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OPPORTUNITIES IN INDUSTRIAL DECARBONIZATION: DELIVERING BENEFITS FOR THE ECONOMY AND THE CLIMATE

HEARING

BEFORE THE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

ONE HUNDRED EIGHTEENTH CONGRESS

FIRST SESSION

NOVEMBER 15, 2023

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COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

ONE HUNDRED EIGHTEENTH CONGRESS
FIRST SESSION

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OPPORTUNITIES IN INDUSTRIAL DECARBONIZATION: DELIVERING BENEFITS FOR THE ECONOMY AND THE CLIMATE

WEDNESDAY, NOVEMBER 15, 2023

U.S. SENATE,
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS,
Washington, DC.

U.S. Senate Committee on Environment and Public Works Washington, DC.

U.S. Senate Committee on Environment and Public Works Washington, DC.

The committee met, pursuant to notice, at 10:01 a.m. in room 406, Dirksen Senate Office Building, Hon. Thomas R. Carper (chairman of the committee) presiding.

Present: Senators Carper, Whitehouse, Merkley, Markey, Padilla, Fetterman, Capito, Cramer, Ricketts, and Sullivan.

OPENING STATEMENT OF HON. THOMAS R. CARPER, U.S. SENATOR FROM THE STATE OF DELAWARE

Senator CARPER. I am more than pleased, I am delighted to call this hearing to order. Senator Capito will testify I do not often say I am delighted to be chairing the hearing, but today I am. This is great stuff and we are grateful to our witnesses who are here, grateful to Senator Capito and her team, and the folks on our staff as well.

Today's hearing is focused on the next frontier of tackling climate change, decarbonizing the industrial sector of our economy. Our hearing is timely, as some of you may know.

Yesterday, the Biden Administration issued the Fifth National Climate Assessment, which underscored the urgency of addressing climate change and the benefits of doing so. The report found that, on average, adjusting for inflation, in the 1980's, the United States experienced a $1 billion disaster every 4 months. Today, there is one every 3 weeks.

The report also found that if we are going to limit the increase of global warming to 1.5 degrees Celsius, which is our goal, our Country must reach net-zero greenhouse gas emissions by 2050.

Why should we focus on reducing industrial emissions? To answer that question, let me begin by sharing an age-old story of Willie Sutton. I have told this story once or twice in this room. Many of you will recall, he was a notorious bank robber during the Great Depression. He robbed a lot of banks and finally got caught and ended up in front of the judge who said to him, "Mr. Sutton, why do you rob banks?" He replied, "Your Honor, that is where the money is." I think that is a story actually worth retelling today. Willie Sutton's logic can actually apply to all of us as well.

Heavy industry makes products that are central to our lives, including steel, cement, and aluminum. At the same time, the industrial sector is responsible for nearly one-third of global greenhouse gas emissions and represents the third largest source of U.S. emissions, trailing only the transportation and power sectors.

By 2030, the industrial sector is expected to become the largest source of domestic greenhouse gas emissions. I will say that again. By 2030, 7 years from now, the industrial sector is expected to become the largest source of domestic greenhouse gas emissions.

As many of us know, there are real challenges when it comes to decarbonizing the industrial sector. For example, because of the diverse industrial processes we use to make a variety of goods and materials, there isn't a simple one-size-fits-all approach. Instead, we must deploy a variety of different technologies and process changes.

Yet, within these challenges also lies real opportunities. In addition to helping us meet our climate goals, reducing industrial emissions presents great opportunities for us to invest in, among other things, American industry in order to boost our Nation's economic competitiveness.

The benefits of decarbonizing key industrial materials go beyond simply mitigating emissions at individual facilities. By producing materials in cleaner ways, we can reduce emissions throughout supply chains. By investing in the industries that are producing lower carbon materials for our buildings, our roads, and our electric vehicles, we can help support our clean energy transition.

Fortunately, when it comes to decarbonizing the industrial sector of our economy, we are already making progress. That is thanks in no small part to the investments that Congress made in the Bipartisan Infrastructure Law and the Inflation Reduction Act, measures that were written, in no small part, right here in this room.

For example, our Bipartisan Infrastructure Law established the new Office of Clean Energy Demonstrations at the Department of Energy, which included a new Industrial Demonstrations Program. Last Congress, Congress provided $6.3 billion in funding to this program to help deploy technologies to reduce industrial emissions.

The Bipartisan Infrastructure Law also included $8 billion for the development of regional clean hydrogen hubs throughout our Country. I was especially pleased that the Department of Energy awarded funding to the Mid-Atlantic Clean Hydrogen Hub project which includes parts of Delaware, Pennsylvania, and New Jersey. Our hub was one of seven clean hydrogen hubs, including the Appalachian Hydrogen Hub which included the States of West Virginia, Ohio, and Pennsylvania.

These clean hydrogen hubs will provide a reliable supply of clean hydrogen for transportation, industrial processes, and power generation across our Nation. They will create tens of thousands of good-paying jobs in our regions. Let me repeat that. They will create tens of thousands of good-paying jobs in our regions across the Country.

As the largest purchaser of materials in the world, the Federal Government also has a great opportunity to foster demand for low-embodied carbon materials through Federal procurement. We can and we are.

In our committee's title of the Inflation Reduction Act, we provided over $5 billion for the Federal Highway Administration and the General Services Administration to buy materials such as concrete and steel for buildings, roads, and bridges made with low carbon emissions. We also included funding for the EPA to help us better understand the lifecycle greenhouse gas emissions of various construction materials and products. Supporting America's ingenuity and innovators is key to creating cleaner goods here at home, and we will hear from our witnesses about that today.

In closing, the United States can continue to manufacture steel, aluminum, concrete, and other materials while reducing greenhouse gas emissions. By doing so, we can make American industry more competitive on the global stage while addressing climate pollution and creating a lot of good-paying jobs.

To do this, we need collaboration across sectors and stakeholders. Industry leaders, innovative startups, government agencies, environmental organizations, and academia must all work together. And so must we. I think we actually do that pretty well here.

My hope is that today's hearing will help us further our committee's understanding of some of the challenges and opportunities associated with decarbonizing heavy industry. We look forward to hearing from our panel of knowledgeable witnesses and to having a productive and spirited discussion today.

Before we do that, I want to recognize our Ranking Member, Senator Capito, for her good work on this front. I am happy to work with her and her team. Senator Capito, you are recognized.

OPENING STATEMENT OF HON. SHELLEY MOORE CAPITO, U.S. SENATOR FROM THE STATE OF WEST VIRGINIA

Senator CAPITO. Thank you, Mr. Chairman.

I apologize in advance. I have something going on that is causing my voice to disappear. A Senator's voice disappearing is a dangerous thing. Anyway, Senator Carper, thank you for holding this hearing today to examine innovative, bipartisan solutions to manage industrial greenhouse gas emissions. We have achieved the greatest success, I think, as a committee, including on climate, which we have worked on in a bipartisan way.

The Committee's Surface Transportation and Water Infrastructure legislation served as the backbone of the IIJA. The surface transportation portion of the IIJA included a first-of-a-kind subtitle devoted to climate change featuring two new formula programs, one for carbon, one centered on carbon reduction and on resiliency. The IIJA served as a vehicle for many provisions from other committees to address emissions, including industrial emissions. Chairman Carper and I managed that legislation across the floor and so we negotiated many of these positions as well.

Particularly important to me, and the Chairman mentioned this in his statement, the legislation included the Regional Clean Hydrogen Hubs Program administered by the DOE. As you mentioned, one of the seven hubs the DOE recently selected is the Appalachian Regional Clean Hydrogen Hub, known as ARCH2. This hub includes the States of West Virginia, Ohio, and Pennsylvania.

ARCH2 will produce both green hydrogen, which is hydrogen produced through the electrolysis of water, but also blue hydrogen, which is hydrogen produced from abundant Appalachian natural gas with carbon capture and storage technologies to reduce emissions. When up and running, ARCH2 will supply hydrogen to a broad mix of hard-to-decarbonize industries, from energy to transportation to chemical manufacturing to steel production.

It is no secret that carbon capture, which will be a critical component of the ARCH2 hub, remains capital intensive and has yet to be commercially viable for deployment.

Chairman Carper, I really appreciate your years-long partnership with me in supporting carbon capture as a technology. This is why I have been a longtime supporter of 45Q to advance this technology that will be essential in preventing emissions, and through direct air capture, to reduce atmospheric concentrations of carbon dioxide.

ARCH2 and all other future CCUS developments stand to benefit not only from 45Q, but also from prior legislation out of this Committee, such as the USE IT Act, which Chairman Carper, Senators Barrasso, Whitehouse and I led. Signed into law in 2020, the USE IT Act, when implemented as intended, would ensure all carbon capture projects at all types of facilities can be permitted in a timely fashion.

I said "when implemented as intended" because some of the Administration's recent actions suggest they are not dutifully looking to expedite the permitting of these types of projects. For instance, for broad deployment of CCUS to become feasible, the EPA must approve Class VI injection well applications to securely store the carbon underground. I believe your State is one of only two that have been able to do this on a State basis.

In the IIJA, I supported the inclusion of $50 million for States to obtain primacy of this program, as well as $25 million for the EPA to process those permits at the Federal level. The EPA needs the help because it has historically only approved two of these permits, and it took an average of 6 years each to do this.

The IIJA was signed into law 2 years ago today, November 15, 2021, and only last week did the EPA finally announce the money for States to apply for primacy. In addition to delaying the application process for funding, the Administration has now loaded up the primacy application process with new guidance and directions to address environmental justice that seems designed to slow projects down or suggest they are not safe. Meanwhile, the EPA has not permitted any of the 169 well applications that are now pending.

Instead of focusing on expediting permitting and environmental reviews, the President's Council on Environmental Quality has focused on changing the rules of the road for the NEPA process. The Administration's recent proposal, instead of simplifying the environmental review and permitting process as Congress directed in the recent debt limit legislation, would add hurdles to these processes and expand the scope of reviews, opening projects up to increased delays and legal challenges.

I do not want to suggest hydrogen and CCUS are our only tools for reducing industrial emissions, but I think we need to take note of the regulatory headwinds we are facing. I support other bipartisan solutions to reducing industrial emissions, such as utilizing advanced nuclear for industrial purposes. My bipartisan nuclear bill with the Chairman, the ADVANCE Act, includes a number of important policies to deploy advanced nuclear to do just that.

No matter how good the bipartisan solutions this committee and others enact to address climate change are, our efforts will never be realized if the projects they support are never built due to permitting challenges and a slew of new EPA regulations. Regulations such as the forthcoming Particulate Matter 2.5 National Ambient Air Quality Standards, NAAQS, that the Administration is rumored to plan finalizing at a level that will plunge much of the Country into nonattainment, requiring stricter permitting or offsets for new infrastructure or industrial facilities.

Regulations such as the Clean Power Plan 2.0 will undermine reliability and drive up the cost of power for manufacturing with its unachievable short-term targets. Antiquated regulations like the New Source Review will stymie upgrades at existing power plants and manufacturing facilities. The list goes on and on.

I urge my colleagues to continue to work with me on permitting reform and updating outdated environmental regulations, areas within this Committee's jurisdiction, so we can ensure that emissions-reducing technologies can actually get out into the market and make a difference.

Thank you to all of the witness here today and I look forward to our discussion and learning more about your efforts to reduce carbon emissions.

Senator CARPER. Senator Capito, thank you. I thought you sounded great. If Kevin and I end up coming down with this tomorrow, I will know where it came from.

Senator CAPITO. I don't want to ruin anyone's holiday.

Senator Carper. Hopefully, you will be better really soon.

As you know, we all serve on a number of different committees. In some cases, those committees are meeting right now. One I serve on is a going to have a markup and I need to be there to vote. In a little bit I will slip out and go vote. I have to go out to a place called the swamp for a few minutes before that for a quick presser. In the meantime I appreciate that Senator Capito keeping the trains on schedule. I have had a chance to read your testimonies and hopefully, I will have a chance to hear most of it before you finish.

Now I want to turn to our esteemed panel of witnesses. We are grateful to two of you for joining us today in person. I understand one of the witnesses is also under the weather, maybe with COVID or something. We hope she will be feeling better soon.

First, we are going to hear from Dr. Abigail Regitsky, the Senior Manager, U.S. Policy and Advocacy Team at Breakthrough Energy, a network of investment funds, non-profits and philanthropic programs and policy efforts, working together to scale the technologies that are needed to achieve net-zero emissions by 2050. In this role, Dr. Regitsky is responsible for implementing Breakthrough Energy's climate policy priorities with a focus on industrial decarbonization and innovation.

She earned her Ph.D. in Material Sciences and Engineering from the Massachusetts Institute of Technology, MIT, and brings a wealth of knowledge of industrial de-carbonization. Our oldest son is a graduate of MIT. I could barely spell MIT when I was at Ohio State. Fortunately, we have sons who are a lot smarter than me.

Our second witness is Dr. Leah Ellis, CEO and Co-Founder of Sublime Systems, Inc., a Massachusetts-based company, beginning to commercialize a breakthrough low carbon cement manufacturing process. Dr. Ellis, how do you pronounce the university in Canada you went to?

Ms. ELLIS. Dalhousie.

Senator CARPER. She started Sublime Systems with a colleague at MIT during her tenure as a post-doc fellow there. To date, Sublime Systems has begun to scale their technology that eliminates the need for fossil fuels in cement production. I am interested in hearing more about that.

Third, we will hear from Ms. Shannon Angielski, President of the Clean Hydrogen Future Coalition. When my wife asks me, what did you do today, I will say I met with the President and she will be impressed.

She is President of the Clean Hydrogen Future Coalition, a diverse group of stakeholders to promote clean hydrogen as a critical pathway for decarbonization.

Ms. Angielski has spent her career developing and advocating for clean energy and carbon management policies with a particular focus on hydrogen as well as carbon capture utilization and sequestration.

We thank you again for appearing before the committee today. We will now begin our witness testimony.

We will lead off with Dr. Regitsky. Please proceed with your statement when you are ready.

STATEMENT OF ABIGAIL REGITSKY, SENIOR MANAGER, U.S. POLICY AND ADVOCACY, BREAKTHROUGH ENERGY

Ms. REGITSKY. Chairman Carper, Ranking Member Capito, and members of the committee, thank you for the opportunity to appear before you today.

I am honored to represent Breakthrough Energy, a network founded by Bill Gates to scale the technologies we need to reach net-zero emissions by 2050. Following 8 years of work, we just published our first State of the Transition Report to share the progress being made and the challenges that remain ahead.

Innovation is at the heart of Breakthrough Energy's mission, and more than any other sector, industry cannot decarbonize without innovation. The industrial sector is responsible for transforming raw materials into the products of our daily lives, like the cement in our buildings and bridges and the steel in our cars and appliances. It has been the engine of American economic development.

It also accounts for nearly a fourth of U.S. greenhouse gas emissions and about one-third of global emissions. While sectors like power and transport are expected to continue reducing emissions, industrial emissions are expected to stay flat and could even increase, likely making it the top source of U.S. emissions in the future.

In part, the slow progress comes from industry's reputation of being hard to abate. This is largely because the main sources of emissions are essential to how industrial goods are manufactured today, namely emissions from industrial heat and process emissions from chemical reactions.

For example, steel making requires temperatures over 2000 degrees Celsius. The raw material for cement contains CO2 that is released when it is made.

The good news is that many U.S. companies are actively working on breakthrough technologies to address these emissions, as well as reduce and eliminate air, land and water pollutants. This will bring tangible health and quality of life benefits for the workers in industrial factories and the fenceline communities surrounding them.

Several solutions are cross-cutting and can be applied in many sectors. These include energy and material efficiency, electrification, the use of hydrogen and other low carbon fuels and feedstocks and carbon management. One promising example is thermal energy storage, which stores renewable energy as heat and then delivers this heat for use in industry.

For every cross-cutting area, building enabling infrastructure, like more transmission, will be critical, as is robust community engagement on the risks and benefits of each technology. In addition to cross-cutting technologies, each sector can benefit from tailored solutions. For example, one company is developing a fully electric process that reduces iron ore and makes steel in one step. While promising, many of these technologies are relatively immature and for those close to market readiness, barriers still remain, such as high capital costs, long factory lifetime, low profit margins, and competition from other countries.

Smart policies that address the entire innovation cycle from R&D to deployment will be critical to accelerating the path to market. Policies must support the supply of clean industrial technologies through investments in RD&D and financial incentives. Congress recognized this in passing the Clean Industrial Technology Act, introduced by Senator Whitehouse and Ranking Member Capito as part of the Energy Act of 2020. Then through the Infrastructure Bill and the Inflation Reduction Act, Congress provided a historic $6.3 billion for industrial demonstration projects.

Industry applied for nearly ten times the program's budget, indicating the need for future funding. Complementary public procurement or buy-clean policies can create sizable markets for low emissions goods. The IRA included over $5 billion for Federal procurement of low carbon construction materials. It is critical that these programs target materials with the lowest possible embodied emissions available today.

Furthermore, new policies will be needed to provide long term offtake such as through advance market commitments or contracts for difference, which will unlock further investments. To maximize these domestic investments, climate aligned trade policies must address potential emissions leakage.

As a first step, policies must build the data infrastructure to reliably measure and report embodied carbon which underpins the effective design of all the above policies. Fortunately, Congress is increasingly paying bipartisan attention to these issues.

