re-priced annually; however, home owners often have longer-term time horizons of 30 years or more on their real estate investments. As a result of this duration mismatch, home owners could be exposed to the risk of higher costs, in the form of rising premiums (which could be appropriate to reflect rising risks), or impacts on the availability of insurance. Similarly, debt levels in many places are also at thresholds, so knock-on effects on relatively illiquid financial instruments like municipal bonds should also be considered.

— **Regressive.** The poorest communities and populations within each of our cases typically are the most vulnerable. Across all 105 countries in our analysis, we find an increase in at least one of six indicators of socioeconomic impact by 2030. Emerging economies face the biggest increase in potential impact on workability and livability. Poorer countries also rely more on outdoor work and natural capital and have less financial means to adapt quickly. Climate change can bring benefits as well as costs to specific areas, for example shifting tourism from southern to northern Europe.

— **Under-prepared.** While companies and communities have been adapting to reduce climate risk, the pace and scale of adaptation are likely to need to significantly increase to manage rising levels of physical climate risk. Adaptation is likely to entail rising costs and tough choices that may include whether to invest in hardening or relocate people and assets. It thus requires coordinated action across multiple stakeholders.

Climate change is already having substantial physical impacts at a local level; these impacts are likely to grow, intensify, and multiply

Earth's climate is changing, and further change is unavoidable in the next decade and in all likelihood beyond. The planet's temperature has risen by about 1.1 degrees Celsius on average since the 1880s.[7] This has been confirmed by both satellite measurements and by the analysis of hundreds of thousands of independent weather station observations from across the globe. The rapid decline in the planet's surface ice cover provides further evidence. This rate of warming is at least an order of magnitude faster than any found in the past 65 million years of paleoclimate records.[8]

The average conceals more dramatic changes at the extremes. In statistical terms, distributions of temperature are shifting to the right (towards warmer) and broadening. That means the average day in many locations is now hotter ("shifting means"), and extremely hot days are becoming more likely ("fattening tails"). For example, the evolution of the distribution of observed average summer temperatures for each 100-by-100-kilometer square in the Northern Hemisphere shows that the mean summer temperature has increased over time (Exhibit E2). The percentage of the Northern Hemisphere (in square kilometers) that experiences a substantially hotter summer—a two-standard-deviation warmer average temperature in a given year—has increased more than 15 times, from less than 1 percent to 15 percent. The share of the Northern Hemisphere (in square kilometers) that experiences an extremely hot summer—three-standard-deviation hotter average temperature in a given summer—has increased from zero to half a percent.

Averages also conceal wide spatial disparities. Over the same period that the Earth globally has warmed by 1.1 degrees, in southern parts of Africa and in the Arctic, average temperatures

7 NASA GISTEMP (2019) and Nathan J. L. Lenssen et al., "Improvements in the GISTEMP uncertainty model," *Journal of Geophysical Resources: Atmospheres*, June 2019, Volume 124, Number 12.

8 Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science*, August 2013, Volume 341, Number 6145; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," *Proceedings of the National Academy of Sciences*, March 2014, Volume 111, Number 9.

have risen by 0.2 and 0.5 degrees Celsius and by 4 to 4.3 degrees Celsius, respectively.[7] In general, the land surface has warmed faster than the 1.1-degree global average, and the oceans, which have a higher heat capacity, have warmed less.

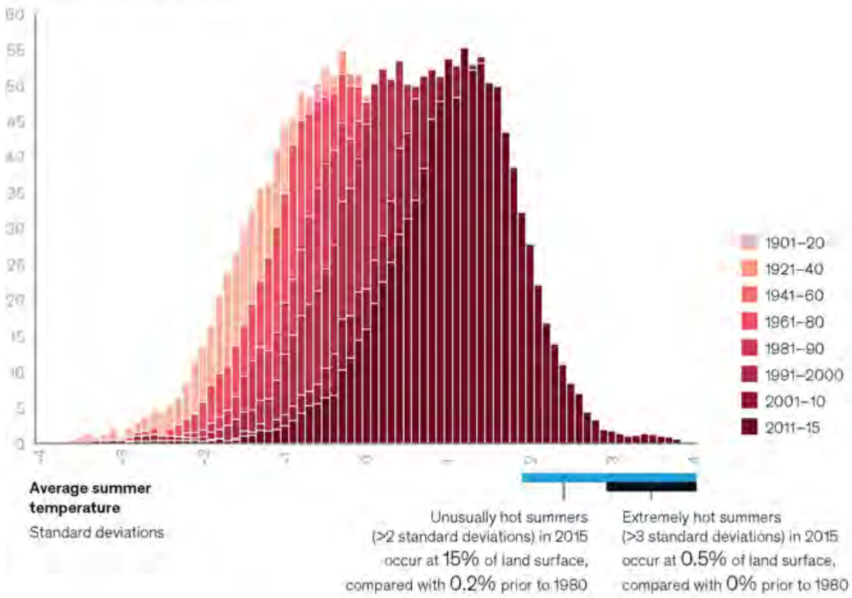
Looking forward, further change is unavoidable over the next decade at least, and in all likelihood beyond. The primary driver of the observed rate of temperature increase over the past two centuries is the human-caused rise in atmospheric levels of carbon dioxide (CO_2) and other greenhouse gases, including methane and nitrous oxide.[8] Since the beginning of the Industrial Revolution in the mid-18th century, humans have released nearly 2.5 trillion tonnes of CO_2 into the atmosphere, raising atmospheric CO_2 concentrations from about 280 parts per million by volume (ppmv) to 415 ppmv, increasing at more than 2 ppmv per year.

Exhibit E2

A small shift in the average can hide dramatic changes at the extremes.

Frequency of local temperature anomalies in the Northern Hemisphere

Number of observations, thousands



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7 Goddard Institute for Space Studies (GISS), GISTEMP Reanalysis dataset (2019).

8 Between 98 and 100 percent of observed warming since 1850 is attributable to the rise in atmospheric greenhouse gas concentrations, and approximately 75 percent is attributable to CO_2 directly. The remaining warming is caused by short-lived greenhouse gases like methane and black carbon, which, because they decay in the atmosphere, warm the planet as a function of rate (or flow) of emissions, not cumulative stock of emissions. Karsten Haustein et al., "A real-time Global Warming Index," *Nature Scientific Reports*, November 13, 2017; Richard J. Millar and Pierre Friedlingstein, "The utility of the historical record for assessing the transient climate response to cumulative emissions," *Philosophical Transactions of the Royal Society*, May 2018, Volume 376, Number 2119.

Carbon dioxide persists in the atmosphere for hundreds of years.[11] As a result, in the absence of large-scale human action to remove CO_2 from the atmosphere, nearly all of the warming that occurs will be permanent on societally relevant timescales.[12] Additionally, because of the strong thermal inertia of the ocean, more warming is likely already locked in over the next decade, regardless of emissions pathway. Beyond 2030, climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.[13]

With increases in global average temperatures, climate models indicate a rise in climate hazards globally. According to climate science, further warming will continue to increase the frequency and/or severity of acute climate hazards across the world, such as lethal heat waves, extreme precipitation, and hurricanes, and will further intensify chronic hazards such as drought, heat stress, and rising sea levels.[14] Here, we describe the prediction of climate models analyzed by WHRC, and also publicly available data for a selection of hazards for an RCP 8.5 scenario (Exhibits E3 and E4):

— **Increase in average temperatures.**[15] Global average temperatures are expected to increase over the next three decades, resulting in a 2.3-degree Celsius (+0.5/-0.3) average increase relative to the preindustrial period by 2050, under an RCP 8.5 scenario. Depending on the exact location, this can translate to an average local temperature increase of between 1.5 and 5.0 degrees Celsius relative to today. The Arctic in particular is expected to warm more rapidly than elsewhere.

— **Extreme precipitation.**[16] In parts of the world, extreme precipitation events, defined here as one that was a once in a 50-year event (that is, with a 2 percent annual likelihood) in the 1950–81 period, are expected to become more common. The likelihood of extreme precipitation events is expected to grow more than fourfold in some regions, including parts of China, Central Africa, and the east coast of North America compared with the period 1950–81.

— **Hurricanes.**[17] While climate change is seen as unlikely to alter the frequency of tropical hurricanes, climate models and basic physical theory predict an increase in the average severity of those storms (and thus an increase in the frequency of severe hurricanes). The likelihood of severe hurricane precipitation—that is, an event with a 1 percent likelihood annually in the 1981–2000 period—is expected to double in some parts of the southeastern United States and triple in some parts of Southeast Asia by 2040. Both are densely populated areas with large and globally connected economic activity.

— **Drought.**[18] As the Earth warms, the spatial extent and share of time spent in drought is projected to increase. The share of a decade spent in drought conditions is projected to be up to 80 percent in some parts of the world by 2050, notably in parts of the Mediterranean, southern Africa, and Central and South America.

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[11] David Archer. *"Fate of Fossil Fuel CO_2 in geological time."* Journal of Geophysical Research, March 2005, Volume 110.

[12] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1. David Archer. *"Fate of Fossil Fuel CO_2 in geological time."* Journal of Geophysical Research, March 2005, Volume 110; H. Damon Matthews & Susan Solomon. *"Irreversible does not mean unavoidable."* Science. April 2013, Volume 340, Issue 6131.

[13] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1; H. Damon Matthews & Ken Caldeira, "Stabilizing climate requires near zero emissions". *Geophysical Research Letters* February 2008, Volume 35; Myles Allen et al, *"Warming caused by cumulative carbon emissions towards the trillionth ton."* Nature, April 2009, Volume 485.

[14] This list of climate hazards is a subset, and the full list can be found in the full report. The list is illustrative rather than exhaustive. Due to data and modeling constraints, we did not include the following hazards: increased frequency and severity of forest fires, increased biological and ecological impacts from pests and diseases, increased severity of hurricane wind speed and storm surge, and more frequent and severe coastal flooding due to sea-level rise.

[15] Taken from KNMI Climate Explorer (2019), using the mean of the full CMIP5 ensemble of models.

[16] Modeled by WHRC using the median projection from 20 CMIP5 Global Climate Models (GCMs). To accurately estimate the probability of extreme precipitation events, a process known as statistical bootstrapping was used. Because these projections are not estimating absolute values, but rather changes over time, bias correction was not used.

[17] Modeled by WHRC using the Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019. Time periods available for the hurricane modeling were 1981–2000 baseline, and 2031–50 future period. These are the results for two main hurricane regions of the world; other including the Indian sub-continent were not modeled.

[18] Modeled by WHRC using the median projection of 20 CMIP5 GCMs, using the self-correcting Palmer Drought Severity Index (PDSI). Projections were corrected to account for increasing atmospheric CO_2 concentrations.

Exhibit E3

Climate hazards are projected to intensify in many parts of the world.

Based on RCP 8.5

Today	2030	2050

Increase in average annual temperature

Shift compared to preindustrial climate

°C

0–0.5 | 0.6–1.0 | 1.1–1.5 | 1.6–2.0 | 2.1–2.5 | 2.6–3.0 | 3.1–3.5 | 3.6–4.0 | 4.1–4.5 | 4.6–5.0 | 5.1–5.5 | 5.6–6.0 | 6.1–6.5 | 6.6–7.0 | >7.0

Extreme precipitation

Change of likelihood compared to 1950–81 of an 1950–81 50-year precipitation event

≤1x | 1–2x | 2–3x | 3–4x | >4x

Hurricane (precipitation)

Change of likelihood in 2040 compared with 1981–2000 of a 1981–2000 100-year hurricane

Southeast United States

- ≤1.0x
- 1.1–1.5x
- 1.6–2.0x
- >2.0x

Southeast Asia

- ≤1.00x
- 1.01–1.25x
- 1.26–1.75x
- 1.76–2.25x
- 2.26–3.00x
- >3.00x

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

Exhibit E4

Climate hazards are projected to intensify in many parts of the world (continued).

Based on RCP 8.5

Today	2030	2050

Drought frequency[1]

% of decade in drought

0 | 1–10 | 11–20 | 21–40 | 41–60 | 61–80 | >80

Lethal heat wave probability[2]

% p.a.

≤2 | 3–5 | 6–10 | 11–15 | 16–30 | 31–45 | 46–60 | >60

Water supply

Change in surface water compared with 2018 (%)
Boundaries on the map represent water basins

>70% decrease | 41–70% decrease | 20–40% decrease | Near normal | 20–40% increase | 41–70% increase | >70% increase

1. Measured using a three-month rolling average. Drought is defined as a rolling three month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature and precipitation-based drought index calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to -4 (extremely dry).
2. A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in the shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

- **Lethal heat waves.**[19] Lethal heat waves are defined as three-day events during which average daily maximum wet-bulb temperature could exceed the survivability threshold for a healthy human being resting in the shade.[20] Under an RCP 8.5 scenario, urban areas in parts of India and Pakistan could be the first places in the world to experience heat waves that exceed the survivability threshold for a healthy human being, with small regions projected to experience a more than 60 percent annual chance of such a heat wave by 2050.

- **Water supply.**[21] As rainfall patterns, evaporation, snowmelt timing, and other factors change, renewable freshwater supply will be affected. Some parts of the world like South Africa and Australia are expected to see a decrease in water supply, while other areas, including Ethiopia and parts of South America, are projected to experience an increase. Certain regions, for example, parts of the Mediterranean region and parts of the United States and Mexico, are projected to see a decrease in mean annual surface water supply of more than 70 percent by 2050. Such a large decline in water supply could cause or exacerbate chronic water stress and increase competition for resources across sectors.

The socioeconomic impacts of climate change will likely be nonlinear as system thresholds are breached and have knock-on effects

Climate change affects human life as well as the factors of production on which our economic activity is based and, by extension, the preservation and growth of wealth. We measure the impact of climate change by the extent to which it could disrupt or destroy stocks of capital—human, physical, and natural—and the resultant socioeconomic impact of that disruption or destruction. The effect on economic activity as measured by GDP is a consequence of the direct impacts on these stocks of capital.

Climate change is already having a measurable socioeconomic impact. Across the world, we find examples of these impacts and their linkage to climate change. We group these impacts in a five-systems framework (Exhibit E5). As noted in Box E1, this impact framework is our best effort to capture the range of socioeconomic impacts from physical climate hazards.

[19] Modeled by WHRC using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 GCMs. Models were independently bias corrected using the ERA-Interim dataset.

[20] We define a lethal heat wave as a three-day period with maximum daily wet-bulb temperatures exceeding 34 degrees Celsius wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35 degrees Celsius wet-bulb, and large cities with significant urban heat island effects could push 34C wet-bulb heat waves over the 35C threshold. At this temperature, a healthy human being, resting in the shade, can survive outdoors for four to five hours. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See the India case and our technical appendix for more details. Analysis based on an RCP 8.5 scenario.

[21] Taken from the World Resources Institute Water Risk Atlas (2018), which relies on 6 underlying CMIP5 models. Time periods of this raw dataset are the 20-year periods centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base dataset.

Exhibit E5

Socioeconomic impact of climate change is already manifesting and affects all geographies.

Impacted economic system		Area of direct risk	Socioeconomic impact	How climate change exacerbated hazard
Livability and workability	1	2003 European heat wave	$15 billion in losses	2x more likely
	2	2010 Russian heat wave	~55,000 deaths attributable	3x more likely
	3	2013–14 Australian heat wave	~$6 billion in productivity loss	Up to 3x more likely
	4	2017 East African drought	~800,000 people displaced in Somalia	2x more likely
	5	2019 European heat wave	~1,500 deaths in France	~10x more likely in France
Food systems	6	2015 Southern Africa drought	Agriculture outputs declined by 15%	3x more likely
	7	Ocean warming	Up to 35% decline in North Atlantic fish yields	Ocean surface temperatures have risen by 0.7°C globally
Physical assets	8	2012 Hurricane Sandy	$62 billion in damage	3x more likely
	9	2016 Fort McMurray Fire, Canada	$10 billion in damage, 1.5 million acres of forest burned	1.5 to 6x more likely
	10	2017 Hurricane Harvey	$125 billion in damage	8–20% more intense
Infrastructure services	11	2017 flooding in China	$3.55 billion of direct economic loss, including severe infrastructure damage	2x more likely
Natural capital	12	30-year record low Arctic sea ice in 2012	Reduced albedo effect, amplifying warming	70% to 95% attributable to human-induced climate change
	13	Decline of Himalayan glaciers	Potential reduction in water supply for more than 240 million people	~70% of global glacier mass lost in past 20 years is due to human-induced climate change

Source: R. Garcia-Herrera et al., 2010; [illegible]

Individual climate hazards could impact multiple systems. For example, extreme heat may affect communities through lethal heat waves and daylight hours rendered unworkable, even as it shifts food systems, disrupts infrastructure services, and endangers natural capital such as glaciers. Extreme precipitation and flooding can destroy physical assets and infrastructure while endangering coastal and river communities. Hurricanes can impact global supply chains, and biome shifts can affect ecosystem services. The five systems in our impact framework are:

— **Livability and workability.** Hazards like heat stress could affect the ability of human beings to work outdoors or, in extreme cases, could put human lives at risk. Heat reduces labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent overexertion. Increased temperatures could also shift disease vectors and thus affect human health.

— **Food systems.** Food production could be disrupted as drought conditions, extreme temperatures, or floods affect land and crops. A changing climate could both improve and degrade food system performance while introducing more or less volatility. In some cases, crop yields may increase; in other cases, thresholds could be exceeded beyond which some crops fail entirely.

— **Physical assets.** Physical assets like buildings could be damaged or destroyed by extreme precipitation, tidal flooding, forest fires, and other hazards. Hazards could even materially affect an entire network of assets such as a city's central business district.

— **Infrastructure services.** Infrastructure assets are a particular type of physical asset that could be destroyed or disrupted in their functioning, leading to a decline in the services they provide or a rise in the cost of these services. For example, power systems could become less productive under very hot conditions. A range of hazards including heat, wind, and flooding can disrupt infrastructure services. This in turn can have knock-on effects on other sectors that rely on these infrastructure assets.

— **Natural capital.** Climate change is shifting ecosystems and destroying forms of natural capital such as glaciers, forests, and ocean ecosystems, which provide important services to human communities. This in turn imperils the human habitat and economic activity. These impacts are hard to model but could be nonlinear and in some cases irreversible, such as glacier melting, as the temperature rises. In some cases, human mismanagement may play a role—for example, with forest fires and water scarcity—but its extent and impact are multiplied by climate change.

The nine distinct cases of physical climate risk in various geographies and sectors that we examine, including direct impact and knock-on effects, as well as adaptation costs and strategies, help illustrate the specific socioeconomic impact of the different physical climate hazards on the examined human, physical, or natural system. Our cases cover each of the five systems across geographies and include multiple climate hazards, sometimes occurring at the same location. Overall, our cases highlight a wide range of vulnerabilities to the changing climate.

Specifically, we looked at the impact of climate change on livability and workability in India and the Mediterranean; disruption of food systems through looking at global breadbaskets and African agriculture; physical asset destruction in residential real estate in Florida and in supply chains for semiconductors and heavy rare earth metals; disruption of five types of infrastructure services and, in particular, the threat of flooding to urban areas; and destruction of natural capital through impacts on glaciers, oceans, and forests.

Our case studies highlight that physical climate risk is growing, often in nonlinear ways. Physical climate impacts are spreading across regions, even as the hazards grow more intense within regions.

To assess the magnitude of direct physical climate risk in each case, we examine the severity of the hazard and its likelihood; the exposure of people, assets, or economic activity to the hazard; and the extent to which systems are vulnerable to the hazard. Researchers have examined insurance data on losses from natural disasters and found that most of the increase in direct impact to date has come more from greater exposure than from increases in the climate hazards themselves.[22] Changes in climate itself in the future are likely to play a bigger role. As the Earth warms, hazards will become more intense and or more frequent. Since physiological, human-made, and ecological systems have evolved or been optimized over time for historical climates, even small changes in hazard intensity can have large consequences if physical thresholds for resilience are breached.

Indeed, thresholds exist for all systems we have examined. For example: the human body functions at a stable core temperature of about 37 degrees Celsius, above which physical and mental functioning could be fatally impaired; corn yields can decline significantly above 20 degrees Celsius; cell phone towers have typically been built to withstand certain wind speeds above which they may fail (Exhibit E6).

The impacts, once such thresholds are crossed, could be significant. For example, by 2030 in an RCP 8.5 scenario, absent an effective adaptation response, we estimate that 160 million to 200 million people in India could live in regions with a 5 percent average annual probability of experiencing a heat wave that exceeds the survivability threshold for a healthy human being (without factoring in air conditioner penetration).[23]

Outdoor labor productivity is also expected to fall, thus reducing the effective number of hours that can be worked outdoors (Exhibit E7). As of 2017, in India, heat-exposed work produces about 50 percent of GDP, drives about 30 percent of GDP growth, and employs about 75 percent of the labor force, some 380 million people.[24] By 2030, the average number of lost daylight working hours in India could increase to the point where between 2.5 and 4.5 percent of GDP could be at risk annually, according to our estimates.

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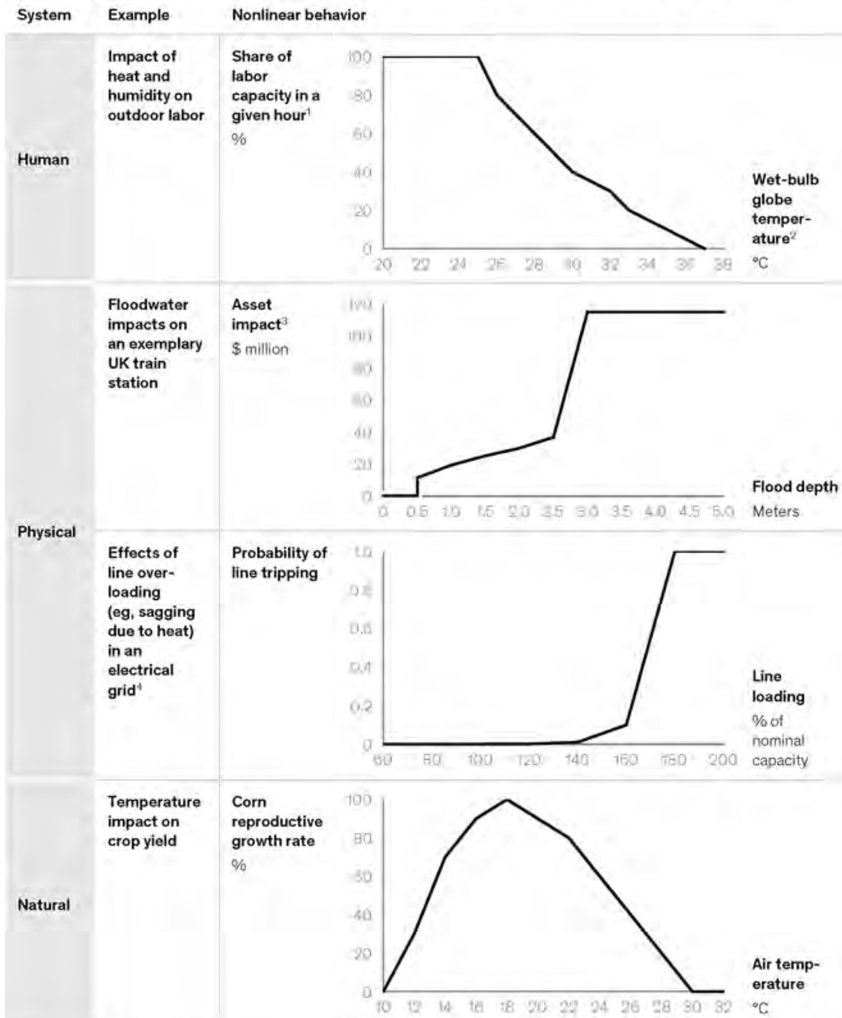
[22] Various researchers have attempted to identify the role played by each of these factors in driving economic losses to date. Insurance records of losses from acute natural disasters like floods, hurricanes, and forest fires show a clear upward trend in losses in real terms over time, and analyses show that the majority of this is driven by an increase in exposure. This is based on normalizing the real losses for increases in GDP, wealth, and exposure to strip out the effects of a rise in exposure. See for example, Roger Pielke, "Tracking progress on the economic costs of disasters under the indicators of the sustainable development goals," *Environmental Hazards*, 2019, Volume 18, Number 1. The work by Pielke finds no upward trend in economic impact after normalizing the damage data, and indeed a decrease in weather /climate losses as a proportion of GDP since 1990. Other researchers find a small upward trend after accounting for effects of GDP, wealth, and population, suggesting some potential role of climate change in losses to date. See for example, Fabian Barthel and Eric Neumayer, "A trend analysis of normalized insured damage from natural disasters," *Climatic Change*, 2012, Volume 113, Number 2; Robert Muir-Wood et al., "The search for trends in a global catalogue of normalized weather-related catastrophe losses," Climate Change and Disaster Losses Workshop, May 2006; and Robert Ward and Nicola Ranger, *Trends in economic and insured losses from weather-related events: A new analysis*, Centre for Climate Change Economics and Policy and Munich Re, November 2010. For example, Muir-Wood et al. conduct analysis of insurance industry data between 1970 to 2005 and find that weather-related catastrophe losses have increased by 2 percent each year since the 1970s, after accounting for changes in wealth, population growth and movement, and inflation (notably, though, in some regions including Australia, India, and the Philippines, such losses have declined). Analysis by Munich Re finds a statistically significant increase in insured losses from weather-related events in the United States and in Germany over the past approximately 30 to 40 years.

[23] A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34 degrees Celsius wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35 degrees Celsius wet-bulb, and large cities with significant urban heat island effects could push 34C wet-bulb heat waves over the 35C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance.

[24] Exposed sectors include exclusively outdoor sectors such as agriculture, mining, and quarrying, as well as indoor sectors with poor air-conditioning penetration, including manufacturing, hospitality, and transport. Reserve Bank of India, Database on Indian Economy, dbie.rbi.org.in/DBIE/dbie.rbi?site=home.

Exhibit E6

Direct impacts of climate change can become nonlinear when thresholds are crossed.



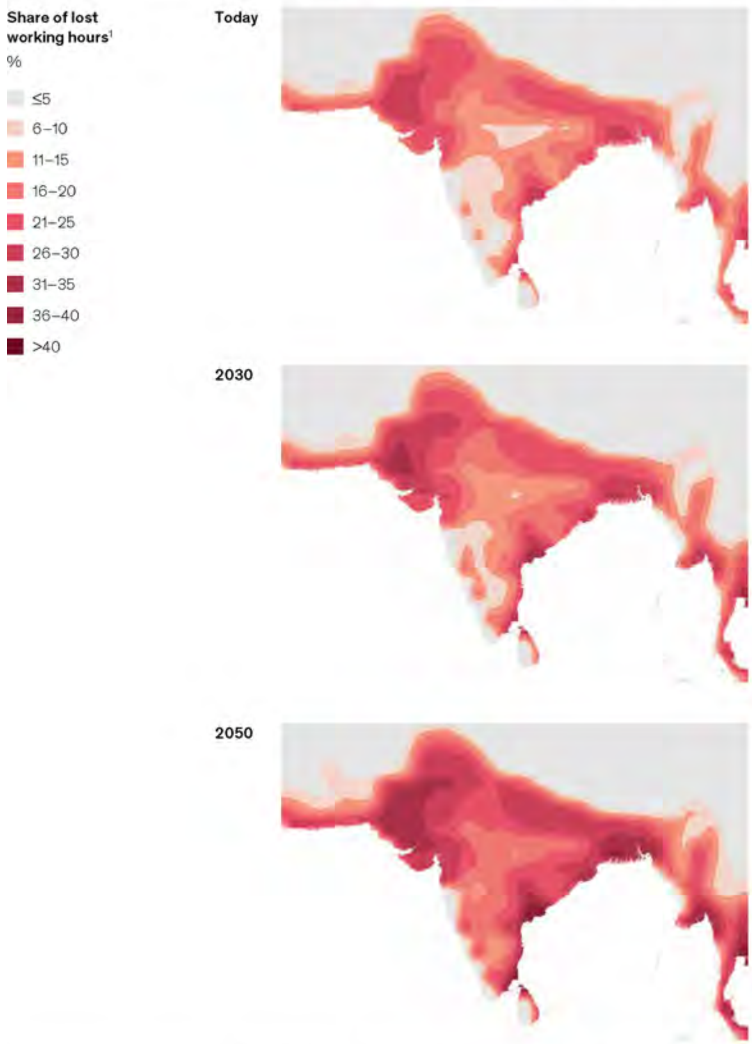
1. Immediate effect; longer exposure will cause rapidly worsening health impacts. Humans can survive exposure to [illegible] wet-bulb temperatures for between four to five hours. During this period, it is possible for a small amount of work to be performed, which is why the working hours curve does not approach zero at [illegible] WBGT (which, in the shade, is approximately equivalent to 35C wet-bulb).
2. Based on in-shade wet-bulb globe temperature (WBGT). WBGT is defined as a type of apparent temperature which usually takes into account the effect of temperature, humidity, wind speed, and visible and infrared radiation on humans.
3. Average cost of a new build train station globally used for asset impact/cost on UK train station; salvageable value is assumed zero once asset passes destruction threshold.
4. Both acute events (eg, flooding, fires, storms) and chronic changes in climatic conditions (eg, heat) can affect the grid and may lead to outages.