For example, Senators Coons, Cramer and several members of this committee introduced the PROVE IT Act. On average, U.S. industry already boasts lower emissions intensity production internationally and decarbonization investments will only strengthen this carbon advantage and increase global market share. Others are also developing trade policies to address carbon leakage and competitiveness. This includes Senator Whitehouse's Clean Competition Act and Senators Cassidy's and Graham's Foreign Pollution Fee Act.

Breakthrough Energy supports bipartisan discussions to develop trade policy that bolsters the competitiveness of domestic industries and puts a spotlight on manufacturing emissions abroad to incentivize industrial decarbonization around the world.

Addressing industrial emissions will also safeguard manufacturing's role as a critical piece of the U.S. economy. This year, the manufacturing sector employed 13 million Americans. For every one manufacturing worker, 4.4 workers are added to the economy overall. Thus, investing in this sector will pay dividends in economic growth and revitalize communities that have suffered decades of progressive deindustrialization.

In summary, without intervention, the industrial sector is set to become the highest emitting U.S. sector in the next decade. Addressing industrial emissions depends on a full spectrum approach of supply side investments, demand side market creation, trade policies and data infrastructure.

Decarbonizing industry not only aids net zero goals but enhances American competitiveness, retains and creates manufacturing jobs and benefits worker and community health.

The world is on the brink of a clean industrial revolution, and America is poised to take the lead. I urge the members of this committee and Congress to not let this opportunity pass us by.

The prepared statement of Ms. Regitsky follows:]

Breakthrough Energy

Statement before the

U.S. Senate Committee on Environment & Public Works

Opportunities in Industrial Decarbonization: Delivering Benefits for the Economy and the Climate

Testimony of:

Abigail Regitsky, PhD
Senior Manager, U.S. Policy and Advocacy
Breakthrough Energy

November 15, 2023

Chairman Carper, Ranking Member Capito, and Members of the Committee:

Thank you for the opportunity to appear before you today to discuss the benefits and opportunities of industrial decarbonization.

My name is Abigail Regitsky, and I am a Senior Manager on the U.S. Policy and Advocacy team at Breakthrough Energy, a network founded by Bill Gates of investment funds, nonprofit and philanthropic programs, and policy efforts working together to scale the technologies we need to achieve net-zero emissions by 2050. Following eights years of dedicated work since the creation of Breakthrough's first initiative, this week we published our first State of the Transition Report to share the progress being made across every major sector of the economy and the challenges that remain ahead. Industry—or what we call the Manufacturing Grand Challenge—features prominently in the Report, and I look forward to sharing our thoughts on this critical issue today.

Innovation is at the heart of Breakthrough Energy's mission and theory of change, and more than any other sector, industry cannot decarbonize without innovation. So, before detailing our approach to industrial decarbonization, it is informative to share our approach to innovation. Above all, we view innovation as the only path to achieve net-zero emissions while also delivering clean, affordable, and reliable energy and goods to support a high standard of living for all people around the world. In particular, innovation will help us lower, and eventually eliminate, the green premium—the additional cost of using a clean technology over a more emissions-intensive option. We aim to accelerate the innovation cycle through a combination of **investments** throughout technology lifecycles and smart, market-friendly public and private sector **policies**.

Breakthrough Energy has three flagship programs that make investments along technology discovery, development, and deployment.

Breakthrough Energy Fellows is a technology focused incubator program, which supports early-stage entrepreneurs to take their climate discoveries out of the lab. In addition to these Innovator Fellows, we support Business Fellows with extensive industry experience to advise Innovator Fellows in developing their technologies and building their businesses. Through two cohorts over the last two years, we have supported 63 Fellows, across 38 projects and 11 countries, in several areas critical to industrial decarbonization.

Breakthrough Energy Ventures (BEV)—the first initiative in the Breakthrough network—is a venture capital firm that invests only in technologies that have the potential to reduce emissions by 500 megatons per year, roughly one percent of annual global emissions. Unlike other venture capital firms, BEV is highly technical, deploys patient capital, and is comfortable taking enormous risks to help startups further develop their technologies and companies for commercialization. Over the last six years, BEV has invested nearly $2B in over 100 companies, many of which are developing game changing technologies to decarbonize industrial heat, cement, and steel, among others.

Breakthrough Energy Catalyst deploys capital to support first-of-a-kind commercial scale projects to help derisk new climate technologies and overcome the final "valley of death" of technology innovation. Catalyst works with climate tech companies to advance their projects from development to funding and ultimately, to construction. Once derisked, it will be easier for the next project to attract funding from traditional infrastructure investors, which will be needed for a technology to scale. This year, Catalyst added manufacturing as an area of focus for project selections.

Alongside these investment initiatives, Breakthrough Energy's policy teams work with government, private sector, and civil society partners to enact policies that accelerate innovation at every step and ensure markets around the world are primed for new clean technologies. I will spend the bulk of my testimony covering Breakthrough's U.S. policy framework to accelerate industrial decarbonization.

Overview

The industrial sector is responsible for transforming raw materials into major components necessary to our daily lives: the cement in our buildings and bridges, the steel in our cars and appliances, the clothes we wear, the books we read, the plastic containers that keep our food and drinks safe and fresh. It has been the engine of American economic development and will continue to drive progress in emerging economies around the world. It also accounts for nearly one fourth of U.S. greenhouse gas (GHG) emissions and about one third of global emissions. While sectors like power and transport are expected to continue reducing emissions over the next decade, industrial emissions are likely to stay flat and could even increase, making it the top source of U.S. emissions in the future if current trends hold. Unlike areas like clean electricity, building efficiency and electrification, and light-duty transportation, the majority of technologies necessary to decarbonize industry still need to be developed and commercialized, and a robust policy framework has been lacking. Industry will require ample technological innovation and the right policies to accelerate innovations from lab to market to widescale deployment to achieve net-zero emissions by midcentury.

Breakthrough Energy recognized this gap several years ago, first through the launch of BEV and subsequent investments into emerging technology companies tackling industrial emissions, followed by complementary work to advance industrial sector policies to support technology innovation and commercialization. Since then, the debut of increasing country and corporate net-zero commitments has forced deeper consideration of the role of the industrial sector in achieving these goals, and we have seen increased interest from policymakers, companies, philanthropy, and civil society on the issue. While achieving a net-zero industrial sector will be difficult, the progress of the last few years only boosts my confidence and optimism that it is a challenge we can and will overcome through public and private sector collaboration and where American innovation is poised to lead.

In my testimony, I will briefly cover:

- Industrial decarbonization challenges and benefits
- Technological solutions, with a focus on cement and steel
- Policy progress and opportunities

Industrial Decarbonization Challenges and Benefits

The industrial sector accounted for 23% of U.S. GHG emissions in 2021. When emissions from the generation of electricity are divided into end-uses, industry accounted for 30% of emissions, tied with buildings as the largest emitting U.S. sectors.[1] Cement, iron and steel, and chemicals and refining are the big three industrial emitting sectors, accounting for about 70% of CO_2 emissions from industry globally and nearly 50% of industrial emissions in the United States.[2] Industry has a reputation of being "hard-to-abate," largely because the main sources of emissions are intrinsic to how industrial goods are manufactured today: emissions from heat (principally delivered through the combustion of fossil fuels) and process emissions from the chemical reactions necessary to transform raw materials to usable products. These are the primary technical challenges facing industry, which will require innovations in using less heat and non-emitting heat sources, as well as developing completely new ways of industrial production that avoid heat altogether and use new feedstocks to eliminate CO_2 as a byproduct. And while these challenges are common across industrial sectors, the diversity of products and processes under the industry umbrella means that each sector will often need unique solutions to these challenges, emphasizing the importance of robust innovation support for each sector. Additional challenges for the industrial sector include high capital costs for decarbonization improvements and clean greenfield facilities, long asset lifetimes with minimal downtime, low profit margins, and significant trade exposure. These multiple challenges will be difficult to overcome, but American ingenuity is up to the task and the solutions uncovered will present benefits beyond climate progress alone.

On average, U.S. industry already boasts lower emissions intensity production than many of its foreign counterparts, giving America a "carbon advantage" compared to many of its trading partners. Meanwhile, in 2019, the United States imported more than 1.2 gigatons of embodied emissions—larger than any other country, with the greatest portion coming from China—showcasing the significance of traded emissions, or the "carbon loophole." These phenomena offer a unique opportunity: strengthen the U.S. carbon advantage while closing the carbon loophole. As the United States rightfully aims to reduce emissions within its borders, using smart policies to address imported emissions will not only properly account for and reduce the emissions from U.S. consumption, but it will also ensure that domestic investments in decarbonization reward American manufacturers with an increasing domestic and global market share for cleaner goods. For example, a 2022 Boston Consulting Group (BCG) study projected ~$11T in global clean steel sales through 2050, with the U.S. domestic market reaching ~$30B in 2050—double the net income of U.S. steelmakers in 2022.[3] Another study found that adopting a U.S. border carbon policy could help domestic steel and aluminum producers increase their annual revenues by $8.5B and $6B, respectively, by 2030.

Addressing industrial emissions will also safeguard manufacturing's role as a critical piece of the U.S. economy. In September 2023, the manufacturing sector employed 13 million Americans, and for every one manufacturing worker, 4.4 workers are added to the economy overall.[4] Thus, investing in this sector will pay dividends in economic and job growth. It is also an opportunity to reinvest in deindustrialized areas of the country, where manufacturing jobs have declined over the last several decades. For example, the same BCG study estimated the creation of ~30,000 average annual jobs from possible investments in clean steel through 2050. As industries evolve

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[1] U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 (April 2023).
[2] U.S. Department of Energy, Pathways to Commercial Liftoff: Industrial Decarbonization (September 2023).
[3] U.S. International Trade Administration, U.S. Steel Executive Summary (2023).
[4] National Association of Manufacturers, Facts About Manufacturing (2023).

to new forms of clean manufacturing, it will be important to make sure the existing and future workforce has the skills necessary to fulfill this employment potential.

In addition to the direct economic and jobs benefits of industrial decarbonization, cleaning up industrial processes will also bring health benefits for the workers in industrial factories and the fence-line communities surrounding them. Along with GHG emissions, industrial production releases criteria air pollutants (e.g., particulate matter (PM), sulfur dioxide, nitrogen dioxide), as well as hazardous air pollutants and toxic air, land, and water pollutants. A recent study focused on the U.S. iron and steel, cement, aluminum, and metallurgical coke industries estimated that elimination of PM emissions and its precursors could avoid 1,250 to 2,830 deaths each year. It also estimated reductions in the occurrence of respiratory and cardiac events, related hospital admissions and emergency room visits, and lost workdays. Converting fossil fuel combustion to clean heat sources will play a significant part in reducing these criteria air pollutant emissions, but many are attributed to the industrial processes themselves. As entrepreneurs develop completely new ways of making industrial goods, there will be an opportunity to ensure that new designs reduce or eliminate these emissions as much as possible.

To secure these multiple benefits from industrial decarbonization, the government must play a leading role in helping manufacturers overcome the many challenges that stand in their way. As with any new technology, there will be technical and financial risks that the private sector cannot bear alone, where public investment must fill the gap and be comfortable with taking measured risks. Industrial decarbonization also presents the opportunity of public and private sector collaboration (e.g., existing manufacturers partnering with startups that provide technology solutions), where multiple entities can share the overall risk burden. With smart, transparent policies, these risks can be mitigated but not entirely eliminated. Innovation is inherently a feedback loop of progress, failure, learning, and eventual success, and no steps can be skipped. Alongside innovation support, industrial policy can help ensure favorable market conditions for technology adoption, such as seeding demand for clean industrial goods at home and abroad.

Technological Solutions

Despite the heterogeneity among industrial subsectors, there are common cross-cutting technology solutions that could be applied in multiple subsectors to reduce emissions and are necessary to achieve emissions reductions in an economically and technologically feasible way. The exact applications and extent to which these technologies will be deployed in each subsector will vary, and there may be trade-offs and competition between subsectors for technologies with potential resource constraints. With that in mind and roughly mirroring the decarbonization pillars identified in the Department of Energy's (DOE's) Industrial Decarbonization Roadmap, industry should generally pursue these technological approaches in the following order:

- **Energy and materials efficiency and circularity**: Reductions in energy and material waste through process efficiency gains, circular approaches, including demand reduction;
- **Electrification**: Electrification of industrial production processes and heat sources;
- **Hydrogen (and other zero-carbon fuels and feedstocks)**: Producing and utilizing zero-carbon chemical energy sources like hydrogen; and
- **Carbon management:** Capturing carbon to prevent unavoidable carbon emissions from release, removing carbon dioxide from the atmosphere, and safely storing or utilizing captured and removed carbon.

In general, **energy efficiency** solutions should be maximized, as they reduce overall energy use and therefore minimize system costs. Traditional energy efficiency measures include upgrading to more efficient equipment, utilizing waste heat, combined heat and power, and other process-specific solutions. Increasingly, systems approaches, like strategic energy management and smart manufacturing, can yield further energy savings, as systems are electrified and digitized. Importantly, investments in efficiency measures should consider the overall context of the energy transition and long-term emissions reductions to avoid lock-in of outdated technologies for short-term gains in efficiency (e.g., increasingly efficient fossil-fuel-based equipment and vehicles vs. electrification as the grid becomes cleaner).

Alongside energy efficiency, **materials efficiency and circularity** should also be maximized to reduce emissions and costs by minimizing the need for processing of raw materials and manufacturing finished goods. Typical options include efforts taken during the production process and at end of life (i.e., reducing, reusing, recycling, and remanufacturing). Opportunities that target other parts of the value chain can also be considered, such as increasing product lifetimes, increasing product utilization through new business models, and designing for efficiency and disassembly. In some cases, pursuing materials efficiency tools, such as certain types of recycling, could increase energy use and emissions, so it will be necessary to closely investigate potential trade-offs.

Electrification of industrial production methods and process heat across several subsectors can make a significant contribution to overall industrial decarbonization, but it will depend on the continued decarbonization of the grid, including sufficient buildout of new clean electricity generation and transmission. Technological options at different levels of maturity include industrial heat pumps, resistive heaters, electric boilers, and electric kilns and crackers. Commercialization of thermal energy storage (TES) technologies capable of leveraging variable power sources for industrial use will also be important. Many companies are developing TES solutions, with several commercial systems available for customer purchase.

Where electrification is not a viable option—for a range of technical and non-technical reasons bespoke to each project—**hydrogen** and carbon management offer optionality. Because hydrogen's production and use tends to be less energy efficient than direct electrification, and more energy efficient technology pathways will typically be lower cost and less land- and resource-intensive, the lowest-cost and most-resource efficient net zero pathways tend to use hydrogen in a targeted way—only where it is required as a feedstock, where energy dense fuels are needed, and in large-scale applications with high heat needs and high uptime requirements. Hydrogen can be used as a direct reducing agent of iron ore in lower emissions steelmaking processes, can serve as a source of high grade heat when combusted, and as a feedstock for a variety of chemical processes. To enable hydrogen's role in industrial decarbonization, it is critical to support innovation in both methods to cost-effectively produce clean hydrogen and ways to use the clean hydrogen in new industrial applications.

Similarly, **carbon management** will be necessary to achieve net-zero industrial sector emissions by midcentury, but it should be deployed only when other technological options have been exhausted or are not yet commercially available to realize near-term emissions reductions at a larger scale. With current mature capture technologies (e.g., amine-based chemical adsorption processes), the purer the CO_2 stream, the cheaper the cost of capture. For lower-purity CO_2 streams that are not yet profitable to capture, cost reductions can come from economies of scale and learning by doing, as well as innovation in new capture technologies and modularization.[5] For industrial subsectors with process and combustion emissions, separation of these sources (or elimination of combustion emissions through process heat decarbonization) can also yield high-purity process CO_2 streams that are more economical to capture. Once captured, the majority of CO_2 emissions will need to be safely and permanently stored for maximum climate benefit. In the industrial sector, utilization can also play a small but increasing role as a permanent storage solution, such as through building materials and plastics.

Sector-Specific Technologies

Net-zero modeling typically finds that different mixes of the cross-cutting industrial decarbonization approaches above can reduce most of the emissions for every industrial subsector. However, each subsector has other unique emerging technologies that may be able to reduce emissions more efficiently and affordably in the future but do not yet have clear costs established in the literature to enable widespread inclusion in models. Supporting these sector-specific technologies is critical to lowering green premiums beyond currently modeled net-zero pathways to improve the likelihood of emissions reductions being achieved in the U.S. and abroad. Below, I will provide some examples of specific solutions for two sectors: cement and concrete, and iron and steel, which are also featured in Breakthrough Energy's State of the Transition Report.

Concrete and steel are two of the most widely used materials in the world and comprise the two highest emitting industrial sectors globally. They are largely made using the same technologies that have been perfected over centuries to create the relatively cheap, abundant, strong, and low emissions-intensity structural materials the world relies on today. While there are some opportunities for material efficiency and material substitution in certain use cases to reduce individual project demands for concrete and steel, the need for more infrastructure buildout in emerging economies and to improve resilience in a changing climate means that these foundational materials are here to stay. Fortunately, several innovative technologies to decarbonize these industries are on the horizon, along with already commercial, scalable solutions that can provide reductions in the near-term. Different types of policies will be needed to accelerate development of pre-commercial technologies and uptake of commercial solutions, both of which will be critical to achieve net zero.

Cement and Concrete

Concrete is composed of aggregates (e.g., gravel and sand), water, and cement, which acts as the glue that binds everything together. Cement only makes up 10-15% of the concrete mixture but is responsible for ~90% of the emissions associated with concrete. To produce cement, limestone ($CaCO_3$), clay, and other raw materials are heated to nearly 1500°C, which drives the CO_2 from the limestone ($CaCO_3 \rightarrow CaO + CO_2$) and forms a cement intermediary, called clinker. This reaction is responsible for the vast majority of cement emissions due to the process emissions and high heat required. The clinker is then ground

[5] U.S. Department of Energy, Pathways to Commercial Liftoff: Carbon Management (April 2023).

with calcium sulfate and other additives to make cement.[6] Cement made from nearly entirely clinker is called ordinary portland cement (OPC).

This status quo provides five main categories for reducing emissions from concrete, which generally go from most to least commercially ready in the following order:

- Use less concrete in construction
- Use less cement in concrete
- Use less clinker in cement
- Decarbonize clinker production
- Use decarbonized alternative cement chemistries

Use less concrete in construction

This involves avoiding over-designing and over-building with concrete to meet sufficient structural performance requirements with less material. It could also include substituting concrete with other building materials where possible, such as timber.

Use less cement in concrete

It is possible to use less cement in concrete by adding supplementary cementitious materials (SCMs) to a concrete mix, which could decrease the cement content to 5% or lower. Traditional SCMs already in use by industry include fly ash (a byproduct of coal combustion) and steel slag (a byproduct of the traditional steelmaking process).[7] These should be used as much as possible, but their supply will be limited as the processes they rely on continue to decline. To solve this problem, one company is creating engineered SCMs from relatively abundant raw materials available close to existing concrete supply chain infrastructure. Their first commercial production facility is set to break ground in Texas in 2024. Cement content can also be lowered by optimizing other parts of the concrete mixture, such as using a size gradient of aggregates to allow for better distribution throughout the concrete without additional binder.

Use less clinker in cement

SCMs can also help use less clinker in cement by being blended directly with clinker to produce blended cements. On average around the world, cements contain ~70% clinker.[8] Portland limestone cement (PLC) is a common blended cement used in the United States for over a decade, which blends up to 15% limestone with clinker to achieve up to 10% CO_2 reduction. A newer blended cement involves grinding limestone and calcined clays with 50% clinker to produce cement with up to 40% fewer emissions. Another company uses proprietary admixtures to enable use of optimized SCM cement blends with clinker content as low as 25%.

[6] U.S. Department of Energy, Pathways to Commercial Liftoff: Low-Carbon Cement (September 2023).
[7] National Concrete Pavement Technology Center, Cementitious Materials.
[8] International Energy Agency, Cement.

Decarbonize clinker production

While the above strategies can dramatically reduce the embodied emissions of concrete, getting to net-zero emissions requires decarbonizing clinker production, which can be accomplished through two main options. One option involves adjustments to the current production method by using a combination of cross-cutting technologies: decarbonizing the heat source required for calcination through electrification or low-carbon fuels and using carbon capture on the now high purity stream of process emissions. One company is attempting to do this using an indirectly heated kiln and already has projects with multiple partners around the world. Either decarbonizing heat or carbon capture alone could also be adopted separately to reduce emissions, but it would likely not result in full decarbonization. The second option is to develop entirely new ways of producing clinker to avoid emissions. One company is developing a method to make clinker from calcium silicate rocks, a noncarbonate raw material that will not release CO_2 in its processing. They recently received third-party certification that their cement is identical to standard OPC, confirming their product as a drop-in replacement for much of the cement used today. Another company is developing an electrochemical process for producing clinker, which would increase the CO_2 stream purity while reducing the overall amount of CO_2 byproduct, enabling easier pairing with carbon capture.

Use decarbonized alternative cement chemistries

Alternative cement chemistries involve using non-clinker-based binders for cement. There are a wide variety of different chemistries being developed and in use in small segments of the market today, but they are unlikely to scale without wider adoption of performance specifications, where projects are not required to follow traditional cement and concrete recipes. One example is a company using noncarbonate feedstocks and industrial wastes to electrochemically produce a reactive calcium- and silicate-based cement that meets the existing performance specification for hydraulic cements. Another company creates non-hydraulic calcium silicate cement that cures with CO_2 instead of water.

Bonus pathway: carbon storage

In addition to eliminating the emissions from cement production, the non-cement components of concrete can also be used to permanently store carbon, creating a potential revenue stream for captured carbon (from cement and other industrial processes, as well as direct air capture) and the possibility of carbon-negative concrete. One company combines captured CO_2 with calcium from waste sources to produce synthetic limestone aggregate.

Iron and Steel

At its most basic elements, steel is an alloy of iron and carbon. There are three general steps required to turn mined iron oxide ore into steel: reduction of the iron oxide into metallic iron (ironmaking), separation of ore impurities, and alloying with carbon and other minor elements to produce steel (steelmaking).[9]

[9] World Steel Association, The steelmaking process.

There are two main technologies for ironmaking in use today: blast furnaces (BFs) and direct reduced iron (DRI). BFs melt and reduce iron ore with metallurgical coal, reaching temperatures of up to 2300°C, to produce pig iron. In the melt state, ore impurities separate from the pig iron into slag, which can then be used in other industries (i.e., SCMs for cement and concrete). DRI involves reducing iron ore without melting and can use a variety of fuels/reductants (e.g., natural gas, coal, biomass, hydrogen) at temperatures below 1200°C. Natural gas is the most common DRI fuel used in the U.S. today. This lower temperature process is more energy- and emissions-efficient than BFs, but the lack of a melt stage leaves impurities in the DRI, requiring the use of only high purity ore, beneficiated ore, or an additional melting step (all adding increased costs) to achieve the same level of purity as pig iron. Ironmaking accounts for the majority of emissions in the overall steelmaking process, due to the high temperatures (delivered through fossil fuel combustion) and use of carbon as a reducing agent to remove the oxygen from iron oxide, forming CO_2.

There are also two main ways to make steel today: basic oxygen furnaces (BOFs) and electric arc furnaces (EAFs). BOFs take melted pig iron from BFs combined with some steel or iron scrap and use pure oxygen to melt the scrap, adjust the carbon (and other elemental) content of the pig iron and further remove impurities. EAFs largely recycle steel scrap by melting the scrap in electric furnaces and adjusting the steel composition through the addition of pig iron or DRI and other elements and reduction via oxygen. Primary steelmaking often refers to processes that turn iron ore into virgin steel (e.g., BF-BOF, DRI-EAF), while secondary steelmaking (i.e., EAF only) recycles scrap steel (with some primary steel input) into new steel products. Secondary steelmaking is significantly less emissions intensive than primary steelmaking, with the main source of emissions coming from the electricity used to power the EAF.

With multiple current steelmaking pathways, there are many options for reducing emissions, but they broadly fall into the following categories, again roughly going from most to least commercially ready in the following order:

- Use less steel in products
- Use more secondary steel
- Decarbonize current steelmaking processes
- Develop new net-zero primary steel production processes

Use less steel in products

As with concrete, using less steel involves avoiding over-design and over-building with current products and potentially developing new, better-performing steel alloys that enable even further material efficiency. There are also opportunities for material substitution in certain applications (e.g., aluminum or composites).

Use more secondary steel

This would minimize the need for primary steelmaking, which is responsible for the majority of steelmaking emissions. The ability to do this will depend on two factors: scrap steel availability and impurity management. Almost all steel is already recycled, and as more and more primary steel products reach end-of-life, this will naturally inject more scrap steel into the market, though with large geographical imbalances in availability. For example, in a developed economy like the United States, secondary steelmaking already accounts for 70% of steel production and all scrap is exhausted.

The second constraint is impurities, which increase in concentration as scrap is recycled again and again and is the reason why EAFs still need some pig iron or DRI to add to scrap. This currently limits recycled steel from use in applications that need higher quality steel, such as automobiles and defense. Overcoming the impurity problem in recycled steel will be critical, requiring innovations in separations technologies and steel forming processes that can handle higher impurity levels. One company is trying to do this by designing a hot-rolling fabrication alternative, which is conducted at lower temperatures and can, therefore, withstand higher impurity levels in the processing.

Decarbonize current steelmaking processes

The main route to decarbonize secondary steelmaking is to switch EAFs to clean electricity, which could involve a combination of grid decarbonization and onsite clean electricity generation, potentially paired with energy storage. This is key to enable full decarbonization with increasing recycled steel usage.

For primary steelmaking, DRI can be decarbonized by using clean hydrogen as the fuel and reductant source, eliminating both emissions sources and producing hydrogen-DRI (H_2-DRI). The two most advanced greenfield H_2-DRI-EAF projects are both in Sweden, only possible through a combination of cheap hydropower for producing green hydrogen, purchase commitments from buyers, government support, and strong collaborations across the steel value chain. Without any one of these factors, costs would likely be too high to compete with existing primary steelmaking. Both projects will also need high purity ore. Another steelmaker plans to build a greenfield H_2-DRI plant and melters to integrate it with existing BOFs, which should enable supply from lower grade ores and utilization of existing assets. Existing DRI facilities using natural gas could blend clean hydrogen to reduce emissions but would need equipment retrofits to be able to use 100% hydrogen for full decarbonization. For geographies where clean hydrogen is too costly to produce or procure, DRI using fossil fuels could be paired with carbon capture at additional cost but would require access to permanent CO_2 storage (CCS) or sufficient utilization opportunities (CCU).

The main option for BF-BOFs for deep decarbonization is carbon capture, which has the same costs and limitations as DRI-CCS/CCU. Moreover, this would require greenfield BF-BOFs using the best available technology, whereas retrofitting existing BF-BOFs with carbon capture is unlikely to reach more than 50% emissions reductions due to insufficient capture rates. It is possible that innovations in carbon capture technologies could deliver deeper reductions.

The use of certain biomass as a low-carbon fuel for DRI or BF processes could also provide a pathway for near-zero emissions (or even net-negative emissions if employing CCS/CCU). However, the competition for an already scarce resource with other industries for use as feedstock and the need to aggregate large quantities of biomass for a single ironmaking facility make this pathway unlikely to scale.

Develop new net-zero primary steel production processes

Given the limitations in every pathway to decarbonizing current primary steelmaking routes, innovation in completely new processes to replace ironmaking and/or steelmaking has the potential to create intrinsically net-zero processes with lower costs at scale.

One option is to use hydrogen as a reducing agent, like H_2-DRI, but to conduct the process at melt temperatures, enabling the use of lower grade iron ores. One company is aiming to do this with clean electricity as the energy source for smelting the iron in this hydrogen-electric approach. The process could produce iron or steel, depending on the addition of other inputs (e.g., scrap steel and/or refining elements).

Another option is to use clean electricity alone to directly reduce iron ore, eliminating both process heat and chemical process emissions and bypassing the need to first use electricity to produce clean hydrogen. One company is developing a process called molten oxide electrolysis, which performs the electrochemical reduction above the melt temperature, combining ironmaking and steelmaking in one, decarbonized step. Another company is developing a low-temperature electrochemical process, which produces high purity iron plates that can be processed in existing EAF infrastructure to produce high quality steel. Importantly, both technologies can use lower grades of iron ore, solving a major issue with H_2-DRI.

Combinations of these diverse technologies will have different costs (depending on energy costs, feedstock costs, and other geographical factors) and varying levels of residual emissions, but all should theoretically be able to reach close to net-zero emissions steelmaking.[10] How costs evolve over time and where supportive policies are put in place will significantly impact which technologies fully commercialize and scale over the next several years.

Policy Progress and Opportunities

While the last several years have shown exciting technological progress to decarbonize industry, many of these technologies are relatively early in their innovation lifecycle and need to undertake significant development and commercialization to reach wide deployment. Even for the already commercial technologies or those close to hitting the market, economic and non-cost barriers remain, preventing broader adoption. Smart policies that address the entire innovation cycle will be critical to accelerating technology advancement and market uptake in line with reaching our climate goals.

Due to the diversity of industrial subsectors and variety of technological solutions for reducing emissions, Breakthrough Energy largely follows a sector- and technology-agnostic policy framework that enables technologies to compete on a level playing field and leaves room for further innovation. Our policy priority areas generally fall into the following categories:

- Supporting **supply** of low-GHG industrial technologies and products through research, development, and demonstration (RD&D) investments and financial incentives;

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[10] Mission Possible Partnership, Making Net-Zero Steel Possible (September 2022).

- Supporting public and private **demand** for low-GHG products to create markets and buyers to pull technologies forward and foster an environment for further investment;
- Employing **climate-aligned trade policies** and international cooperation to address carbon leakage, secure domestic industrial competitiveness, and influence global industrial emissions reductions; and
- Developing **foundational data infrastructure and analytical capabilities** that underpin the effective design and implementation of the above policies.

Thanks to the action of Congress in recent years, we've made significant strides in nearly every priority area and are poised to witness demonstrable progress enabled by key policies in the Energy Act of 2020, the Infrastructure Investment and Jobs Act (IIJA), the CHIPS and Science Act of 2022 (CHIPS), and the Inflation Reduction Act of 2022 (IRA). I will briefly outline examples of this progress and highlight where additional policy action will be needed.

Foundational Data and Analytics

Power sector decarbonization efforts have benefited from the ability to analyze different policies and decarbonization scenarios using multiple energy system models. Industrial sector modeling capabilities are far behind what is needed to be able to provide the same level of support for understanding the impacts of industrial policies. Industrial modeling resources can be expanded through (1) individual model improvements, (2) better coordination and collaboration among modelers, and (3) increased data availability and aligned technology assumptions for model inputs. DOE, the Energy Information Administration, and the National Labs comprise critical pieces of the industrial modeling ecosystem and can play leading roles in model and data improvement with additional resources and direction. These models should aim to better understand impacts of domestic policies, as well as internationally relevant policies around climate and trade.

To enable emissions intensity comparisons between industrial products and provide a basis for claiming cleaner production processes, there must be robust, transparent data infrastructure to support creation and use of environmental product declarations (EPDs), which are the bases for the procurement policies described below. EPDs are third party-verified documents created using international standards that report the embodied GHG emissions associated with producing a given product, based on life cycle assessment models. The Embodied Carbon in Construction Calculator (EC3) is a free database of construction material EPDs and a complementary impact calculator for building design and material procurement. The Environmental Protection Agency (EPA) received $250M in the IRA to provide technical assistance and funding for the production of EPDs by domestic manufacturers to enable their participation in public sector efforts to procure substantially cleaner materials.

Investments (Supply)

DOE is the primary federal agency responsible for industrial RD&D and requires adequate support for supply-side investments. Congress recognized the importance of industrial innovation in passing the Clean Industrial Technology Act of 2019—introduced by Senator Whitehouse and Ranking Member Capito—as part of the Energy Act of 2020. As a result of DOE reorganization and new funding streams from recent legislation, multiple offices across DOE address industrial decarbonization, namely the Industrial Efficiency and Decarbonization Office (IEDO) and Advanced Materials and Manufacturing Technologies Office (AMMTO) on the applied research and development (R&D) side, and the Office of Manufacturing Energy Supply Chains (MESC) and the Office of Clean Energy Demonstrations (OCED) on the demonstration and deployment side. To realize its full potential in supporting industrial innovation, DOE needs (1) increased funding across every office involved in industrial decarbonization through the annual appropriations process and other legislative vehicles and (2) durable high-level leadership to plan and execute DOE's industrial decarbonization strategy and ensure coordination between the relevant offices, such as through a new Assistant Secretary for Industrial Innovation.

To illustrate just the industrial R&D funding gap, it is informative to look at the President's FY2024 Budget Request for certain applied R&D technology offices. Solar and wind, two relatively mature renewable energy technologies that have already significantly come down the cost curve due to decades of public support, received budget requests of $379M and $385M, respectively. Meanwhile, IEDO, which is responsible for applied R&D for all industrial sector technologies largely at much earlier stages of maturity, received a similar budget request of $394M. It is difficult to imagine progress at the pace necessary for midcentury industrial decarbonization if IEDO has to split the same amount of resources as wind energy R&D across every industrial subsector. At minimum, a tripling of the current request to cover the three biggest emitters (chemicals, steel, and cement) would be a more reasonable request to meet the challenges IEDO is being asked to help solve. Given likely constraints of limited resources, one approach to rebalance R&D funding is through portfolio planning across DOE programs, which would allocate federal funding to different technologies based on a set of criteria (e.g., emissions reduction potential, complexity, maturity) rather than on historical funding levels.

For later stage support and investments, OCED received a historic $6.3B through IIJA and IRA for first- to early-of-a-kind commercial scale industrial decarbonization demonstration projects. DOE is currently reviewing applications for this Industrial Demonstrations Program and anticipates announcing awardee selections in early 2024. With up to 50% cost share and a maximum grant amount of $500M, this demonstration funding will be game changing in advancing commercial scale transformative projects that would have otherwise not moved forward or could have taken years or decades to break ground. While this level of funding for industrial decarbonization demonstrations is unprecedented, the summary of concept papers submitted reveals that it is still not enough. DOE received interest from projects requesting over $60B in federal funds, nearly ten times the total budget of the program. Furthermore, many breakthrough technologies were still too early in their development to qualify for the program. When these solutions are ready for their first commercial scale project in several years, it is imperative that DOE has funding to support them. Though not focused solely on industrial emissions, the Loan Programs Office (LPO) will also be critical to support nth-of-a-kind facilities for widescale deployment.