Source: Dunne et al., 2013, adjusted according to Foster et al., 2018; Hermeaux, 2019; Kimura et al., 2016; CATDAT global database of historic flooding events; McKinsey Infrastructure benchmark costs; EU Commission Joint Research Centre damage functions database; historical insurance data and expert answers; interviews on failure thresholds; McKinsey Global Institute analysis

Exhibit E7

The affected area and intensity of extreme heat and humidity is projected to increase, leading to a higher expected share of lost working hours.

Based on RCP 8.5



1. Lost working hours include loss in worker productivity as well as breaks, based on an average year that is an ensemble average of climate models.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center

Economic and financial systems have similarly been designed and optimized for a certain level of risk and increasing hazards may mean that such systems are vulnerable. We have already noted that supply chains are often designed for efficiency over resiliency, by concentrating production in certain locations and maintaining low inventory levels. Food production is also heavily concentrated; just five regional "breadbasket" areas account for about 60 percent of global grain production. Rising climate hazards might therefore cause such systems to fail, for example if key production hubs are affected. Finance and insurance have vulnerabilities, too; while they were designed to manage for some level of risk, intensifying climate hazards could stretch their limits. For example, consider the residential real estate market in Florida (Exhibit E8). Home owners rely on insurance to build financial resilience against risks like floods, but premiums could rise in the face of increasing risk and insurance does not cover devaluations of home prices. Lenders may bear some risk if home owners default. Among other possible repercussions, federal governments have been acting as backstops but may need to be prepared to finance more.

Other cases we examined highlight large knock-on impacts when thresholds are breached. These come about in particular when the people and assets affected are central to local economies and those local economies are tied into other economic and financial systems.

Ho Chi Minh City, a city prone to monsoonal and storm surge flooding, is one example. We estimate that direct infrastructure asset damage from a 100-year flood today would be on the order of $200 million to $300 million. This could rise to $500 million to $1 billion in 2050, assuming no additional adaptation investment and not including real estate–related impacts. Beyond this direct damage, we estimate that the knock-on costs could be substantial. They would rise from $100 million to $400 million today to between $1.5 billion and as much as $8.5 billion in 2050. We estimate that at least $20 billion of new infrastructure assets are currently planned for construction by 2050, more than doubling the number of major assets in Ho Chi Minh City (Exhibit E9). Many of these new infrastructure assets, particularly the local metro system, have been designed to tolerate an increase in flooding. However, in a worst-case scenario such as a sea-level rise of 180 centimeters, these thresholds could be breached in many locations.[25]

A further example from our case studies, that of coastal real estate in Florida, shows how climate hazards could have unpredictable financial impacts. The geography of Florida, with its expansive coastline, low elevation, and porous limestone foundation, makes it vulnerable to flooding. Absent any adaptation response, direct physical damages to real estate could grow with the changing climate. Average annual losses for residential real estate due to storm surge from hurricanes amount to $2 billion today. This is projected to increase to about $3 billion to $4.5 billion by 2050, depending on whether exposure is constant or increasing.[26] For a tail 100-year hurricane event, storm surge damages could rise from $35 billion today to between $50 billion and $75 billion by 2050.

[25] This scenario is extreme, and the probability of it occurring by 2050 is negligible. Nonetheless, it illustrates that infrastructure planned for completion in or shortly before 2050 could experience another step change in risk at some point in 2060 or beyond if significant mitigation does not take place.

[26] Analysis conducted by KatRisk; direct average annual losses to all residential real estate (insured and uninsured properties). This is the long-term average loss expected in any one year, calculated by modeling the probability of a climate hazard occurring multiplied by the damage should that hazard occur, and summing over events of all probabilities. Analyses based on sea level rise in line with the US Army Corps of Engineers high curve, one of the recommended curves from the Southeast Florida Regional Climate Change Compact. Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, *Unified sea level rise projection: Southeast Florida*, October 2015. More broadly, considering the hurricane hazard, while total hurricane frequency is expected to remain unchanged or to decrease slightly as the climate changes, cumulative hurricane rainfall rates, average intensity, and proportion of storms that reach Category 4–5 intensity are projected to increase, even for a 2°C or less increase in global average temperatures. Thomas Knutson et al., *Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming*, American Meteorological Society, 2019. Range based on assessing how exposure varies; from constant exposure to exposure based on historical rates of growth of real estate.

Exhibit E8

Who holds the risk?

Overview of stakeholders in Florida residential real estate market

Stakeholders → Transactions

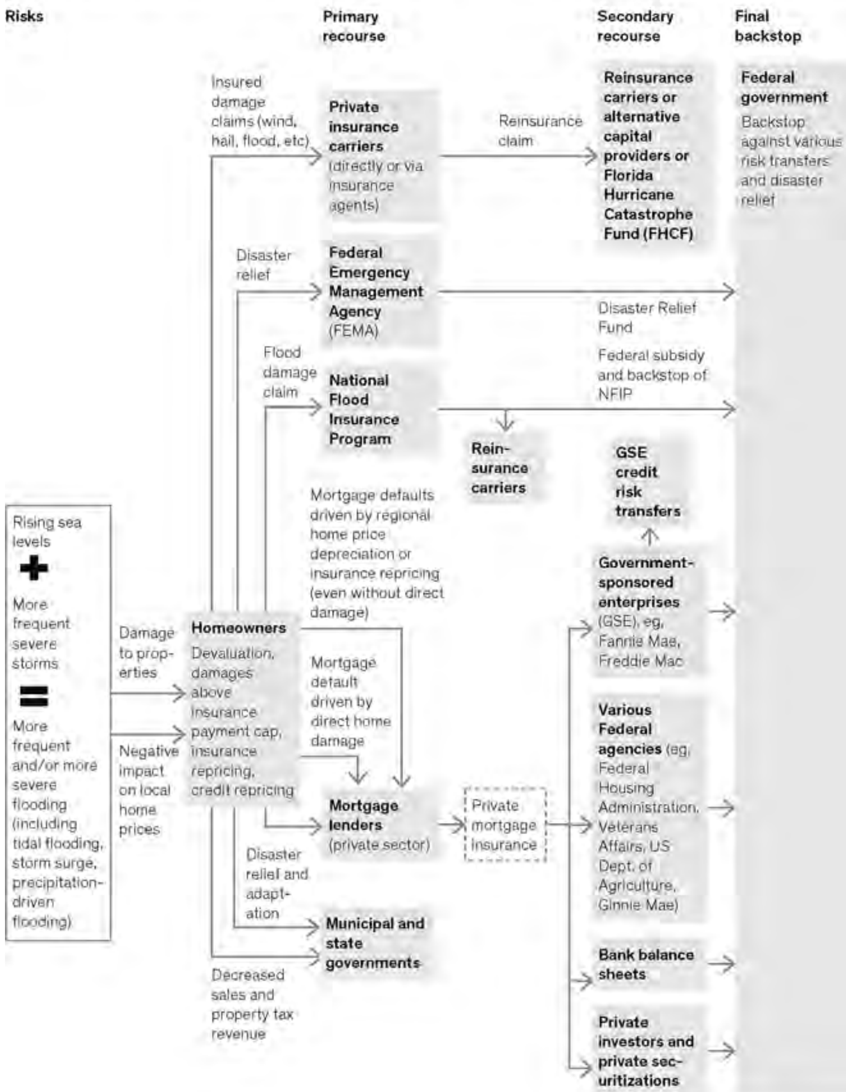
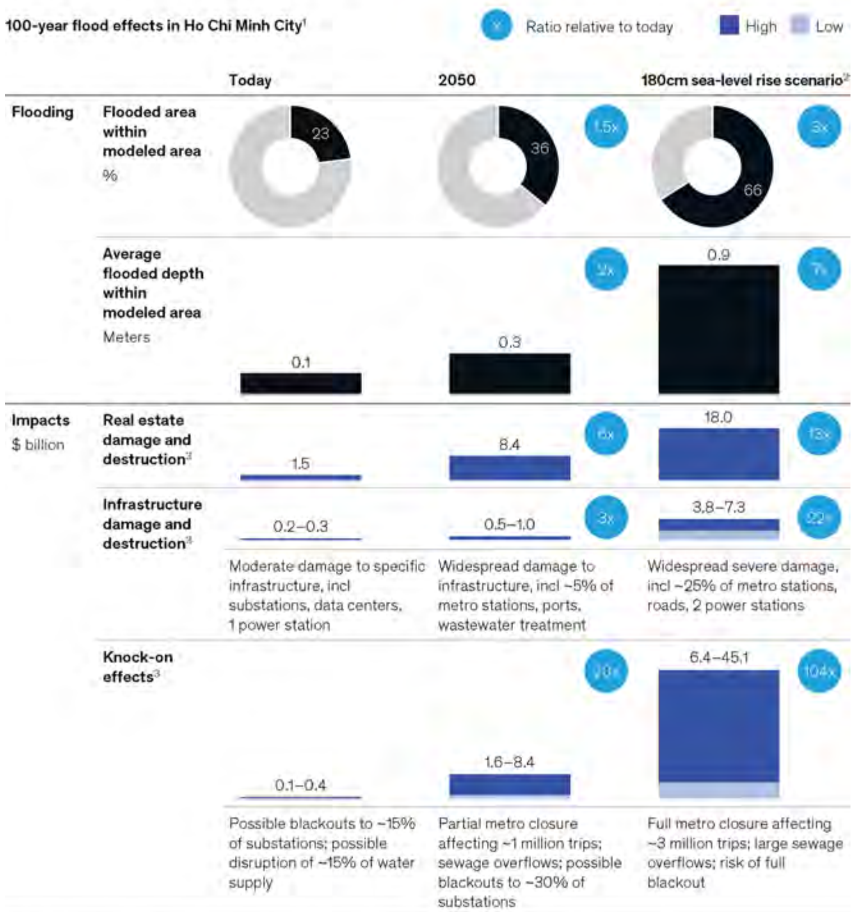


Exhibit E9

Ho Chi Minh City could experience 5 to 10 times the economic impact from an extreme flood in 2050 vs today.

Based on RCP 8.5



1. Repair and replacement costs. Qualitative descriptions of damage and knock-on effects are additional to previous scenarios.
2. Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
3. Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure, includes loss of freight movement and data revenues, and lost working hours due to a lack of access to electricity, clean water, and metro services. Adjusted for economic and population growth to 2050 for both 2050 and 180cm sea-level rise scenarios.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Following standard practice, we define future states (current, 2030, 2050) as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998–2017, in 2030 as the average between 2021–40, and in 2050 between 2041–60. Assumes no further adaptation action is taken. Figures may not sum to 100% because of rounding.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; ECLAC; EU Commission; HAZUS; Oxford Economics; People's Committee of Ho Chi Minh City; Scussolini et al., 2017; UN; Viet Nam National University, Ho Chi Minh City; World Bank historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

These numbers do not include the potential devaluation of flooding affected real estate. Exposed homes could see a devaluation of $30 billion to $80 billion, or about 15 to 35 percent, by 2050, all else being equal.[27] Lower real estate prices could in turn have knock-on effects, including forgone property tax revenue (a major source of state income), reduced wealth and spending by home owners, reduced, halted, or reversed resident inflow, and forced changes in government spending. For example, rough estimates suggest that the price effects discussed above could impact property tax revenue in some of the most affected counties by about 15 to 30 percent (though impacts across the state could be less, at about 2 to 5 percent). Business activity could be negatively affected, as could the availability and/or price of insurance and mortgage financing in high-risk counties. Financial markets could bring these risks forward, and the recognition of large future changes could lead to price adjustments. Awareness of climate risk could make long-duration borrowing more expensive or unavailable and reduce valuations, for example. This recognition could happen quickly, with the possibility of cascading consequences.

Climate change could create inequality—simultaneously benefiting some regions while hurting others. For example, rising temperatures may boost tourism in areas of northern Europe while reducing the economic vitality of southern European resorts. The volume of water in basins in northern Africa, Greece, and Spain could decline by more than 15 percent by 2050 even as volume in basins in Germany and the Netherlands increases by between 1 and 5 percent.[28] The mild Mediterranean climate is expected to grow hotter—by 2050, the climate in the French port city of Marseille could more closely resemble that of Algiers today—which could disrupt key sectors such as tourism and agriculture.[29]

Within regions, the poorest communities and populations within each of our cases typically are the most vulnerable to climate events. They often lack financial means. For example, acute climate events could trigger harvest failure in multiple breadbasket locations—that is, significantly lower-than-average yields in two or more key production regions for rice, wheat, corn, and soy. We estimate that the chance of a greater than 15 percent yield shock at least once in the decade centered on 2030 could rise from 10 percent today to 18 percent, while the chance of a greater than 10 percent yield shock occurring at least once could rise from 46 to 69 percent.[30] Given current high grain stocks, totaling about 30 percent of consumption, the world would not run out of grain. However, historical precedent suggests that prices could spike by 100 percent or more in the short term, in the event of a greater than 15 percent decline in global supply that reduces stocks. This would particularly hurt the poorest communities, including the 750 million people living below the international poverty line.

The global socioeconomic impacts of climate change could be substantial as a changing climate directly affects human, physical, and natural capital

While our case studies illustrate the localized impacts of a changing climate, rising temperatures are a global trend. To understand how physical climate hazards could evolve around the world, we developed a global geospatial assessment of climate impacts over the next 30 years covering 105 countries.[31] We again rely on our framework of the direct impacts of climate change on five human, physical, and natural systems. For each system we have identified one or more measures

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27 Analysis supported by First Street Foundation, 2019. Ranges based on whether homes that frequently flood (>50x per year), see more significant devaluations or not. Note that other factors could also affect the prices of homes and that has not been factored in. Much of the literature finds that, at least historically, prices of exposed properties have risen slower than prices of unexposed properties, rather than declined in absolute terms. For further details, see the Florida case study.

28 World Resources Institute Water Risk Atlas, 2018.

29 Jean-Francois Bastin et al., Understanding climate change from a global analysis of city analogues. PLoS ONE 14(7): e0217592, 2019.

30 To estimate the likelihood, we employ crop models from the AgMIP model library that translate outputs from climate models into crop yields for each modeled grid cell. Using all available climate models over a period of 20 years, we construct a probability distribution of yields for each crop in each grid cell. Note that we are taking into account potentially positive effects on plant growth from higher CO_2 levels ("CO_2 fertilization"). Analysis is based on an assumption of no improvements in agricultural productivity (consistent with our "inherent risk" framing). See breadbasket case for further details.

31 To conduct this analysis, we have relied on geospatial climate hazard data, including from Woods Hole Research Center analysis of CMIP5 Global Climate Model output, the World Resources Institute, the European Center for Medium-Range Weather Forecasts and data from Rubel et al. (obtained from the National Oceanic and Atmospheric Administration). We used geospatial data on population, capital stock, and GDP from the European Commission Global Human Settlement (GHS) and the UN *Global Assessment Report on Disaster Risk Reduction*, as well as data from other sources as described in Chapter 4. Notably, we have focused our analysis on a subset of possible climate hazards: lethal heat waves, heat and humidity and its impact on workability, water stress, riverine flooding, drought, and the impact of increased temperature and changes in precipitation on biome shifts. Analysis based on an RCP 8.5 scenario.

to define the impact of climate change, often building on the risk measures used in our case studies, and choosing the best possible measures based on broad country coverage and data availability.[32] For example, for livability and workability, we use the measures of the share of population living in areas projected to experience a non-zero annual probability of lethal heat waves as well as the annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions. This is similar to the approach followed in our India case study.

We find that all 105 countries are expected to experience an increase in at least one major type of impact on their stock of human, physical, and natural capital by 2030. Intensifying climate hazards could put millions of lives at risk, as well as trillions of dollars of economic activity and physical capital, and the world's stock of natural capital. The intensification of climate hazards across regions will bring areas hitherto unexposed to impacts into new risk territory.

— **Livability and workability.** By 2030, under an RCP 8.5 scenario, our research suggests that between 250 million and 360 million people could live in regions where there is a non-zero probability of a heat wave exceeding the threshold for survivability for a healthy human being in the shade (a measure of livability, without factoring in air conditioner penetration).[33] The average probability of a person living in an at-risk region experiencing such a lethal heat wave at least once over the decade centered on 2030 is estimated to be approximately 60 percent.[34] Some exposed regions will have a lower probability, and some regions higher. By 2050, the number of people living in regions exposed to such heat waves could rise further, to between 700 million and 1.2 billion, again without factoring in an adaptation response via air conditioner penetration. This reflects the fact that some of the most heavily populated areas of the world are usually also the hottest and most humid, and, as described below, these areas are becoming even hotter and more humid. Today, air conditioner penetration is roughly 10 percent across India, and roughly 60 percent across China.[35] The global average number of working hours that could be lost due to increasing heat and humidity in exposed regions (a measure of workability impacts) could almost double by 2050, from 10 percent to 15 to 20 percent. This is because more regions of the world are exposed, and the ones that are exposed would see higher intensity of heat and humidity effects. We used these projections to estimate the resulting GDP at risk from lost working hours. This could amount to $4 trillion to $6 trillion globally at risk by 2050 in an average year (Exhibit E10). This the equivalent of 2 to 3.5 percent of 2050 GDP, up from about 1.5 percent today.[36]

[32] The indicators used in our geospatial analysis include: share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves, annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions, water stress as measured by the annual demand of water as a share of annual supply of water (these three are measures of livability and workability, and are considered in our India case and Mediterranean cases), annual share of capital stock at risk of flood damage in climate-exposed regions (asset destruction and infrastructure services; similar measures of capital stock damage are used in our Florida and Inundation cases), share of time spent in drought over a decade (measure of food systems; we also consider the impact of drought in our Mediterranean case), share of land surface changing climate classification annually (measure of natural capital; this was used for our geospatial analysis to allow us to develop a global measure of natural capital risk). Notably, drought is the one measure of hazard rather than risk used in this framework. This was done because of data limitations with obtaining data on impacts on agricultural yield by country, since the AgMIP climate models used to project agricultural yields tend only to be used for relatively large breadbasket regions, rather than at a country level. We are able to use the AgMIP results to provide global trends on breadbaskets and results pertaining to large breadbasket regions; however, such results were not included in the country-by-country analysis. We also excluded risk due to hazards like hurricanes, storm surge, and forest fires due to challenges obtaining sufficiently granular and robust data across countries. See Chapter 4 for details.

[33] Here, as before, lethal heat wave refers to a three-day period with average daily maximum wet-bulb temperatures exceeding 34 degrees Celsius. This temperature was chosen because urban areas with a high urban heat island effect could amplify 34°C ambient temperatures over the 35°C wet-bulb survivability threshold. These numbers are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cool island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance. Additionally, these numbers assume no air-conditioning protection, and as such should be considered an upper bound. See Chapter 2 for details. Analysis based on an RCP 8.5 scenario.

[34] This calculation is a rough approximation. It assumes that the annual probability of roughly 9 percent applies to every year in the decade centered around 2030. We first calculate the cumulative probability of a heat wave not occurring in that decade, which is 91 percent raised to the power of 10. The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number.

[35] India Cooling Action Plan Draft, Ministry of Environment, Forest & Climate Change, Government of India, September 2018; The Future of Cooling in China, IEA, Paris, 2019.

[36] The range here is based on the pace of sectoral transition across countries. GDP at risk will be higher if a greater portion of the economy is occupied in outdoor work. The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions.

Exhibit E10

GDP at risk from the effect of extreme heat and humidity on effective working hours is expected to increase over time.

Based on RCP 8.5

GDP at risk from working hours impacted by heat and humidity (direct effect only, scenario of no sectoral transitions)

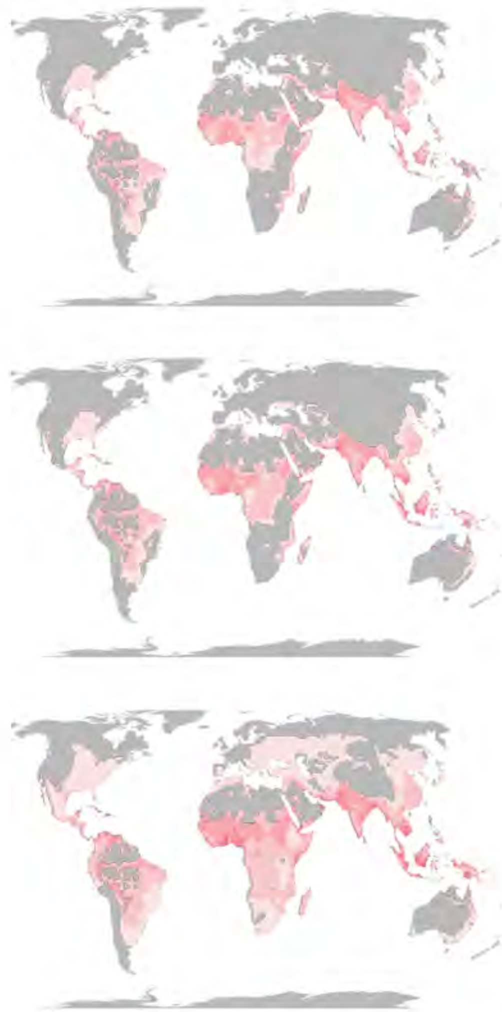
%

- ≤0.1
- 0.2–1.0
- 1.1–5.0
- 5.1–10.0
- 10.1–15.0
- 15.1–20.0
- >20

Today

2030

2050



Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. These maps do not consider sectoral shifts when projecting impact on labor productivity into the future—the percentage and spatial distribution of outdoor labor are held constant. For this analysis, outdoor labor is considered to include agriculture, construction, and mining and quarrying only, and knock-on impacts on other sectors are not considered. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: IHS Markit Economics and Country Risk; Woods Hole Research Center; McKinsey Global Institute analysis

- **Food systems.** Our research suggests an increase in global agricultural yield volatility that skews toward worse outcomes. For example, by 2050, the annual probability of a greater than 10 percent reduction in yields for wheat, corn, soy, and rice in a given year is projected to increase from 6 to 18 percent.[37] The annual probability of a greater than 10 percent increase in yield in a given year is expected to rise from 1 percent to 6 percent. These trends are not uniform across countries and, importantly, some could see improved agricultural yields, while others could suffer negative impacts. For example, the average breadbasket region of Europe and Russia is expected to experience a 4 percent increase in average yields by 2050. While the annual probability of a greater than 10 percent yield failure there will increase, from 8 percent to 11 percent annually by 2050, the annual probability of a bumper year with a greater than 10 percent higher-than-average yield in the same period will increase by more, from 8 percent to 18 percent.

- **Physical assets and infrastructure services.** Assets can be destroyed or services from infrastructure assets disrupted from a variety of hazards, including flooding, forest fires, hurricanes, and heat. Statistically expected damage to capital stock from riverine flooding could double by 2030 from today's levels and quadruple by 2050. Data availability has made it challenging to develop similar estimates for the much larger range of impacts from tidal flooding, fires, and storms.[38]

- **Natural capital.** With temperature increases and precipitation changes, the biome in parts of the world is expected to shift. The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. For this report, we have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.[39] For example, tropical rainforests exist in a particular climatic envelope that is defined by temperature and precipitation characteristics. In many parts of the world, this envelope could begin to be displaced by a much drier "tropical Savannah" climate regime that threatens tropical rainforests. Today, about 25 percent of the Earth's land area has already experienced a shift in climate classification compared with the 1901–25 period. By 2050, that number is projected to increase to about 45 percent. Almost every country will see some risk of biome shift by 2050, affecting ecosystem services, local livelihoods, and species' habitat.

Countries with the lowest per capita GDP levels are generally more exposed

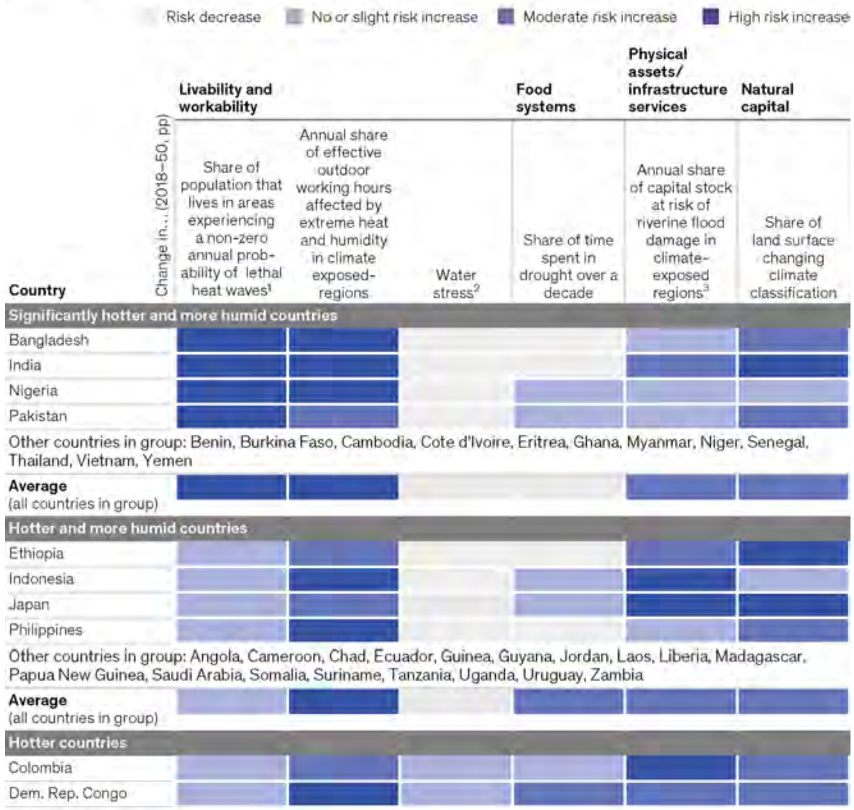
While all countries are affected by climate change, our research suggests that the poorest countries are generally more exposed, as they often have climates closer to dangerous physical thresholds. The patterns of this risk increase look different across countries. Broadly speaking, countries can be divided into six groups based on their patterns of increasing risk (Exhibits E11, E12, and E13).[40]

[37] Global yields based on an analysis of six global breadbaskets that make up 70 percent of global production of four crops; wheat, soy, maize, and rice. Cumulative likelihood calculated for the decade centered on 2030 and 2050 by using annual probabilities for the climate state in the 2030 period, and the 2050 period respectively. Annual probabilities are independent and can therefore be aggregated to arrive at a cumulative decadal probability. Yield anomalies here are measured relative to the 1998-2017 average yield.
[38] See Chapter 4 for details.
[39] The Köppen climate system divides climates into five main climate groups with each group further subdivided based on seasonal precipitation and temperature patterns. This is not a perfect system for assessing the location and composition of biomes; however, these two characteristics do correlate very closely with climate classification, and therefore this was assessed as a reasonable proxy for risk of disruptive biome changes.
[40] These patterns were primarily based on looking at indicators relating to livability and workability, food systems, and natural capital. The annual share of capital stock at risk of riverine flood damage in climate-exposed regions indicator was considered but was not found to be the defining feature of any country grouping aside from a lower-risk group of countries.

Exhibit E11

We identify six types of countries based on their patterns of expected change in climate impacts.

Based on RCP 8.5



1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value of risk.

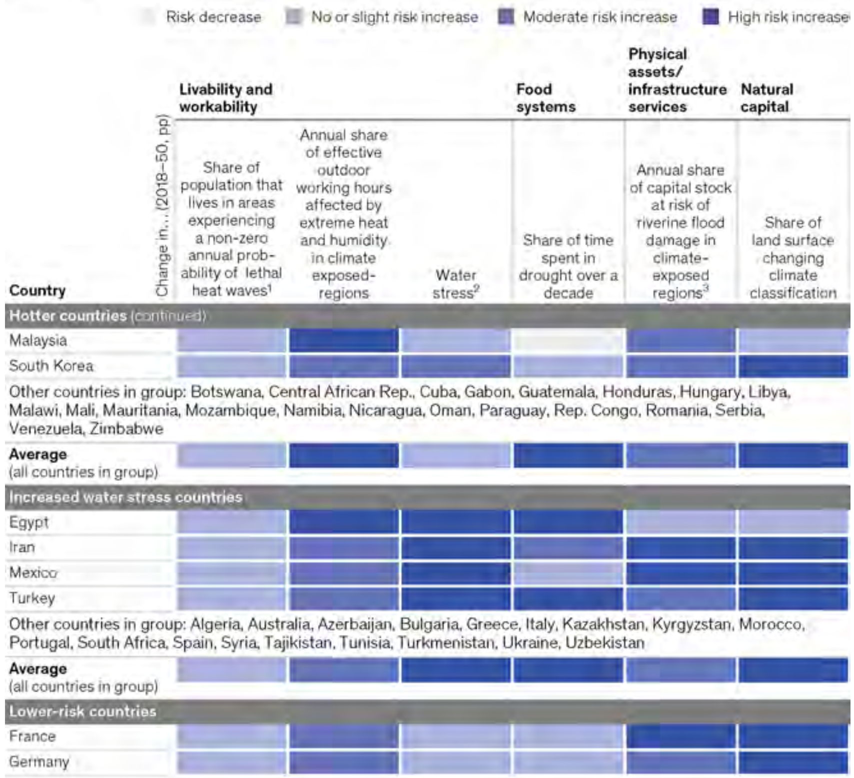
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit E12

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
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3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

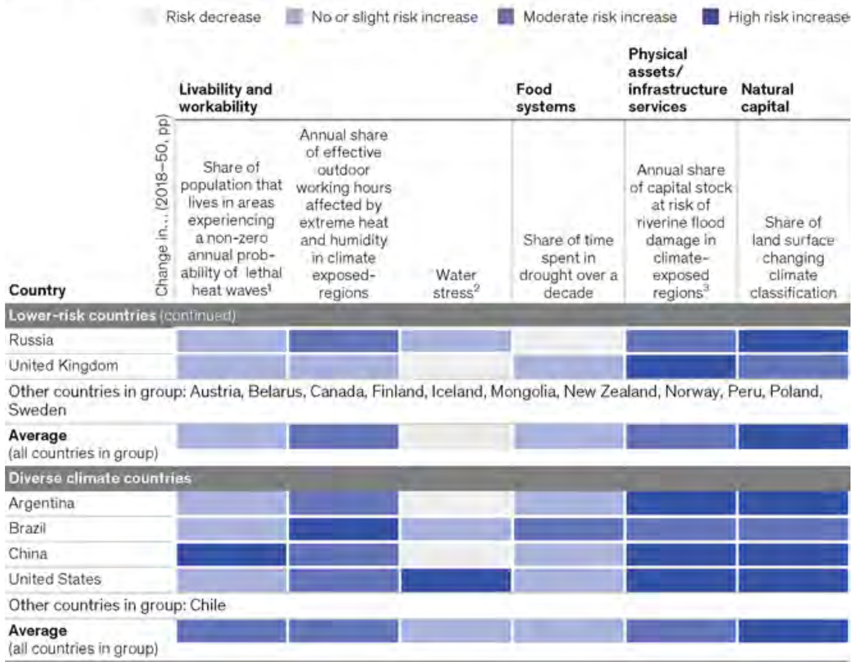
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi-model ensemble and bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit E13

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



Change in potential impact, 2018–50[4] (percentage points)

Risk decrease	n/a	n/a	<0	<0	<0	n/a
Slight risk increase	0.0–0.5	0.0–0.5	0–3	0–3	0–0.05	0–5
Moderate risk increase	0.5–5.0	0.5–5.0	3–7	3–7	0.05–0.10	5–10
High risk increase	>5.0	>5.0	>7	>7	>0.10	>10

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.
4. Calculated assuming constant exposure. Constant exposure means that we do not factor in any increase in population or assets, or shifts in the spatial mix of population and assets. This was done to allow us to isolate the impact of climate change alone. [illegible] on the spread observed across countries within the indicator.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; [illegible] and Kellett, 2010; McKinsey Global Institute analysis

- **Significantly hotter and more humid countries.** Hot and humid countries such as India and Pakistan are expected to become significantly hotter and more humid by 2050. Countries in this group are near the equator in Africa, Asia, and the Persian Gulf. They are characterized by extreme increases in heat and humidity impacts on workability, as well as a decrease in water stress. The potential livability impact that countries in this group face is projected to increase, because of the combination of heat and humidity.

- **Hotter and more humid countries.** This group includes the Philippines, Ethiopia, and Indonesia. These countries are typically between the equator and the 30-degree north and 30-degree south lines of latitude. They face a large potential increase in heat and humidity impacts on workability but may not become so hot or humid that they exceed livability thresholds. Water stress is also expected to decrease for these countries.

- **Hotter countries.** This group includes Colombia, the Democratic Republic of Congo, and Malaysia. Many countries in this group are near the equator. They are characterized by a large increase in heat and humidity impact on workability but are not expected to become so hot or humid that they pass livability thresholds. This group of countries is not expected to become wetter, and some of these countries could even become substantially drier and see increased water stress.

- **Increased water stress countries.** This group includes Egypt, Iran, and Mexico, which intersect the 30-degree north or south line of latitude. They are characterized by a large increase in water stress and drought frequency, and among the largest increases in biome change. In these locations, Hadley cells (the phenomenon responsible for the atmospheric transport of moisture from the tropics, and therefore location of the world's deserts) are expanding, and these countries face a projected reduction in rainfall.

- **Lower-risk increase countries.** This group includes Germany, Russia, and the United Kingdom. Many countries in this group lie outside the 30-degree north and south lines of latitude and are generally cold countries. Some are expected to see a decrease in overall impact on many indicators. These countries are characterized by very low levels of heat and humidity impacts and many countries are expected to see decreases in water stress and time spent in drought. As these countries grow warmer, they will likely see the largest increase in biome change as the polar and boreal climates retreat poleward and disappear. The share of capital stock at risk of riverine flood damage in climate-exposed regions could also potentially increase in some of these countries.

- **Diverse climate countries.** The final group consists of countries that span a large range of latitudes and therefore are climatically heterogeneous. Examples include Argentina, Brazil, Chile, China, and the United States.[41] While average numbers may indicate small risk increases, these numbers mask wide regional variations. The United States, for example, has a hot and humid tropical climate in the Southeast, which will see dramatic increases in heat risk to outdoor work but is not projected to struggle with water scarcity. The West Coast region, however, will not see a big increase in heat risk to outdoor work, but will struggle with water scarcity and drought. In Alaska, the primary risk will be the shifting boreal biome and the attendant ecosystem disruptions.

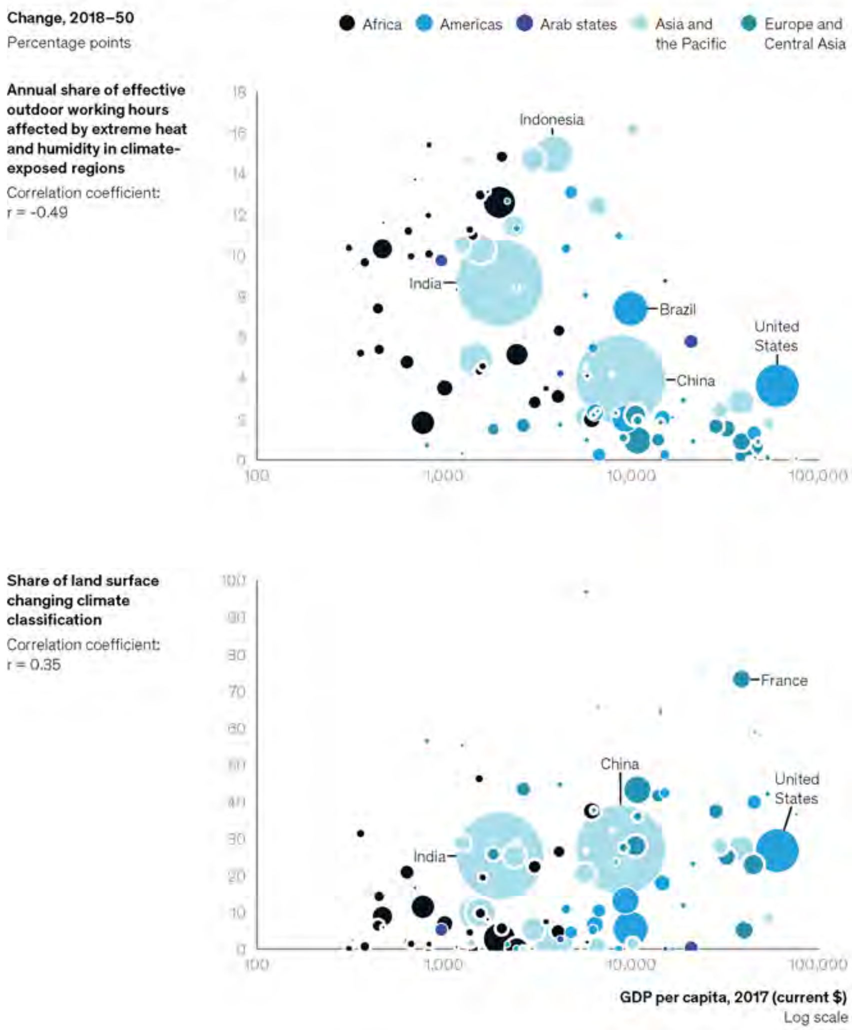
The risk associated with the impact on workability from rising heat and humidity is one example of how poorer countries could be more vulnerable to climate hazards (Exhibit E14).

[41] To some extent, many countries could experience diversity of risk within their boundaries. Here we have focused on highlighting countries with large climatic variations, and longitudinal expanse, which drives different outcomes in different parts of the country.

Exhibit E14

Countries with the lowest per capita GDP levels face the biggest increase in risk for some indicators.

Based on RCP 8.5



Note: Not to scale. See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.
Source: Woods Hole Research Center; Rubel and Kottek, 2010; IMF; World Bank; UN; McKinsey Global Institute analysis

When looking at the workability indicator (that is, the share of outdoor working hours lost to extreme heat and humidity), the top quartile of countries (based on GDP per capita) have an average increase in risk by 2050 of approximately one to three percentage points, whereas the bottom quartile faces an average increase in risk of about five to ten percentage points. Lethal heat waves show less of a correlation with per capita GDP, but it is important to note that several of the most affected countries—Bangladesh, India, and Pakistan, to name a few—have relatively low per capita GDP levels.

Conversely, biome shift is expected to affect northern and southern latitude countries. Since many of these countries have higher per capita GDP levels, this indicator shows a positive correlation with development levels.

Leaders will need to better understand the impacts of physical climate risk, while accelerating adaptation and mitigation

In the face of these challenges, policy makers and business leaders will need to put in place the right tools, analytics, processes, and governance to properly assess climate risk, adapt to risk that is locked in, and decarbonize to reduce the further buildup of risk. In Box E3 that concludes this summary, we present a range of questions that stakeholders could consider as they look to manage risk.

Integrating climate risk into decision making

Much as thinking about information systems and cyber-risks has become integrated into corporate and public-sector decision making, climate change will also need to feature as a major factor in decisions. For companies, this will mean taking climate considerations into account when looking at capital allocation, development of products or services, and supply chain management, among others. For cities, a climate focus will become essential for urban planning decisions. Financial institutions could consider the risk in their portfolios.[40] Moreover, while this report has focused on physical risk, a comprehensive risk management strategy will also need to include an assessment of transition and liability risk, and the interplay between these forms of risk.

Developing a robust quantitative understanding is complex, for the many reasons outlined in this report. It requires the use of new tools, metrics, and analytics. Companies and communities are beginning to assess their exposure to climate risk, but much more needs to be done. Lack of understanding significantly increases risks and potential impacts across financial markets and socioeconomic systems, for example, by driving capital flows to risky assets in risky geographies or increasing the likelihood of stakeholders being caught unprepared.

At the same time, opportunities from a changing climate will emerge and require consideration. These could arise from a change in the physical environment, such as new places for agricultural production, or for sectors like tourism, as well as through the use of new technologies and approaches to manage risk in a changing climate.

One of the biggest challenges could stem from using the wrong models to quantify risk. These range from financial models used to make capital allocation decisions to engineering models used to design structures. As we have discussed, there is uncertainty associated with global and regional climate models, underlying assumptions on emissions paths, and, most importantly, in translating climate hazards to potential physical and financial damages. While these uncertainties are non-negligible, continued reliance on current models based on stable historical climate and economic data presents an even higher "model risk."

[40] See, for example, *Getting physical: Scenario analysis for assessing climate-related risks*, Blackrock Investment Institute, April 2019.

Three examples of how models could be inappropriate for the changing climate are as follows:

— **Geography.** Current models may not sufficiently take into account geospatial dimensions. As this report highlights, direct impacts of climate change are local in nature, requiring understanding exposure to risk via geospatial analysis. For example, companies will need to understand how their global asset footprint is exposed to different forms of climate hazard in each of their main locations and indeed in each of the main locations of their critical suppliers.

— **Non-stationarity.** Given the constantly changing or non-stationary climate, assumptions based on historical precedent and experience will need to be rethought. That could include, for example, how resilient to make new factories, what tolerance levels to employ in new infrastructure, and how to design urban areas. Decisions will need to take into consideration that the climate will continue to change over the next several decades.

— **Sample bias.** Decision makers often rely on their own experiences as a frame for decisions; in a changing climate, that can result in nonlinear effects and thus lead to incorrect assessments of future risk.

Accelerating the pace and scale of adaptation

Societies have been adapting to the changing climate, but the pace and scale of adaptation will likely need to increase significantly. Key adaptation measures include protecting people and assets, building resilience, reducing exposure, and ensuring that appropriate financing and insurance are in place.

— **Protecting people and assets.** Measures to protect people and assets to the extent possible can help limit risk. Steps can range from prioritizing emergency response and preparedness to erecting cooling shelters and adjusting working hours for outdoor workers exposed to heat. Hardening existing infrastructure and assets is a key response. According to the UN Environment Programme, the cost of adaptation for developing countries may range from $140 billion to $300 billion a year by 2030. This could rise to $280 billion to $500 billion by 2050.[43] Hardening of infrastructure could include both "gray" infrastructure—for example, raising elevation levels of buildings in flood-prone areas—and natural capital or "green" infrastructure. One example of this is the Dutch Room for the River program, which gives rivers more room to manage higher water levels.[44] Another example is mangrove plantations, which can provide storm protection.

Factoring decisions about protection into new buildings will likely be more cost-effective than retrofitting.[45] For example, infrastructure systems or factories may be designed to withstand what used to be a 1-in-200-year event. With a changing climate, what constitutes such an event may look different, and design parameters will need to be reassessed. Estimates suggest that $30 trillion to $50 trillion will be spent on infrastructure in the next ten years, much of it in developing countries.[46] Designing such infrastructure with climate risk in mind may help reduce downstream repair and rebuilding costs. Moreover, infrastructure that specifically helps protect assets and people will be needed, for example cooling technologies including green air-conditioning (high energy efficiency HVAC powered by low carbon power, for example), emergency shelters, and passive urban design.

[43] Anne Olhoff et al., *The adaptation finance gap report*, UNEP DTU Partnership, 2016.
[44] See Room for the River, ruimtevoorderivier.nl/english/.
[45] Michael Della Rocca, Tim McManus, and Chris Toomey, *Climate resilience: Asset owners need to get involved now*, McKinsey.com, January 2009.
[46] *Bridging global infrastructure gaps*, McKinsey Global Institute, June 2016; *Bridging infrastructure gaps: Has the world made progress?* McKinsey Global Institute, October 2017.

- **Building resilience.** Asset hardening will need to go hand-in-hand with measures that make systems more resilient and robust in a world of rising climate hazard. Building global inventory to mitigate risks of food and raw material shortages is an example of resilience planning, leveraging times of surplus and low prices. To make the food system more resilient, private and public research could be expanded, for example on technology that aims to make crops more resistant to abiotic and biotic stresses. As noted, climate change challenges key assumptions that have been used to optimize supply chain operations in the past. Those assumptions may thus need to be rethought, for example by building backup inventory levels in supply chains to protect against interrupted production, as well as establishing the means to source from alternate locations and/or suppliers.

- **Reducing exposure.** In some instances, it may also be necessary to reduce exposure by relocating assets and communities in regions that may be too difficult to protect, that is, to retreat from certain areas or assets. Given the long lifetimes of many physical assets, the full life cycle will need to be considered and reflected in any adaptation strategy. For example, it may make sense to invest in asset hardening for the next decade but also to shorten asset life cycles. In subsequent decades, as climate hazards intensify and the cost-benefit equation of physical resilience measures is no longer attractive, it may become necessary to relocate and redesign asset footprints altogether.

- **Insurance and finance.** While insurance cannot eliminate the risk from a changing climate, it is a crucial shock absorber to help manage risk.[47] Insurance can help provide system resilience to recover more quickly from disasters and reduce knock-on effects. It can also encourage behavioral changes among stakeholders by sending appropriate risk signals—for example, to homeowners buying real estate, lenders providing loans, and real estate investors financing real estate build-out.

  Instruments such as parametrized insurance and catastrophe bonds can provide protection against climate events, minimizing financial damage and allowing speedy recovery after disasters. These products may help protect vulnerable populations that could otherwise find it challenging to afford to rebuild after disasters. Insurance can also be a tool to reduce exposure by transferring risk (for example, crop insurance allows transferring the risk of yield failure due to drought) and drive resilience (such as by enabling investments in irrigation and crop-management systems for rural populations who would otherwise be unable to afford this).

  However, as the climate changes, insurance might need to be further adapted to continue providing resilience and, in some cases, avoid potentially adding vulnerability to the system. For example, current levels of insurance premiums and levels of capitalization among insurers may well prove insufficient over time for the rising levels of risk; and the entire risk transfer process (from insured to insurer to reinsurer to governments as insurers of last resort) and each constituents' ability to fulfil their role may need examination. Without changes in risk reduction, risk transfer, and premium financing or subsidies, some risk classes in certain areas may become harder to insure, widening the insurance gap that already exists in some parts of the world without government intervention.

  Innovative approaches will also likely be required to help bridge the underinsurance gap. Premiums are already sometimes subsidized—one example is flood insurance, which is often nationally provided and subsidized. Such support programs however might need to be carefully rethought to balance support to vulnerable stakeholders with allowing appropriate risk signals in the context of growing exposure and multiple knock-on effects. One answer might be providing voucher programs to help ensure affordability for vulnerable populations, while maintaining premiums at a level that reflects the appropriate

[47] Goetz von Peter, Sebastian von Dahlen, and Sweta Saxena, *Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes*, BIS Working Papers, Number 394, December 2012.

risk. Trade-offs between private and public insurance, and for individuals, between when to self-insure or buy insurance, will need to be carefully evaluated. In addition, underwriting may need to shift to drive greater risk reduction in particularly vulnerable areas (for example, new building codes or rules around hours of working outside). This is analogous to fire codes that emerged in cities in order to make buildings insurable. Insurance may also need overcome a duration mismatch; for example, homeowners may expect long-term stability for their insurance premiums, whereas insurers may look to reprice annually in the event of growing hazards and damages. This could also apply to physical supply chains that are currently in place or are planned for the future, as the ability to insure them affordably may become a criterion of growing significance.

Mobilizing finance to fund adaptation measures, particularly in developing countries, is also crucial. This may require public-private partnerships or participation by multilateral institutions, to prevent capital flight from risky areas once climate risk is appropriately recognized. Innovative products and ventures have been developed recently to broaden the reach and effectiveness of these measures. They include "wrapping" a municipal bond into a catastrophe bond, to allow investors to hold municipal debt without worrying about hard-to-assess climate risk. Governments of developing nations are increasingly looking to insurance/reinsurance carriers and other capital markets to improve their resiliency to natural disasters as well as give assurances to institutions that are considering investments in a particular region.

– **Addressing tough adaptation choices.** Implementing adaptation measures could be challenging for many reasons. The economics of adaptation could worsen in some geographies over time, for example, those exposed to rising sea levels. Adaptation may face technical or other limits. In other instances, there could be hard trade-offs that need to be assessed, including who and what to protect and who and what to relocate. For example, the impact on individual home owners and communities needs to be weighed against the rising burden of repair costs and post-disaster aid, which affects all taxpayers

  Individual action will likely not be sufficient in many interventions; rather, coordinated action bringing together multiple stakeholders could be needed to promote and enable adaptation. This may include establishing building codes and zoning regulations, mandating insurance or disclosures, mobilizing capital through risk-sharing mechanisms, sharing best practices within and across industry groups, and driving innovation. Integrating diverse perspectives including those of different generations into decision making will help build consensus.

Decarbonizing at scale

An assessment and roadmap for decarbonization is beyond the scope of this report. However, climate science and research by others tell us that the next decade will be decisive not only to adapt to higher temperatures already locked in but also to prevent further buildup of risk through decarbonization at scale.[48] Stabilizing warming (and thus further buildup of risk) will require reaching net-zero emissions, meaning taking carbon out of future economic activity to the extent possible, as well as removing existing CO_2 from the atmosphere to offset any residual hard-to-abate emissions (that is, achieving negative emissions).[49] An important consideration in this context is that climate science also tells us a number of feedback loops are present in the climate system, such as the melting of Arctic permafrost, which would release significant amounts of greenhouse gases. If activated, such feedback loops could cause significant further warming, possibly pushing the Earth into a "hot house" state.[50] Scientists estimate that restricting warming to below 2 degrees Celsius would reduce the risk of initiating many of the serious feedback loops, while further restricting warming to 1.5 degrees Celsius would reduce the risk of initiating most of them.[51] Because warming is a function of cumulative emissions, there is a specific amount of CO_2 that can be emitted before we are expected to reach the 1.5- or 2-degree Celsius thresholds (a "carbon budget").[52] Scientists estimate that the remaining 2-degree carbon budget of about 1,000 $GtCO_2$ will be exceeded in approximately 25 years given current annual emissions of about 40 $GtCO_2$.[53] Similarly, the remaining 1.5-degree carbon budget is about 480 $GtCO_2$, equivalent to about 12 years of current annual emissions. Hence, prudent risk management would suggest aggressively limiting future cumulative emissions to minimize the risk of activating these feedback loops. While decarbonization is not the focus of this research, decarbonization investments will need to be considered in parallel with adaptation investments, particularly in the transition to renewable energy. Stakeholders should consider assessing their decarbonization potential and opportunities from decarbonization.

[48] Christina Figueres, H. Joachim Shellnhuber, Gail Whiteman, Johan Rockstrom, Anthony Hobley, & Stefan Rahmstorf, "Three years to safeguard our climate". Nature. June 2017.

[49] Jan C. Minx et al. (2018) "Negative emissions – Part 1: Research landscape and synthesis." *Environmental Research Letters*. May 2018, Volume 13, Number 6.

[50] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences*, August 2018, Volume 115, Number 33; M. Previdi et al. "Climate sensitivity in the Anthropocene." *Royal Meteorological Society*, 2013. Volume 139; Makiko Sato et al. "Climate sensitivity, sea level, and atmospheric carbon dioxide." *Philosophical Transactions of the Royal Society*, 2013. Volume 371.

[51] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences*, August 2018, Volume 115, Number 33; Hans Joachim Schellnhuber, "Why the right goal was agreed in Paris," *Nature Climate Change*, 2016, Volume 6; Timothy M. Lenton et al., "Tipping elements in the Earth's climate system," *Proceedings of the National Academy of Sciences*, March 2008, Volume 105, Number 6; Timothy M. Lenton, "Arctic climate tipping points," *Ambio*, February 2012, Volume 41, Number 1; Sarah Chadburn et al., "An observation-based constraint on permafrost loss as a function of global warming," *Nature Climate Change*, April 2017, Volume 7, Number 5; and Robert M. DeConto and David Pollard, "Contribution of Antarctica to past and future sea-level rise," *Nature*, March 2016, Volume 531, Number 7596.

[52] This budget can increase or decrease based on emission rates of short-lived climate pollutants like methane. However, because of the relative size of carbon dioxide emissions, reducing short-lived climate pollutants increases the size of the carbon budget by only a small amount, and only if emission rates do not subsequently increase; H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1.

[53] Richard J. Millar et al., "Emission budgets and pathways consistent with limiting warming to 1.5°C," *Nature Geoscience*, 2017, Volume 10; Joeri Rogelj et al., "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature*, July 2019, Volume 571, Number 7765.

Box E3

Questions for individual stakeholders to consider

All stakeholders can respond to the challenge of heightened physical climate risk by integrating it into decision making. Below we outline a broad range of questions that stakeholders may consider as they prepare themselves and their communities for physical climate risk, based on their risk exposure and risk appetite. Stakeholders may fall into one or more categories (for example, a nonfinancial corporation may also conduct investment activities).This list is not exhaustive and the implications of the changing climate will prompt others.

Insurers

- Should we continue to invest in forward-looking climate-related modeling capabilities in order to better price climate risk in insurance products and quantify value at risk from climate change in today's portfolio and future investments?
- Could we further drive innovations in insurance products, for example by developing new parametric insurance products that can help reduce transaction costs in writing and administering insurance policies, and by considering coverage caps and public-private partnerships?
- Could we offer risk advisory services to complement standard insurance products including educating target communities on the present and future risks from climate change and developing tool kits for building adaptation and resilience?
- What are possible new measures and incentives to encourage risk-reducing behavior, for example by rewarding implementation of adaptation measures such as hardening physical assets?
- Where insurance can help reduce risk without inducing buildup of further exposure, how can we work with reinsurers, national insurance programs, governments, and other stakeholders to make coverage affordable (for example, crop insurance for smallholder farmers)?

Investors and lenders

- How could we use recommendations of the Task Force on Climate-related Financial Disclosures to develop better risk management practices?[1] Should investees and borrowers be encouraged to make appropriate financial disclosures of climate risk in order to increase transparency?
- How could we integrate climate risk assessments into portfolio allocation and management decisions, including via stress tests and quantifying climate value at risk (VAR) in portfolios using probabilistic forward-looking models that reflect physical climate risk, based on the best available science?
- Is it possible to incorporate climate risk into new lending and investment activity by understanding its potential impact on different geographies and on loans and investments of differing durations, and then adjusting credit policies to reflect VAR for future investments?
- What opportunities exist for capital deployment in sectors and product classes with increasing capital need driven by higher levels of climate change, such as resilient infrastructure bonds?
- In what innovative ways could capital be deployed to fill the growing need for adaptation, especially in areas where business models currently do not provide an operating return (for example, marrying tourism revenues to coral reef protection, providing long-term finance for wastewater treatment systems tied to flood cost reduction, or developing country adaptation funds, possibly with risk-sharing agreements with public financial institutions)?
- How could we best educate debtors on current and future climate risks, including developing tool kits and data maps to help build investee information and capabilities?

Regulators, rating agencies, and central banks

- What could be appropriate measures to increase risk awareness (for example, providing guidance on stress testing, supporting capability building on forward-looking models, or supporting risk disclosures)?
- How could we encourage sharing of best practices across private-sector entities, for example through convening industry associations or publishing risk management tool kits?
- How could we help manage the risk of discontinuous movement of capital, or "capital flight," based on climate change, including considering whether and how to adjust the sovereign risk ratings of low-income, highly climate-exposed countries?

[1] *Final report: Recommendations of the Task Force on Climate-related Financial Disclosures*, Task Force on Climate-related Financial Disclosures, June 2017.

Companies outside the financial sector

- What opportunities exist to convene the industry around physical risk, including by building knowledge that is sector- and region-specific?

- How could we incorporate a structured risk-management process that enables good decision making and integrates an assessment of physical and transition climate risk into core business decisions (for example, sourcing, capital planning, and allocation decisions)?

- How might climate change affect core production (risk of disruption or interruption of production, increased cost of production factors); sourcing and distribution (risk of disruption of the upstream supply chain or the downstream distribution, delaying or preventing inflow of inputs and distribution of goods, increasing costs or reducing product prices); financing and risk management (risk of reduced availability or increased cost of financing, insurance, and hedging); and franchise value (risk of declining value of investments and goodwill, disruption of right to operate or legal liabilities)? What business model shifts will be needed?

- How big and urgent are the most relevant climate change risks and what countermeasures should be taken to adapt to and manage them, based on risk appetite (for instance, if risks to sourcing of inputs have been recognized, identifying alternate suppliers or raising inventory levels to create backup stock; or if climate exposure is expected to drive market shifts or impact terminal value of assets, reallocating growth investment portfolio)?

Governments

- How could we integrate an understanding of physical climate risk into policy and strategic agendas especially around infrastructure and economic development planning, including by investing in probabilistic future-based modeling of physical climate impact?

- How could we best address areas of market failure and information asymmetry in the community (for example, making hazard maps readily available, providing adaptation finance directly to affected communities) and agency failures (for instance, in flood insurance)?

- Based on assessments of risk and cost-benefit analysis, how could we plan and execute appropriate adaptation measures, especially physical hardening of critical assets such as public infrastructure? How to think about measures that involve difficult choices—for example, when to relocate versus when to spend on hardening?

- How could we integrate diverse voices into decision making (for example, using public forums or convening local communities) to support more effective adaptation planning, and help identify and reduce distributional effects (for example, unexpected costs of adaptation measures on neighboring communities)?

- How could we best ensure financial resilience to enable adaptation spending and support disaster relief efforts, including drawing on global commitments and multilateral institutions, and collaborating with investors and lenders?

- Do we need to play a role in the provision of insurance, including potential opportunities for risk pooling across regions, and if so, where?

Individuals

- Am I increasing my personal and peer education and awareness of climate change through dialogue and study?

- Do I incorporate climate risk in my actions as a consumer (for example, where to buy real estate), as an employee (for instance, to inform corporate action), and as a citizen?

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Economic Research:

Why It May Make Economic Sense To Tackle Global Warming

Dec 05, 2018

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Key Takeaways

- Global warming of 3 degrees C. is likely to cost us 2% of global output. It is set to affect emerging and developing economies much more than developed ones.
- Uncertainty about the costs of climate change and its characteristics of a global public good, which give rise to the free-rider problem, explain why policymakers and market participants have not done enough to cut carbon emissions.
- Putting a global price tag on carbon would be the first best solution to fight global warming. Because of coordination problems, our second-best option is therefore change initiated at regional, country, and local levels--as well as by markets.
- Capital allocation toward green investment may be considered as a competitive differentiator in portfolios and a strategy to achieve sustainable business models.
- Technological hurdles are impeding a quick shift to a low-carbon economy, suggesting investment in this space is set to grow in importance and will likely be met by public support.

Climate change is no longer a problem for the future. It has already started to alter the functioning of our world. Every year seems to bring more climate-related shocks--such as floods, hurricanes, harsh winters, and hotter summers--that weigh on economic activity. As temperatures climb, the occurrence of natural disasters is set to rise: Recent research shows that under business-as-usual carbon emissions, the risk of extreme heatwaves and floods is likely to increase by 50% this century (Mann et al., 2018). This means the global economy will increasingly have to cope with the consequences of global warming.