In addition to grants and loans, tax incentives can help bring down the costs of deployment-ready technologies to help them scale. DOE is supporting Treasury on implementation of the 48C advanced energy project credit, allocated at $10B through the IRA and expanded to include industrial emissions reductions. In previous iterations, 48C was also oversubscribed, indicating a large appetite from the private sector to take advantage of these credits. Relevant technology-specific tax credits are further discussed below.

On increased coordination, DOE has recently created a Joint Strategy Team (JST) to act as a coordinating body for their industrial decarbonization work, which we think is a step in the right direction. To maintain effectiveness, the JST will need durable structures with clear leadership and authority, as well as the resources for staff capacity. The Senate Appropriations Committee recognized this need for industrial emissions coordination, recommending a $3.5M line item for this express purpose, which Breakthrough Energy fully supports. In the future, DOE should consider placing this coordination function under the new Assistant Secretary for Industrial Innovation mentioned above.

Market Creation (Demand)

To create demand for lower-carbon industrial goods, it is necessary to (1) change current markets to favor existing, commercial technologies with lower emissions intensity and (2) shape future markets to provide offtake for emerging technologies to enable their commercialization. Breakthrough Energy considers four main areas that address one or both of these needs:

- **Public procurement –** direct government purchasing of industrial products;
- **Policies to facilitate future demand –** public policies that enable future public or private offtake;
- **Private procurement –** corporate commitments to purchase cleaner goods; and
- **Sectoral standards –** performance requirements or regulations on industrial goods or facilities.

Public Procurement

Governments purchase one third to one half of all cement and about one fifth of all steel, so public procurement policies that target green products—often called Buy Clean or green public procurement (GPP)—can create sizable markets for low-GHG industrial goods. Buy Clean policies are typically centered on procurement standards—emissions intensity limits for public purchase of industrial goods—and framed by data transparency through EPDs and public investments to support reducing the emissions intensity of domestic industry to meet increasingly stringent procurement standards.

The IRA included funding of over $5B for federal agency procurement of low-embodied carbon construction materials, with the majority of funding going to the General Services Administration (GSA) for federal buildings and the Federal Highway Administration (FHWA) for federally supported infrastructure. GSA recently announced plans to allocate their funding to over 150 projects across the country, and we anticipate FHWA to release funding to eligible states and local jurisdictions in the coming months. Both agencies will use an EPA interim determination to guide product emissions intensity limits that projects must meet to receive IRA funding. It is critical that these programs target materials with the lowest possible embodied carbon emissions and push the bounds of what suppliers can produce today.

While the IRA funding for clean procurement is unprecedented, for Buy Clean to reach its full potential, the federal government would need to adopt a Buy Clean standard that covers all agency purchases and increases stringency over time. It will also be important to augment federal clean procurement with state procurement efforts, which often cover different buildings and infrastructure. Several states (e.g., CA, CO, MN, NY, and OR) have already passed some form of Buy Clean standard, which could help create momentum for a federal standard in the future. Cities and states can also adopt embodied carbon requirements in building codes, which apply beyond publicly owned buildings to reach an even greater market.

GPP has also gained interest globally, with the UN Industrial Deep Decarbonization Initiative (IDDI) as the main convening platform to encourage more countries to commit to green procurement pledges, help foster dialogue between countries to aid in implementation, and facilitate harmonization of policies and standards across countries. The U.S. government should maintain close engagement with IDDI to ensure U.S. perspectives are represented in international commitments.

Policies for Future Demand

While Buy Clean creates new markets for commercially available lower emissions goods, most current public procurement policies are not designed to create tangible demand to enable commercialization and financing of near-zero breakthrough technologies for industrial decarbonization. Policymakers should explore new policy options to create this future demand and offtake, such as through advance market commitments or contracts for difference. DOE released a request for information on these types of demand-side policy measures for green cement/concrete and steel (among other products).

Private Procurement

In addition to public sector procurement, private sector procurement efforts can use the same EPD data infrastructure and policy framework as public programs. For example, Amazon, Google, Meta, and Microsoft penned an open letter inviting industry collaboration for how to accelerate the delivery of green concrete for data centers. In the near-term, these efforts help to address opportunities for already commercial technologies. On the other hand, the First Movers Coalition (FMC), an initiative created by the U.S. State Department and the World Economic Forum, is attempting to leverage the collective demand from private sector purchase commitments to create early markets for clean steel, cement/concrete, aluminum, chemicals, and other heavy industrial products. FMC commitments are forward-looking and aim to stimulate demand for technologies not yet in the market. For steel, FMC recently launched their Near-Zero Steel 2030 Challenge to enable bilateral offtake agreements. In partnership with FMC, RMI launched a Sustainable Steel Buyers Platform to foster long-term offtake agreements in the North American market.

Sectoral Standards

Beyond creating initial markets for cleaner industrial goods through public and private procurement, Breakthrough Energy envisions a clean products standard (CPS) as a longer-term policy priority for widescale deployment of industrial decarbonization technologies. Using the same data infrastructure as Buy Clean, a CPS would set a decreasing emissions intensity benchmark for each covered product (e.g., cement or steel), which all domestic manufacturers and importers would need to meet. A CPS would provide industry with a predictable glidepath to reach net-zero and could be designed to reward producers that outperform the benchmark to incentivize further innovation. Thus, a well-designed CPS could address both current and future markets for existing commercial products and emerging technologies, respectively.

Cross-Cutting Solutions Policies

As the collective understanding of the different roles for technology solutions in different sectors and subsectors becomes more sophisticated, there will be a need to employ technology-specific policies, especially in cases where there may be limited resources or trade-offs between adopting a technology in one sector versus another. In all cases, specific infrastructure needs will be critical to efficient and economic deployment, as well as robust community engagement on the risks and benefits of each technology. Here, I will focus on policies for a subset of the complementary cross-cutting technologies discussed above.

Electrification

The IRA includes several tax credits that can indirectly and directly help incentivize industrial electrification. In general, all the clean electricity production and investment tax credits should decrease overall costs of clean electricity that can be used by industry, or in the case of onsite generation, directly reduce costs of constructing or operating the clean energy asset. Potentially more relevant for industry is the 45X clean manufacturing production tax credit, which includes eligibility for battery modules. Treasury and the IRS are currently drafting rules for claiming these credits, which will determine whether TES will be eligible for 45X under the battery module definition. Ensuring that TES is able to claim 45X would help accelerate scaling of TES production and drastically reduce capital costs for industrial projects incorporating electrification through TES.

To more broadly enable industrial electrification, additional policy support will be needed to incentivize switching to electrification technologies like industrial heat pumps and TES, properly plan for increased industrial load alongside clean generation and transmission buildout, and address electricity market barriers to TES participation.

Research shows that to maximize the emissions reductions benefits delivered by the IRA, the United States must more than double the historical pace of electricity transmission expansion. However, accelerating the construction of high-voltage, interregional lines will require the reimagination of nearly a century of transmission policy. Breakthrough Energy supports efforts to thoughtfully streamline transmission siting and permitting in a way that facilitates deployment of critical clean infrastructure while maintaining our nation's bedrock environmental protections.

Hydrogen

Recent hydrogen policies, including the passage of the 45V hydrogen tax credit in the IRA and the regional clean hydrogen hubs program in IIJA, have focused on generating a cost-competitive supply of clean hydrogen. The 45V tax credit in particular has resulted in an important discourse on how to adequately balance two objectives embedded in the credit's innovative design: reducing emissions while enabling the scale up of emerging clean hydrogen technologies. Striking this balance will be difficult to do, but it is clear that additional guardrails are necessary to ensure grid-connected hydrogen projects demonstrably do not cause additional pollution, by procuring new clean power from the same region and as close in time to when the electrolyzer is running. It is possible to define and phase-in these guardrails so that they ensure truly clean hydrogen production will scale. This and other recent policies would help reduce operational costs of switching to clean hydrogen, however, these incentives do not ensure that supplies will be used in a targeted way to decarbonize industrial processes and other priority sectors. Given the additional capital cost barriers associated with switching to hydrogen-based processes, and non-cost barriers associated with encouraging industrial facilities to commit to making that switch, more policy support for demand-side uptake is needed.

DOE is currently developing its own demand-side support mechanism for utilizing hydrogen, which may provide up to $1B to close the cost premium gap for hydrogen used in industrial projects related to the selected hydrogen hubs. Their intent is to select one or more independent entities to execute this demand-side price support mechanism before the end of this year and collaborate with the entities in the first half of next year to undertake public and stakeholder feedback for the specific design of the mechanism. This demand-side support will be critical to ensuring not only sufficient demand for the expected supply from the hydrogen hubs, but also that the demand the program supports targets priority end-uses, like industrial decarbonization, that may have a lower willingness to pay and would otherwise not come to the table at this earlier stage of clean hydrogen production.

In addition to economically matching supply and demand, the enabling infrastructure needed to safely transport and store hydrogen to physically get the supply to the demand will be an important consideration for clean hydrogen applications. The choice of transport and storage technology can have a big impact on overall project costs and decarbonization potential, so policymakers must carefully think through how to efficiently and adequately incentivize and unlock developers' ability to build enabling infrastructure while avoiding over-subsidizing buildout that could lead to suboptimal climate outcomes.

Carbon Management

First introduced in 2008, 45Q provides a tax credit for CO_2 storage or usage. The IRA expanded and extended 45Q, including increasing the credit value for industrial applications to $85/tonne of CO_2 permanently stored and $60/tonne of CO_2 utilized. While this increase provides additional incentives for high purity, low capture cost applications (e.g., ethanol, natural gas processing), it is likely insufficient to fully cover the higher costs of lower purity sources (e.g., cement, steel), which will need additional cost reductions or other sources of revenue. The combination of 45Q with capex subsidies from other DOE programs, such as the $6.3B Industrial Demonstrations Program or the $2.5B Carbon Capture Demonstration Projects Program funded by IIJA (which requires two projects in the industrial sector) could provide enough incentives for a handful of low-purity applications to advance over the next several years.

To secure permanent emissions reductions, carbon capture will require transportation and distribution infrastructure for delivery to geologic sequestration facilities or utilization sites. Efficient buildout of shared infrastructure will help reduce individual project costs. The United States is not technically limited in its storage capacity, but buildout has been held back by the permitting times for storage wells. Storage needs the full suite of legal and regulatory policies, like long term liability transfer, indemnification funding, and state primacy, in order to scale safely. The magnitude of transportation infrastructure deployment will depend on the adoption of viable alternatives to carbon capture (e.g., electrification, clean hydrogen, new sector-specific production methods) and on the need for CO_2 as a feedstock into other processes (e.g., as an input with hydrogen to make e-fuels and e-chemicals).

Sector Specific Policies

Cement and Concrete

Infrastructure and building construction rely heavily on standards and specifications, which are often prescriptive and dictate the types of materials used in projects. The construction industry is also very risk averse and slow to change practices. These factors create barriers for adopting innovative technologies and materials, like low-carbon cement and concrete, that warrant specific attention.

Overcoming these barriers will require collaboration between industry stakeholders, policymakers, standardization organizations, and academia on a suite of complementary activities. Developing new methods for third party testing and validation of innovative technologies and materials that demonstrate their performance can decrease perceived risk from potential buyers and users. Alongside testing, some new materials may require updated industry standards and specifications to enable use in real projects. On top of updates to allow specific new materials, there should be a broader push to move the industry from prescriptive specifications that limit innovation to performance specifications, which allow any material to be used, as long as it meets performance characteristics that can be evaluated with robust testing and validation. State departments of transportation can play a leading role in the evolution to performance specifications, given the regional variation in the industry and their outsize influence in setting specification norms within their markets.

Successful demonstrations of new materials and technologies in low-risk construction projects or specific demonstration facilities (e.g., MnROAD pavement test track) can also help accelerate their adoption. Policy can help enable these demonstrations by providing funding to cover the extra costs associated with using the new technology or material, both the cost of the material itself and non-material costs, like additional testing, measurements, and labor costs to allow sufficient time that may be needed when learning to work with a new material. Fortunately, the IRA low-embodied carbon procurement funding at GSA and FHWA are designed to cover these exact costs and can help spur these types of demonstration projects across the country.

For broader innovative material adoption, education and awareness within the industry will be critical. The existing and new workforce will need training to break from traditional norms and learn how to regularly work with new technologies.

Iron and Steel

In the United States, two types of steelmaking dominate: integrated BF-BOFs and standalone EAFs, with a handful of DRI plants running on natural gas. U.S. emissions from iron and steel production have decreased over the last couple of decades, largely due to declining overall production and increased share (about two thirds) of production through EAF secondary steelmaking. The ratio of primary to secondary steelmaking is generally reversed in the rest of the world, which results in U.S. steel, on average, having one of the lowest emissions intensities among major steel producing countries. However, as previously discussed, there is not enough scrap supply to completely replace primary steelmaking capacity, and there are high end applications of steel (i.e., automobiles) that require higher quality steel that can currently only be provided through primary steelmaking. Thus, U.S. steel decarbonization cannot rely solely on secondary EAF methods and necessitates strategies for enabling primary steelmaking to transition to net-zero processes through further R&D, commercialization, and deployment policy support.

Congress authorized a steel RD&D program in CHIPS (originally the Steel Upgrading Partnerships and Emissions Reduction (SUPER) Act of 2021), which will require appropriations to execute. For H_2-DRI pathways (and any others involving the use of clean hydrogen), the 45V tax credit and hydrogen hubs program will help increase supply and decrease costs of clean hydrogen, lowering operational costs, while the DOE Industrial Demonstrations Program could provide a capex subsidy to further lower costs of this and other capital-intensive pathways. One study found that the current U.S. policy environment enables multiple configurations of brownfield and greenfield H_2-DRI-based steelmaking facilities to be financially viable. Despite these findings, of the nearly 30 announced H_2-DRI projects globally, none are in the United States. This warrants further attention, especially as DOE stands up its hydrogen demand program and reviews selections for the Industrial Demonstrations Program, alongside already announced hydrogen hub awardees.

For setting standards in demand-side policies, in the near term, it will be important to distinguish between primary and secondary steelmaking in determining product emissions intensity limits, so as to continue incentivizing decarbonization of primary steelmaking and the creation of primary steel EPDs, as well as secondary steelmaking. EPA's interim determination for the use of IRA funding proposes a bifurcated steel procurement standard to address this issue. As more data on individual steelmaking facilities becomes available (i.e., the percentage of scrap content used to manufacture a steel product), phasing in a sliding scale standard based on scrap percentage rather than production process—aligned with the international ResponsibleSteel standard, IDDI, and FMC—would be a more effective, technology-neutral option that would be more inclusive to innovative technologies.

Climate and Trade

The United States imports a large quantity of carbon-intensive manufactured goods, accounting for over one gigaton of embodied carbon, providing a further imperative for U.S. climate policy to address emissions produced abroad as well as at home. Additionally, for energy intensive trade exposed industries located in the U.S. to invest in decarbonization, trade policy must first address potential emissions leakage which would undermine industrial competitiveness and emissions goals. For a global system of climate-aligned trade to develop, research and consensus building on measurement and tracking of embodied carbon data is needed. It is encouraging to see Congress increasingly paying attention to this issue, with Members on both sides of the aisle working on proposals.

On enhancing embodied carbon data availability, Senators Coons and Cramer—with several Members of this Committee—introduced the PROVE IT Act of 2023, which would direct the DOE to study the emissions intensity of U.S. products relative to those produced in other countries.

While non-governmental organizations have published valuable estimates of America's "carbon advantage" and online tools for visualizing the embodied carbon in trade flows, a government-led study with access to real facility data from existing industry reporting will be necessary to underpin any kind of domestic policy addressing embodied emissions from imports, as well as to inform U.S. responses to policies adopted by other trading partners, like the EU Carbon Border Adjustment Mechanism (CBAM). With U.S. manufacturers increasingly developing EPDs to take advantage of domestic public and private clean procurement efforts, there is also an opportunity to maximize EPD data interoperability with the data infrastructure informing climate-aligned trade policies.

Building off of the ideas in the PROVE IT Act, Senators are also developing U.S. border adjustment or import fee policies to address carbon leakage and competitiveness. Last Congress, Senator Whitehouse introduced the Clean Competition Act, which would create a carbon border adjustment mechanism that charges energy intensive imports, while simultaneously incentivizing the domestic reduction of industrial emissions. Many U.S. industries are already much cleaner than their foreign counterparts, and ensuring domestic industries continue to decarbonize will help American manufacturers maintain their competitive advantage under increasing international climate-aligned trade regimes. Last month, Senator Cassidy—with co-sponsorship from Senator Graham—introduced the Foreign Pollution Fee Act, which would impose a fee on imports of select energy and industrial goods, depending on the relative emission intensity of their production compared to average U.S. production. Importantly, the bill would leverage these fees to create international partnerships to address industrial emissions, using climate competition to promote collaboration. Both of these proposals provide key pieces of a U.S. climate-aligned trade policy that could ultimately build toward global collaboration to clean up industry and trade by leveling the playing field for domestic and foreign producers alike, creating a race to the top. Breakthrough Energy supports further bipartisan discussions to develop a climate and trade policy that ensures domestic industries can maximize their clean investments to bolster competitiveness and puts a spotlight on manufacturing emissions abroad to incentivize industrial decarbonization around the world.