The latest United Nations Climate Change Conference, COP24, is bringing together experts and policymakers over the next two weeks (Dec. 2-14) to assess progress toward implementing the 2015 Paris Agreement and mitigating global warming. A recent report by the U.N.'s Intergovernmental Panel on Climate Change (IPCC) shows that global warming is already affecting our lives and that limiting global warming to 1.5 degrees Celsius is becoming increasingly unrealistic. Here, we look at the economic implications of climate change, why progress in reducing our emissions has been slow, and ways policymakers and markets can still act to mitigate global warming.

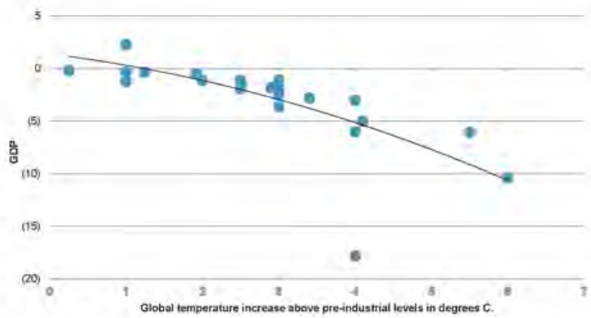
The Cost Of Inaction Rises Along With Global Warming

Research shows that global warming is costly. More frequent extreme weather events that damage infrastructure will lead to faster capital depreciation. This will lower the rate of return on these investments and thus the incentives for capital accumulation. Increased temperatures are set to affect the labor supply through higher heat-related morbidity and mortality, as well as weigh on workers' productivity, as hotter days tend to be associated with a reduction in working hours.

Putting all these factors together, studies find that global warming of 3 degrees C., which is the estimated trajectory based on countries' current pledges since 2015, would lower global output by 2%. Warming of 6 degrees C., which is slightly above upper estimates of the business-as-usual carbon emissions scenario, would push global output 8% lower (Nordhaus and Moffat 2017). Granted, current estimates are rough, given the large number of assumptions needed to model climate change. This suggests we might even be underestimating the costs of climate change. Yet, one robust result is that the higher the temperature, the more damaging climate change will be--and in a nonlinear way (see chart 1).

Chart 1 | Download Chart Data

Estimates Of The Impact Of Global Warming On Output Suggest The Cost Of Climate Change Rises With Temperatures
Note: Data points show estimates of the impact of global warming on global output from a number of studies

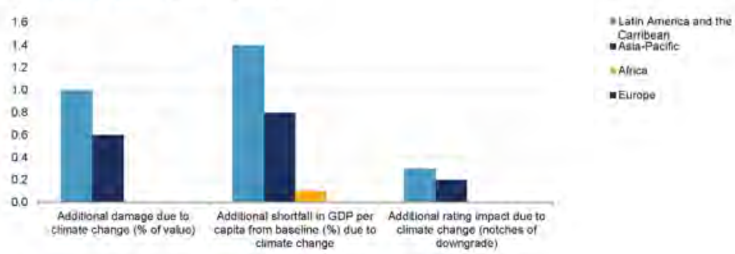


Sources: Nordhaus and Moffat, 2017: "A Survey of Global Impacts of Climate Change: Replication, Survey Methods, And a Statistical Analysis," S&P Global Ratings.

Studies also find that climate change will not be uniform across countries and thus have important distributional effects. Emerging and developing economies in the Caribbean, Asia, and Africa are most exposed to climate change (see charts 2 and 3). By contrast, advanced economies will suffer less from global warming. This is not only because they are better prepared than emerging or developing economies, but also because they are located in colder regions today. This wealth redistribution is likely to exacerbate migration flows to wealthier regions, putting pressure on land use and social systems.

Chart 2 | Download Chart Data

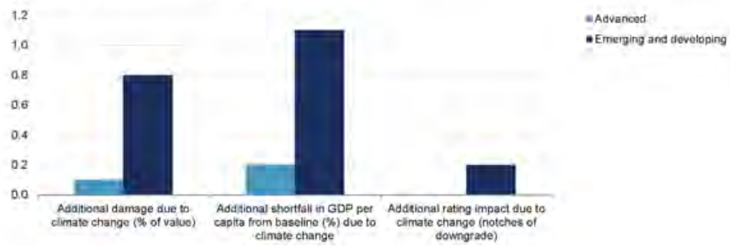
Average Impact Of Climate Change, By Region



Source: "The Heat Is On: How Climate Change Can Impact Sovereign Ratings," S&P Global Ratings, Nov. 25, 2015.

Chart 3 | Download Chart Data

Average Impact Of Climate Change, By Income Group



Source: "The Heat Is On: How Climate Change Can Impact Sovereign Ratings," S&P Global Ratings, Nov. 25, 2015.

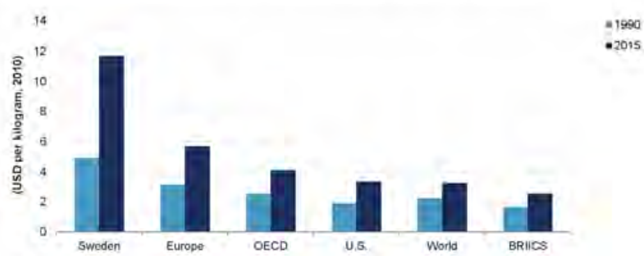
Climate change also represents a challenge for policymaking as it raises uncertainty about the state of the economy. In the long term, its costs are a clear downside risk to growth but also a source of increased volatility. As extreme weather events occur more often, they will also damage economic activity in a nonpredictable way. In the short term, policymakers will have more trouble disentangling the effects of climate change from the effects of other policies on the underlying state of the economy. For example, statisticians have struggled to identify seasonality in first-quarter U.S. GDP numbers linked to colder winters.

So Why Have We Done So Little To Lower Carbon Emissions?

Although it is clear that the cost of inaction rises with higher temperatures, the world has struggled to lower carbon emissions (see chart 4). Limiting global warming to 1.5 degrees C. now seems almost out of reach. According to the latest IPCC report, it would imply lowering carbon emissions to net zero by 2050. So why have we struggled to tackle global warming?

Chart 4 | Download Chart Data

The World's CO2 Productivity Improved Only 46% Over The Past 25 Years, While Output Doubled
Production-based CO2 productivity, GDP per unit of energy-related CO2 emissions



Sources: OECD, S&P Global Ratings. BRIICS--Brazil, Russia, India, Indonesia, China, South Africa.

One big hurdle is that its cost remains uncertain and the worst effects will occur in the future, once they are irreversible. This makes it difficult to compute the opportunity cost for acting now. If we discount the future too much, there is little ground for action today. The Trump Administration's announcement to withdraw from the Paris Agreement even suggests that some see no need to redirect resources toward greener energy to mitigate climate change or lead climate initiatives that carry significant economic benefits.

Another issue, which explains why policymakers have struggled to coordinate globally, is that climate change has all the characteristics of a global public good. A country has little incentive to change its behavior on its own since emissions are diffuse across borders and reducing them is costly, giving rise to the free-rider problem. For some policymakers, the worry is that firms might relocate their activity to countries with weaker environmental standards. Meanwhile, though they are the most affected by climate change, developing countries have less funds available to fight against it and may prefer to target other priorities, such as reducing poverty.

Meanwhile, the market on its own is unlikely to reach an optimal equilibrium, because most consumers and companies do not directly feel or internalize the cost of climate change. Although global warming is increasingly affecting consumers and firms through more frequent floods, hurricanes, and wildfires, it still comes with problems of attribution. It remains unclear that all of the impact is due to climate change. What's more, only a small number bear the costs, which are massive. The others do not feel the consequences of global warming and are more worried that a switch to greener spending may hurt their purchasing power or profits. In short, without a nudge or fiscal incentives, private consumption and activity will not actively seek to mitigate the impact of higher emissions on climate change.

A Few Avenues To Mitigate The Cost Of Inaction

Putting a global price tag on carbon would be the most efficient way to reduce carbon emissions. Taxing carbon or limiting its use would ensure that firms and consumers internalize the cost of global warming today. This is also the recommendation of policy experts (for example at IPCC, OECD, World Bank, and International Monetary Fund). The High-Level Commission on Carbon Prices recommends a carbon price of USD50-USD100 per ton of CO_2 by 2030 to achieve the Paris Agreement goal. However, the coordination problems we have outlined above have made it difficult to put that into place.

The second-best approach is to initiate change at other regional, country, or local levels. Importantly, this gives countries more flexibility to design policy in line with their priorities and constraints, and removes the difficulty of reaching a global compromise. In terms of carbon pricing, this is where most progress has happened so far. Finland and Poland put a carbon tax in place in 1990, the EU created the first Emission Trading System (ETS) in 2005, and other jurisdictions have replicated these efforts since then. With China set to put its ETS in place in 2020, the World Bank estimates that all regional, national, and supranational initiatives will cover about 20% of global emissions. The next step toward a global carbon price would be for countries that have already established an ETS to link them together--similar to the current Swiss-EU initiative. While this is a big improvement, this is far from a global carbon tax.

Beyond carbon pricing, policymakers have many other ways to support a greener economy. They can foster greener investments and behaviors through fiscal policy, regulation, increased awareness by civil society and more climate-friendly public infrastructure. If well-designed, those policies can provide immediate economic and social benefits. To name a few, decreasing the reliance of an economy on fuel reduces its exposure to oil-price shocks; switching to less-polluting cars provides direct health benefits; and better-insulated homes reduce the energy bill for households.

Investing in resilience to climate change in the most exposed regions can help smooth the distributional effects of global warming. It can also be an immediate source of growth, as those regions tend to be less developed. Given that developing countries have tighter budget constraints, developed countries could think of green development aid.

Markets also have a role to play in climate change mitigation. As the cost of global warming is increasingly visible and rising, it is only rational for markets to start pricing its cost. All other things being equal, companies that integrate environmental goals in their strategy are more likely to achieve sustainable long-term value creation, especially if environmental regulation goes into a similar direction. In some industries, energy also represents an important proportion of operating costs, meaning gaining in energy efficiency may lead to productivity gains. With consumers and investors becoming more aware of the consequences of climate change, there is also a case for providing "environmentally friendly" alternatives. Indeed, we can see that there is increased demand for such instruments from the fast-growing green bonds market, which may surpass $200 billion in 2018, after reaching $160 billion in 2017 (see "Untapped Potential: How The Green Economy Is Broadening," published on Nov. 5, 2018). Interestingly, more than 90% of labeled green bonds have been rated investment grade.

Taking Advantage Of Sustainable Investment

As global decarbonization intensifies, so too has awareness about "green" investment--that is, investment considered environmentally beneficial. This kind of capital allocation may be considered a competitive differentiator in portfolios due to the potential for assets with improved cash flow, greater risk mitigation, and a more sustainable business model in the long term.

Against this backdrop, we have seen a plethora of diverse industries--many from traditionally "nongreen" sectors, including metals, mining, petrochemicals, heavy industry, energy, and power--looking to broaden sustainability strategies. What's driving development? In part, greater awareness of climate risks by corporates, investors, and wider society that has been an outgrowth of national and regional climate initiatives.

China's recent surge of investment into clean energy and sustainability initiatives signals an acceleration of the country's agenda to become a green superpower. It already accounts for nearly 71% of global production of solar panel technology and manufactures more lithium ion batteries than any other country in the world. China's greening policies, an integral part of the country's transformative Belt and Road Initiative, could represent an acknowledgement of the role that sustainable investment plays in attracting foreign capital. Indeed, the country's energy and climate goals for 2015 to 2020 are estimated to require between US$480 billion and US$640 billion of investment. And by 2040, China plans to have invested in excess of US$6 trillion into low-carbon power generation and clean technologies, which, if fulfilled, could far exceed that of many EU countries and even the U.S. (see "Greener Pastures: China Cuts A Path To Becoming A Green Superpower," published on Nov. 5, 2018).

Such ambitious and publicized targets emanating from China have fostered rivalry in other corners of the globe. This, combined with the Trump Administration's announcement to withdraw from the Paris Agreement, have sparked concerns in the U.S. that technological developments will stall in a more isolationist environment. Yet hope for the U.S. remains in the form of state-led initiatives. This September, Jerry Brown, Governor of California, formally announced the state's commitment to achieving a carbon-neutral economy. To this end, he signed SB 100, a mandate to set California on a path to deriving 100% of its power from clean sources by 2045, up from today's figure of 35%. California now also boasts a carbon-trading system that includes transport fuels and a low-carbon fuel standard, both of which are likely to promote development of advanced biofuels and associated technologies. California represents the largest state in the U.S. by population and economic output, and other states are following suit, introducing heightened renewable standards, implementing energy efficiency targets, and developing decarbonizing technologies, though, for the moment, these initiatives are largely clustered on the West Coast and in the northeastern part of the country.

The EU-wide goal of reducing CO_2 emissions by 40% compared to 1990 levels by 2030 has served to raise the profile of global sustainability efforts. Even oil-rich Norway has been looking to decarbonize further, tightening its standards with a focus on its transportation sector, where there is still room for improvement.

Technological Disruptors And Moving Forward

For both private investors looking to diversify their portfolios and governments looking to fight global warming, investment in low-carbon and renewable energy sources will likely grow in importance. If low-carbon projects and renewables are to proliferate, the energy supply needs to be guaranteed. To provide vital backup to the grid and bridge supply shortfalls during intermittent weather, energy storage via batteries will need to improve and become commonplace. But there is still some way to go, suggesting there might be a case for increased public support for the technology. For example, storage capabilities would have to increase 200-fold to meet California's renewables target. But once capacity increases, growth could be exponential. And as renewables technology advances, forecasts can be benchmarked against real operating performance, providing more clarity and data, and ultimately encouraging increased investor appetite for renewables assets.

Overcoming technological hurdles and navigating complex political and regulatory environments are imperative for green investment to continue to grow. Low-carbon power projects reside at the intersection of economics and politics, where the continued deployment of energy technologies will require ongoing access to capital markets. Even with improved economics, this will require a higher level of transparency about the performance and cost of these assets. This may be an expensive proposition in the short term but one that may well pay off in the future.

Related Research

S&P Global Ratings

- Greener Pastures: China Cuts A Path To Becoming A Green Superpower, Nov. 19, 2018
- Untapped Potential: How The Green Economy Is Broadening, Nov. 5, 2018
- Paris Agreement Climate Pledges: Where Will The Money Come From? Nov. 6, 2017
- Climate Finance A Year After Paris: Driving Politics Into Action, Nov. 8, 2016
- The Heat Is On: How Climate Change Can Impact Sovereign Ratings, Nov. 25, 2015
- Paris Agreement: A New Dawn For Tackling Climate Change, Or More Of The Same? Jan. 18, 2016

- Reversing Global Warming Requires Nothing Less Than A Global Effort, Nov. 16, 2015

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- Mann et al. (2018): "Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification," Michael E. Mann, et al., Science Advances, Vol. 4, No. 10, Oct. 31, 2108
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This report does not constitute a rating action.

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GLOBAL INSIGHTS • APRIL 2019

Getting physical

Scenario analysis for assessing climate-related risks

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Introduction

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A series of recent extreme weather events – from hurricanes and wildfires in the U.S. to heat waves in Europe and floods in Japan – have put a spotlight on climate-related risks. Yet the implications for investment portfolios – stemming from a rising frequency and intensity of such events – have been notoriously hard for investors to grasp.

Why? First, the effects of slower-moving physical changes such as rising sea levels can seem distant. This causes investors to discount pressing climate-related risks already lurking in portfolios. Second, the risks are hard to model. New climate patterns mean long-dated historical data are a poor guide to the future. Investors using models overly reliant on the past are missing the big picture. Third, the risks have been hard to pinpoint. Drilling down on physical risk to the exact geographical location and asset level is key for investors – think of potential damage to commercial real estate or electric power plant facilities. But analyzing huge amounts of climate data properly and effectively is a challenge.

The good news: Recent advances in climate and data science make it easier to overcome these hurdles and separate the signal from the noise. BlackRock's collaboration with Rhodium Group combines our asset-level expertise with the latest climate science and big-data capabilities. The result – generating some 160 terabytes of data – is a granular picture of investment-relevant physical climate risks. We can now assess direct physical risks to assets on a local level – today and under different future climate scenarios. We can also estimate knock-on effects, such as the impact on energy demand, labor productivity and economic activity.

These tools give us unique insight into the severity, dispersion and trajectory of climate-related risks. This helps us assess whether the risks are adequately priced by markets. Our early findings suggest investors must rethink their assessment of vulnerabilities. Weather events such as hurricanes and wildfires are underpriced in financial assets, including U.S. utility equities. A rising share of municipal bond issuance is set to come from regions facing climate-related economic losses. And many high-risk commercial properties are outside official flood zones.

Understanding and integrating these insights on climate-related risks can help enhance portfolio resilience, we believe. Our first step focuses on assets and companies in the U.S. We plan to extend the analysis across regions, asset classes and sectors as data availability improves. Yet our early work already strengthens our conviction that sustainable investing is increasingly a *"why not?"* proposition.

CONTENTS

Summary

- **We show how physical climate risks vary greatly by region, drawing on the latest granular climate modeling and big data techniques.** We focus on three sectors with long-dated assets that can be located with precision: U.S. municipal bonds, commercial mortgage-backed securities (CMBS) and electric utilities. Hurricanes pose a threat to the finances of southern U.S. states; rising sea levels make coastal real estate vulnerable; and power plants in the Southwest have exposure to extreme heat. A localized assessment of such risks under different climate scenarios can provide investors with 1) a sharp lens for risk management and diversification; and 2) an informed basis for engaging with companies and issuers about their climate resiliency and capital spending plans.
- **Extreme weather events pose growing risks for the credit worthiness of state and local issuers in the $3.8 trillion U.S. municipal bond market.** We translate physical climate risks into implications for local GDP – and show a rising share of muni bond issuance over time will likely come from regions facing economic losses from rising average temperatures and related events. Some 58% of metropolitan areas face climate-related GDP hits of 1% or more by 2060–2080 under a "no climate action" scenario, we find. We zoom in on the highest risk areas – and explain the importance of assessing muni issuers' resolve and financial ability to fund adaptation projects to mitigate climate risks. We see potential to extend this analysis to sovereign issuers, including emerging markets.
- **Hurricane-force winds and flooding are key risks to commercial real estate.** Our analysis of recent hurricanes hitting Houston and Miami finds that roughly 80% of commercial properties tied to affected CMBS loans lay outside official flood zones – meaning they may lack insurance coverage. This makes it critical to analyze climate-related risks on a local level. We show how the economic impacts of a warming climate could lead to rising CMBS loan loss rates over time.
- **Aging infrastructure leaves the U.S. electric utility sector vulnerable to climate shocks such as hurricanes and wildfires.** We assess the exposure to climate risk of 269 publicly listed U.S. utilities based on the physical location of their plants, property and equipment. A key conclusion: The risks are underpriced. Electric utilities with exposure to extreme weather events typically suffer temporary price and volatility shocks in the wake of natural disasters. We find some evidence that the most climate-resilient utilities trade at a premium. We believe this premium could increase over time as the risks compound and investors pay greater attention to the dangers.

AUTHORS

   

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Setting the scene

We explain how changes to the climate – and related extreme weather events – pose tangible risks to investment portfolios today, not just years in the future.

The climate is changing, societies are adapting, and technologies are catching up. This dynamic creates risks and opportunities for investors. The implications of climate change are playing out across four key channels: physical, technological, regulatory and social. See BlackRock's ***Adapting portfolios to climate change*** of 2016 for more. Advances in data and analytics now give us growing conviction in our ability to measure and manage these key risks.

In this piece we go deep on physical risk. Increasing global temperatures are leading to measurable changes in our habitat, such as rising sea levels, droughts, wildfires and storms. The trend of rising average temperatures is boosting the frequency at which extreme weather events occur, as well as their intensity. These changes are affecting our economy *today*.

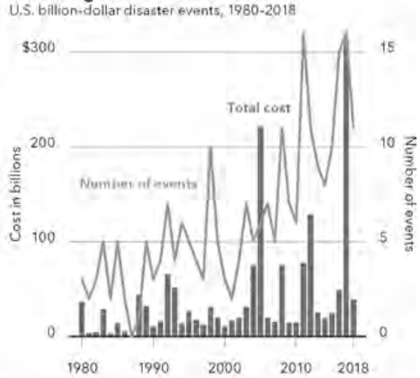
The implications for investors go beyond coastal real estate. Think of agriculture (crop yields), insurance (property and casualty premiums) and electric utilities (risks to plants; peak electricity demand). The damage from storms, floods and heat waves can also disrupt corporate supply chains – and pressure public finances, posing risks to municipal and sovereign bond holders.

The number of natural disasters causing $1 billion-plus in damages has been on a steady rise, as shown in the *Mounting costs* chart. Related insurance claims hit a record $144 billion in 2017, but with much of the exposure uninsured, losses totaled $337 billion, according to 2018 ***Swiss Re data***. The data show wildfires caused a record $21 billion of damage globally in 2017, while a trio of hurricanes – Harvey, Maria and Irma – caused losses equivalent to 0.5% of U.S. GDP. This highlights a risk to investors. The rising incidence of extreme weather events over time could lead to spiking property and casualty insurance premiums, and reduced or even denied coverage if insurers shy away from underwriting risks that have become too great or uncertain. Investors need to get ahead of these risks.

We combine our asset-level expertise and cutting-edge climate modeling from Rhodium's work with a consortium of scientists and data experts to examine how the risks look today – and how they may evolve over time under different climate scenarios. See Rhodium's paper ***Clear, Present and Underpriced: The Physical Risks of Climate Change*** for a summary of its approach.

The climate modeling and data we purchased from Rhodium allow us to assess direct physical risks such as probabilities of flooding and hurricane-force winds – on a localized level across the U.S. This helps us estimate potential direct financial damages, as well as knock-on effects such as the impact of rising temperatures on crop yields or labor productivity. ***See page 7*** for details. We refer to these direct physical impacts and their indirect economic impacts collectively as climate-related risks. Many of the vulnerabilities are local. Example: Infrastructure on the U.S. Gulf Coast is at risk from wind and storm surge damage by hurricanes. Communities in the U.S. West are increasingly at risk from wildfires.

Mounting costs
U.S. billion-dollar disaster events, 1980-2018



Sources: BlackRock Investment Institute, with data from NOAA National Center for Environmental Information NCEI, October 2018. Notes: The line shows the number of climate events with losses exceeding $1 billion. The data include droughts, flooding, severe storms, tropical cyclones, wildfires, winter storms and freezes. The bars show the total cost. The data are adjusted for inflation using 2018 dollars.

Climate complacency

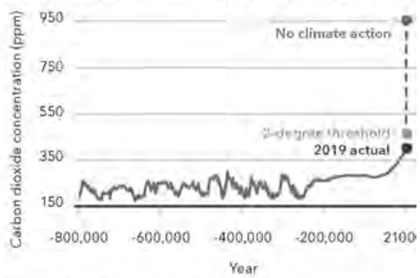
One of the most striking implications of our work drawing on the latest climate research: How much more pronounced the risks are today, compared with just a few decades ago. The risks that hurricanes pose to commercial properties, for example, have increased meaningfully, we find. *See page 13* for details. Investors who are not thinking about climate-related risks, or who view them as issues far off in the future, may need to recalibrate their expectations. Some physical changes – such as slowly rising sea levels – can seem outside of a traditional investment horizon. Yet the most pressing risks, such as exposure to hurricanes, wildfires and droughts, are clear and present – and often hidden in investors' portfolios *today*.

Our research suggests many of these risks are not priced in. Why? First, financial markets tend to be short-sighted – and underestimate risks that appear uncertain and distant. This may lead to a discounting of physical risks that are already biting. Second is a lack of tools and data. Example: Risk managers often rely on outdated flood zone maps to assess risks to real estate. Short-sighted policy and regulatory requirements can exacerbate this problem. Hurricane modelers look at 100 years of history to gauge future risks. But data prior to 1980 are patchy. And the past is of limited use as a guide to the future when averages (global temperatures and hurricane probability) are rising over time. Consider that Houston has seen three "one-in-500-year" flooding events since 2015, Houston's Harris County Flood Control District said in 2017. Bottom line: Looking backward over long periods results in underpricing the financial impact of climate-related risks.

Physical climate models can help fill the gap – and provide a more accurate assessment of the probability of a range of extreme weather events occurring in any given year. The challenge: Climate modeling is an evolving science. Different models point to different outcomes, with wide bands of uncertainty. Standard approaches to valuing the effects of rising global temperatures look at average predicted impacts for large regions – sometimes the entire globe. Yet recent computational advances make it possible for us to analyze the risks on a localized level.

Hockey stick

Global atmospheric concentration of CO_2, 800,000 B.C.–2100



Sources: BlackRock Investment Institute, with data from the U.S. Environmental Protection Agency, March 2019. Notes: The chart shows the concentration of carbon dioxide in the atmosphere over time, measured in parts per million (ppm). The data until 1950 are from historical ice core studies from the European Project for Ice Coring in Antarctica project. Post-1959 numbers are direct measurements taken at Mauna Loa, Hawaii. The 2019 actual data point is as of January 31. The 2-degree threshold is the CO_2 concentration at which global average temperatures are predicted to rise by 2°C from pre-industrial levels by end-century, as estimated by the IPCC. The "no climate action" scenario assumes ongoing use of fossil fuels and a CO_2 concentration of 940 parts per million (ppm) by 2100.

Hot today; hotter tomorrow

Scientists have long cited a clear linear relationship between the level of carbon dioxide (CO_2) in the atmosphere and warmer temperatures (the "greenhouse effect"). Temperatures over land and ocean have already gone up an average 1.2°C (2.2°F) since the mid-1800s, and significantly more at the Earth's poles, according to data from the National Oceanic and Atmospheric Administration (NOAA). CO_2 concentrations in the atmosphere are at a higher level than they have been for the past 800,000 years. See the *Hockey stick* chart.

How much warming can the Earth tolerate before experiencing the most destructive effects of climate change? The threshold of 2 degrees Celsius (3.6 °F) above "preindustrial" temperature levels rings alarm bells for many scientists. Recent trends in emissions suggest the 2-degree threshold is unlikely to hold. See the green dot in the chart. A "no climate action" trajectory (the orange dot) assuming ongoing use of fossil fuels would lead to a roughly 4°C (7°F) increase in average global temperatures by 2100, according to the Intergovernmental Panel on Climate Change (IPCC). Uncertainty around the path of carbon emissions means it is prudent to consider alternative scenarios when assessing climate-related risk. *See page 7* for more.

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Investment applications

We detail our framework for assessing climate-related risks under different scenarios – and pinpoint the potential risks to assets across the U.S.

The physical risks posed by climate change were tough to model until recently. Advances in big data and cloud computing now enable us to zoom in on these risks on a 20 km (12 miles) by 20 km level across the U.S. We present a snapshot of our evolving research in this paper. It draws on Rhodium's work with the *Climate Impact Lab*, combining historical climate and socioeconomic data with physical climate modeling. This work – a collaborative project between data gurus, econometricians and climate scientists – leverages millions of simulations. Our efforts to apply the data to U.S. assets required 600,000 hours of CPU processing power – and generated 160 terabytes of data – the equivalent of 120 million 1980's-era 3.5 inch floppy disks.

The analysis includes knock-on impacts of rising average temperatures. Many such effects are non-linear. Corn yields, for example, start to drop sharply when daily high temperatures exceed 84°F (29°C). And electricity demand tends to follow a U-shape, rising at extreme low and high temperatures. See the *Turning points* charts.

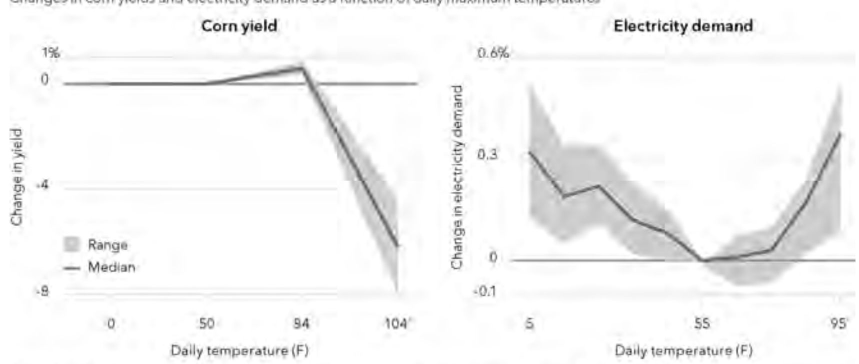
The focus of our initial work is U.S. municipal bonds (*pages 10-12*), CMBS (*pages 13-14*) and electric utility equities (*pages 15-17*). The reason: These asset classes are backed by long-duration physical assets of known location. We start by assessing the risks to these asset classes today. Too often, assessments of physical climate risk start by looking decades into the future. This overlooks risks that are already present.

How to gauge the related risks on assets? Our process:

1. Determine which assets have a readily identifiable physical location (e.g., properties of CMBS loans).
2. Overlay the asset locations with climate data to assess exposures to relevant direct physical risks such as hurricanes – today and in the future.
3. Link climate data to relevant second-order financial and socioeconomic implications.
4. Analyze if these risks are priced in and/or insured, and determine if the company/issuer has the resolve and financial capacity to adapt.

Turning points

Changes in corn yields and electricity demand as a function of daily maximum temperatures



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The ranges shown are the 95% confidence interval (two standard deviation range). All analysis is from Rhodium Group. Corn estimates draw on county-level U.S. agricultural production data from the U.S. Department of Agriculture over 1950-2005 to identify the relationship between temperature changes and average yields, using the methodology of *Schenkler and Roberts (2009)*. Electricity demand draws on two studies measuring the effect of climate variables on energy demand: *Deschenes and Greenstone (2011)* examine state-level annual electricity demand from 1968 to 2002 using data from the U.S. Energy Information Adminstration. *Auffhammer and Aroonruengsawat (2011)* study monthly building-level electricity consumption for California households.

Plotting paths

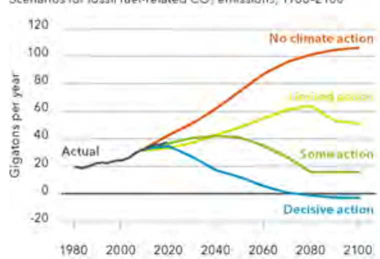
Global climate scenarios are central to our analysis. The climate modeling community has settled on several plausible pathways for the future path of carbon emissions. To account for uncertainty around these future pathways, we consider four scenarios, reflected in the *Plotting paths* chart below: These range from the "no climate action" scenario (orange line) that assumes continued burning of fossil fuels; to a "decisive action" scenario (blue line) that assumes aggressive policy actions to curb emissions.

The latter is the goal of the 2015 Paris Climate Agreement, which aims to keep the average increase in global temperatures to well below 2°C by the end of the 21st century. Actual emissions growth (gray line in the chart) has the world on a path to higher-warming scenarios, posing risks to assets.

Rhodium draws on 21 advanced global climate models to calculate probability-weighted indicators of physical climate changes – such as temperature, rainfall and hurricane risk – for each of these emissions scenarios. See ***Rhodium's article*** in the Journal of Applied Meteorology and Climatology (Oct 2016) for details. The goal: to answer what we know both about the physical risks today, and how those risks may evolve in the future.

Plotting pathways

Scenarios for fossil fuel-related CO_2 emissions, 1980-2100



Sources: BlackRock Investment Institute, with data from Rhodium, March 2019. Notes: CO_2 emissions include fossil fuel combustion and cement production. The chart lays out the four representative concentration pathways (RCPs) commonly used as scenarios in climate modeling, as defined by the Intergovernmental Panel on Climate Change. "No climate action" (known as RCP 8.5) assumes ongoing fossil fuel use, with atmospheric CO_2 concentrations reaching 940 ppm by 2100. "Limited action" (RCP 6.0) sees CO_2 concentrations rising to around 670 ppm by 2100. In "some action" (RCP 4.5), CO_2 concentrations stabilize at around 550 ppm. Decisive action (RCP 2.6) sees aggressive policy action resulting in negative net emissions (see shaded blue area) by late in the century, with CO_2 concentration of 384 ppm by 2100.

SCENARIO ANALYSIS

How can governments, companies and investors best incorporate climate risks into their decision making? Scenario analysis plays a key role. The Financial Stability Board's ***Task Force on Climate-Related Financial Disclosures*** has resulted in a hearty pick-up in analysis. The TCFD, of which BlackRock is a member, separates climate risks into two categories.

- **Transition risks:** The risks to businesses or assets that arise from policy, legal, technological and/or market changes as the world seeks to transition to a lower-carbon economy. See ***Sustainability: the future of investing*** for details on our approach.
- **Physical risks:** The risks to entities or assets from the climate changes already occurring and expected to continue in the years ahead under different greenhouse gas emissions scenarios.

Physical risks pose the greatest threat in the "no climate action" or "limited action" scenarios, both of which likely lead to significant increases in average global temperatures. Transition risks take on greater relevance in a "decisive action" scenario that involves tough regulatory actions to curb emissions, breakthroughs in clean energy, and a more limited rise in temperatures.

Given our focus on physical risks in this piece, we concentrate on the "no climate action" scenario. We see this as a tough, but plausible, scenario for stress-testing investment portfolios. This is in line with the TCFD's recommendation that entities consider "challenging" scenarios for risk management. Scenarios are not forecasts. And they do not equal sensitivity analysis (to a particular factor). The idea is to challenge conventional wisdoms about the future.

Scenarios draw attention to key factors that will drive future developments. This, in turn, can help in assessing how resilient an organization is against potential disruptions. Does it have the ability to adapt to the changes – and take advantage of related opportunities? Does it have plans in place to mitigate the risks? Scenarios can provide investors with a framework for answering such questions.

A glimpse into the future

How might some of the risks play out? Average temperatures show some striking potential changes under a "no climate action" risk scenario of ongoing fossil fuel use.

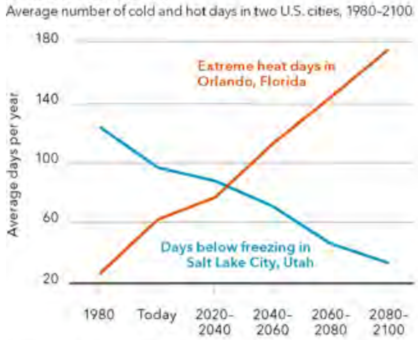
Example: The number of freezing days in Salt Lake City, Utah, could fall by as much as 75% by the end of the century from 1980 levels. By contrast, Disney World in Orlando, Florida, could see the average number of annual days with extreme heat spike to almost half the year. See the *A tale of two cities* chart below.

Up to 26% of U.S. metropolitan areas would likely see more than 100 days a year of 95°F (35°C) heat by 2060-2080, versus around 1% today, the estimates show. This would have important knock-on implications:

- Lower productivity in regions that rely on outdoor labor such as agriculture and construction work;
- Rising mortality rates as the incidence of extreme heat rises in hotter states such as Texas;
- Greater energy expenditure to cool buildings, particularly in the U.S. South West;
- Lower agricultural output due to declining crop yields in hotter states such as Arizona.

A tale of two cities

Average number of cold and hot days in two U.S. cities, 1980-2100



Sources: BlackRock Investment Institute, with data from Rhodium, March 2019. Notes: The chart shows the average annual number of cold days in Salt Lake City, Utah, when the temperature falls below 32°F (0°C), and the number of hot days in Orlando, Florida above 95°F (35°C). 1980 data are actual. "Today" represents the 2010-2030 estimate. Estimates are from Rhodium and assume a "no climate action" scenario. We show the upper bound of the 66%, or "likely" range. Rhodium's estimates draw on 21 general circulation models to assess probabilities of temperature, precipitation and other climate variables.

Changing world

Estimated "no climate action" impacts vs. 1980, 2019-2100

	Today	2020-2040	2040-2060	2060-2080	2080-2100
Sea level rise (feet)					
Houston	1.2	1.6	2.5	3.6	4.9
New York	0.9	1.2	1.9	2.9	4.0
Hurricane damage (annualized % GDP loss)					
New York	0.2	0.2	0.2	0.4	0.6
Miami	2.5	2.5	2.8	3.3	3.9
Change in agricultural output (annualized % GDP gain/loss)					
Pine Bluff, Ark.	-0.9	-1.2	-2.7	-3.7	-3.8
Jamestown, N.D.	1.0	2.4	5.2	6.5	5.0
Change in energy expenditure (annualized as % of GDP)					
Tucson, Ariz.	0.3	0.5	0.8	1.2	1.6
Minneapolis	-0.11	-0.12	-0.13	-0.14	-0.14

Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: All estimates are from Rhodium Group and assume a "no climate action" scenario. We show the upper bound of the 66%, or "likely" range of outcomes to illustrate a plausible risk scenario. Sea level rise (in feet) is from 1980. Hurricane damage, agricultural output and energy expenditure show annualized GDP gains/losses as a result of physical changes in the climate since 1980. For details on Rhodium's methodology see *Estimating economic damage from climate change in the United States*, Science (June 2017).

How large are the potential effects? Pretty big, under a "no climate action" scenario. Tucson, Arizona, for example, would be spending more than 1% of GDP annually on additional energy costs by late century. See the *Changing world* table above. Declining potential for agriculture, as extreme heat reduces crop yields, would be shaving up to 4% annually off the GDP of Pine Bluff, Arkansas. By contrast, Jameston, North Dakota, for example, would gain a GDP boost from warming.

Sea levels are set to rise meaningfully, exposing much coastal property to potential losses. Rhodium's work shows that sea levels in Houston are more than a foot higher today than in 1980. This rise is likely to swell to as much as five feet by the end of the century under current emissions trends, the estimates show. New York City would see likely sea level rises of up to three feet by 2080, exposing roughly $73 billion of property to potential losses. Hurricanes are a key driver. We can estimate potential damages by combining historical loss rates with building-level exposure data and cutting-edge hurricane modeling. The result: Potential annualized storm hits of as much as 3% of GDP to Miami and other coastal cities.

Net impacts

How to gauge the overall economic impact of climate-related risks on a region? Rhodium's work allows us to estimate this under different scenarios. To illustrate, the *Mapping the damage* graphic below visualizes the expected changes to GDP across the U.S. under a "no climate action" scenario in 2060–2080.

The biggest likely losers: the Gulf Coast region, the South Atlantic seaboard and much of Arizona. See the orange tones in the map. A handful of colder states see potential for modest GDP gains. Yet the risks are asymmetric: Some 58% of U.S. metro areas would see likely GDP losses of up to 1% or more, with less than 1% set to enjoy gains of similar magnitude, we estimate. Florida tops the danger zones, with Naples, Panama City and Key West seeing likely annual GDP losses of up to 15% or more, mostly driven by coastal storms. Note these are average annual estimates; losses would likely come in big weather-driven shocks that could be much larger for a given year. The losses are not baked in: Decisive action could mitigate carbon emissions and cities can spend on adaptation measures to increase their resiliency. But the vulnerabilities revealed in the analysis have important implications for municipal bond issuers and investors, as discussed in the next chapter.

58% Estimated share of U.S. metro areas with 1%-plus climate-related GDP losses by 2080

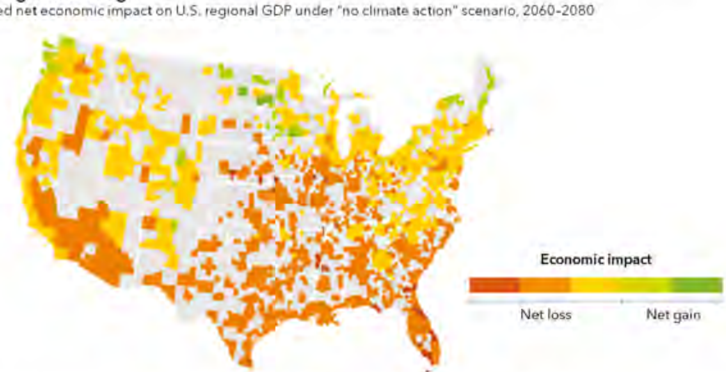
Getting a better handle on physical climate risk, down to the asset level, can add an important tool to an investor's toolkit. This is particularly valuable for portfolios of assets that are geo-locatable – and have decades-long lifespans. This is why we initially focus on U.S. municipal bonds, CMBS and electric utilities.

Our analysis is just a first step. We aim to extend the work to other regions, asset classes and sectors. Future challenges include applying the methodology to multinationals with complex supply chains, as well as to services companies. The latter requires assessing how exposed a company's key markets are to climate risks.

There is inherent uncertainty in climate modeling and weather scenarios. This means there is uncertainty in our estimates of that risk today – and even more so in the future. Yet we believe our work to better measure physical risks today – and under different scenarios in the future – is an important starting point. It can help reveal risks that may be mispriced in portfolios today, and how those risks may change over time.

Mapping the damage

Estimated net economic impact on U.S. regional GDP under "no climate action" scenario, 2060–2080



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The map shows the projected GDP impact in 2060–2080 on U.S. metropolitan areas under a "no climate action" scenario. Climate changes are measured relative to a 1980 baseline. The analysis includes the effect of changes in crime and mortality rates, labor productivity, heating and cooling demand, agricultural productivity for bulk commodity crops, and expected annual losses from coastal storms. It accounts for correlations across these variables and through time – and excludes a number of difficult to measure variables such as migration and inland flooding. See Rhodium Group's March 2019 paper *Clear, Present and Underpriced: The Physical Risks of Climate Change* for further details on its methodology. Forward-looking estimates may not come to pass.

Municipal bonds

We show how climate-related risks threaten the economies – and creditworthiness – of many U.S. state and local issuers, and provide a framework for assessing these risks.

Climate-related risks are underappreciated in the U.S. municipal bond market. Hurricanes, floods and other extreme weather pose a host of financial challenges for state and local issuers. A lot is at stake. The market has $3.8 trillion of outstanding debt, according to late-2018 Federal Reserve data. Consider the following:

- The cost of cleanups after extreme weather, funding mitigation projects to forestall future damages, and rising flood insurance premiums can lead to higher debt levels. This has big implications for general obligation (GO) bonds – those backed by the credit and tax power of states and cities.
- The tax base of a municipality could shrink if large-scale natural disasters lead to a population drain (such as that experienced by Puerto Rico in the wake of Hurricane Maria in 2017) and declining property prices. Some municipalities offer property tax relief in the aftermath of natural disasters, exacerbating the hit to their revenues.
- Gradual changes to the climate – such as rising temperatures and sea levels – can change patterns of land use, employment and economic activity. Businesses may relocate to other regions, also eroding the local tax base.
- Revenue bonds tied to specific projects – such as those issued by water and sewer utilities – may suffer direct harm from sea level rise, floods or droughts.

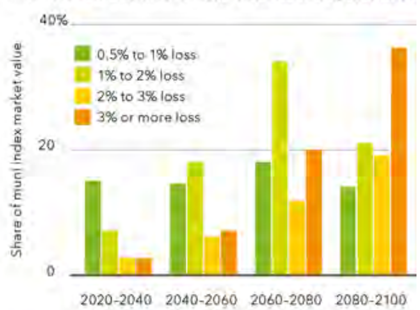
Credit rating agencies are paying increased attention to these risks. Moody's in 2017 warned that climate change would have a growing negative impact on the creditworthiness of U.S. state and local issuers – particularly those without sufficient adaptation and mitigation strategies. Yet such strategies can be costly. One example: Florida's governor in January said the state wanted to spend $2.5 billion over four years to address environmental issues, including the effects of rising sea levels.

Climate models suggest such financial challenges are only set to intensify. Our work shows a rising share of U.S. metropolitan statistical areas (MSAs) will likely face escalating climate-related risks in the coming decades. This analysis breaks down the potential net economic impact – relative to where GDP would have been absent the effects of climate change – on each of the 383 U.S. MSAs under a "no climate action" scenario. It includes estimates of direct impacts, such as the expected losses from hurricane damage, as well as second-order effects such as changes in mortality rates, labor productivity, energy demand and crop yields.

Within a decade, more than 15% of the current S&P National Municipal Bond Index (by market value) would be issued by MSAs suffering likely average annualized economic losses of up to 0.5% to 1% of GDP. See the *A growing burden* chart. This would have big implications for the creditworthiness of MSAs – and their ability to fund adaptation projects. The impacts are set to grow more severe in the decades ahead, as the chart shows.

A growing burden

Muni index share at risk of climate-related GDP loss, 2020-2100



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: We use the S&P National Municipal Bond Index to represent the muni market. The chart shows the estimated market value share of the muni market exposed to GDP losses of various magnitude through 2100 under a "no climate action" scenario. For example, roughly 20% of the market value of the current muni index is expected to come from regions suffering annualized average losses of up to 3% or more of GDP from climate change by 2060-2080. We use the upper bound of the 66%, or "likely," range of losses to illustrate a plausible risk scenario.

Location, location, location

The impact of climate-related risks varies widely, with coastal and southern states hit hardest. The *What's the damage?* chart shows the range of projected effects over time for the 15 largest MSAs, which make up almost 40% of the muni market. Our work suggests all major MSAs are already suffering mild to moderate losses today – the result of cumulative changes to the climate since our 1980 baseline year. Topping the list of damages: Miami, Florida, with estimated annualized GDP losses of more than 1% today – and potential for these losses to grow to an annualized 4.5% of GDP by the end of the century. These would be mostly driven by hurricanes and rising sea levels. Note this is a high-risk scenario; aggressive global efforts to curb carbon emissions would put projected losses on a more moderate path.

Seattle, with its relatively temperate climate, shows the most resilience with little projected damage to GDP over time. The New York City region faces annual losses equivalent to roughly 1% of GDP by late century. The projected losses are not set in stone. Larger, more diversified MSAs such as New York are in a better position to fund adaptation and mitigation projects. The city has pledged to spend $20 billion over 10 years to make buildings and infrastructure more climate resilient.

Blissful ignorance?

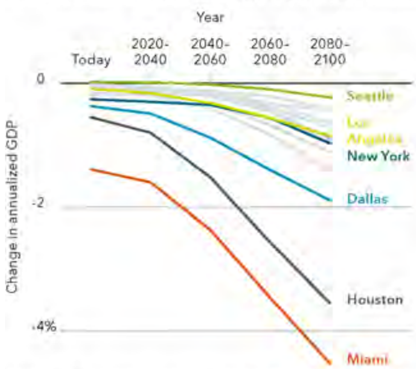
Are markets pricing in any of these future risks? One approach to finding out is to compare similar bonds located in climate-sensitive and non-climate-sensitive areas and review their prices (spreads). Such comparative spot-checks of municipal bonds do not reveal significant differences in valuation, we find.

For example, we considered two bonds with similar characteristics: Jupiter, Florida is an area beset by the hurricanes that affect the greater Miami region. Jupiter's location and its numerous waterways make the city especially vulnerable to tropical storms and hurricanes. By contrast, Neptune, New Jersey is far more insulated against severe storms.

We compared a Jupiter water revenue bond against a Neptune bond with fairly similar characteristics (taking coupon, maturity, callability, and the sector into account). The result: They had almost identical yields after adjusting for the credit quality of the two bonds (AA vs A rating). If climate-related risks were being considered as a key factor, we would have expected the Neptune bond to carry a lower yield (higher price) than the Jupiter bond. We found similar results for other spot checks of bonds in areas of high and low climate risk.

What's the damage?

Estimated climate impact on GDP of top-15 U.S. MSAs by economic weight, 2018-2100



	GDP ($ bln)	Debt ($ bln)	Share of muni index
New York	1,718	203	9.5%
Los Angeles	1,044	86	3.9%
Chicago	680	74	3.3%
Dallas	535	64	3.0%
Washington D.C.	530	45	2.0%
San Francisco	500	71	3.3%
Houston	490	51	2.4%
Philadelphia	445	25	1.2%
Boston	439	67	3.2%
Atlanta	385	34	1.6%
Seattle	356	30	1.4%
Miami	345	33	1.5%
San Jose	275	13	0.6%
Detroit	261	12	0.6%
Minneapolis	260	25	1.2%

Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The cities shown represent the top-15 U.S. metropolitan statistical areas (MSAs) by GDP. The chart shows projected annualized GDP losses (upper bound of the 66%, or "likely," range) due to cumulative changes in the climate since 1980 under a "no climate action" scenario. Today is represented by a 2010-2030 estimate. The table shows the GDP, total outstanding municipal bond issuance, and each MSA's weight in the S&P National Municipal Bond Index. The MSAs shown are greater urban areas; for example, Los Angeles includes Long Beach and Anaheim, California.

The FEMA put

How to explain the municipal bond market's apparent complacency around climate-related risks? We offer a handful of possible explanations:

- **Lack of attention:** Investors have been slow to give serious consideration to climate change, partly due to a lack of granular data for modeling the risks. This mindset is slowly changing. Credit analysts often note that they do consider the location of revenue sources but don't quantify their concerns by building an additional risk premium into spreads.
- **Time horizon:** The most dire projected impacts will come in future decades, beyond the traditional time horizon of most investors and credit rating agencies – and the duration of the average muni bond (16 years). This may lead to a discounting of risks that are already present today.
- **Insurance:** Bonds in climate-sensitive regions are often insured, thus diminishing investor concerns about storm hits. This is a key reason why muni bond prices tend to fall after heavy storm damage, but recover quickly after.
- **The "FEMA put:"** Areas devastated by storms have typically been rebuilt with funding from the Federal Emergency Management Agency (FEMA). Investors assume the bonds are insulated from climate-related risks, with FEMA providing something akin to a put option that preserves the bonds' par value.

We find little evidence that climate-related risks are priced into the municipal bond market today. Yet this dynamic should change over time, in our view. Insurance coverage in climate-affected areas is likely to become more costly – if still available.

The "FEMA put" could become less reliable if mounting disaster costs were to overwhelm FEMA's financial capacity or political will to respond. Political uncertainty around FEMA's structure and mandate only exacerbate this risk. And large-scale extreme weather events such as recent U.S. hurricanes could jolt investor sentiment. As these trends intensify and some of the risks play out, we could see a climate-proof premium emerging. We believe bonds issued by climate-resilient states and cities are likely to trade at a premium to those of vulnerable ones over time.

Assessing resilience

Our analysis shows climate-related risks are real and growing for the municipal bond market. This suggests long-term climate predictions should be taken into account when assessing an issuer's debt structure. And it makes it increasingly important for investors to look at the preparedness of states and municipalities when assessing their creditworthiness.

Some issuers are tapping the green bond market to fund mitigation efforts. Columbia, South Carolina, for example, recently issued the first tranche of a $95 million project to shore up its stormwater drainage system. How to gauge if such efforts are sufficient? Among the key questions we believe investors should be asking:

- Does the issuer have long-term plans – and the financial capacity to finance projects that increase resilience against climate risks?
- Do local ordinances or policies encourage inefficient rebuilding (in vulnerable areas) after storm hits?
- Is insurance coverage adequate for the most relevant risks?
- Do water and sewer utilities have plans in place for droughts and floods?
- Is the local economy diversified enough to absorb climate-related shocks?

Limited disclosure on such plans is one of the challenges investors face. This challenge cuts across asset classes. Providing a disclosure framework is a key goal of the TFCD described on page 8.

We believe our work connecting climate data and assets forms a starting point for assessing the risks. Pinpointing areas that are likely to expect the greatest climate impacts in coming decades can inform asset allocation and security selection decisions. And we see potential to use similar techniques to shine a light on climate risks faced by sovereign issuers, including emerging markets. Bottom line: Climate risk exposure analysis can help assess vulnerabilities of U.S. municipal issuers. We see this as a useful risk-management tool – and a valuable starting point for institutional investors to engage with issuers about their mitigation and adaptation measures.

Commercial real estate

Extreme weather and other climate-related events pose a risk to commercial real estate. We zoom in on hurricane and flood risk and estimate potential losses to the sector.

Climate-related risks are a growing concern for owners of commercial mortgage backed securities. Assets underlying CMBS loans – such as office buildings, retail properties and lodging – can have lifespans of several decades, subjecting them to climate risks that are set to intensify over time. Many assets underpinning CMBS portfolios are located in regions that are vulnerable to the increasing incidence of severe storms. Case in point: New York, Houston and Miami alone made up one-fifth of CMBS properties by market value in the Bloomberg Barclays Aggregate Index, as of March 2019.

Two hurricanes in 2017 illuminated these risks:

- Hurricane Harvey, a Category 4 storm that hit the Houston area, affected over 1,300 CMBS loans. This was roughly 3% of the market as of late 2017, based on our estimates that overlaid impacted properties on to FEMA flood zone maps. Irma, a Category 4 storm that made landfall in Florida, affected almost 1,000 CMBS loans, or 2% of the CMBS universe.
- Some 80% of the commercial properties damaged in both storms, according to our analysis, lay outside official flood zone maps. This indicates they could have had insufficient flood insurance.

Hurricanes pose big risks to commercial property in the form of extreme winds (from blown windows to structural damage) and flooding (damage to basements and electrical systems). Category 4 and 5 wind speeds, in particular, can create outsized damage to properties. These risks are already a reality.

To illustrate, we overlaid Rhodium's hurricane modeling onto the U.S. CMBS market, as proxied by roughly 60,000 commercial properties in BlackRock's proprietary CMBS database. The median risk of one of these properties being hit by a Category 4 or 5 hurricane has risen by 137% since 1980, we found. Within three decades, the risk of being hit by a Category 5 hurricane is projected to rise 275% under a "no climate action" scenario. See the *Stormy weather* chart.

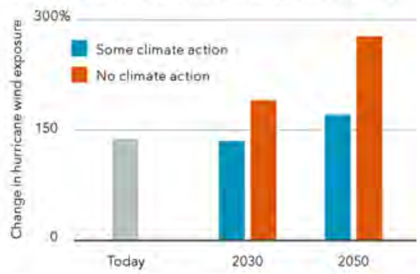
275% Rise in Category 4/5 hurricane risk by 2050

The risks to the CMBS market posed by rising average temperatures are varied, and go beyond the direct physical damages from storms and floods. They include:

- Higher insurance premiums or decreased insurance coverage.
- Rising operational costs such as energy use for air cooling systems.
- Greater capex needs to make buildings more resilient (think of backup generators, water-pumping systems and reinforcement of building exteriors).
- Increased delinquencies as tenants default or walk away from properties after extreme weather events.
- Potential hits to valuations and declining liquidity of properties in vulnerable areas.

Stormy weather

Change in Category 4/5 hurricane wind exposure since 1980



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The chart shows the change in median hurricane wind exposure in the CMBS market, represented by around 60,000 commercial properties in BlackRock's CMBS database. The bars represent the estimated change in the median probability of Cat 4 or 5 hurricane winds touching properties relative to 1980 under "no climate action" and "some climate action" scenarios. "Today" is a 2010-2030 estimate. We use the Saffir-Simpson Wind Scale ("Cat" 1–5) to rate hurricane wind speed. Wind fields are estimated by Rhodium using the LICRICE wind field model. For details see S. Hsiang and A. Jina, *"The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones,"* NBER Working Paper, Jul. 2014.

Focus on flooding

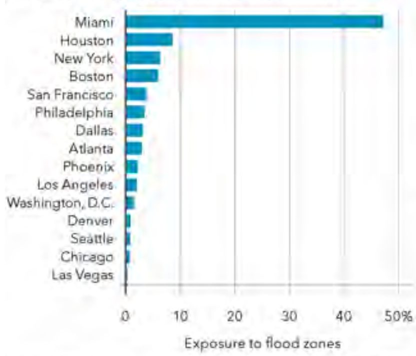
Borrowers contributing assets to CMBS deals are required to have wind insurance as part of their broader "hazard insurance." This does not cover flood risk. Flood insurance is required only if the commercial property is located within FEMA-designated flood zones.

To estimate the official footprint of the flood hazard, we mapped 60,000 properties in our CMBS universe onto FEMA flood maps, using an algorithm that sorted through 830,000 geospatial blocks across the U.S. Based on our analysis, around 6% of the properties in the CMBS market lie in FEMA flood zones. This percentage varies greatly by region. Miami tops the exposures, with almost half of commercial properties situated in flood zones. See the *Flood water* chart.

Recent hurricanes hitting cities such as Houston suggest FEMA flood maps understate true risks. And flood risk is set to intensify. Based on our mapping of the CMBS universe onto Rhodium's data, the number of properties subject to 1% or more storm surge risk per annum would rise by 1800% by 2060-2080 under "no climate action." To be sure, many commercial real estate sponsors take out flood insurance even when properties lie outside flood zones. Yet such insurance may not always be available, and "uninsured" flood exposure is set to rise.

Flood water

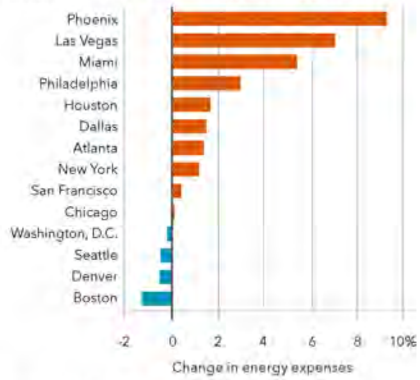
U.S. CMBS market exposure to official flood zones, 2019



Sources: BlackRock Investment Institute, with data from FEMA and BlackRock's CMBS property database, March 2019. Notes: The chart shows the market value share of properties in the U.S. CMBS market that lie within FEMA-designated flood zones in selected U.S. urban centers. We use BlackRock's CMBS property database, containing around 60,000 underlying commercial properties, as a proxy for the CMBS market.

Rising bills

Impact of climate change on energy expenses, 2060-2080



Sources: BlackRock Investment Institute, with data from Rhodium Group, 2019. Notes: The analysis assumes a "no climate action" scenario and takes the upper bound of the 66%, or "likely" range, to illustrate a plausible risk scenario.

Energy or utility expenses make up around 15% of operating expenses for commercial buildings, according to our analysis of 100,000 property financial records. Rising temperatures could inflate these bills. Based on Rhodium's data, energy expenses would rise by up to 9% (Phoenix) under "no climate action." See the *Rising bills* chart. These estimates likely underestimate the costs, as they do not account for electricity rate rises.

What impact could this have on property cash flows and commercial loan defaults? We used an illustrative CMBS model to estimate changes in default rates on commercial mortgages in the Bloomberg Barclays Aggregate Index. Our inputs: CMBS properties' current financials and Rhodium's estimated GDP changes by MSA over 2060-2080 under "no climate action." We then projected the impact on key real estate metrics such as vacancies, rents and tenant renewals. The result: The average expected loss rate on CMBS deals would rise to 3.8% from 3.2% absent the climate-related impact. Defaults and losses would be higher in areas of greatest impact. The estimates do not include the direct financial damages caused by storm hits. More frequent storms may also inflate building maintenance and insurance costs, which by our calculation average roughly 20% in CMBS properties. Bottom line: Climate-related risks are significant today – and set to grow in the future.