As the United States contemplates a domestic border adjustment policy, it will also be important to begin working with other countries on a path forward toward international cooperation on climate and trade, such as through a climate alliance or carbon club. Because countries are adopting different domestic policies to tackle climate change and some, like the EU, are already in the process of implementing a CBAM tied to their internal carbon pricing system, it is unrealistic to expect all countries to agree on a single, harmonized climate policy framework. Rather, the goal should be to facilitate policy interoperability, primarily through agreement on using product emissions intensity as a key metric and cooperation on data measurement, reporting, and transparency.

There are several international fora where cooperation on climate and trade is being considered. The United States and the EU continue to negotiate a Global Arrangement on Sustainable Steel and Aluminum (GASSA), which would address non-market excess capacity and carbon intensity of these goods and allow tariff-free trade between the two jurisdictions. The G7 is another group of key countries, which could help nucleate an international alliance on climate and trade. Notably, the G7 climate, energy, and environment ministers included several points on climate and trade cooperation in their official communique this year, including an emphasis on emissions intensity as a key factor for implementing policy instruments.

Conclusion

Without further intervention, the industrial sector will likely become the highest-emitting U.S. sector within the next decade. Addressing industrial emissions will require accelerated innovation, enabled by supportive policies throughout the R&D, demonstration, commercialization, and deployment stages of a technology's lifecycle, including supply-side investments, demand-side market creation, climate-aligned trade policies, and supporting data and analytical infrastructure. Decarbonizing industry will not only contribute to achieving net-zero emissions, but it will also bolster American competitiveness, retain and create good-paying manufacturing jobs, and provide positive health impacts to workers and surrounding communities.

The world is on the brink of a clean industrial revolution, and America is poised to take the lead. I urge the Members of this Committee and Congress to not let this opportunity pass us by.

Senator CAPITO.

[Presiding.] Thank you. Thank you very much.

Now we will hear from Dr. Ellis.

STATEMENT OF LEAH ELLIS, CEO AND CO-FOUNDER, SUBLIME SYSTEMS, INC.

Ms. ELLIS. Chairman Carper, Ranking Member, Capito and members of the committee, thank you for hosting today to discuss the important role the Federal Government plays in accelerating low carbon building materials.

I am the CEO of Sublime Systems, a company commercializing low carbon cement. I am here to talk to you about the extraordinary opportunities enabled by industrial decarbonization. These include fostering innovation, attracting talent, creating jobs, boosting domestic manufacturing, and fighting global climate change. This is a win-win that energizes myself and my colleagues, as well as my peers, in many adjacent industries.

Today's cement manufacturing is responsible for 8 percent of global CO2 emissions. If the industry were a country, it would be the third largest emitter after China and the U.S.

Today's cement is made in massive fossil fuel kilns running at temperatures up to 1,400 degrees Celsius to cook limestone, which releases CO2 as it decomposes in the kiln. I started Sublime Systems with the mission of having a swift and massive impact in reducing these emissions.

At Sublime, we use electrochemistry instead of heat to turn non-carbonate minerals into cement. Our process runs at room temperature and entirely on electricity. This avoids both the limestone and the fossil fuel emissions that I mentioned before.

Our cement is fully compliant with industry accepted performance-based standards and we can produce over 100 tons of cement per year in our pilot facility, which we are scaling quickly.

The public sector has a unique ability to accelerate cement's decarbonization. Collectively, it deploys 60 percent of all the cement used in America through the building of public infrastructure. You have admirably responded to this challenge in several ways, many of which we can't fit into my allotted 5 minutes, but I will highlight a few.

Sublime has received Department of Energy ARPA-E funding which enabled us to de-risk our technology as it spun out of the university, which allowed us to attract venture capital investment. Second, both the General Services Administration and the Federal Highway Administration have recently allotted billions to the use of low carbon construction materials. Sublime has already noticed increasing customer interest in response to these policies and we urge Congress to consider making such initiatives permanent.

We have collaborated with other low carbon cement developers to encourage further policy adoption. The Decarbonize Cement and Concrete Alliance is focused on procurement policy, demand support measures and early adopter platforms, as well as another critical lever, production tax credits.

The existing 45Q tax credit rewards technologies that capture carbon, but it does not reward technologies such as ours that avoid CO2 emissions in the first place. We encourage technology-agnostic implementation of tax credits to create a level playing field for all industrial technologies that avoid CO_2 emissions and address climate change.

I would like to acknowledge the DOE's Office of Clean Energy Demonstrations, OCED, as a vital initiative for helping technologies create products at scale and unleash the transformational job opportunities in the process. Sublime is currently engaged with OCED for potential funding of our first commercial facility, and we are confident in our prospects.

However, if we are ultimately not selected, we believe this will primarily reflect how many quality innovations are seeking this money. I urge Congress to make this program permanent and to generously fund it until the American economy is decarbonized.

Decarbonizing industry offers an opportunity to spur an American manufacturing revival, especially in communities that have been left behind. We have used the Justice40 screening tool and policy tools to identify the location of our first commercial plant, a western Massachusetts site in a disadvantaged community census tract. This city formerly housed a booming paper industry. We are already collaborating with city officials, community organizers, non-profits and unions to ensure that our plant delivers maximum benefits to residents.

We have signed a strategic partnership focused on high quality jobs with United Steelworkers, and we are exploring a collaboration with the Smithsonian Science Education Center. We expect to create 70 benefits-bearing jobs, and many of these roles will not require an advanced degree, making them accessible to those who have not gone to college.

We know that the clean energy transition can be a just transition. It can also be a prosperous one, bringing an industrial boom, the likes of which we have not seen in hundreds of years.

The fact that you are hosting this hearing today is already quite impactful in highlighting the climate and economic opportunities within. I thank you for your work in this and for your time today, and we look forward to your continued partnership.

Thank you.

The prepared statement of Ms. Ellis follows:]

Sublime Systems

Testimony of Dr. Leah Ellis, Chief Executive Officer and Co-founder

Sublime Systems

Before the

Committee on Environment and Public Works

United States Senate

Regarding

"Opportunities in Industrial Decarbonization: Delivering Benefits for the Economy and the Climate"

November 15, 2023 at 10:00 a.m.

Chairman Carper, Ranking Member Capito, and Members of the Committee, thank you for hosting me today and offering me the opportunity to share industry perspectives on the critical role the federal government plays in accelerating demand and adoption of cleaner building materials such as ours. As the Chief Executive Officer of Sublime Systems — a company beginning to commercialize a breakthrough low-carbon cement manufacturing process to replace a process that today results in 8% of global CO_2 emissions — I can attest to the positive impact that legislation and executive action is making on the marketplace.

While I am best positioned to share perspectives on cement and concrete, I think I can appropriately represent my colleagues in other industries in saying that industrial decarbonization provides extraordinary opportunities. These include fostering innovation and enhancing competitiveness, drawing talent, creating new job opportunities for Americans who have been marginalized by transitions in other industries, boosting domestic manufacturing while reducing dependence on foreign imports, and producing goods that significantly lower emissions that contribute to climate change and threaten national security.

Decarbonizing industries such as cement is a critical lever in fighting climate change, as they are large contributors to CO_2 emissions and have been widely regarded as tough to abate — until now.

This is truly a win-win-win opportunity that energizes myself and my colleagues in our work, and I am so grateful to have the opportunity to speak about it with you all today.

The Next American Frontier

In looking at the technologies that have helped reduce emissions and fight climate change, we all must acknowledge the incredible momentum in transitioning our fossil-fueled grid to a cleaner, greener one, with the increased adoption of wind, solar and hydro. The benefits of investments in electric vehicle technology and adoption are increasingly coming to fruition. Together, both industries provide an important stream of new job opportunities that boost the American economy, and they do it while working to protect our planet from the devastating effects of climate change.

The next frontier in the fight to mitigate climate change is industrial decarbonization — particularly carbon avoidance technologies.

I started Sublime Systems with the mission of having a swift, massive, and enduring impact on global CO_2 emissions by decarbonizing cement, the key ingredient in concrete. I am a dual citizen educated in a top Canadian institution, but I returned to the U.S. to work on this problem because I care. I am not alone in this trajectory, as many of America's brightest young minds want to work on fighting climate change, too. Investors are noticing this trend in talent. They tell me they are putting their money where America's talent is flowing: into cleantech.

I came to the problem of cement as a battery scientist who recognized that new advances in that field and their role in fighting climate change were now incremental, relative to industries like cement that were high-emitting and had primarily remained untouched for 150+ years. My co-founder and I imagined that we could instead harness the progress in renewable energy generation and storage to transform the processes that were born of the cheap fossil fuels of the Industrial Revolution, long before we understood the harm they cause to our planet.

The Scope of the Opportunity

Cement manufacturing has relied on these fossil fuels for 150+ years — and as an industry is now responsible for 8% of global CO_2 emissions. If cement were a country, it would be the third highest emitter, after the US and China. This is a function of how it is made and of its scale — cement is the most consumed material on Earth, after water. Today's cement, ordinary portland cement or OPC for short, is made in massive, industrial kilns that need to reach temperatures of 1400°C to produce the required chemical reactions. This of course can only be achieved by burning fossil fuels, usually bituminous coal. That contributes to about half of cement's carbon footprint. The remaining emissions come from the use of the feedstock limestone, which is half CO_2 by weight. Limestone needs to thermally decompose to form reactive cement, so it releases all that CO_2 into the air when it is burned inside the kiln.

The result is roughly one ton of CO_2 is emitted for every ton of portland cement produced. And we currently produce 4 billion tons of cement per year across the globe. If we aim to achieve net-zero by 2050 and limit global warming to 1.5 °C, we must eliminate cement's CO_2 emissions. However, at the same time, cement is the strongest and most durable building material, and we must keep building if we are to shelter the world's growing and urbanizing human population. It is estimated that 70% of the infrastructure that will exist in 2050 is not yet built. We need cement now more than ever — therefore, we need a breakthrough approach to low-carbon cement production.

It is critical that we recognize the current incumbent cement industry for taking admirable, swift action in the last few years to decarbonize with the tools currently available. Our contacts in the industry have marveled at how quickly they have changed after decades of doing it the same way. They have reduced emissions primarily through adopting Portland Limestone blended cements, which have about 10% lower CO_2 emissions, or displacement of the high-carbon cement binder with much lower-carbon supplementary cementitious materials These achievements should be celebrated as impactful in an industry with such a large footprint. Still, there is much more work to be done. As such, a number of innovators have emerged in recent years to reimagine how we produce cement and cementitious products to further accelerate that decarbonization.

Sublime Systems' Contribution to Industrial Decarbonization

At Sublime, we are avoiding both the heating and process emissions typical of cement manufacturing by electrifying the entire production process. We use a water-splitting electrolyzer to chemically break down the bonds in inert minerals and turn them into the reactive components of cement: calcium and silica. This process runs at ambient temperature entirely on electricity — a premise that is increasingly exciting as renewable electricity gets cheaper, more ubiquitous, and more reliable[1]. And we can use a range of abundantly available minerals and raw materials as feedstocks, which do not release CO_2 when broken down. The result is a cement can be mixed with water to gel, harden, set, and endure in concrete the same way that today's high-emitting OPC does. Our Sublime Cement™ is fully compliant with the performance-based specification for hydraulic cement, ASTM C1157, allowing it to be specified in building projects in the U.S. and abroad (Appendix 1, Sublime Systems Press Release). And we are now in the process of working hand in hand with the users of cement, ready mix concrete producers, to verify that it all works within their current infrastructure.

Public Sector Leadership Has Already Proven Potent

The public sector's investment in decarbonization is not only an investment in the economy and our future way of life on this planet, but in the case of cement and concrete, it's an investment in the future availability of low-carbon products the public sector uses to serve the public. As the fiscal sponsors of the bridges, buildings, roadways, and ports of entry that connect our entire economy, our federal, state, and municipal governments deploy 50-60% of all cement used in America. In the case of cement and concrete, industrial decarbonization directly affects the tools you have at your disposal to conduct the people's business. The future can literally be paved with innovation wrought by policies you pass today.

You have commendably responded to this challenge. Your attention, oversight, legislation, and engagement have spurred significant progress. This is evident in how customers are increasingly engaging with companies like Sublime Systems and other pioneers in low-carbon

[1] https://www.eia.gov/todayinenergy/detail.php?id=55239).

cement and concrete production. With an existing eagerness to decarbonize, your efforts have provided established industry players and innovators alike, such as Sublime Systems, with crucial tools that mitigate risks and fund the foundational aspects of decarbonization.

Using power of the largest purchaser to buy clean and reduce embodied carbon

Visionary leadership has been demonstrated through both executive orders and congressional statutes, initiating the use of the world's largest buyer's power to adopt clean construction materials. The domain of procurement, inherently complex, is witnessing monumental changes. The introduction of additional funding, revamped procurement processes, and the adoption of preferential selection criteria prioritizing materials with reduced global warming potential are commendable steps.

The General Services Administration (GSA) recently implemented a congressional mandate, with remarkable speed, to allocate $2.15 billion for the procurement of low-embodied carbon (LEC) construction materials. This implementation aligns with the Federal Buy Clean Initiative. The GSA has earmarked projects nationwide to incorporate LEC materials: 16 large-scale capital projects utilizing $561 million, 99 smaller projects employing $507 million, and 39 Land Port of Entry Projects using $935 million.

Additionally, Congress allocated $2 billion to the Federal Highway Administration (FHWA) to promote the use of lower-emissions materials in highway construction and discourage the expansion of lanes for single-occupant vehicles. The FHWA Administrator will use these funds to incentivize or reimburse for the additional costs of lower-emissions materials.

Sublime Systems is rapidly expanding its manufacturing capabilities. Upon commercial availability, our materials are expected to rank in the top 1 percentile for low-embodied carbon. This positions the builders we supply to competitively bid for such programs. We urge Congress to consider making such initiatives a permanent aspect of government procurement for building materials.

EPA's assistance in developing robust environmental product declarations

Thanks to your legislative initiatives, the Environmental Protection Agency (EPA) is now funded to foster the development, standardization, and transparency of Environmental Product Declarations (EPDs) for construction materials and products. The EPA was directed to offer grants, technical assistance, and tools essential for quantifying the embodied carbon in construction materials. The agency has launched a grant program to aid businesses in manufacturing construction materials and products. This program assists in developing and verifying EPDs and supports states, Indian Tribes, and nonprofit organizations aiding these businesses.

Sublime Systems is creating multiple products that could reduce embodied carbon in construction and plans to seek EPA support to develop EPDs. Even if we do not receive EPA support, it is clear that our economy's current approach to carbon accounting is limited and primarily driven by voluntary efforts from industry leaders committed to sustainability. Nonetheless, this program will introduce a level of rigor that lights the way for a genuine shift to clean manufacturing.

At Sublime we pride ourselves in our innovation that maximally avoids carbon emissions, rather than emitting and cleaning up after it with capture technology. A recent third-party validation showed our process shrinks the global warming potential of cement manufacturing by 90%, relative to today's OPC production (Appendix 2, Sublime Systems Press Release). We believe such carbon avoidance technologies provide the most durable, reliable solution in fighting climate change. We do not want to put carbon into the atmosphere if technology can enable us not to. And we know that our world will one day move on from fossil fuels, so we have designed a process that will not rely on them at all.

Scaling through the final "valley of death"

In the process of scaling large-scale industrial technology, companies often encounter a challenging phase known as the final 'valley of death.' During this phase, although the products are functional and commercially available, they may not be price-competitive until production is scaled up to the very large sizes needed to achieve economies of scale. Recent visionary actions by Congress have effectively bridged this valley, at least temporarily, offering crucial support to companies during this pivotal stage. The congressional formation of the Office of Clean Energy Demonstrations is an extraordinary mechanism.

Sublime Systems is inspired by the Department of Energy's (DOE) leadership in forming public-private cooperative agreements that scale with technology. These efforts began with foundational research funded by ARPA-E, advanced through small-scale, market-facing tests by the Industrial Efficiency and Decarbonization Office (IEDO), and further supported by large-scale project financing through the Loans Programs Office (LPO). Congressional leaders and the DOE have created a vital link between IEDO and LPO by establishing OCED. This office is specifically tailored to address the challenges of scaling from IEDO support to securing full commercial-scale loan guarantees.

Sublime Systems is currently engaged with OCED to explore a cooperative agreement for the development of our first commercially relevant facility. I'll be back in a couple of weeks with key team members for the final interview to determine if there is a mutual fit. We are confident in our prospects to manifest congressional intent for this program. However, if we do not receive the grant funding, we believe it will primarily reflect just how many high-quality innovations are seeking this money. There were over 400 applications in the initial pool, with over 100 applications encouraged to proceed with the intensive application process. Regardless of Sublime's outcome for this particular round of funding, I strongly urge congress to make this program permanent and generously fund it until the American economy is decarbonized. There are more projects, more jobs, more private-sector cost-sharing, and more decarbonization to be unlocked.