Electric utilities

We find extreme weather events are not priced into the equities of U.S. electrical utilities – and introduce a climate risk exposure framework that can help uncover such risks.

Climate-related risks pose big challenges for the electric power sector. Aging infrastructure and older design standards leave power generating assets vulnerable to extreme weather events such as wildfires and hurricanes. Power outages as a result of such incidents pose broader risks to the economy – via lost productivity. They can also trigger capital losses for investors. Utilities can mitigate some of the risks via insurance, disaster recovery plans and physical hardening of facilities, but many companies are likely underprepared.

Are climate-related risks priced into the equities of electric utilities? We sought to find out. Our analysis starts by examining the geolocation of every U.S. electric power plant, as well as planned generation as reported to the U.S. Department of Energy. We plot the locations below, by fuel source, with the size of the bubbles indicating generation capacity. We then traced the ownership of the 4,500 power plants that were publicly owned, aggregating them into a hypothetical portfolio of 269 traded utility companies.

Our analysis divides weather events into two types of shocks: acute shocks with immediate impact, such as hurricanes and wildfires; and chronic events such as high temperatures, flooding and droughts.

Acute climate shocks have the most severe direct physical impact, such as damage to generating facilities. Chronic events tend to play out over longer time periods and wider areas of impact. Droughts, for example, affect thermal coal-fired or nuclear plants that require cooling water drawn from rivers or reservoirs. Declining intake water levels can hurt plant efficiency, or even trigger temporary shutdowns that cause financial losses.

Our historical study included 233 extreme weather events across the United States – those causing more than $1 billion in damages as estimated by the NOAA – dating back as far as 1980. We choose first to zoom in on hurricanes. These made up roughly 15% of these historical events – and have typically caused the most damage.

Sources of power

U.S. electric utility plants by fuel source, 2019

Sources: BlackRock Investment Institute and BlackRock Sustainable Investing, with data from EIA, March 2019. Notes: The chart plots the location of more than 8,000 U.S. electric power plants, as well as planned generation as reported to the U.S. Department of Energy. The bubbles are sized in proportion to each site's power generation capacity.

Not priced

Our hypothesis: Extreme weather risks already threaten utility stocks – and are set to rise in frequency and intensity over time – but are not fully priced in. To measure this embedded risk, we evaluate the impact on company valuation that results from an extreme weather event. If investors believe utilities have fully mitigated their exposure to climate-related risks, then stock prices should not react to the event. Our methodology:

1. Determine an "epicenter" location and the day of occurrence ("day zero"). For hurricanes, this was the date and location where the storm made landfall.
2. Establish a zone of influence; this is 300 kilometers for a hurricane (the average radius).
3. Isolate the power plants operating in the affected zone and the listed parent companies that own them. Calculate the megawatt capacity of each affected power plant as a share of that utility's total generative capacity. This gives us a proxy for the revenue of each company that may be disrupted.
4. Create a hypothetical portfolio of the affected companies, weighted in proportion to the percentage of revenues affected.
5. Study the financial impact of the weather event on stock prices and volatility.

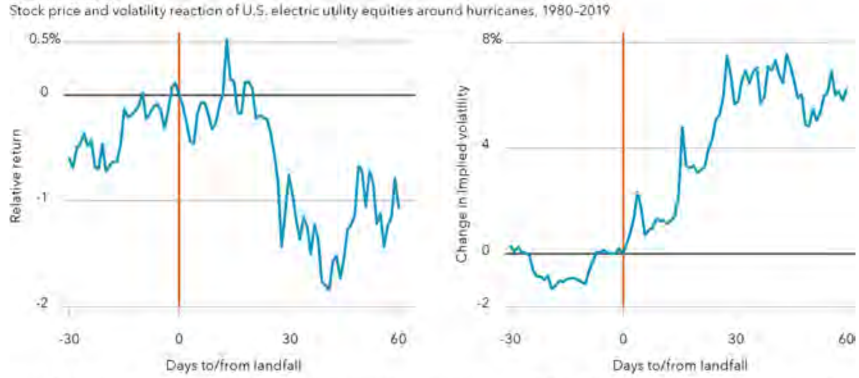
We first investigated if hurricane impacts had a broad effect on the utility sector by analyzing the price response of the S&P Utility Index around such events. We found no discernable impact on prices. Next, we studied the price and volatility impacts from hurricanes on the affected utilities and found the following results:

- Stock prices typically come under pressure for a period of about 40 days after the event – and incur a loss of about 1.5% relative to the sector index.
- The implied volatility of options on impacted utilities increases by about 6 percentage points in the 30 days after impact.
- After a short period, stock returns tend to converge back toward industry averages, while volatility eases from peaks. See the *Storm shock* charts.

Our analysis told a similar story for wildfires, albeit with more muted price effects. What does all of this tell us? Investor reaction ahead of forecasted hurricanes is muted because the exact location of landfall – and the power plants that will be affected – are not known with certainty. After the event, investors sell stocks of affected utilities, reflecting concern that the true economic losses are not fully known. The swift recovery of utility stocks suggests investors perceive an "over-reaction" to the hurricane impacts – and eventually "forget" the event.

Storm shock

Stock price and volatility reaction of U.S. electric utility equities around hurricanes, 1980-2019



Sources: BlackRock Investment Institute and BlackRock Sustainable Investing, with data from Bloomberg and NOAA, March 2019. Notes: Our study includes all hurricanes in the NOAA's database since 1980. Day zero is the day of each hurricane landfall. We isolate the power plants within 300 km from the location of the landfall, and identify their parent companies. We then form a hypothetical portfolio of affected companies, weighted in proportion to their revenues affected as implied by their generation capacity as a share of the total capacity of the group. We compare the total return of this hypothetical portfolio to the S&P 500 Utilities Index to arrive at the relative return. Implied volatility is calculated from the OptionMetrics database.

Scoring utilities

Our next step: Developing a framework to estimate the climate risk exposures of publicly traded utilities, in a bid to quantify hidden risks for investors. We do this by combining the exposure to extreme weather at each power plant location with an assessment of the materiality of that exposure, based on historical losses and forward-looking climate modeling. For details, see ***Climate Risk in the U.S. Electric Utility Sector: A case study***, by A. Bertolotti, D. Basu and K. Akallal (2019).

Note: Our analysis is plant-centric. It does not account for potential damages to transmission and distribution networks; liability risks; or increased capex needs over time as increased energy demand for cooling burdens grids with higher peak loads in summertime. We assign each type of weather event a relative impact score on a 1-10 scale. Hurricanes sit at the top of this scale, posing direct physical threats to generating plants and water intake structures. See the *Risk by risk; plant by plant* table below. The potential impact of climate events on power plants varies not only by location but also by the fuel source. Example: Wind energy is vulnerable to variations in wind patterns caused by severe storms. Solar energy, by contrast, is more exposed to extreme heat, which curbs the efficiency of photovoltaic panels.

We reflect these nuances by assigning a weight to each type of weather event by fuel source. We see gas (35% of total U.S. generation capacity according to 2018 EIA data) and coal-fired power plants (27%) as exposed to a broader swath of climate risks, including wildfires, high temperatures, floods and drought.

High temperatures, defined as days with a maximum temperature above 95°F (32°C), pose a meaningful risk to almost all types of fuel sources across the U.S. – and are often associated with other types of weather shocks such as wildfires.

For wind energy (representing around 7% of U.S. generating capacity) we assign a high risk weight to hurricanes – the main material climate risk we see for this fuel source. Wind turbines are typically designed to cut out in extreme wind, to prevent damage to rotors.

For hydroelectric power plants, hurricanes, droughts (drops in reservoir levels reduce generation efficiency) and floods (potential structural damage) are the greatest risks in our framework.

Our work with Rhodium suggests the type of extreme weather events detailed below are likely to intensify in frequency and magnitude in the decades ahead. This means investors need to start assessing the risks today.

Risk by risk; plant by plant

BlackRock's climate risk exposure framework for electric utilities

	Extreme weather event	Hurricanes	Wildfires	High temperatures	Floods	Droughts
	Relative impact (1-10 scale)	10	7	5	4	4
		Weight of extreme weather event exposure (%)				
Fuel source	Gas (35% of U.S. generation capacity)	38	13	19	15	15
	Coal (27%)	38	13	19	15	15
	Nuclear (19%)	38	13	19	15	15
	Hydro (7.0%)	26	18	13	21	21
	Wind (6.6%)	63	22	16	0	0
	Solar (1.6%)	49	17	24	10	0
	Geothermal (0.4%)	44	16	22	18	0

Sources: BlackRock's Sustainable Investing and BlackRock Investment Institute, with data from EIA, U.S. Department of Energy, Rhodium Group and Verisk Maplecroft, March 2019. Notes: The table illustrates how we combine plant-level climate exposure scores into a single parent company exposure score. "Relative impact" shows BlackRock's assessment of the financial materiality of each type of extreme weather event, on a scale of 1–10, with 10 being the most material. Impact scores are based on historical loss rates. We then determine which type of weather events are most material for each fuel source. Weather events that pose direct risks to a particular fuel source are assigned a weight of 1; those posing indirect risks are given a weight of 0.5; and those with no impact are assigned a zero weight. We multiply these impact weights by the relative impact score for each event type. The results are translated into percentage exposure weights that sum to 100 for each fuel source. Share of generation capacity figures are based on 2018 EIA data.

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Putting it all together

We aggregate the average physical risk across all power plants to arrive at a total climate risk score for each utility. This enabled us to examine another key question: Do utilities with greater climate resilience trade at a premium? We examined the relationship between the climate scores of the utilities in our study with each companies' 10-year average price-to-earnings ratio. The result of this regression analysis: The most climate-resilient utilities tend to trade at a slight premium to their peers, while the most vulnerable carry a slight discount. We found similar results using price-to-book ratios. This gap may become more pronounced over time as weather events turn more extreme and frequent – and more investors factor climate change into their risk/return analysis.

There are limits to our scoring approach. It aggregates the average physical risk across all power plants for each utility. Yet catastrophic losses can occur if the financial impacts caused to or by a single power plant extend beyond the damages to the actual plant. This was the case for a California utility in 2018, when the liabilities from fires caused by its equipment crippled the company. See the *How exposed is my power plant?* map below for a geographic representation of our climate risk scores by power plant.

How can investors use this information? Two potential applications:

1. **Risk management:** Geolocating power plants and determining their physical climate exposure allows utilities investors to better assess their exposures – and any concentration of risk to a particular type of extreme weather event. Geographic diversification can help offset these risks, since the most acute climate risks tend to strike in specific locations.
2. **Engagement:** Are companies doing enough to mitigate the rising risk of financial damage from climate events? Are their capex plans aligned? Granular analysis of the risks facing a particular utility – reflected in our risk exposure scores – can form the basis for larger investors to engage with corporate management teams on issues of concern.

We conclude that climate-related risks are real for utilities, but mostly not priced in. This has important implications. Overweighting companies with low climate risk exposure and underweighting those with high exposure may pay off as the risks compound over time. Investors also will need to include climate-related risks in their analysis of financial risks and opportunities. This is most relevant for long-term investors, as the probability of experiencing more frequent and intense extreme weather rises the longer a position is held.

How exposed is my power plant?

BlackRock Climate Exposure Scores for U.S. power plants, 2019

Sources: BlackRock Investment Institute, with data from Rhodium Group, Verisk Maplecroft and U.S. Department of Energy, 2019.
Notes: The chart plots the location of each U.S. electric power plant and is color coded according to BlackRock's assessment of its climate exposure, according to the framework presented on page 17. For illustrative purposes only. Risk is expressed in standard deviations. A score of -3 (high climate risk) points to an exposure that is three standard deviations worse than the mean exposure of the plants in our study.

RELATED RESOURCES FROM BLACKROCK

Adapting portfolios to climate change, September 2016
https://www.blackrock.com/corporate/literature/whitepaper/bii-climate-change-2016-us.pdf

BlackRock ESG Investment Statement, July 2018
https://www.blackrock.com/corporate/literature/publication/blk-esg-investment-statement-web.pdf

BlackRock Mission Statement on Sustainability, 2018
https://www.blackrock.com/corporate/literature/publication/blk-sustainability-mission-statement-web.pdf

BlackRock's Approach to Sustainability, 2018
https://www.blackrock.com/corporate/responsibility

Exploring ESG: A practitioner's perspective, June 2016
https://www.blackrock.com/investing/literature/whitepaper/viewpoint-exploring-esg-a-practitioners-perspective-june-2016.pdf

Sustainability: the future of investing, January 2019
https://www.blackrock.com/corporate/literature/whitepaper/bii-sustainability-future-investing-jan-2019.pdf

Sustainable investing: a "why not" moment, May 2018
https://www.blackrock.com/corporate/literature/whitepaper/bii-sustainable-investing-may-2018-us.pdf

The Investment Stewardship Ecosystem, July 2018
https://www.blackrock.com/corporate/literature/whitepaper/viewpoint-investment-stewardship-ecosystem-july-2018.pdf

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Schlenker, Wolfram and Michael J. Roberts. "*Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change.*" Proceedings of the National Academy of Sciences of the United States of America, Sept. 15, 2009

The ***BlackRock Investment Institute (BII)*** provides connectivity between BlackRock's portfolio managers; originates economic, markets and portfolio construction research; and publishes investment insights. Our goals are to help our fund managers become even better investors and to produce thought-provoking investment content for clients and policymakers.

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A Fundamental Reshaping of Finance

Dear CEO,

As an asset manager, BlackRock invests on behalf of others, and I am writing to you as an advisor and fiduciary to these clients. The money we manage is not our own. It belongs to people in dozens of countries trying to finance long-term goals like retirement. And we have a deep responsibility to these institutions and individuals – who are shareholders in your company and thousands of others – to promote long-term value.

Climate change has become a defining factor in companies' long-term prospects. Last September, when millions of people took to the streets to demand action on climate change, many of them emphasized the significant and lasting impact that it will have on economic growth and prosperity – a risk that markets to date have been slower to reflect. **But awareness is rapidly changing, and I believe we are on the edge of a fundamental reshaping of finance.**

The evidence on climate risk is compelling investors to reassess core assumptions about modern finance. Research from a wide range of organizations – including the UN's Intergovernmental Panel on Climate Change, the BlackRock Investment Institute, and many others, including new studies from McKinsey on the socioeconomic implications of physical climate risk – is deepening our understanding of how climate risk will impact both our physical world and the global system that finances economic growth.

Will cities, for example, be able to afford their infrastructure needs as climate risk reshapes the market for municipal bonds? What will happen to the 30-year mortgage – a key building block of finance – if lenders can't estimate the impact of climate risk over such a long timeline, and if there is no viable market for flood or fire insurance in impacted areas? What happens to inflation, and in turn interest rates, if the cost of food climbs from drought and flooding? How can we model economic growth if emerging markets see their productivity decline due to extreme heat and other climate impacts?

Investors are increasingly reckoning with these questions and recognizing that climate risk is investment risk. Indeed, climate change is almost invariably the top issue that clients around the world raise with BlackRock. From Europe to Australia, South America to China, Florida to Oregon, investors are asking how they should modify their portfolios. They are seeking to understand both the physical risks associated with climate change as well as the ways that climate policy will impact prices, costs, and demand across the entire economy.

These questions are driving a profound reassessment of risk and asset values. And because capital markets pull future risk forward, we will see changes in capital allocation more quickly than we see changes to the climate itself. **In the near future – and sooner than most anticipate – there will be a significant reallocation of capital.**

Climate Risk Is Investment Risk

As a fiduciary, our responsibility is to help clients navigate this transition. Our investment conviction is that sustainability- and climate-integrated portfolios can provide better risk-adjusted returns to investors. And with the impact of sustainability on investment returns increasing, we believe that sustainable investing is the strongest foundation for client portfolios going forward.

In a **letter to our clients** today, BlackRock announced a number of initiatives to place sustainability at the center of our investment approach.

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sustainability-related risk, such as thermal coal producers; launching new investment products that screen fossil fuels; and strengthening our commitment to sustainability and transparency in our investment stewardship activities.

Over the next few years, one of the most important questions we will face is the scale and scope of government action on climate change, which will generally define the speed with which we move to a low-carbon economy. This challenge cannot be solved without a coordinated, international response from governments, aligned with the goals of the Paris Agreement.

Under any scenario, the energy transition will still take decades. Despite recent rapid advances, the technology does not yet exist to cost-effectively replace many of today's essential uses of hydrocarbons. We need to be mindful of the economic, scientific, social and political realities of the energy transition. Governments and the private sector must work together to pursue a transition that is both fair and just – we cannot leave behind parts of society, or entire countries in developing markets, as we pursue the path to a low-carbon world.

While government must lead the way in this transition, companies and investors also have a meaningful role to play. As part of this responsibility, BlackRock was a founding member of the Task Force on Climate-related Financial Disclosures (TCFD). We are a signatory to the UN's Principles for Responsible Investment, and we signed the Vatican's 2019 statement advocating carbon pricing regimes, which we believe are essential to combating climate change.

BlackRock has joined with France, Germany, and global foundations to establish the Climate Finance Partnership, which is one of several public-private efforts to improve financing mechanisms for infrastructure investment. The need is particularly urgent for cities, because the many components of municipal infrastructure – from roads to sewers to transit – have been built for tolerances and weather conditions that do not align with the new climate reality. In the short term, some of the work to mitigate climate risk could create more economic activity. Yet we are facing the ultimate long-term problem. We don't yet know which predictions about the climate will be most accurate, nor what effects we have failed to consider. But there is no denying the direction we are heading. **Every government, company, and shareholder must confront climate change.**

Improved Disclosure for Shareholders

We believe that all investors, along with regulators, insurers, and the public, need a clearer picture of how companies are managing sustainability-related questions. This data should extend beyond climate to questions around how each company serves its full set of stakeholders, such as the diversity of its workforce, the sustainability of its supply chain, or how well it protects its customers' data. Each company's prospects for growth are inextricable from its ability to operate sustainably and serve its full set of stakeholders.

The importance of serving stakeholders and embracing purpose is becoming increasingly central to the way that companies understand their role in society. **As I have written in past letters, a company cannot achieve long-term profits without embracing purpose and considering the needs of a broad range of stakeholders.** A pharmaceutical company that hikes prices ruthlessly, a mining company that shortchanges safety, a bank that fails to respect its clients – these companies may maximize returns in the short term. But, as we have seen again and again, these actions that damage society will catch up with a company and destroy shareholder value. By contrast, a strong sense of purpose and a commitment to stakeholders helps a company connect more deeply to its customers and adjust to the changing demands of society. **Ultimately, purpose is the engine of long-term profitability.**

Over time, companies and countries that do not respond to stakeholders and address sustainability risks will encounter growing skepticism from the markets, and in turn, a higher cost of capital. Companies and countries that champion transparency and demonstrate their responsiveness to stakeholders, by contrast, will attract investment more effectively, including higher-quality, more patient capital.

Important progress improving disclosure has already been made – and many companies already do an exemplary job of integrating and reporting on sustainability – but we need to achieve more widespread and standardized adoption. While no framework is perfect, BlackRock believes that the Sustainability Accounting Standards Board (SASB) provides a clear set of standards for reporting sustainability information across a wide range of issues, from labor practices to data privacy to business ethics. For evaluating and reporting climate-related risks, as well as the related governance issues that are essential to managing them, the TCFD provides a valuable framework.

We recognize that reporting to these standards requires significant time, analysis, and effort. BlackRock itself is not yet where we want to be, and we are continuously working to improve our own reporting. Our SASB-aligned disclosure is available on our website, and we will be releasing a TCFD-aligned disclosure by the end of 2020.

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climate-related risks in line with the TCFD's recommendations, if you have not already done so. This should include your plan for operating under a scenario where the Paris Agreement's goal of limiting global warming to less than two degrees is fully realized, as expressed by the TCFD guidelines.

We will use these disclosures and our engagements to ascertain whether companies are properly managing and overseeing these risks within their business and adequately planning for the future. In the absence of robust disclosures, investors, including BlackRock, will increasingly conclude that companies are not adequately managing risk.

We believe that when a company is not effectively addressing a material issue, its directors should be held accountable. Last year BlackRock voted against or withheld votes from 4,800 directors at 2,700 different companies. Where we feel companies and boards are not producing effective sustainability disclosures or implementing frameworks for managing these issues, we will hold board members accountable. **Given the groundwork we have already laid engaging on disclosure, and the growing investment risks surrounding sustainability, we will be increasingly disposed to vote against management and board directors when companies are not making sufficient progress on sustainability-related disclosures and the business practices and plans underlying them.**

Putting sustainability at the center of how we invest

[illegible]

› Read our letter to clients

Accountable and Transparent Capitalism

Over the 40 years of my career in finance, I have witnessed a number of financial crises and challenges – the inflation spikes of the 1970s and early 1980s, the Asian currency crisis in 1997, the dot-com bubble, and the global financial crisis. Even when these episodes lasted for many years, they were all, in the broad scheme of things, short-term in nature. Climate change is different. Even if only a fraction of the projected impacts is realized, this is a much more structural, long-term crisis. **Companies, investors, and governments must prepare for a significant reallocation of capital.**

In the discussions BlackRock has with clients around the world, more and more of them are looking to reallocate their capital into sustainable strategies. If ten percent of global investors do so – or even five percent – we will witness massive capital shifts. And this dynamic will accelerate as the next generation takes the helm of government and business. Young people have been at the forefront of calling on institutions – including BlackRock – to address the new challenges associated with climate change. They are asking more of companies and of governments, in both transparency and in action. And as trillions of dollars shift to millennials over the next few decades, as they become CEOs and CIOs, as they become the policymakers and heads of state, they will further reshape the world's approach to sustainability.

As we approach a period of significant capital reallocation, companies have a responsibility – and an economic imperative – to give shareholders a clear picture of their preparedness. And in the future, greater transparency on questions of sustainability will be a persistently

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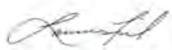
serving all stakeholders – your shareholders, customers, employees, and the communities where you operate. In doing so, your company will enjoy greater long-term prosperity, as will investors, workers, and society as a whole.

Sincerely,



Larry Fink
Chairman and Chief Executive Officer

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Where we stand

Corporate sustainability

We put an unwavering focus on long-term sustainability and ensure it's embedded across our entire business.

› **Learn more**

Investment stewardship

We engage with companies to inform our voting and promote sound corporate governance that is consistent with sustainable, long-term value creation.

› **Learn more**

› **Answers to sustainability questions**
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AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2018EF000922

Special Section:
Resilient Decision-Making for a Riskier World

Key Points:
- The global economic gains from complying with the Paris Climate Accord are shown to be substantial across 139 countries
- With the comparative case of RCP8.5 (4°C), the global gains from complying with the 2°C target (RCP4.5) are US$17,489 billion per year
- The relative damages from not complying with the 2°C target to Sub-Sahara Africa, India, and Southeast Asia are especially severe

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The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord

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Abstract Computable general equilibrium (CGE) models are a standard tool for policy analysis and forecasts of economic growth. Unfortunately, due to computational constraints, many CGE models are dimensionally small, aggregating countries into an often limited set of regions or using assumptions such as static price-level expectations, where next period's price is conditional only on current or past prices. This is a concern for climate change modeling, since the effects of global warming by country, in a fully disaggregated and global trade model, are needed, and the known future effects of global warming should be included in forward-looking forecasts for prices and profitability. This work extends a large dimensional intertemporal CGE trade model to account for the various effects of global warming (e.g., loss in agricultural productivity, sea level rise, and health effects) on Gross Domestic Product (GDP) growth and levels for 139 countries, by decade and over the long term, where producers look forward and adjust price expectations and capital stocks to account for future climate effects. The potential economic gains from complying with the Paris Accord are also estimated, showing that even with a limited set of possible damages from global warming, these gains are substantial. For example, with the comparative case of Representative Concentration Pathway 8.5 (4°C), the global gains from complying with the 2°C target (Representative Concentration Pathway 4.5) are approximately US$17,489 billion per year in the long run (year 2100). The relative damages from not complying to Sub-Sahara Africa, India, and Southeast Asia, across all temperature ranges, are especially severe.

Plain Language Summary This work shows considerable global economic gains from complying with the Paris Climate Accord for 139 countries. For example, with the comparative case of a temperature increase of four degrees, the global gains from complying with the 2° target are approximately US$17,489 billion per year in the long run (year 2100). The relative damages from not complying to Sub-Sahara Africa, India, and Southeast Asia are especially severe.

1. Introduction

The cumulative effects of global climate change will depend on how the world responds to increasing emissions. The evidence indicates that climate change has already resulted in extreme weather events and sea level rises (SLRs), with added threats to agricultural production in many parts of the world (United Nations, 2018; World Bank, 2016). However, standard economic forecasts of the impact of climate change very considerably, with early estimates showing mild effects on the world economy (see, e.g., Nordhaus, 1991; Tol, 2002). Some of these views have softened subsequently (Nordhaus, 2007; Tol, 2012), but aggregate damages still remain relatively small for most temperature ranges.

Both Weitzman (2012) and Stern (2016), among others, have warned that current economic modeling may seriously underestimate the impacts of potentially catastrophic climate change and emphasize the need for a new generation of models that give a more accurate picture of damages. In particular, Stern (2016) has pointed out two key weaknesses of the current class of economic models: their limited spatial coverage, including averaged impacts across countries and regions, and unreasonable assumptions on the discount rate, which translate into a relative lack of forward-looking behavior in economic forecasts and resulting negative impacts on future generations.

Indeed, there have been relatively few attempts to examine the full global, disaggregated, and intertemporal effects of climate change on GDP using large-scale economic modeling, modeling that would capture all of the trading patterns, spillover effects, and economic linkages among countries in the global economic system over time. To date, given its computational complexity, computable general equilibrium (CGE) modeling has largely concentrated on individual country effects or on dynamic models with limited numbers of countries or regions and an absence of forward-looking behavior, that is, so-called recursive dynamic models with static or adaptive price-level forecasts. These recursive dynamic models have value, but the assumption that future price-level expectations are based only on current and past values is broadly incongruent with known future projections of various climate change outcomes and resulting trade effects (Kompas & Ha, 2017).

In this work, we extend the results of recent and innovative large-scale economic modeling, Global Trade Analysis Project (GTAP)-INT (Kompas & Ha, 2017), to account for the effects of various Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) on global temperature, which result in a 1–4°C increase in global warming. Our model is fully disaggregated with forward-looking behavior, spanning across 139 countries and 57 broad commodity groups, with full computational convergence over a period of 200 years. In numerical simulations, we show the potential economic gains from following the Paris Climate Accord to the year 2100. It is important to note that we do not calculate the costs of implementing the Accord, but we do carefully measure the avoided damages (as potential losses in GDP) as the benefit of compliance.

As is well known, the Paris Accord targets to hold the increase in the global average temperature below 2.0°C above preindustrial levels and to pursue efforts to limit temperature increases to 1.5°C above preindustrial levels (United Nations, 2015). Following this agreement, United Nations members are committed to *intended nationally determined contributions* (INDCs), which provide estimates of their aggregate greenhouse gas (GHG) emission levels in 2025 and 2030. With the implementation of the INDCs, aggregate global emission levels would be lower than in pre-INDC trajectories (United Nations, 2016). The agreement also aims to further support the ability of countries to deal with the impacts of climate change (United Nations Framework Convention on Climate Change [UNFCCC], 2018a) and is seen as providing an essential road map for the human response to reduce emissions and build in further climate resilience.

Section 2 below provides a brief review of climate change agreements and the international framework. Section 3 highlights some of the previous literature on CGE modeling on the economic effects of climate change. Section 4 details our data, the model approach, and the results. Section 5 evaluates the long-term impacts by RCP scenario and the potential global economic gains of complying with the Paris Climate Accord. Section 6 provides some added discussion and a few closing remarks.

2. Climate Agreement and Scenario Context

Since 1850, the Earth's surface has become successively warmer and especially so over the past three decades. From 1880 to 2012, global average temperature (calculated with a linear trend for combined land and ocean surface temperature) shows a warming of 0.85 [0.65–1.06]°C (Intergovernmental Panel on Climate Change [IPCC], 2014). Emissions grew more quickly between 2000 and 2010, and carbon dioxide (CO_2) levels have increased by almost 50% since 1990. Under the effect of climate change, oceans have warmed, the amounts of snow and ice have diminished, and sea levels have risen. The global average sea level increased by 19 cm from 1901 to 2010 and is predicted to raise 24–30 cm by 2065 and 40–63 cm by 2100 (United Nations, 2018). The IPCC's Fifth Assessment Report (IPCC, 2014) has clearly confirmed human influence on the climate system. The report also indicates that the recent anthropogenic emissions of GHG are the highest in history and have already generated widespread impacts on human and ecological systems.

To counter these impacts, the past two decades have been marked by a sequence of international initiatives and agreements to stabilize GHG emissions. The UNFCCC, for example, was first introduced in 1992 to limit average global temperature increases. The UNFCCC is one of the three intrinsically linked Rio Conventions, adopted at the Rio Earth Summit in 1992. The other two Conventions are the UN Convention on Biological Diversity and the Convention to Combat Desertification (United Nations Framework Convention on Climate Change, 2018b). Since then, other major international climate change frameworks have progressed, including the Kyoto Protocol (1997), along with the Copenhagen Accord (2009), the Durban Platform for Enhanced

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Action (2011), the adoption of the Doha Amendment to the Kyoto Protocol (2012), the IPCC Fifth Assessment Report (IPCC, 2014), and the adoption of the Paris Agreement in 2015 (based on United Nations Framework Convention on Climate Change, 2018c, 2018d).