In addition to increased funding to scale industrial decarbonization demonstration projects, Department of Energy analysts have produced best-in-class reports on the market conditions, obstacles, and opportunities. DOE's series of commercial liftoff reports explore the role of heavy industry in achieving our net zero by 2050 targets (Appendix 3, DOE Liftoff Report). The report on low carbon cement underscored that alternative production methods for cement — a category Sublime occupies — is a leading strategy to decarbonize cement and concrete, with rapid scaling in the 2030s after materials demonstrate cost and performance adhering to existing standards in the late 2020s. This is notable because the alternative production strategy is on the same viability pathway as carbon capture storage and utilization (CCUS) technologies, which have been around for many decades.

In this context, Sublime's hypothesis is that the best investment of capital on decarbonization should <u>increase</u> production of cement. This increases domestic manufacturing, creates jobs, and comes with the added benefit of offsetting foreign imports, which account for 20 to 25% of the cement we use in America.

As a consequence of avoiding process emissions, Sublime avoids the need for costly CCUS and related infrastructure. We're hearing significant concern from policymakers in geographies like California regarding the feasibility of building carbon dioxide transportation pipelines, which appears to be gaining broader awareness by government agencies.

<u>Serving environmental and economic justice at the same time</u>

Crosscutting a number of initiatives promoted both by Congress and the departments responsible for government spending on a clean energy transition is an extraordinary opportunity. There are communities across the nation that have historically been marginalized, burdened by pollution, and underfunded. Addressing these issues offers a chance to simultaneously fulfill multiple policy objectives, including the transformation of heavy industrial manufacturing and support for marginalized communities.

A prime example of such policy innovation is Justice40. The aim of Justice40 is to rectify these disparities by: 1) directing a substantial portion of federal investment in sectors like clean energy, transit, affordable housing, training, and workforce development to the communities most in need; 2) mitigating environmental hazards in these areas and fostering healthier, more sustainable living conditions; 3) creating job and economic opportunities in green sectors, offering pathways to economic security and prosperity; 4) encouraging active participation of disadvantaged communities in decision-making to ensure tailored policy and investment outcomes; and 5) establishing mechanisms to monitor and assess the impact of these investments on underserved communities, ensuring accountability and effective resource utilization.

Sublime Systems was founded to have a swift and massive impact on global carbon dioxide emissions by decarbonizing cement. Delivering additional tangible benefits to neighbors near Sublime facilities is inherent to Sublime's broader mission in service to humanity and the planet. Sublime welcomes the opportunity to not only rethink a cleaner cement manufacturing process, but also the way communities engage with clean tech companies throughout the entire project lifecycle.

Aligned with Justice40, Sublime Systems prides itself in the fact that bringing our technology and product to market will create many high-quality American manufacturing jobs, many of will not require an advanced degree, making them accessible to a greater portion of our population that does not go to college. Today we operate a pilot-scale facility today can produce over 100 metric tons of cement annually, but we are ultimately working towards a 1-million-ton-per-year Megaplant, which would put us on the same scale as today's cement majors. A key step before that is our first commercial facility, which will produce 30,000 tons of our low-carbon cement annually and will commercially and technically de-risk our product.

In western Massachusetts, the anticipated site of this first-commercial low carbon cement manufacturing plant, Sublime and the local community are already working to serve that dual mission. Neither the climate crisis nor our neighbor's urgent health and human needs can wait for a sequenced approach to community organizing. So Sublime is working closely with city officials, "grasstop organizers," and citizens to ensure that every step of the way, from development, to construction, to operation, the demonstration plant delivers necessary, impactful, and intentional local benefits in direct correlation to the current and evolving needs of its community.

Sublime Systems incorporated the Climate and Economic Justice Screening Tool directly into our project siting criteria, alongside supply chain, feedstock, energy, and market considerations. This served as an initial proxy for "community demand," (albeit potentially an inaccurate proxy). Sublime has confirmed actual community demand in the community for the workforce development and economic benefits generated by the proposed plant through direct and robust community engagement. Sublime's leader in this engagement is a lifelong resident deeply knowledgeable about the social and political considerations relevant to the community. Sublime is heartened by sentiments voiced by local community organizers to "to think of this as your community when you come in" along with their commitment to helping Sublime integrate into the community.

In the context of being good neighbors, Sublime firmly believes that the update to American manufacturing and enrichment of local communities must be done without exacerbating cumulative exposure burdens. Not only do we drastically reduce CO_2 emissions, but our efficient electrochemical process completely avoids several operations known to emit locally harmful pollutants like NO_x, SO_x, dioxins, mercury, and combustion-related particulates.

Sublime has proactively engaged with unions for both construction and operations jobs to ensure the greatest benefit flows to the greatest number. We signed a strategic partnership agreement focused on high quality jobs with the United Steelworkers tied directly to OCED and the Community Benefits Plans they require as part of implementation. Further, a portion of Sublime's advanced manufacturing technology jobs require experience in clean technology concepts and techniques not commonly found in today's workforce or education curricula, and thus require additional workforce training that some unions are very well-positioned to support training, as well as community colleges and public schools. We recognize we are but one of many innovative companies that can replicate this dynamic of advancing green technology and creating a new skilled workforce.

The decarbonization of American industry offers an unparalleled opportunity to spur an American manufacturing revival, in particular serving communities that have been long been overlooked and left behind in decades of offshoring and digital transformation. The production of novel clean industrial technology can spur high-quality American jobs for all skill and education levels. We have seen this already, with companies like Form Energy selecting a former West Virginia steel mill site as the location for its iron-air battery manufacturing plant — and bringing hundreds of new jobs for local residents with it. At Sublime we expect to create 70 high quality, benefits-bearing jobs with our first commercial facility, a fact recognized by recent state and local tax credits awarded to us. We are also partnering closely with the city to provided needed training and education to qualify residents for these jobs. We are excited about the potential to collaborate on this project, with the Smithsonian Science Education Center, who will work with Holyoke and the surrounding districts to enrich their STEM learning in middle and high school.

Clean Energy Infrastructure Underpins Success

As Deputy Secretary of Energy David Turk says, industrial decarbonization will not have a silver bullet, and instead a "silver buckshot." Central to the success of technologies like those developed by Sublime Systems and others involved in decarbonizing industry is the need for abundant, affordable electricity, water, and sustainable transportation. Planning for this infrastructure, which includes transmission, permitting, funding, tax incentives, and public sector partnerships, must consider the requirements of a dynamic and decarbonizing industrial sector.

As a pivotal player in the transition to a sustainable energy future, your role in supporting the expansion of clean energy generation, such as solar, wind, hydro, and nuclear power, is crucial. Your initiatives in providing financial incentives, like subsidies or tax breaks, play a key role in lowering the economic barriers associated with renewable energy projects. This support not only makes these projects more feasible for private investors but also aligns with broader environmental and sustainability goals.

We encourage the continued development and implementation of policies that efficiently integrate renewable energy into the national grid. Your efforts to streamline the permitting processes for renewable energy projects are noteworthy and essential. By simplifying and accelerating the approval processes, you are enabling quicker completion and operation of these projects.

According to the U.S. Energy Information Administration (EIA), the U.S. electric power sector operated about 74 gigawatts (GW) of solar photovoltaic capacity at the end of 2022, which is about three times the capacity at the end of 2017. Solar capacity is expected to expand by another 63 GW (84%) by the end of 2024, reflecting a substantial growth trajectory. Similarly, U.S. wind power capacity, which has grown by more than 60% since 2017 to about 143 GW, is forecasted to increase by approximately 12 GW over the next two years.

The trend in clean energy capacity addition in the U.S. is moving towards a greater share of electricity generation from renewable sources. Wind and solar accounted for 14% of U.S. electricity generation in 2022 and are forecasted to rise to 16% in 2023 and 18% in 2024. This increase is being driven primarily by new investments in solar and wind generating capacity.

Looking Ahead

Sublime Systems is grateful to this committee, your colleagues in Congress, and to the civil servants and appointees you oversee for the incredible work already under way. In the face of recent news of planetary boundaries being breached, it gives me hope that you are putting America in a global leadership position, brilliantly tying economic prosperity with climate action.

However, more work remains if we are to avoid the worst climate changing impacts such as mass crop failures, famine, disease, and mass human migration driven by un-survivable wet-bulb temperatures and ecosystem collapse. Your continued leadership and climate-aligned, economy-centered policies can accelerate the multi-domain, multi-sector changes we need.

Aligned with this, Sublime Systems is a founding member of the Decarbonized Cement and Concrete Alliance (DC_2). DC_2 is a coalition of innovative companies at the forefront of the global effort to reduce carbon emissions from cement and concrete. Our ten current members — Biomason, Blue Planet Systems, Brimstone, CarbonBuilt, Chement, Fortera, Minus Materials, Queens Carbon, Sublime Systems, and Terra CO2 — are pioneering American venture- and private-sector-backed climate technology companies dedicated to delivering ultra-low carbon, carbon-neutral, and carbon-negative cement and concrete solutions. Collectively, our technologies rethink production processes and feedstocks, introduce novel materials, and utilize or sequester CO_2 directly in concrete — all with a goal of decarbonizing the cement and concrete sector.

Together, we advocate for state and federal policies that accelerate the deployment and commercialization of decarbonized cement and concrete in North America. These policies are designed to capitalize on and expand the growing demand for low-carbon building materials from various stakeholders, including infrastructure owners, designers, contractors, ready-mix suppliers, and government agencies. A primary goal of our advocacy is to create and enhance avenues for scaling up the low-carbon cement and concrete industrial base, thereby delivering innovative products and creating U.S. manufacturing jobs essential to the net-zero economy (Appendix 4, Decarbonized Cement and Concrete Alliance Policy Presentation).

We believe additional policy, in addition to those already implemented, can have an even greater acceleration on industrial decarbonization:

> **Production tax credits**: Per dollar, per kilogram of carbon abated, low-carbon cement and concrete is one of the most efficient taxpayer investments in avoiding carbon. Production Tax Credits have successfully supported the growth of the solar and wind energy industries, and the same approach will work to decarbonize cement and

concrete. We seek technology-agnostic production tax credits that recognize the production of materials that result in a lowered global warming potential of the final concrete products. Borrowing from successful congressional playbooks can further accelerate the adoption of low-carbon cement and concrete. The existing 45Q tax credit rewards technologies that capture and store carbon but does not reward technologies that avoid emitting carbon in the first place.

Demand support measures: As noted in the DOE Liftoff Report, "There is limited use of project finance for cement in the U.S. today; in conversations with numerous investors and large cement companies, no recent instance could be identified in which a project finance model was used. Moreover, large investment firms often have limited experience with cement projects and may not have analysts focused on cement companies, given their limited market capitalization." As the ultimate end-user and buyer of over half of the cement used in the nation, the public sector has a role in making demand signal for low-carbon cement bankable for risk-averse investors and enable project finance at scale. The DOE notes that "large-end customers must develop a procurement model that provides greater offtake certainty for low-carbon cement plants. To de-risk projects sufficiently, such a model could need to have ... direct, legally enforceable contract between the cement plant and a creditworthy end customer ... guaranteed offtake for most or all of a plant's output for the investment period, with some guarantee regarding price..."

Transformational procurement policies (not incremental): Procurement policies that are attempting to buy clean and accelerate innovation can be blunted by incrementalist, or supply-limited product offerings. We seek to dramatically decarbonize the industrial base, and as such support procurement rules that strengthen the public sector's ability to anticipate, support, and reward transformational innovation over incremental improvements.

Early adopter platforms: We seek to use the power of the public sector to convene sandbox testing, pilot projects, and lab testing on behalf of the entire construction community to build confidence. DC_2 recognizes that engineers and contractors have valid concerns about using materials manufactured using new processes. To this end, we would advocate for public sector initiatives that can help to make this validation process more efficient for the marketplace.

Aside from our work collectively with DC_2, we see an additional opportunity to better connect this work to human health. As you know, EPA has long elevated industrial standards and protected public health by setting emissions standards under Section 111 of the Clean Air Act. Because EPA has never set greenhouse standards for cement, there is no clear public-health protecting mandate to align public and private investments for the industry. EPA informed the D.C. Circuit that it was researching its path forward over a decade ago. Now that new technologies and decarbonization strategies, like Sublime's, have come online and could provide a path forward, there is an opportunity to revisit this. We would urge the Committee to discuss this gap with EPA, and to advocate for standards that can elevate our collective approach in the coming years.

Conclusion

The fact that you are hosting this very hearing today on industrial decarbonization, drawing public attention and imagination toward what is possible and where we can go, is already quite impactful, and we thank you for that. Without a platform like this hearing, it would be very difficult for the right stakeholders to know about the promise and progress of industrial decarbonization and carbon avoidance technology, so we thank you again for this invitation.

I'd like to take a moment to recognize Jesse Benck, Brandon Williams, Joe Hicken, Glen Junor, Becky Gallagher, Greg Williams, Mike Corbett, Mike Stern, Cayman Somerville, Raffi Mardirosian, Erin Glabets, Mariya Layurova, Kyle Dominguez, Brian MacDonald, Mattias Ferber and my co-founder Yet-Ming Chiang and many team members I do not have time to acknowledge here. My testimony today is supported by an extraordinary team in addition to so much support from industry experts, financiers, think tanks, and lawmakers like you. Decarbonization of heavy industry is all-hands on deck, and I am energized and blessed to be working with such smart and impassioned people.

In closing, we know that the clean transition can be a just transition. It can also be a prosperous one, bringing an industrial boom the likes of which we have not seen in hundreds of years. We thank you for the work you are doing in this and for your time today — and we look forward to continued partnership.

Sublime Systems

APPENDIX 1

businesswire
A BERKSHIRE HATHAWAY COMPANY

Sublime Systems

Sublime Systems Receives Key ASTM Performance Designation for Its Ultra-Low Carbon Cement, Clearing the Path to Commercializing Fossil-Fuel-Free Cement at Scale

Third party verifies that Sublime Cement™ is as strong and durable as today's ordinary portland cement (OPC), whose production makes more greenhouse gases than all passenger vehicles combined on planet Earth

September 15, 2023 08:00 AM Eastern Daylight Time

SOMERVILLE, Mass.--(BUSINESS WIRE)--Sublime Systems, developers of the only fossil-fuel-free, scalable, drop-in replacement for traditional cement in concrete, announced that its product has obtained ASTM C1157 designation. This industry standard specifies performance requirements across parameters including strength development, durability, and low shrinkage and cracking, and is being increasingly adopted as the industry moves towards performance-based standards. Obtaining the ASTM C1157 designation enables Sublime Cement™ to be used compliantly under major U.S. and international building codes, unlocking a path for it to replace OPC at scale and massively lower the carbon output of global construction infrastructure.

Cement production is currently responsible for 8 percent of global CO_2 emissions. About half the emissions come from the fossil-fuel-fired kilns needed to decompose limestone into lime, and the remaining CO_2 is emitted as a byproduct of this chemical reaction. Sublime Systems' fossil-fuel-free process forgoes both these steps, replacing the legacy kilns with an electrochemical approach that makes cement at ambient temperature and uses renewable electricity to extract calcium and silicates from a diversity of non-carbonate raw materials. Sublime Cement™ manufactures with a "true-zero" (as opposed to net-zero) approach — it does not require offsets or additional carbon capture and storage (CCS) infrastructure to reduce emissions.

"Sublime was founded to have a swift, massive, and enduring impact on global CO_2 emissions, and we've designed our process to avoid CO_2 at every step, rather than polluting and cleaning up afterwards," Sublime Co-Founder and CEO Leah Ellis, PhD said. "At the same time, we take our responsibility in manufacturing a next-generation product very seriously — we need to make a high-performing cement that is safe and easy to adopt. Data-driven performance-based standards, like ASTM C1157, allow us to solve the right problems: safety and carbon avoidance, rather than adherence to a legacy recipe. Passing the ASTM C1157 standard is an important milestone in showing that Sublime's low-carbon cement innovation integrates into the same quality concrete building material that the construction industry requires."

The ASTM C1157 specification is a performance-based standard, a category that is being widely adopted by a range of industries as they allow for novel materials that can be produced with minimal emissions while maintaining rigorous and data-driven standards for safety and performance. ASTM C1157 has more stringent strength requirements than older hydraulic cement standards, ASTM C150 for OPC and ASTM C595 for blended cements, both of which contain prescriptive and performance requirements.

To achieve the ASTM C1157 compliance, Sublime provided its cement to a Cement and Concrete Reference Laboratory-certified third-party for testing. Sublime Cement™ — which is based on the recipe for Roman cement — exceeded all ASTM C1157 General Use performance requirements and outperformed many samples of OPC in ultimate strength and durability. These results suggest the extension of the final product's long-term service life relative to today's industry standard. Sublime is currently conducting additional tests measuring its cement's performance in concrete through third-party ready-mix concrete labs and in field use cases. Sublime's operational pilot facility has a current design capacity of >100 tonnes of cement per year, and the company is commissioning its first commercial plant for 2025.

"Sublime is on course to make CO_2-free cement that performs better and costs less than what pours out of concrete trucks today," said Clay Dumas, general partner at Lowercarbon Capital. "Now, the ASTM C1157 designation paves the way for global adoption of the world's cleanest cement."

It is estimated that 70% of the infrastructure that will exist in 2050 to shelter the world's growing urban population remains unbuilt. To balance such global construction goals with emissions reductions targets means a low-carbon approach like Sublime's becomes essential to not only meet this demand but also surpass the performance of current standards. It is critical to gain the confidence of the entire ecosystem of buyers in next-generation cement, spanning ready-mix concrete suppliers, concrete contractors, architects, engineers, general contractors, building owners, and government agencies. Sublime is in discussions with customers across these constituencies and is actively planning for its first field pours in Q4 2023.

"The global construction industry understands the importance of decarbonization of cement and concrete but has to balance this with the responsibility of executing large infrastructure projects that satisfy current specifications and maintain durability requirements," said Jim Carreira, technical director at Boston Sand and Gravel. "Sublime's ASTM C1157 compliance is an important step in increasing the industry's confidence in shifting towards a drastically decarbonized material that performs like the material our industry currently relies on."

"Thoughtful owners, designers, and contractors have long recognized that performance-oriented specifications asking for what is needed, instead of telling the suppliers what to do, result in the better value solutions," said Don Davies, a structural engineering leader with projects in 18 countries and more than 50 major metropolitan centers. "With proper testing and data back-up, we have long seen ASTM C595 and the fully performance-oriented ASTM C1157 cements as the low carbon keys to our future. I am personally excited with how these next-generation materials, like the C1157 Sublime Cement™, will more rapidly slash emissions in concrete."

Sublime continues to add to its coalition of partners ready and willing to adopt low-carbon cements and decarbonize their supply chains. To learn about partnership opportunities for integrating Sublime Cement™ into your projects, connect with our team at partnerships@sublime-systems.com.

About Sublime Systems

Sublime Systems is on a mission to have a swift and massive impact on global CO_2 emissions with a breakthrough process that can manufacture cement without fossil fuels or limestone. Sublime replaces the industry's legacy kilns with an electrochemical process that makes cement at ambient temperature, extracting calcium and silicates from an abundance of raw materials to make cement. This novel approach bypasses both CO_2 process emissions and heating emissions, without the need for post-combustion carbon capture, producing ASTM C1157-compliant Sublime Cement™ as a drop-in replacement for ordinary portland cement in concrete. Sublime was founded at MIT by Leah Ellis, PhD, and Prof. Yet-Ming Chiang, both respected experts in materials science, electrochemical systems, and sustainability research. The company has raised more than $50M from a leading consortium of climate tech investors, ARPA-E funding, and strategic investor Siam Cement Group, the largest cement producer in Southeast Asia. It currently operates a pilot plant with a >100-tonnes-per-year production capacity. Learn more at sublime-systems.com.

Contacts

Media
Erin Glabets
Head of Communications
media@sublime-systems.com

Social Media Profiles

Sublime Systems on Twitter

Sublime Systems on LinkedIn

Sublime Systems

APPENDIX 2

businesswire
A BERKSHIRE HATHAWAY COMPANY

Sublime Systems

Sublime Systems Receives Life Cycle Assessment Validating its Electrified Cement Manufacturing Process Enables >90% Greenhouse Gas Emissions Reduction

A screening life cycle assessment conducted by Climate Earth, the leading provider of environmental product declarations for the concrete industry, validated Sublime's path to drastically reducing the carbon footprint of cement relative to today's ordinary portland cement

October 26, 2023 08:00 AM Eastern Daylight Time

SOMERVILLE, Mass.--(BUSINESS WIRE)--Sublime Systems, developers of the only fossil-fuel-free, scalable, drop-in replacement for traditional cement in concrete, announced a screening life cycle assessment (LCA) validating its process can eliminate more than 90% of the global warming potential (GWP) of cement manufacturing, when compared to today's ordinary portland cement (OPC). Climate Earth, the leading provider of environmental product declarations (EPDs) for the concrete industry, conducted this LCA according to a widely accepted industry method, avoiding controversial and unproven offset methodologies frequently used to enable the continued burning of fossil fuels — such as carbon capture, forestry credits, co-product mineralization, and lifetime CO_2 absorption.

The cradle-to-gate screening LCA leverages engineering estimates of Sublime Systems' full-scale commercial manufacturing process and was conducted in conformance with ISO 21930, which is used for the development of EPDs for construction products and services. It found Sublime's manufacturing process resulted in a GWP of 72 kg CO_2/tonne for a 100% Sublime Cement™ blend, compared to the 922 kg CO_2/tonne GWP found in the EPD for industry-wide average OPC in the United States. The remaining emissions were largely related to the mining and transportation of feedstocks and waste and wastewater treatment, processes that are primarily upstream and downstream of Sublime's core manufacturing innovations. Sublime's screening LCA also showed drastically reduced acidification and eutrophication potentials (among others) without increased water consumption, reflecting a lower environmental footprint and permitting timeline compared to today's OPC.

"As our company developed this breakthrough process, we were mindful that the construction industry wouldn't respond well to shining white knights with splashy in-house PowerPoints claiming they're saving the world," said Sublime Systems CEO and Co-Founder, Leah Ellis, PhD. "Seeing is believing, and we are grateful to be partnering with Climate Earth, the leader in these critical analyses for the concrete industry. Apples-to-apples comparisons using rigorous industry-accepted standards are foundational to driving real climate solutions and giving our stakeholders confidence in Sublime Cement™ as a powerful decarbonization tool in their arsenal."

Sublime Systems is advancing a fully electrified process for manufacturing cement without requiring the use of fossil fuels or limestone. This carbon-avoidance approach harnesses clean, renewable sources of electricity and a wide range of calcium-containing raw materials to produce the same final hardened phase in concrete that the global construction industry requires today. Sublime Cement™ does not rely on carbon capture and storage infrastructure to reduce CO_2 emissions, enabling cost parity to OPC when produced at scale — without dependence on carbon credits or carbon penalties.

"Sublime has shown incredible rigor in specifying their manufacturing process, enabling our team to confidently quantify the environmental impact of their electrochemical cement manufacturing process," said Climate Earth President and CEO, Chris Erickson. "We are excited to continue working with the company on future EPDs that will help accelerate industry adoption of Sublime Cement™ as a next-generation, low-carbon building material of the future."

Sublime Systems is currently engaging its construction industry partners for its first major construction projects this quarter and is actively planning its first commercial facility, which will produce tens of thousands of metric tons of low-carbon cement per year. Sublime Cement™ functions as a fully drop-in replacement for OPC in concrete today and complies with ASTM C1157, a widely adopted fully performance-based industry specification for hydraulic cement. To learn more about integrating Sublime Cement™ into your construction projects, contact partnerships@sublime-systems.com.

About Sublime Systems

Sublime Systems is on a mission to have a swift, massive, and enduring impact on global CO_2 emissions with a breakthrough process that can manufacture cement without fossil fuels or limestone. Sublime replaces the industry's legacy kilns with an electrochemical process that makes cement at ambient temperature, extracting calcium and silicates from an abundance of raw materials to make cement. This novel approach bypasses both CO_2 process emissions and heating emissions, without the need for post-combustion carbon capture, producing ASTM C1157-compliant Sublime Cement™ as a drop-in replacement for ordinary portland cement in concrete. Sublime was founded at MIT by Dr. Leah Ellis and Prof. Yet-Ming Chiang, both respected experts in materials science, electrochemical systems, and sustainability research. The company has raised more than $50M from a leading consortium of climate tech investors, ARPA-E funding, and strategic investor Siam Cement Group, the largest cement producer in Southeast Asia. It currently operates a pilot plant with a >100-tonnes-per-year production capacity. Learn more at sublime-systems.com.

About Climate Earth

Climate Earth is the first and only global provider of on-demand, digital EPDs and business intelligence tools for the concrete industry. Climate Earth's mission is to increase transparency and help concrete producers accelerate product innovation for low carbon concrete with on-demand EPDs and advanced digital tools that measure, analyze, and project environmental impacts. Founded in 2008 and based in Richmond, California, Climate Earth systems have automated EPD creation for over 900 ready mix, block and cement plants worldwide and have generated nearly 60,000 third party verified EPDs. For more information visit: www.climateearth.com.

Contacts

Media

Erin Glabets
Head of Communications, Sublime Systems
media@sublime-systems.com

Jules Conde
Marketing Manager, Climate Earth
Jules@Climateearth.com

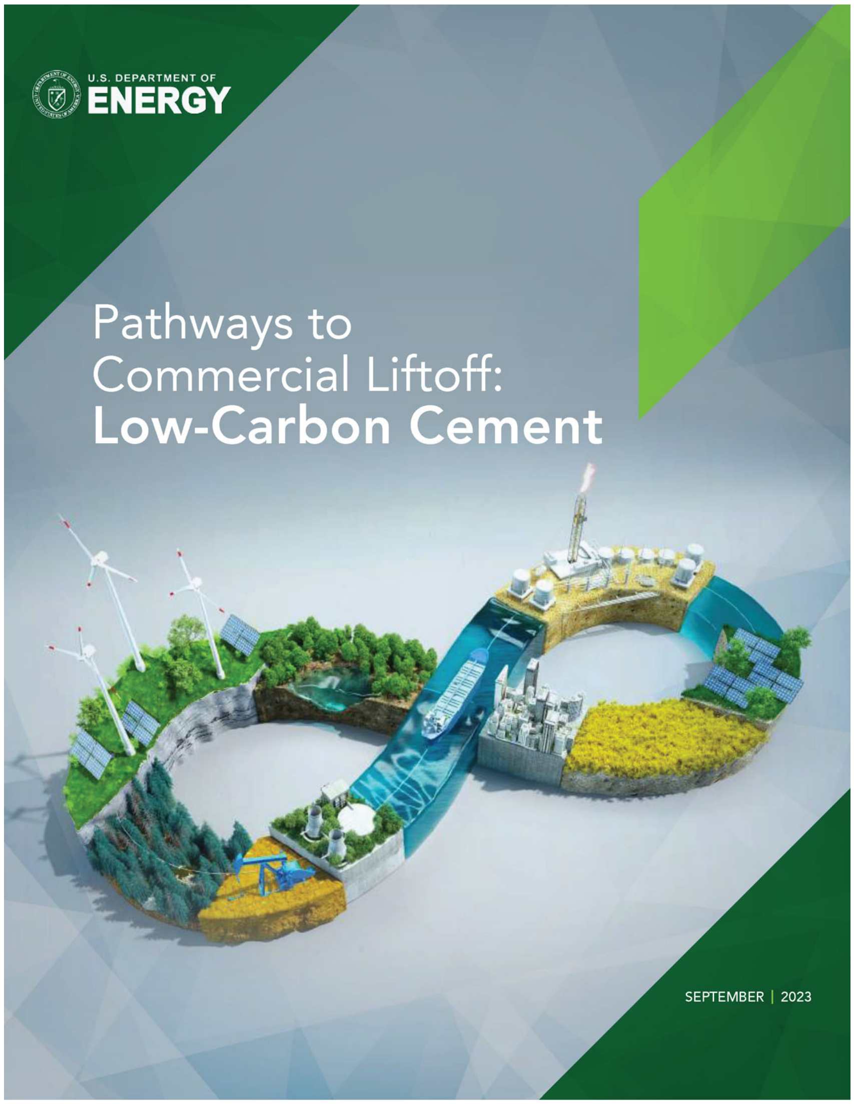
Social Media Profiles

Sublime Systems on Twitter

Sublime Systems on LinkedIn

Sublime Systems

APPENDIX 3


U.S. DEPARTMENT OF
ENERGY
Pathways to
Commercial Liftoff:
Low-Carbon Cement
SEPTEMBER | 2023

Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff. Please direct all inquiries and input to Liftoff@hq.doe.gov. Input and feedback should not include business-sensitive information, trade secrets, proprietary or otherwise confidential information. Please note that input and feedback provided are subject to the Freedom of Information Act.

Authors

Authors of the Pathway to Commerical Liftoff Industrial Decarbonization:

Loan Programs Office: Sam Goldman

Industrial Efficiency and Decarbonization Office: Paul Majsztrik, Isabelle Sgro Rojas (Energetics)

Office of Fossil Energy and Carbon Management: Mani Gavvalapalli, Raj Gaikwad, Tony Feric

Office of Manufacturing and Energy Supply Chains: Kelly Visconti

Office of Policy: Brandon McMurtry

Cross-cutting Department of Energy leadership for the Pathway to Commercial Liftoff effort:

Office of Technology Transitions: Vanessa Chan, Lucia Tian

Office of Clean Energy Demonstrations: Kelly Cummins, Melissa Klembara, Theresa Christian

Office of Policy: Neelesh Nerurkar

Loan Programs Office: Jigar Shah, Jonah Wagner

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Office of Clean Energy Demonstrations: Maressa Brennan, Kristen Hoesch, Katie Harkless, G. Jeremy Leong

Office of Technology Transitions: Katheryn Scott

Office of Energy Efficiency and Renewable Energy: Carolyn Snyder

Industrial Efficiency and Decarbonization Office: Avi Shultz, Joe Cresko

Advanced Materials and Manufacturing Technologies Office: Nick Lalena

Office of Fossil Energy and Carbon Management: Bradford Crabtree, Jennifer Wilcox, Rory Jacobson

Loan Programs Office: Richa Chaturvedi, Anna Blaustein

Office of Economic Impact and Diversity: Shalanda Baker, Sara Wylie

Bioenergy Technology Office: Valerie Reed, Jay Fitzgerald

Office of Manufacturing and Energy Supply Chains: Giulia Siccardo

Hydrogen and Fuel Cell Technologies Office: Sunita Satyapal, Neha Rustagi, Tomas Greene

Office of Policy: Maya Goodwin

Argonne National Laboratory: Aymeric Rousseau

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Purpose of this report

These Pathway to Commercial Liftoff Reports aim to establish a common fact base and ongoing dialogue with the private sector around the path to commercial Liftoff for critical clean energy technologies across core U.S. industries. Their goal is to catalyze more rapid and coordinated action across the industry and the full technology value chain.

This Pathway to Commercial Liftoff report specifically focuses on decarbonizing cement production. It is one report in a multi-part series focused on industrial decarbonization. The Industrial Decarbonization Liftoff series provides an overview of the pathways to decarbonization across the eight industrial sectors of focus in the Inflation Reduction Act (IRA[1]): chemicals, refining, iron and steel, food and beverage processing, pulp and paper, cement, aluminum, and glass.[i] DOE has conducted deep analysis and developed reports in the Liftoff series focusing on chemicals & refining and cement. All other industrial sectors have been covered in the Pathway to Commercial Liftoff: Industrial Decarbonization report.

1 Inflation Reduction Act of 2022, Pub. L. 117–169, 136 Stat. 1818 (2022)

Glossary

Term	Definition
ARL[2]	Adoption readiness level (1–9); Represents important factors for private sector uptake beyond technology readiness, including value proposition, market acceptance, resource maturity, and license to operate
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CCUS[3]	Carbon capture, utilization, and storage
Commercial Liftoff	"Liftoff" represents the point where solutions become largely self-sustaining markets that do not depend on significant levels of public capital and instead attract private capital with a wide range of risk
Demonstration stage	Technology in a stage of the RDD&D continuum where the objective is to determine the technical and commercial feasibility of new technologies
Deployable stage	Technology in a stage of the RDD&D continuum where the objective is to develop commercial deployments
DOT	Department of Transportation (state or federal)
EEJ	Energy and environmental justice
Embodied carbon	Emissions released during the life cycle of a material, including through extraction of raw materials, manufacturing, transportation, utilization, and end of life
EPD	Environmental product declaration (assessment and declaration of a product's environmental impact, particularly its embodied carbon content)
FECM	DOE Office of Fossil Energy and Carbon Management
FOAK	First of a kind
GCCA	Global Cement and Concrete Association
IEDO	DOE Industrial Efficiency and Decarbonization Office
IRA	Inflation Reduction Act of 2022 (Pub. L. 117-169)
KTPA	Thousand tonnes per year
LCA	Life cycle assessment (assessment of environmental impact, particularly emissions, from a product's full life cycle)
MTPA	Million tonnes per year
NOAK	Nth of a kind

2 Adoption Readiness Levels (ARL): A Complement to TRL | Department of Energy

3 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

Term	Definition
NPV	Net present value
OPC	Ordinary Portland Cement (traditional Portland cement formulation, typically composed of ~95% clinker and ~5% gypsum)
OPEX	Operating expenditure
PCA	Portland Cement Association
PLC	Portland Limestone Cement (blended cement in which up to 15% of clinker is substituted with ground limestone)
RDD&D	Research, development, demonstration, and deployment (RDD&D) continuum—defines the path to commercialization where a technology starts as an innovative idea in research, moves to development where the first prototype is created, proceeds to demonstration where the solution is tested in the real world and ending with commercial-scale deployment. Although RDD&D is a continuum, the pathways across stages are not always linear, and technologies may need to go back to earlier stages to be refined.
R&D / Pilot stage	Technology in a stage of the RDD&D continuum where the objective is to discover and determine the technical feasibility of new technologies in a lab or in small pilots
TRL[4]	Technology readiness level (1–9); Metric used for describing technology maturity. It is a measure used by many U.S. government agencies to assess the maturity of evolving technologies (e.g., materials, components, devices) before incorporating that technology into a system or subsystem
45Q	Tax incentive that encourages carbon capture, utilization, and storage (CCUS) projects
45V	IRA tax incentive that encourages the production of clean hydrogen

4 Technology Readiness Assessment Guide | Department of Energy

Executive Summary

The U.S. cement industry must accelerate decarbonization progress dramatically to keep pace with sector-wide net-zero goals. Cement represents ~7–8% of global CO2 emissions and ~1–2% of U.S. CO2 emissions (~70 MT CO2 /year). [ii, iii] Scaling green cement will be critical for the U.S. to achieve net zero overall and will position the U.S. to lead global efforts to decarbonize the sector, including through deployment of U.S.-developed technologies.