According to the United Nations Framework Convention on Climate Change (2018b), the UNFCCC Convention (1994), developed from the Montreal Protocol (1987; one of the most successful multilateral environmental treaties at that time), binds member states to act in the interests of human safety, facing scientific uncertainty. The Convention aims to stabilize GHG emissions *at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system*. As such, targeted GHG emission levels "should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" (United Nations Framework Convention on Climate Change, 2018b). Following the Convention, the industrialized country members in the Annex I parties, countries belonging to the Organization for Economic Cooperation and Development, including 12 countries with *economies in transition* from Central and Eastern Europe, which are major sources of GHG emissions, are mandated to do the most to cut emissions. By the year 2000, the Annex I parties were expected to reduce emissions to 1990 levels (United Nations Framework Convention on Climate Change, 2018b).

In addition, the Kyoto Protocol, which was adopted in Kyoto in December 1997 and entered into force for many countries in February 2005, was a major climate change agreement that set internationally binding emission reduction targets. Under the principle of *common but differentiated responsibilities*, the Protocol places a heavier burden on developed nations, which are legally bound to emission reduction targets following two phases of commitment periods, given by 2008–2012 and 2013–2020 (United Nations Framework Convention on Climate Change, 2018e). The Paris Climate Accord (adopted in 2015 to which 175 parties have ratified to date) further intensifies the effort toward sustainable low-carbon development, requiring a worldwide response to climate change. In the Paris Accord, both developed and developing countries have committed to reducing emissions by 2030, using 2005 as the base year. As indicated, the Paris Accord is designed to keep global temperatures in this century to a rise "well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2018f, 2018a).

To assist with the understanding of future long-term socioeconomic and environmental consequences of climate change, along with the analysis of potential mitigation and adaptation measures, various future scenarios are widely used in climate change research (van Vuuren & Carter, 2014). The IPCC has used climate scenarios from 1990 forward (SA90) following IS92 and the Special Report on Emissions Scenarios in 2007. These scenarios were developed and applied sequentially from the socioeconomic factors that influence GHG emissions to atmospheric and climate processes. As is generally known, the sequential approach led to inconsistency and delays in the development of emission scenarios (Moss et al., 2010). From 2006, the climate research community initiated a new *parallel approach* to developing scenarios, where model development progresses simultaneously rather than sequentially (Moss et al., 2010; van Vuuren et al., 2014). The work of van Vuuren and Carter (2014) provides a summary of the new scenario framework comprising two key elements: (1) Four RCP scenarios representing the possible future development of GHG emissions and concentrations of different atmospheric constituents affecting the radiative forcing of the climate system and (2) five SSP scenarios providing narrative descriptions and quantitative prediction of possible future developments of socioeconomic variables. These two sets of scenarios provide an integrated framework, or a scenario matrix architecture, to account for the various possible effects of global warming (van Vuuren et al., 2014).

Since both sets of scenarios (i.e., the social development and radiative forcing) eventually lead to different surface temperature increases, they can be reconciled into similar groups with comparable temperature increases. As indicated, van Vuuren and Carter (2014) provide suggestions for such reconciliation of the new RCP and SSP scenarios, in which most of the SSP scenarios can be mapped with the four RCP scenarios (see van Vuuren & Carter, 2014, for the detailed discussion of scenarios and reconciliation tables).

The simulations in our own work thus fully examine the impact on the world economy of global warming in the range from 1 to 4°C, which roughly covers all four possible RCP scenarios from RCP2.6 to RCP8.5. Our individual simulations can be further mapped by comparing final temperature increases with the median temperature rise by RCP scenarios in IPCC (2014), using the reconciliation tables in van Vuuren and Carter (2014).

3. CGE Modeling and the Economic Effects of Climate Change

Climate change is a global and long-term phenomenon, which requires global coordination and a forward-looking policy approach. Global dynamic CGE models are, therefore, a natural candidate for climate change impact assessment and policy analysis. Rational, intertemporal responses cannot be made using naive static or adaptive price-level expectations, which are essentially backward looking, or with highly aggregated regional, rather than country-specific, approaches. Unfortunately, due to technical difficulties, current economic and CGE modeling of the effects of climate change lack both adequate time (forward-looking) and spatial (country-disaggregated) coverage.

As a whole, CGE models encompass standard policy analysis and forecasting approaches for GDP growth, incomes, and the global economic system. Since the pioneering work of Johansen (1960), with a basic one country model, CGE models have grown both in size and complexity. Modern CGE models are now (at least potentially) truly global with as many as 140 interactive regional economies (Aguiar et al., 2016; Corong et al., 2017; Hertel, 1997) and can be solved over a long time horizon in a recursive (e.g., Dixon & Rimmer, 2002; Ianchovichina & Walmsley, 2012) or intertemporal framework (e.g., Ha et al., 2017; McKibbin & Wilcoxen, 1999). With the implementation of time (intertemporal) and spacial (regional and country-specific) dimensions, the size of CGE models has grown exponentially posing a serious challenge to current computational methods. Current software packages such as GEMPACK or GAMS, which use a serial direct LU solver (see Ha & Kompas, 2016), are incapable of solving large intertemporal CGE models. Dixon et al. (2005) indeed has shown that with these models, using over 100 industries or commodity groups, it is only possible to solve the system simultaneously for a relatively small number of time periods.

Due to computational constraints, current CGE models are also normally limited to either static or recursive approaches. Static CGE models compare an economy over two discrete time points: the current period before an exogenous shock and either a short-run period or a long-run period after the shock is realized. The main difference between the short- and long-run cases is whether the capital stock is fixed or allowed to freely adjust (in response to an exogenous shock), designated by short- or long-run closure. Hertel et al. (2010) used such a static CGE-GTAP model to simulate the impact of climate change on the world economy in the year 2030 via shocks in agricultural production. Although the model can be used to analyze the impact of climate change in the long run, it cannot provide any intermediate and time path effects from climate change. It is also dimensionally constrained, that is, even with the comparison of only two time periods, Hertel et al.'s (2010) approach can only account for 34 countries/regions. In practice, it is rare to see CGE models, static or recursive, that are solved with a full countrywide database (up to 100 countries/regions or more).

In a search for a more comprehensive approach, recursive models extend the static CGE model beyond a one-period comparative analysis by solving the system recursively, year after year, over an unspecified but extended time horizon. Bosello et al. (2006, 2007), for example, used a variant of the CGE-GTAP model, GTAP-E, to simulate the impact of climate change-induced effects on human health (Bosello et al., 2006) and sea level increases (Bosello et al., 2007) to the world economy up to 2050. (The GTAP-E framework, Burniaux & Truong, 2002, is an extension of the GTAP model, Hertel, 1997, with more detailed energy inputs in the model's production structure.) The model is first run recursively to calibrate the baseline scenario from an initial calibration year to 2050; then shocks to labor productivity, expenditure for health services (public and private), and SLRs are introduced to form comparative effects of climate change-induced effects for human health in particular. For the expenditure on health services, Bosello et al. (2006) impose a shift in parameter values which would produce the required variation in expenditure if all prices and income levels remained constant. The model is simulated for eight regions of the world. An extension of the ICES model (Eboli et al., 2010), another modification of the GTAP-E model, is also a good example of a multiregion recursive dynamic modeling approach to analyze the effects of temperature change on economic growth and wealth distribution globally. In a more elaborate application, Roson and der Mensbrugghe (2012) use the recursive ENVISAGE model to simulate the economic impact of climate change via a range of impact channels: sea level increases, variations in crop yields, water availability, human health, tourism, and energy demand.

A key limitation of these recursive models is their lack of forward-looking behavior, relying instead on static or adaptive price-level expectations, and successive single period calculations. Economic agents, in other words, only respond to shocks in the current year (or past years) and ignore otherwise known future changes in, for example, climate conditions, no matter how severe they may be. In other words, responses in economic behavior only occur once the shocks are realized. In addition, even though recursive models are solved one period at a time, successively, they normally can only solved for a relatively small number of countries, regions, and sectors, given computational constraints. Thus, they cannot use the available and fully disaggregated country data to facilitate computation.

There have been a few attempts to breakout of the traditional recursive dynamic modeling approach, building instead a forward-looking, global intertemporal model for climate change analysis. McKibbin et al. (2009), for example, use their G-CUBED model (McKibbin & Sachs, 1991; McKibbin & Wilcoxen, 1999) to form an intertemporal global economy to predict future CO_2 emissions under different scenarios. The model in Dixon et al. (2005) is another approach, using rational expectations of future prices to model intertemporal behavior. These are valuable methods, but they too suffer from either limited dimension (McKibbin et al., 2009, with only 14 countries and 12 sectors in) or with difficulties guaranteeing convergence to a solution as in the case of the rational expectations approach.

Outside of the context of the CGE modeling of global intertemporal economies, there are a number of examples of economic assessments of the effects of climate change using more basic models, where damage functions range from low to extreme levels. Tol (2002), for example, estimated the impact of a 1°C warming on the world economy based on a suit of existing and globally comprehensive impact studies. Tol, 's estimations are somewhat inconclusive. The impacts on world GDP with a 1°C warming range from +2% to −3% depending on whether a simple sum or a global average value method is used. Using an estimated damage function for the U.S. economy and extrapolated to the world economy, Nordhaus (1991) also finds mild effects from climate change impacts of 1%, or at most 2%, on the global economy. These views have been modified more recently, as indicated above, but total damages are still relatively small.

Alternatively, Weitzman (2012) has warned that we might be considerably underestimating the welfare losses from climate change by using conventional quadratic damage functions and a *thin-tailed* temperature distribution and suggests severe limits on GHG levels to guard against catastrophic climate risks. A study by the Global Humanitarian Forum (2009) also provides a worrisome picture of the social impacts (e.g., on environment and health) of climate change in the developing world. The loss from global warming, here, includes climate-related deaths from worsening floods and droughts, malnutrition, the spread of malaria, and heat-related ailments. According to Global Humanitarian Forum (2009), the current global warming process already causes 300,000 deaths and US$125 billion in economic losses annually.

Our paper addresses the above weaknesses of current economic analysis and CGE modeling of the effects of climate change by applying new solution methods, developed for solving intertemporal CGE models with very large dimension (Ha & Kompas, 2016, 2014; Ha et al., 2017; Kompas & Ha, 2017), modifying and extending the preliminary results of the effects of climate change contained in Kompas and Ha (2017) to different RCP scenarios. As such, we provide the first example of a large-scale and intertemporal computational modeling of the economic effects of global warming, across all 139 countries in the GTAP database, for various temperature changes. The added, large-dimensional precision matters to the final estimates and disaggregation by country is especially important here. Although the effects of climate change on global average GDP may be large or small, depending on RCP scenario, the effects on individual countries can be enormous across various RCPs. Averaging across such countries into regions severely masks these effects.

4. GTAP-INT Model Framework, Data, and Climate Change Results

The modeling approach applied in this study is an intertemporal CGE version of the GTAP model, termed GTAP-INT in Ha et al. (2017). GTAP is a global economic model that estimates the interactions of economic activities and effects among countries or regions under various exogenous shocks (Hertel, 1997).

We use GTAP version 6.2 to be consistent with our previous research (Ha et al., 2017). We are aware of the publication of GTAP version 7, where commodities and activities are separated so that a single producer can produce more than one product (Corong et al., 2017). However, in the most recent GTAP database (version 9), which we employ, a producer can produce only one product (see Aguiar et al., 2016). Therefore, we expect no substantive difference in our work between GTAP version 6.2 and version 7 simulation results with the current database.

The intertemporal version of GTAP model consists of blocks of supply and demand equations for producers, households, investment demand, and governments, indexed by country and at each point in time. Producers use inputs, or factors of production, such as land, labor and capital, and other intermediate goods, to deliver commodities which are sold on international and domestic markets. Households make decisions between savings and the consumption of various commodities, foreign and domestic, from their income, less taxes. In an individual economy, the total demand for a product (from international and domestic sources) equals the supply of that product, with corresponding price linkages and market clearing conditions. Global savings, investment, and transportation is also modeled (Ha et al., 2017; Hertel, 1997).

The GTAP model, in its current form, is run either as a static model or as a recursive dynamic model with assumed static or adaptive price-level expectations (Kompas & Ha, 2017). A key benefit of the GTAP-INT model is that it allows producers, in particular, to look forward, to choose how much to invest in capital stocks over time to maximize profits in the long run. A fully defined intertemporal version of the GTAP model was first developed in Ha et al. (2017), where fixed capital formation and given allocations of investment across regional blocks of countries are replaced by long-run profit conditions. The version of GTAP-INT in Kompas and Ha (2017) extends this work to very large dimensions using a new solution method and allowing for multiple countries and time periods. In the context of climate change, GTAP-INT allows producers to respond to foreseeable climate change impacts immediately, in terms of how they invest and the choice over what they produce, rather than waiting for climate change impacts to be actually realized and then enter their forecasts for prices and other key variables. In recursive models, alternatively, producers only respond to climate change impacts once they actually occur. The structural equations for GTAP-INT are detailed in Ha et al. (2017) and are not repeated here, save for the key intertemporal condition for profit (dividend) maximization, given by two motion equations for capital accumulation and its shadow price:

$$\dot{k}_{r,t} = I_{r,t} - \delta_r k_{r,t} \tag{1}$$

$$\dot{\mu}_{r,t} = \mu_{r,t}(r_t + \delta_r) - \frac{\phi_{r,t}}{2}\left(\frac{I_{r,t}}{k_{r,t}}\right)^2 p^I_{r,t} - p^k_{r,t} \tag{2}$$

where $k_{r,t}$ is the capital stock in region r at time t (hereafter we supress the indices r and t where appropriate for simplicity), r_t is the world interest rate, $I_{r,t}$ is increment in capital (i.e., investment), δ_r is the depreciation rate, $\mu_{r,t}$ is the shadow price of capital, and $\phi_{r,t}$ is the investment coefficient, which shows how much extra money we must invest in order to obtain a dollar increase in the capital stock; $p^I_{r,t}$ is the price of capital goods; and $p^k_{r,t}$ is the rental price of capital. To solve the model, we use the GTAP model equations to link all global economies over time using forward-backward equations (i.e., equations (1) and (2)) for each country in the GTAP model, given an initial condition (fixed initial capital $k_{r,0}$) and one terminal condition: $\dot{\mu}_{r,T} = 0$ (Kompas & Ha, 2017). As usual in intertemporal models, we take a state steady benchmark as the baseline or as *business as usual*. We then compare this baseline path to parametric changes across different climate change scenarios. This is standard in an intertemporal framework and indeed is the only technical option available to facilitate our large-dimensional modeling.

4.1. Database and Climate Change Damage Functions

As indicated, the database employed in this work is GTAP Data Version 9 (Aguilar et. al., 2016; GTAP, 2017), which consists of 140 countries and regions (we drop one country, Benin, for numerical stability) and 57 commodities with 2011 as the base year. The data set requires the addition of damage functions, which aim to estimate the economic impacts of global warming, in general, and, in particular, in CGE and GTAP modeling. The climate change damage functions applied in this paper largely follow, with some qualifications, Roson and Sartori (2016), where climate change parameters for damages are estimated from a series of meta-analyses for each of the 140 countries and regions in the GTAP version 9 data set. The damage functions applied include the effects of SLR, losses in agricultural productivity, temperature effects on labor productivity and human health, energy demands, and flows of tourism (Roson & Sartori, 2016).

The background for all of this is straightforward. For SLR impacts, following the Fifth IPCC Assessment Report (IPCC, 2014), Roson and Sartori (2016) note that a large number of studies find a connection between global warming and sea level increases. SLR affects the total stock of land and causes erosion, inundation, or salt intrusion along the coastline. As a consequence, the share of land which may be lost depends on several country-specific characteristics. In Roson and Sartori (2016), the relationship between SLR (in meters) and the increase in global mean surface temperature (in degrees Celsius), at the time intervals 2046–2065 and 2080–2100, is based on IPCC (2014), with an added emphasis on land losses in agriculture.

Indeed, economic studies of climate change appear to focus predominantly on agricultural impacts. According to Roson and Sartori (2016), climate change is expected to bring about higher temperatures, a higher carbon concentration, and different patterns in regional precipitation, all of which affect crop yields and agricultural productivity. In Roson and Sartori (2016), in particular, the climate change damage function for agricultural productivity is based on a meta-analysis provided in IPCC (2014), which provides central estimates for variations in the yields of maize, wheat, and rice. Roson and Sartori (2016) elaborate on these results to get estimates of productivity changes for these three crops, in all 140 regions and for the five levels of temperature increase, from 1 to 5°C. The estimation distinguishes between tropical and temperate regions and identifies a nonlinear interpolation function for all cases. Roson and Sartori (2016) also apply the work by Cline (2007) for the estimation of productivity changes for the entire agricultural sector in various regions. In this approach, the variation in agricultural output per hectare is expressed as a function of temperature, precipitation, and carbon concentration.

Estimation of labor productivity loss due to heat stress in Roson and Sartori (2016) is based on a study by Kjellstrom et al. (2009), which produced a graph of *work ability* as the maximum percentage of an hour that a worker should be engaged working. Roson and Sartori (2016) define work ability (a proxy for productivity) as a function of *wet bulb globe temperature*. The heat exposure index, using wet bulb globe temperature (units in °C), is a combination of average temperature and average absolute humidity (Roson & Sartori, 2016). As developed from Kjellstrom et al. (2009), Roson and Sartori (2016) estimate the effect of global warming for different increments in temperatures (ranging from 1 to 5°C) for three labor sectors (agriculture, manufacturing, and services) in each of the GTAP countries.

In Roson and Sartori (2016), estimation of the GTAP human health damage function is developed from Bosello et al. (2006), which, based partly on Tol (2002), develops estimates of the association between temperature increments and a number of added cases of mortality and morbidity of selected diseases, considering, in particular, the direct effect of incremental temperatures for vector-borne diseases (e.g., malaria and dengue), heat- and cold-related diseases, and diarrhea. Given the lack of data, supporting evidence and the scope of the analysis, Roson and Sartori (2016) do not include other diseases mentioned in IPCC (2014), such as hemorrhagic fever, plague, Japanese and tick-borne encephalitis, air quality and nutrition-related and allergic diseases, nor other impact categories mentioned in World Health Organization (2014) such as heat-related mortality in elderly people, or mortality associated with coastal flooding, and so on (Roson & Sartori, 2016).

Given our purposes, we disregard the climate damage functions for tourism and energy demand, also estimated by Roson and Sartori (2016). In terms of tourism, Roson and Sartori (2016) estimate travel flows following Hamilton et al. (2005) of which flows of international tourism are regressed as a function of temperature, land area, length of coastline, and per capita income. However, tourism flows in Roson and Sartori (2016) are regressed simply as an exponential function of temperature with a constant term (for a country's specific condition). This seems inadequate for our otherwise nonlinear specifications. Also, Roson and Sartori (2016) did not consider the other key drivers of tourism flows, including the attractions of natural landscapes, cultural and historical attributes, and, most importantly, the distinction between tourism and other forms of migration for climate change-related movements. Moreover, transforming the tourism effect into a CGE framework, which is based on GDP, implies no difference of income spending between nationals and foreigners inside a country's border and therefore is largely inappropriate.

The climate change effect on household's energy consumption in Roson and Sartori (2016) is estimated and adjusted from De Cian et al. (2013) of which the key drivers are season, sources of energy, and a country's climatic condition. However, for GTAP modeling, other drivers such as the elasticity of fuel use and income, the fuel mix in each country, and variations in standards of living among rich and poor nations matter a great deal. Since these are not included, we suspend this effect, for now, pending the development of a GTAP-E version of GTAP-INT. In any case, the temperature elasticities in De Cian et al. (2013), which are estimated for current climate conditions, would change considerably under various global warming scenarios, and this needs to be analyzed separately and comprehensively and not simply adjusted.

From the above damage function estimations, we design shocks to the GTAP-INT model to simulate the climate change impacts. First, the SLR impact will be simulated as a negative shock to the supply of land, a nonmobile factor of production in GTAP-INT. The shock is region specific, as in Roson and Sartori (2016). Next, negative agricultural productivity will be simulated by a percentage change shock to output-augmenting technical change in agricultural sectors. The shock is also sector and region specific. We aggregate and simulate labor productivity loss and human health damages via a negative labor productivity loss. Again, the labor productivity loss will be region and sector specific. With all the shocks, we assume a linear gradual increase from the current year (2017) with the highest shock occurring in 2100. After 2100, the size of the shock is assumed to remain constant (at the 2100 level), and the model is run forward for 200 years to ensure convergence to a new steady state, which the latter interpreted as long-run losses or impacts. With the time horizon of the model at 200 years, we apply a variable time grid to reduce the dimension of the model (see for details on intertemporal solution methods ; Dixon et al., 1992). Nevertheless, with multiple periods and the full regional and country-specific GTAP model, the size of the model is very large, and we solve the model using only the one-step Johansen method (see for details on the Johansen solution method; Dixon et al., 1992).

4.2. The Economic Effect of Global Warming

Following Riahi et al. (2017), different SSP narratives are characterized by assumptions on future economic growth, population change, and urbanization. As indicated above, Riahi et al. (2017) provide an overview of the main characteristics of five SSPs and related integrated assessment scenarios. The scenario analysis in our work, as discussed in section 2, is based on four different scenarios where the world surface temperature increases from 1 to 4°C to 2100, with RCPs (Moss et al., 2010) mapped to our scenarios by using the predictions of global surface temperature increases in IPCC (2014). As SSPs can also be mapped with RCPs (van Vuuren & Carter, 2014), our scenarios can be seen as a potential realization of scenarios from the Scenario Matrix Architecture (van Vuuren et al., 2014) and are valuable for analyzing climate change and mitigation policies.

For our GTAP-INT results, the dynamic effect of global warming is measured as the change in real GDP in all regions for different global warming scenarios in the range from 1 to 4°C. With lower emissions, for example, global warming is approximated by an increase of 0.85°C as in RCP2.6, where the climate change damage parameters for the 1°C case in Roson and Sartori (2016) can be (approximately) applied. In the extreme case of RCP8.5, without mitigation action (i.e., with *Rocky Road* [SSP 3] and strong *Fossil-Fueled Development* [SSP5] scenarios; Ria et al., 2017), global warming could increase temperatures by as much as 4°C, or perhaps more, by 2100.

For our current purposes, we first focus on *Middle of the Road* (SSP2) as the most likely or *business as usual* scenario. In this case, the path of the world's social, economic, and technological trends does not shift markedly from historical patterns (Riahi et al., 2017). As such, climate change is likely to be RCP6.0 and our scenario with a global warming of 3°C by 2100 can be applied. The results from GTAP-INT on GDP are given in percentage changes in Table 1 (which, with Figure 1, qualify and extend the preliminary results in Kompas & Ha, 2017). The value losses in GDP caused by global warming over the medium and long term for selected countries are contained in Table A1. Table A2 also details the global warming effects decomposed by economic sectors. As indicated, it is important to note that the model is run forward for 200 years, our *long run* for convenience and computational convergence. After the year 2100 no additional shocks are introduced to the model so that convergence is guaranteed. GDP estimates in Table A2 and the calculation of the gains from complying with the Paris Accord are based on outcomes to the year 2100 only.

The results clearly show that the effects of global warming vary by time, region, and economic sectors but tend to increase over time and become much worse in relatively poor African and Asian nations, where the loss in GDP here and in all countries near the equator is most severe (see Table 1 and Figure 1). But, indeed, over the medium term, despite some minor gains in a few European countries, the losses from global warming (at 3°C) dominate a major part of the world (Figure 1).

Using the value of GDP in 2017 from IMF (2018) as the base year, our GTAP-INT results, and economic growth forecasts from SSP2 (Crespo Cuaresma, 2017; International Institute for Applied Systems Analysis, 2018), the approximate global potential loss is estimated to be US$9,593.71 billion or roughly 3% of the 2100 world GDP for 3°C global warming (see Table A1). At 4°C, losses from global warming increase significantly to US$23,149.18 billion. The largest losses in all cases, and for all temperature increases, occur in Sub-Saharan Africa, India, and Southeast Asia.

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Table 1
Impacts of Global Warming (3°C) on the World GDP (% Change/Year)

Country	2027	2037	2047	2067	Long run
Australia	−0.051	−0.107	−0.172	−0.326	−1.083
New Zealand	0.043	0.073	0.087	0.073	−0.798
Rest of Oceania	−0.452	−0.924	−1.422	−2.470	−5.171
China	−0.205	−0.438	−0.692	−1.247	−2.918
Hong Kong	−0.356	−0.765	−1.216	−2.205	−5.288
Japan	−0.042	−0.100	−0.173	−0.356	−1.335
South Korea	−0.025	−0.071	−0.136	−0.313	−1.498
Mongolia	−0.214	−0.415	−0.631	−1.105	−2.710
Taiwan	−0.535	−1.121	−1.740	−3.034	−5.978
Rest of East Asia	−0.819	−1.752	−2.752	−4.849	−9.490
Brunei Darussalam	−0.372	−0.815	−1.308	−2.385	−5.563
Cambodia	−1.175	−2.439	−3.758	−6.482	−12.101
Indonesia	−1.242	−2.594	−4.020	−6.973	−13.267
Laos	−1.039	−2.164	−3.342	−5.765	−10.621
Malaysia	−1.091	−2.293	−3.568	−6.229	−12.118
Philippines	−1.206	−2.592	−4.093	−7.275	−14.798
Singapore	−0.905	−1.958	−3.106	−5.562	−11.652
Thailand	−0.766	−1.605	−2.500	−4.401	−9.243
Vietnam	−0.802	−1.636	−2.500	−4.276	−7.959
Rest of Southeast Asia	−1.342	−2.767	−4.237	−7.234	−12.924
Bangladesh	−0.854	−1.671	−2.491	−4.142	−7.591
India	−1.023	−2.099	−3.222	−5.532	−10.351
Nepal	−0.505	−1.012	−1.537	−2.628	−5.731
Pakistan	−0.483	−1.001	−1.557	−2.753	−6.435
Sri Lanka	−1.129	−2.320	−3.569	−6.154	−11.716
Rest of South Asia	−1.081	−2.105	−3.133	−5.206	−9.606
Canada	0.062	0.111	0.151	0.203	−0.218
United States of America	−0.015	−0.037	−0.067	−0.147	−0.622
Mexico	−0.029	−0.076	−0.147	−0.363	−2.277
Rest of North America	0.015	−0.003	−0.033	−0.127	−0.902
Argentina	−0.061	−0.137	−0.228	−0.450	−1.583
Bolivia	−0.194	−0.388	−0.592	−1.028	−2.332
Brazil	−0.319	−0.658	−1.018	−1.782	−3.843
Chile	0.008	0.001	−0.021	−0.112	−1.158
Colombia	−0.452	−0.916	−1.401	−2.425	−5.532
Ecuador	−0.183	−0.380	−0.594	−1.061	−2.599
Paraguay	−0.630	−1.304	−2.012	−3.482	−6.729
Peru	−0.174	−0.348	−0.526	−0.902	−1.934
Uruguay	−0.055	−0.135	−0.234	−0.482	−1.776
Venezuela	−0.309	−0.636	−0.982	−1.712	−3.614
Rest of South America	−0.028	−0.075	−0.141	−0.321	−1.545
Costa Rica	−0.585	−1.277	−2.038	−3.673	−7.871
Guatemala	−0.215	−0.442	−0.684	−1.206	−2.798
Honduras	−1.025	−2.151	−3.337	−5.802	−11.126
Nicaragua	−1.187	−2.449	−3.757	−6.435	−11.673
Panama	−0.870	−1.823	−2.838	−4.958	−9.580
El Salvador	−0.338	−0.719	−1.136	−2.048	−4.957

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Table 1 *(continued)*

Country	2027	2037	2047	2067	Long run
Rest of Central America	−1.163	−2.391	−3.665	−6.285	−11.646
Dominican Republic	−0.522	−1.150	−1.855	−3.400	−7.934
Jamaica	−0.616	−1.287	−1.999	−3.492	−6.940
Puerto Rico	−0.458	−0.995	−1.587	−2.870	−6.527
Trinidad and Tobago	−0.503	−1.136	−1.842	−3.371	−7.357
Caribbean	−0.771	−1.610	−2.492	−4.320	−8.207
Austria	0.055	0.107	0.151	0.200	−0.486
Belgium	0.043	0.081	0.108	0.128	−0.540
Cyprus	0.025	0.042	0.049	0.024	−0.816
Czech Republic	0.086	0.165	0.231	0.312	−0.567
Denmark	0.037	0.068	0.092	0.112	−0.393
Estonia	0.018	0.028	0.028	−0.008	−0.750
Finland	0.060	0.117	0.165	0.231	−0.254
France	0.048	0.088	0.117	0.141	−0.455
Germany	0.044	0.083	0.112	0.140	−0.415
Greece	0.108	0.200	0.281	0.402	−0.275
Hungary	0.064	0.122	0.168	0.217	−0.590
Ireland	0.055	0.108	0.152	0.196	−0.748
Italy	0.070	0.136	0.190	0.255	−0.588
Latvia	0.060	0.111	0.152	0.196	−0.394
Lithuania	0.092	0.178	0.251	0.353	−0.394
Luxembourg	0.054	0.101	0.138	0.171	−0.600
Malta	0.066	0.130	0.181	0.225	−1.261
Netherlands	0.054	0.101	0.135	0.169	−0.467
Poland	0.074	0.139	0.192	0.253	−0.514
Portugal	0.044	0.083	0.113	0.140	−0.460
Slovakia	0.100	0.193	0.273	0.382	−0.470
Slovenia	0.041	0.071	0.091	0.097	−0.512
Spain	0.044	0.078	0.102	0.113	−0.575
Sweden	0.039	0.074	0.102	0.131	−0.349
United Kingdom	0.034	0.063	0.085	0.101	−0.422
Switzerland	0.016	0.028	0.034	0.029	−0.355
Norway	0.003	0.008	0.007	−0.022	−0.646
Rest of EFTA	0.057	0.111	0.154	0.205	−0.421
Albania	−0.054	−0.114	−0.185	−0.365	−1.461
Bulgaria	0.063	0.115	0.153	0.187	−0.590
Belarus	0.089	0.147	0.191	0.240	−0.249
Croatia	0.010	0.015	0.015	−0.007	−0.454
Romania	0.041	0.076	0.099	0.112	−0.483
Russian Federation	−0.011	−0.016	−0.027	−0.081	−0.936
Ukraine	0.057	0.107	0.149	0.204	−0.250
Rest of Eastern Europe	0.175	0.311	0.432	0.639	0.370
Rest of Europe	0.104	0.198	0.280	0.401	−0.206
Kazakhstan	−0.031	−0.058	−0.089	−0.173	−0.820
Kyrgyzstan	0.009	0.006	−0.011	−0.083	−0.930
Rest of Former Soviet Union	0.012	0.019	0.017	−0.015	−0.564
Armenia	−0.040	−0.079	−0.126	−0.249	−1.350

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Table 1 *(continued)*

Country	2027	2037	2047	2067	Long run
Azerbaijan	−0.174	−0.350	−0.538	−0.953	−2.638
Georgia	−0.025	−0.060	−0.106	−0.231	−1.035
Bahrain	−0.281	−0.630	−1.031	−1.939	−5.138
Iran	−0.167	−0.350	−0.558	−1.047	−3.516
Israel	−0.198	−0.410	−0.632	−1.102	−2.317
Jordan	−0.158	−0.342	−0.555	−1.052	−3.254
Kuwait	−0.218	−0.508	−0.851	−1.639	−4.488
Oman	−0.210	−0.478	−0.786	−1.477	−3.780
Qatar	−0.357	−0.829	−1.387	−2.674	−7.304
Saudi Arabia	−0.378	−0.831	−1.332	−2.422	−5.449
Turkey	0.007	−0.008	−0.045	−0.180	−1.540
United Arab Emirates	−0.457	−1.007	−1.630	−3.024	−7.684
Rest of Western Asia	−0.248	−0.507	−0.783	−1.381	−3.306
Egypt	−0.354	−0.714	−1.086	−1.867	−4.000
Morocco	−0.200	−0.415	−0.640	−1.120	−2.436
Tunisia	−0.227	−0.473	−0.735	−1.303	−3.052
Rest of North Africa	−0.211	−0.417	−0.630	−1.080	−2.394
Burkina Faso	−1.576	−3.278	−5.076	−8.829	−17.058
Cameroon	−0.980	−1.989	−3.031	−5.162	−9.396
Cote d'Ivoire	−1.972	−3.988	−6.034	−10.164	−17.528
Ghana	−2.000	−3.999	−6.028	−10.124	−17.571
Guinea	−0.980	−1.939	−2.932	−4.991	−9.896
Nigeria	−1.674	−3.422	−5.217	−8.874	−15.723
Senegal	−1.270	−2.565	−3.905	−6.666	−13.001
Togo	−2.338	−4.553	−6.787	−11.276	−19.032
Rest of Western Africa	−2.334	−4.091	−5.860	−9.409	−15.566
Central Africa	−0.376	−0.783	−1.223	−2.173	−4.977
South Central Africa	−0.289	−0.587	−0.896	−1.549	−3.320
Ethiopia	−0.759	−1.476	−2.197	−3.656	−6.704
Kenya	−0.744	−1.492	−2.254	−3.813	−7.238
Madagascar	−0.726	−1.486	−2.270	−3.881	−7.212
Malawi	−0.983	−1.995	−3.028	−5.133	−9.266
Mauritius	−0.650	−1.359	−2.113	−3.700	−7.458
Mozambique	−0.837	−1.738	−2.681	−4.639	−8.878
Rwanda	−0.766	−1.531	−2.309	−3.888	−7.047
Tanzania	−0.737	−1.479	−2.237	−3.785	−6.988
Uganda	−0.635	−1.268	−1.912	−3.232	−6.328
Zambia	−0.407	−0.831	−1.272	−2.189	−4.414
Zimbabwe	−0.428	−0.849	−1.283	−2.187	−4.423
Rest of Eastern Africa	−0.874	−1.750	−2.644	−4.461	−8.099
Botswana	−0.148	−0.322	−0.523	−0.993	−3.047
Namibia	−0.088	−0.190	−0.310	−0.610	−2.404
South Africa	−0.130	−0.278	−0.443	−0.823	−2.464
Rest of South African Customs Union	−0.192	−0.407	−0.644	−1.172	−3.045
Rest of the World	−0.078	−0.177	−0.294	−0.577	−1.918

Note. Source: Authors' GTAP-INT calculation.

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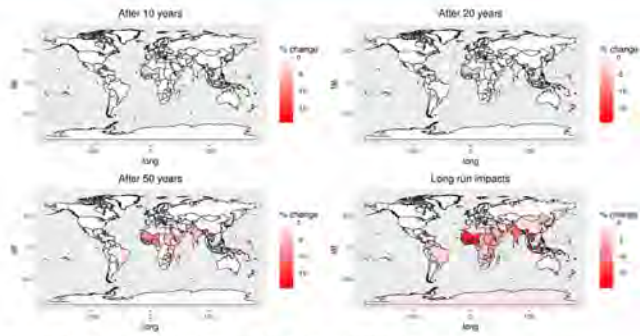

Figure 1. Dynamic impacts of global warming (3°C) on the world GDP (% change/year).

5. Long-Term Potential Impacts by RCP Scenario and Gains From Complying With the Paris Accord

This section compares the long-term impact by different temperature changes from global warming or equivalently different RCPs so that the avoided losses from various responses to climate change can be analyzed and the gains from complying with the Paris Accord can be calculated. Table 2 presents the long-run impacts of different global warming scenarios (1–4°C), which correspond to different RCPs in Moss et al. (2010). The measure is the change in GDP. It is clear that falls in GDP for countries near the equator are especially dramatic.

Indeed, it is interesting to compare our results with the findings of Roson and der Mensbrugghe (2012), using their ENVISAGE model. Although comparable, it is important to note that the model context here is different. Roson and der Mensbrugghe (2012) use a recursive dynamic approach, with adaptive expectations, and their results are only for 15 regions, which will necessarily average outcomes. Our intertemporal approach is dimensionally larger, for 139 countries, and drops the damage functions for tourism and energy use. That said, Roson and der Mensbrugghe (2012) find that the developing and poorer countries in the *rest of Asia* and the *Middle East and North Africa* lose 10.3% to 12.6% of their GDP when the global temperature increases by 4.79°C in 2100. Our larger dimensional model shows, instead, that if global surface temperature increases by 4°C, countries in South East Asia can lose up to 21% of their GDP per year. The picture for developing countries in Africa is even more grim with the GDP losses as high as 26.6% per year (Table 2).

From the above GDP damages, it is possible to calculate the gains from complying with the Paris Climate Accord. Following van Vuuren et al. (2011), we can map our scenarios in terms of their implications for the following climate change policies.

1. The case of 1°C is likely to reflect the lowest emission scenario with the most stringent mitigation policies (or approximately RCP2.6).
2. Implementation of a climate change agreement (e.g., the Paris Accord) would slow global warming to around 2°C by 2100 (or approximately RCP4.5).
3. A medium baseline case with less stringent mitigation policies will push global surface temperatures up to 3°C by 2100 (approximately RCP6).
4. Without any countervailing action to reduce emissions, global warming could increase up to 4°C (or approximately RCP8.5).

The successful achievement of the Paris Accord, which aims to keep global warming at roughly 2°C (or RCP4.5), or less, allows us to calculate the potential benefit of the Accord as the difference in losses between the 4, 3, and 2°C scenarios. Based on the full version of Table 2 from our GTAP-INT simulation results, and Table A1, which represents the value of annual GDP losses in 2100, we can calculate the differences.

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Table 2
Long-Run Impacts of Climate Change Scenarios on the World GDP (% Change/Year)

Country	1°C	2°C	3°C	4°C
Australia	−0.287	−0.642	−1.083	−1.585
New Zealand	−0.144	−0.413	−0.798	−1.269
Rest of Oceania	−1.015	−2.627	−5.171	−8.553
China	−0.755	−1.694	−2.918	−4.597
Hong Kong	−1.314	−3.082	−5.288	−7.655
Japan	−0.182	−0.595	−1.335	−2.412
South Korea	−0.211	−0.731	−1.498	−2.666
Mongolia	−0.789	−1.664	−2.710	−3.981
Taiwan	−1.597	−3.560	−5.978	−8.552
Rest of East Asia	−2.389	−5.709	−9.490	−13.710
Brunei Darussalam	−1.202	−3.134	−5.563	−8.173
Cambodia	−3.509	−7.572	−12.101	−17.183
Indonesia	−3.347	−7.980	−13.267	−19.040
Laos	−3.369	−6.795	−10.620	−15.759
Malaysia	−3.084	−7.145	−12.118	−17.339
Philippines	−4.113	−9.185	−14.798	−20.986
Singapore	−2.729	−6.923	−11.652	−16.566
Thailand	−2.541	−5.749	−9.243	−13.269
Vietnam	−2.223	−4.862	−7.959	−11.641
Rest of Southeast Asia	−3.811	−8.110	−12.924	−18.573
Bangladesh	−2.285	−4.755	−7.591	−11.237
India	−2.922	−6.434	−10.351	−14.622
Nepal	−1.012	−2.881	−5.731	−9.859
Pakistan	−1.901	−3.994	−6.435	−9.338
Sri Lanka	−2.989	−6.941	−11.716	−17.437
Rest of South Asia	−2.778	−6.002	−9.606	−13.880
Canada	−0.096	−0.158	−0.218	−0.321
United States of America	−0.182	−0.392	−0.622	−0.885
Mexico	−0.506	−1.178	−2.277	−3.985
Rest of North America	−0.231	−0.539	−0.902	−1.292
Argentina	−0.360	−0.872	−1.583	−2.610
Bolivia	−0.650	−1.442	−2.332	−3.356
Brazil	−0.615	−1.910	−3.843	−6.829
Chile	−0.323	−0.709	−1.158	−1.674
Colombia	−1.104	−2.714	−5.532	−9.325
Ecuador	−0.741	−1.627	−2.599	−3.801
Paraguay	−1.604	−3.873	−6.729	−10.142
Peru	−0.509	−1.169	−1.934	−2.768
Uruguay	−0.471	−1.023	−1.776	−2.785
Venezuela	−0.649	−1.794	−3.614	−6.339
Rest of South America	−0.459	−0.937	−1.545	−2.446
Costa Rica	−1.407	−4.047	−7.871	−12.928
Guatemala	−0.694	−1.553	−2.798	−4.533
Honduras	−2.751	−6.492	−11.126	−16.521
Nicaragua	−3.020	−6.898	−11.673	−17.264
Panama	−2.197	−5.367	−9.580	−14.457
El Salvador	−0.986	−2.498	−4.957	−8.438

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Table 2 *(continued)*

Country	1°C	2°C	3°C	4°C
Rest of Central America	−1.675	−5.603	−11.646	−18.231
Dominican Republic	−1.850	−4.406	−7.934	−12.171
Jamaica	−1.485	−3.696	−6.940	−10.813
Puerto Rico	−1.269	−3.297	−6.527	−10.536
Trinidad and Tobago	−1.690	−4.150	−7.357	−10.905
Caribbean	−1.864	−4.529	−8.207	−12.605
Austria	−0.122	−0.287	−0.486	−0.728
Belgium	−0.151	−0.330	−0.540	−0.788
Cyprus	−0.194	−0.462	−0.816	−1.481
Czech Republic	−0.169	−0.352	−0.567	−0.842
Denmark	−0.127	−0.252	−0.393	−0.573
Estonia	−0.230	−0.476	−0.750	−1.087
Finland	−0.067	−0.153	−0.254	−0.383
France	−0.139	−0.285	−0.455	−0.662
Germany	−0.118	−0.254	−0.415	−0.608
Greece	−0.048	−0.149	−0.275	−0.708
Hungary	−0.197	−0.390	−0.590	−0.884
Ireland	−0.184	−0.436	−0.748	−1.125
Italy	−0.144	−0.342	−0.588	−0.906
Latvia	−0.140	−0.259	−0.394	−0.564
Lithuania	−0.179	−0.288	−0.394	−0.587
Luxembourg	−0.137	−0.343	−0.600	−0.896
Malta	−0.275	−0.691	−1.261	−2.083
Netherlands	−0.118	−0.275	−0.467	−0.694
Poland	−0.166	−0.332	−0.514	−0.774
Portugal	−0.120	−0.275	−0.460	−0.684
Slovakia	−0.129	−0.285	−0.470	−0.706
Slovenia	−0.139	−0.310	−0.512	−0.764
Spain	−0.147	−0.341	−0.575	−0.871
Sweden	−0.095	−0.211	−0.349	−0.516
United Kingdom	−0.122	−0.260	−0.422	−0.613
Switzerland	−0.094	−0.214	−0.355	−0.522
Norway	−0.160	−0.377	−0.646	−0.967
Rest of EFTA	−0.097	−0.242	−0.421	−0.634
Albania	−0.395	−0.857	−1.461	−2.360
Bulgaria	−0.090	−0.294	−0.590	−0.999
Belarus	−0.176	−0.214	−0.249	−0.617
Croatia	−0.083	−0.216	−0.454	−0.946
Romania	−0.171	−0.329	−0.483	−0.754
Russian Federation	−0.266	−0.568	−0.936	−1.405
Ukraine	−0.153	−0.219	−0.250	−0.382
Rest of Eastern Europe	0.011	0.160	0.370	0.492
Rest of Europe	−0.089	−0.150	−0.205	−0.318
Kazakhstan	−0.371	−0.592	−0.820	−1.137
Kyrgyzstan	−0.377	−0.614	−0.930	−1.500
Rest of Former Soviet Union	−0.239	−0.392	−0.564	−0.888
Armenia	−0.739	−1.050	−1.350	−1.777
Azerbaijan	−0.756	−1.563	−2.638	−4.025

Table 2 *(continued)*

Country	1°C	2°C	3°C	4°C
Georgia	−0.393	−0.680	−1.035	−1.769
Bahrain	−1.440	−3.192	−5.138	−7.303
Iran	−0.894	−2.044	−3.516	−5.365
Israel	−0.743	−1.514	−2.317	−3.416
Jordan	−0.982	−1.998	−3.254	−4.835
Kuwait	−1.315	−2.795	−4.488	−6.387
Oman	−0.996	−2.248	−3.780	−5.482
Qatar	−2.091	−4.618	−7.304	−10.358
Saudi Arabia	−1.650	−3.457	−5.449	−7.773
Turkey	−0.342	−0.842	−1.540	−2.479
United Arab Emirates	−2.207	−4.799	−7.684	−10.976
Rest of Western Asia	−0.829	−1.879	−3.306	−4.985
Egypt	−1.083	−2.377	−4.000	−6.143
Morocco	−0.770	−1.525	−2.436	−3.487
Tunisia	−0.871	−1.836	−3.052	−4.609
Rest of North Africa	−0.653	−1.415	−2.394	−3.639
Burkina Faso	−5.229	−10.894	−17.058	−23.586
Cameroon	−2.276	−5.528	−9.396	−14.480
Cote dIvoire	−4.710	−10.742	−17.528	−25.252
Ghana	−4.857	−10.815	−17.571	−24.983
Guinea	−2.712	−6.093	−9.896	−14.689
Nigeria	−4.528	−9.689	−15.723	−22.250
Senegal	−3.859	−8.189	−13.001	−18.544
Togo	−5.597	−12.221	−19.032	−26.556
Rest of Western Africa	−4.432	−9.769	−15.566	−21.938
Central Africa	−1.013	−2.430	−4.977	−8.362
South Central Africa	−0.961	−2.066	−3.320	−4.894
Ethiopia	−1.862	−4.238	−6.704	−9.416
Kenya	−2.331	−4.706	−7.238	−10.506
Madagascar	−1.976	−4.286	−7.212	−10.993
Malawi	−2.277	−5.683	−9.266	−13.609
Mauritius	−1.829	−4.399	−7.458	−11.245
Mozambique	−2.411	−5.311	−8.878	−12.989
Rwanda	−2.107	−4.490	−7.047	−9.819
Tanzania	−1.546	−4.130	−6.988	−10.825
Uganda	−1.743	−3.652	−6.328	−10.404
Zambia	−1.097	−2.616	−4.414	−6.720
Zimbabwe	−1.261	−2.726	−4.423	−6.502
Rest of Eastern Africa	−2.112	−4.750	−8.099	−11.862
Botswana	−0.710	−1.659	−3.047	−4.873
Namibia	−0.673	−1.464	−2.404	−3.616
South Africa	−0.740	−1.570	−2.464	−3.433
Rest of South African Customs Union	−0.890	−1.923	−3.045	−4.390
Rest of the World	−0.587	−1.227	−1.918	−2.671

Note. Source: Authors' GTAP-INT calculation.

As indicated above, we calculate world GDP in 2100 using 2017 world GDP in US$ (IMF, 2018, from the World Economic Outlook database) and economic growth from the corresponding SSPs (SSP1 for 2 °C, SSP2 for 3°C and SSP5 for 4°C; Crespo Cuaresma, 2017; International Institute for Applied Systems Analysis, 2018). Because the economic forecasts in the SSPs are for a 10-year period, we apply a linear interpolation method to approximate the missing forecasts for the years between and any two predicted time points (similarly for the GDP damage ratios from our simulation results). The results for GDP damages in US$ are available from 2017 to 2100, but only 2100 results are shown in Table A1.

In total, the avoided global GDP losses for the case of 3°C (or equivalently RCP6.0) compared to 2°C are US$3,934.25 billion a year in terms of 2100 GDP. For the case of RCP8.5, or a global warming of 4°C, the avoided global losses in GDP between 4 and 2°C are much larger or US$17,489.72 billion a year in the long run (also in terms of GDP in 2100).

6. Discussion and Concluding Remarks

GHG emission growth and its global warming consequences are a significant threat to the Earth's future. Assessing climate change impacts to the global economy and national incomes, and the potential benefit of climate change agreements, however, is complex, requiring large-scale modeling to even approach a comprehensive answer. For economists, the standard tool is CGE modeling. But, here, save for a few valuable country studies and some dynamic recursive modeling efforts, current models are either dimensionally too small or bound by myopic forecasting rules to be completely useful or compelling. The extension of the GTAP-INT model used in this work fills that gap, providing estimates of global warming damages on GDP and its rate of change for 139 countries in the GTAP database, by various temperature changes, as well as by measures of the benefits of complying with a trade agreement, such as the Paris Climate Accord.

Although GTAP-INT is country detailed and uses forward-looking approaches to forming price and profit expectations, there are a number of significant caveats to be aware of and considerable scope for future research. First, the model dimension does not computationally allow for random shocks or any of the usual jump-diffusion characteristics of a stochastic process that may impact both technology or living standards in the economy, among many other things. This lack of randomness is a serious shortcoming of all CGE modeling, except those with very small dimensions, and it needs to be worked on. There are ways forward, but it will require very large dimensional modeling and the use of parallel processing techniques, at the least, as in the GTAP-INT model and related work (Ha & Kompas, 2016; Ha et al., 2017; Kompas & Ha, 2017).

Second, given the lack of a random component, it is not possible to include the effects of natural disasters or more extreme weather events that occur year to year in the model. The costs of these can be considerable. For now, all that is captured is the effects of SLR, changes in agricultural productivity, and key health effects. Indeed, some of the significant effects of actions concomitant with global warming, such as the effects of air pollution, losses in biodiversity, the spread of invasive species, changes in energy mix, and the costs of significant migration, are also not included. Capturing natural disaster shocks and these other effects is possible in GTAP modeling, but it has not been done for the global economy to date, and this too needs to be worked on.

Third, and finally, although the extension of GTAP-INT to full climate change effects does allow for forward-looking estimates of the possible effects of global warming, the informational requirements here are profound and will not nearly be met in every circumstance or by every producer and consumer. Practically speaking, some forecasts fail to account not only for projected changes in the local and global economy but also for all of the other unpredictable changes that occur. Including randomness in the model framework would help with this, but as it stands the model is benchmarked to perfect foresight settings as a comparator. Designing models with mixed information requirements, that is, ranges of forward-looking forecasts combined over a set of elements with more myopic forecasting rules, is possible, but that work too needs to be done. It is clear, however, that models with only static price forecasting rules are clearly inadequate when climate change is considered. We know that at least some economic agents look forward and endeavor to incorporate this information in their price forecasting. We also know that economic agents revise their forecasts given exogenous shocks at any moment in time, calling again for some stochastic process in the CGE/GTAP model framework.

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With all of the above caveats in mind, the estimates from GTAP-INT do indicate substantial damages and losses in national income from global warming, providing at least a means of comparison across different temperature ranges and countries, regardless of the range of information that is available, perfect or otherwise. The losses in GDP and the gains from complying with the Paris Accord, even in this limited framework, are substantial, as indicated. What is perhaps as equally disturbing is how the percentage fall in GDP varies across the world and is most severe in many of the poorest countries (Table 2). Notable in the list are the dramatic falls in GDP by decade and in the long term, especially, of course, for the 4°C outcome, for Ghana, Nigeria, Cote D'Ivoire, Togo, Honduras, Nicaragua, the Phillipines, Cambodia, and Laos, among others. But Indonesia, Bangladesh, India, Singapore, Central America, East Asia, Thailand, and Vietnam also experience fairly substantial falls. Complying with the Paris Climate Accord would benefit these relatively poor countries, especially so.

It is important to note that the results above also assume that the United States remains in the Paris Accord and that all countries that have agreed to emission reduction targets honor their commitments. This is all questionable.

One final point. The often severe falls in GDP in the long term will put many governments in fiscal stress, since tax revenues are tied to GDP or national income levels. In addition, if global warming is tied to increases in the frequency of weather events and other natural disasters, which invoke significant emergency management responses and expenditures, the pressure on government budgets will be doubly severe. It would be good to form estimates of the extent of these budget pressures.

Appendix A: Impacts of Climate Change on the Global Economy

In this appendix we detail estimates of the long-term losses in GDP per year under various global warming scenarios to the year 2100. We also indicate the long-run impacts of global warming on the economic sectors (or commodity groups) contained in the GTAP database.

Table A1
Estimation of Long-Term GDP Loss per Year Under Global Warming Scenarios (US$ Billion/Year) to the Year 2100

	4°C	3°C	2°C
World total	−23,149.18	−9,593.71	−5,659.47
Sub-Saharan Africa	−8,073.68	−2,889.66	−1,927.78
India	−4,484.96	−2,070.06	−1,149.36
Southeast Asia	−4,158.88	−2,073.09	−1,166.23
China	−1,716.91	−701.75	−394.59
Latin America	−1,371.81	−576.65	−259.82
Rest of South Asia	−1,157.92	−469.98	−283.78
Middle East and North Africa	−1,032.27	−451.96	−241.12
United States of America	−697.77	−223.83	−168.48
Japan	−253.18	−54.43	−23.02
Mexico	−127.70	−55.79	−20.88
Australia	−117.42	−36.87	−23.72
South Korea	−81.44	−14.72	−7.86
Rest of Oceania	−39.65	−14.97	−6.96
Russian Federation	−24.49	−10.88	−6.53
Rest of Former Soviet Union	−9.93	−5.31	−3.85
EFTA	−8.72	−3.01	−2.16
New Zealand	−4.19	−0.77	−0.09
East Asia	−3.35	−1.27	−0.78
Rest of Eastern Europe	1.49	1.28	0.18
Rest of Europe	3.15	1.38	0.63

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Table A1 *(continued)*

	4°C	3°C	2°C
World total	−23,149.18	−9,593.71	−5,659.47
United Kingdom	17.78	4.06	0.35
Germany	23.85	5.38	2.46
France	26.92	7.11	1.80
Italy	32.42	12.20	7.26
Canada	45.29	11.40	5.20
Rest of EU25	64.19	18.47	9.68

Note. The numbers are calculated on the value of predicted GDP to 2100 from data in IMF (2018), International Institute for Applied Systems Analysis (2018), and Crespo Cuaresma (2017).

Table A2
Long-Run Impacts of Global Warming (3°C) on the World's Economic Sectors (% Change)

Economic Sectors	2017	2027	2037	2067	Long run
Paddy rice	−0.026	−0.532	−1.056	−2.687	−4.857
Wheat	0.006	−0.339	−0.699	−1.843	−3.582
Cereal grains nec	−0.012	−0.358	−0.718	−1.859	−3.554
Vegetables, fruit, nuts	−0.012	−0.398	−0.797	−2.040	−3.723
Oil seeds	−0.010	−0.501	−1.012	−2.618	−4.875
Sugar cane, sugar beet	0.015	−0.450	−0.939	−2.493	−4.812
Plant-based fibers	0.182	−0.432	−1.081	−3.144	−6.240
Crops nec	0.001	−0.348	−0.720	−1.914	−3.763
Bovine cattle, sheep and goats, horses	−0.015	−0.293	−0.588	−1.539	−3.102
Animal products nec	−0.007	−0.308	−0.625	−1.646	−3.293
Raw milk	−0.017	−0.334	−0.666	−1.720	−3.362
Wool, silkworm cocoons	−0.090	−0.423	−0.772	−1.877	−3.562
Forestry	−0.020	−0.300	−0.608	−1.645	−3.632
Fishing	−0.008	−0.303	−0.616	−1.619	−3.162
Coal	−0.003	−0.162	−0.345	−0.985	−2.365
Oil	0.006	−0.112	−0.253	−0.763	−1.987
Gas	0.018	−0.021	−0.079	−0.347	−1.431
Minerals nec	−0.018	−0.202	−0.418	−1.200	−3.061
Bovine meat products	−0.002	−0.265	−0.539	−1.421	−2.893
Meat products nec	0.002	−0.204	−0.422	−1.130	−2.384
Vegetable oils and fats	−0.006	−0.384	−0.783	−2.052	−3.980
Dairy products	−0.002	−0.170	−0.348	−0.945	−2.141
Processed rice	−0.029	−0.468	−0.926	−2.363	−4.363
Sugar	−0.016	−0.324	−0.649	−1.693	−3.381
Food products nec	−0.001	−0.201	−0.414	−1.113	−2.369
Beverages and tobacco products	−0.003	−0.158	−0.327	−0.900	−2.073
Textiles	0.003	−0.188	−0.398	−1.107	−2.501
Wearing apparel	0.006	−0.131	−0.282	−0.804	−1.942
Leather products	−0.002	−0.167	−0.346	−0.950	−2.176
Wood products	0.013	−0.063	−0.161	−0.563	−1.907
Paper products, publishing	−0.003	−0.104	−0.221	−0.650	−1.767
Petroleum, coal products	0.003	−0.105	−0.233	−0.703	−1.876
Chemical, rubber, plastic products	−0.002	−0.147	−0.315	−0.914	−2.326
Mineral products nec	−0.020	−0.176	−0.360	−1.053	−2.921
Ferrous metals	−0.024	−0.201	−0.409	−1.174	−3.112

Table A2 *(continued)*

Economic Sectors	2017	2027	2037	2067	Long run
Metals nec	−0.028	−0.224	−0.449	−1.252	−3.084
Metal products	−0.028	−0.162	−0.319	−0.909	−2.515
Motor vehicles and parts	0.013	−0.096	−0.230	−0.745	−2.236
Transport equipment nec	−0.025	−0.203	−0.409	−1.148	−2.894
Electronic equipment	0.011	−0.139	−0.319	−0.994	−2.720
Machinery and equipment nec	0.007	−0.118	−0.271	−0.865	−2.561
Manufactures nec	−0.015	−0.190	−0.389	−1.092	−2.700
Electricity	0.000	−0.115	−0.249	−0.740	−2.006
Gas manufacture, distribution	0.018	−0.132	−0.303	−0.920	−2.440
Water	−0.016	−0.143	−0.288	−0.811	−2.093
Construction	−0.007	−0.132	−0.290	−0.917	−2.829
Trade	−0.004	−0.156	−0.327	−0.934	−2.341
Transport nec	−0.006	−0.142	−0.298	−0.861	−2.248
Water transport	−0.004	−0.204	−0.433	−1.238	−2.972
Air transport	0.000	−0.118	−0.255	−0.747	−1.940
Communication	0.001	−0.101	−0.221	−0.668	−1.880
Financial services nec	0.001	−0.108	−0.237	−0.708	−1.927
Insurance	0.000	−0.097	−0.208	−0.606	−1.591
Business services nec	0.012	−0.042	−0.112	−0.407	−1.495
Recreational and other services	0.004	−0.096	−0.210	−0.623	−1.675
Public Administration, Defense, Education, Health	0.000	−0.104	−0.218	−0.603	−1.420
Dwellings	−0.003	−0.068	−0.160	−0.569	−2.158

Note. Source: Authors' GTAP-INT calculation.

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