Many potential decarbonization approaches are emerging, but nearly all are in pilot stage today in the U.S. and face challenging paths to scale. Combined investment across these approaches would need to reach ~$5–20B cumulatively by 2030 and ~$60–120B cumulatively by 2050 to achieve Liftoff of key technologies and then full decarbonization of the cement industry: [5]

- **An initial set of clinker substitution approaches, alternative fuels, and efficiency measures could abate ~30% of emissions by the early 2030s and ~40% by 2050, while delivering $1B+ of annual savings to industry, if deployed aggressively.**[6] These approaches are broadly high TRL, deployment-ready, and economically viable today.[7] Scale-up could represent a capital formation opportunity of ~$3-8B.
- **Abating the remaining ~60-70% of emissions by 2050 will require approaches that have more difficult economics and still must be demonstrated at commercial scale—namely, carbon capture, utilization, and storage (CCUS) on existing infrastructure and alternative cement production methods.**[8] CCUS could require ~$35–75 in cost improvements or additional revenue per tonne of CO2 and ~$25–55 per tonne of cement to be economically viable with the 45Q tax credit,[9] though there is potential for alternative carbon-capture technologies at lower TRL today to achieve significant cost reductions. Alternative production methods could require $0.5–1.0B in capital expenditure (CAPEX) per plant and still need to validate technology performance and business models at commercial scale. Deployment of these technologies to decarbonize the full cement industrial base could represent a ~$55–110B total capital formation opportunity by 2050.
- **Other measures, including alternative binder chemistries to traditional cements, remain more nascent** and must achieve further technological maturity, improved economics, and customer acceptance to deploy.

Liftoff for all technologies will hinge on creating a strong demand signal from coordinated low-carbon procurement—a signal that may come from the government through public procurement. This demand signal will be vital to incentivize the rapid uptake of new technologies, drive aggressive deployment, and mobilize capital at the required scale. Half of U.S. cement demand is driven by federal and state procurement. [iv, v] With their commanding market share, government agencies and large private buyers are in the leading position to send this demand signal and transform the market.

Supported by low-carbon procurement, technologies could follow four parallel 'tracks' to Liftoff by 2050:

- **Rapid scale-up of clinker substitution, alternative fuels, and efficiency measures from 2023 through the early 2030s,** accelerated by low-carbon procurement standards and high-profile demonstrations of low-clinker cement and concrete blends.

5 Capital formation sizing methodology is available in the appendix.

6 Further scale-up of these technologies through 2050 could abate ~40% of emissions.

7 In general, this report assumes projects and technologies are economically viable if they can clear a 10% internal rate of return and/or are competitive economically with existing production methods and products.

8 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

9 Based on modeling for CCS specifically. CCU is also considered in the body of the report.

- **Full-scale deployment of CCUS retrofits starting in the 2030s**, following initial commercial-scale demonstrations in the mid-to-late 2020s. This deployment would be propelled by coordinated procurement from government and large private buyers, structured to enable investment at the multibillion-dollar scale required.
- **Commercial-scale deployment of alternative production methods for traditional cement products in the 2030s**, likewise following initial demonstrations and with multibillion-dollar capital formation enabled by coordinated procurement.
- **Longer-term scale-up of fundamental alternatives to traditional cement chemistries**, beginning in non-structural, pre-cast, and lower-risk niches and building market share on a longer timeline as standards are updated, market comfort grows, and supply becomes increasingly reliable.

Other emerging technologies are further out from commercialization, but offer promising opportunities for ongoing R&D investment.

Internationally, including in the developing world, pathways to cement decarbonization hinge on large-scale deployment of technologies like CCUS that today are prohibitively expensive outside of wealthy countries. **The U.S. is particularly well-positioned to commercialize and export two business models that could be transformative for global cement decarbonization:**

- **Low-cost CCUS** enabled by a combination of cost reductions from learning effects, commercialization of alternative low-cost capture technologies, and high-value carbon utilization applications.
- **Alternative low-carbon production methods and alternative chemistries** that can achieve cost-parity with or even cost-advantage over traditional cement plants.

Figure ES.1. Four-track pathway to Liftoff

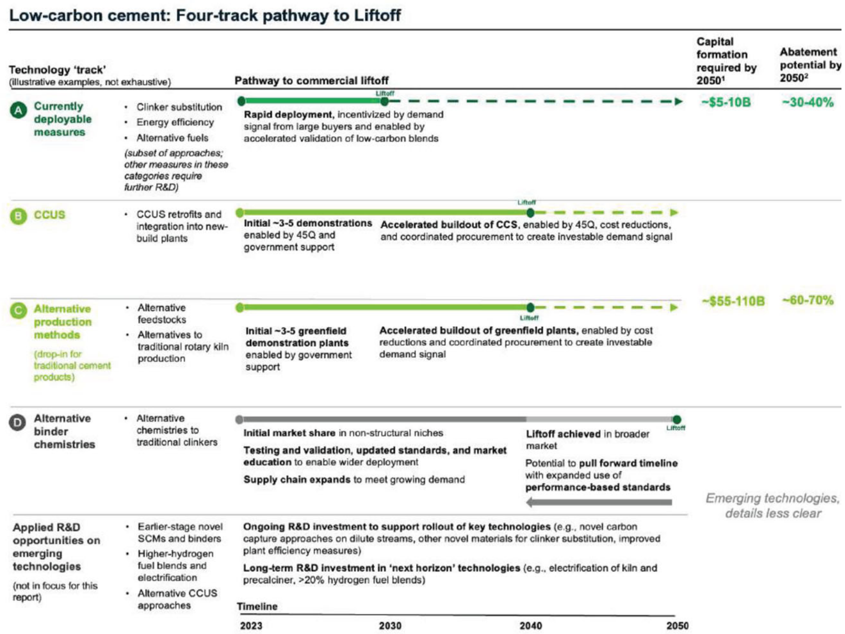

Figure ES.1: Liftoff pathway for the cement sector is split across technologies with varying technology readiness levels (TRLs) / adoption readiness levels (ARLs) and distinct economic, market, and policy constraints and enablers. Four parallel 'tracks' are outlined for different technology types. Other technologies are on a longer timeline and require continuing R&D investment to achieve demonstration and deployment readiness. Track A measures can abate ~30% of emissions by the early 2030s and ~40% of emissions by 2050, while the remaining ~60-70% of emissions will require other technologies in Tracks B, C, and D.

Notes: 1. Capital formation opportunity was estimated according to the methodology detailed in Appendix C and is based on the estimated CAPEX requirement to scale both currently deployable measures and CCUS or alternative production methods across the entire footprint of U.S. cement plants. 2. Abatement potential was estimated using the methodology detailed in Appendix A and assumes the first 30–40% of emissions can be abated by a deployment-ready subset of clinker substitution, alternative fuels, and efficiency measures, with the remaining 60–70% addressed by CCUS and alternative production methods.

Six key challenges must be overcome to scale technologies:

1. The market lacks uniform standards to define low-carbon materials and enable informed procurement.
2. The sector has a ~10 to 20-year adoption cycle for new blends and materials—both from long lead time needed to update standards and a long customer-adoption cycle.
3. The current procurement model is not structured to attract capital at required scale.
4. Decarbonization approaches may come with structural cost increases.

5. Key technologies have performance and cost uncertainty. Others are at lower TRLs and must make further R&D progress to deploy.
6. Projects may lack support from local communities and the public (particularly CCUS projects because of environmental and safety concerns).

Challenges are real but solvable. Six priority solutions could be pursued:

1. Establish shared standards and data ecosystem for low-carbon products.
2. Make targeted interventions to compress the adoption cycle for new blends and materials to ~5–10 years, including:
    - Investing in accelerated testing and validation,
    - Engaging key customers to facilitate the expanded use of low-carbon materials, including adopting performance-based standards, and
    - Providing technical and financial assistance to facilitate adoption in the broader value chain (e.g., small ready-mix companies, subcontractors).
3. Develop alternative procurement models that provide cement projects with firm, long-term offtake commitments to attract risk-averse capital.
4. Develop policy and market models that offset structural costs, including:
    - Providing policy support to offset challenging economics,
    - Supporting premiums with coordinated procurement in the public and private sectors, and
    - Requiring the use of low-carbon materials in construction regulations.
5. For pre-deployment technologies, provide continuing support to accelerate progress along the RDD&D continuum, including:
    - Supporting early project development and creation of archetypal business models and terms for technologies at a higher TRL today, and
    - Continuing to invest in transformative R&D for technologies at a lower TRL today.
6. Implement robust community benefits plans and agreements that are responsive to public concerns, mitigate potential harms, and ensure accountability.

DOE, together with other federal agencies and state and local governments, has tools to address many of these issues and is committed to working with communities and the private sector to accelerate the deployment of green cement technologies, establish the U.S. as a global leader in cement decarbonization, and meet the country's climate, economic, and environmental justice goals.

Government action will play a critical role in validating new approaches and creating strong demand signals. Bold action is also needed by the private sector, including producers, large-scale customers, and financial institutions, which fund them both, to scale these technologies and fundamentally transform the industry. Companies that move first will be best positioned to capitalize on the potential opportunity to capture demand from low-carbon procurement and position themselves to compete in a decarbonized market.

Chapter 1: Introduction

To decarbonize the sector by 2050, the U.S. must deploy novel technologies at all 98 existing U.S. cement plants and at all new-build plants. [vi] New technologies must also be exported internationally to address the ~7–8% of global CO2 emissions from cement. [vii] This report provides a "Pathway to Liftoff" for these key technologies. "Liftoff" represents the point where solutions become largely self-sustaining and can achieve commercial scale without depending on significant levels of public capital, instead attracting private capital with appetite for a wide range of risk.

- **Chapter 2** provides an overview of the current state and emissions profile of the U.S. cement industry, emerging technologies for decarbonization, and structural factors shaping deployment potential.
- **Chapter 3** outlines technology-specific business models, economic and other market dynamics, and the 'tracks' different technologies could follow to scale.
- **Chapter 4** addresses current challenges and potential solutions to unlock Liftoff.
- **Chapter 5** outlines key metrics and milestones along the Pathway.

This report is informed by 60+ interviews and conversations with experts and stakeholders from 40+ companies and organizations. Interviewees cover the entirety of the market ecosystem, including large cement and building-materials companies, start-ups, trade associations covering all major segments of the value chain, investors, and federal and state agencies that are large consumers of cement and concrete. All insights have been aggregated and anonymized so as not to be reflective of any single company or other stakeholder. Additional insight is provided by DOE experts, published studies, and decarbonization roadmaps by DOE, other government agencies, and various industry and third-party academic and research organizations.

This report focuses chiefly on decarbonizing primary cement production (i.e., the measures taken inside the fence line of cement plants), but it will be vital to decarbonize the concrete and construction value chain more broadly and look at emissions over the full life cycle of cement and concrete products.

This effort is technology- and business-model agnostic. It is not meant to comprehensively evaluate all potential technologies and business models that could be deployed. A vast array of different technologies may ultimately develop to meet the needs of a net-zero sector. Indeed, 40+ start-ups were identified in this sector alone, in addition to the various approaches under consideration by already-established cement players.

This report draws on and complements DOE's existing Industrial Decarbonization Roadmap by extending its deep dive into cement and further exploring the market and economic dynamics implicated in a rapid scale-up. Likewise, this report complements many ongoing efforts across federal and state governments to accelerate these technologies' development, commercialization, and deployment.

Chapter 2: Current state and decarbonization challenge

Key takeaways

- **Cement production accounts for ~7–8% of global CO_2 emissions and ~70M tonnes (~1%) of U.S. CO_2 emissions per year**. Decarbonizing the sector will be critical for achieving net zero. By developing, deploying, and commercializing the key technologies domestically and exporting them internationally, the U.S. can take a leading role in global decarbonization.
- **The technical challenge is substantial: ~85% of cement emissions come from the calcination process or high-temperature heat sources.** Getting to net zero will require novel decarbonization measures, many of which do not exist yet at scale. A wide variety of approaches are emerging across different stages of technological and adoption readiness.
- **Government procurement drives ~50% of U.S. demand, giving the public sector an outsized role in accelerating decarbonization.** Yet the cement value chain structure complicates decarbonization efforts: cement is bought through multiple layers of intermediaries, challenging efforts to create a clear demand signal. Other features of the cement market further constrain decarbonization approaches.
- **Industry momentum has been slower to build in the U.S. than in other parts of the world, particularly Europe. However, activity is beginning to accelerate, especially in response to the Inflation Reduction Act (IRA).** Established cement companies have set decarbonization targets and are exploring options, a robust start-up ecosystem has emerged with 40+ companies developing novel cement products, and commercial-scale demonstrations of key technologies are planned for the mid- to late-2020s, facilitated by government support.

Section 2.a: Sector overview – Introduction to cement

Cement is the key ingredient in concrete, the most consumed human-made material on Earth, and is a vital upstream input for housing, built infrastructure, and a wide range of critical construction projects. [viii]

The market today faces challenges meeting intertwined climate and economic development goals. Producing the 4B+ tonnes of cement needed to meet global demand for concrete each year is associated with ~7–8% of annual CO_2 emissions. [ix, x, 10] Global consumption will grow further as developing countries continue to industrialize and urbanize, and cement will be a critical input for infrastructure projects needed as part of the global energy transition.[xi] Cement emissions cannot grow linearly if the sector is to remain on track for decarbonization. In the U.S., the cement sector accounts for ~70M tonnes of annual emissions, ~1–2% of total CO_2 emissions, and ~8% of emissions in the industrial sectors of focus under the Inflation Reduction Act.[xii]

Decarbonizing domestic production will be critical for achieving net zero in the U.S. and creates an opportunity for the U.S. to lead globally on innovation, commercialization, and export of the next generation of low-carbon cement technologies.

Section 2.a.i: Cement production process

Cement is a binder mixed with water and aggregates like sand and gravel to produce concrete. Portland cement, the most widely used type, was developed in the early 1800s and is a mixture of calcium silicates and other compounds derived from limestone and silica sources that hardens when it reacts with water. [xiii]

10 According to the U.S. Geological Survey, in 2022, China was the largest consumer of cement by far, accounting for 51% of the market. India was the second largest, with 8% of the market.

The key ingredient in Portland cement is clinker, a binder material made by sintering limestone and aluminosilicate materials like clay at high heat. Clinker production accounts for the vast majority of emissions in the overall process.

Cement production follows a basic three-step model (Figure 2.1): [xiv]

- **Extraction and preparation of raw materials**. Limestone and other raw materials like clay are quarried, crushed, milled, mixed, and ground to a sufficiently small size.
- **Production of clinker**. The limestone and raw materials mixture is typically preheated in a multi-stage precalciner and fed into a massive cylindrical rotary kiln heated to ~1,400–1,450ºC. Reactions in the kiln produce clinker.
- **Production of cement.** Clinker is cooled, ground to a fine powder, and mixed with gypsum, limestone, and potentially other additives in specific amounts (defined by standards) to form the final cement mix for sale.

85% percent of emissions come from clinker production and are intrinsic to the chemical process or related to the high heat at which it takes place (Figure 2.1): [11, xv]

- 51% of total emissions come from the calcination process used to make clinker, in which CO2 is produced as a byproduct of quicklime (CaO) extraction from limestone (calcium carbonate, $CaCO_3$) in the kiln.
- Another 34% of total emissions come from the fuels used to generate high heat at the kiln—plants typically use coal and coke today and increasingly burn natural gas and some wastes (e.g., tires). [xvi]

Figure 2.1. Cement production process

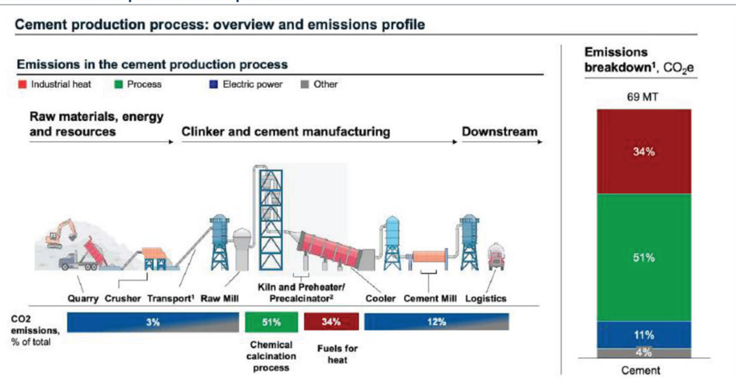

Figure 2.1. Overview of the cement production process with corresponding emissions by source. 85% of emissions come from clinker production in the preheater/precalciner and kiln, of which 51% are intrinsic to the chemical calcination process and 34% come from the combustion of fuels for heat.
Notes: 1. U.S. EPA. (2021). Facility Level GHG Emissions Data from Large Facilities [Data set]. https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal. Visual from Czigler, Thomas, et al. (2020, May). "Laying the foundation for zero-carbon cement." McKinsey and Company. Laying the foundation for a zero-carbon cement industry | McKinsey.

11 These figures are drawn from EPA 2021 facility-level emissions data. Similar figures are given by 2015 U.S. Geological Survey energy-use data, which report 58% of emissions from the process and 42% from energy (of which 8% comes from electricity consumption and 34% from fuels). Hendrik G. van Oss (2020, Jan.). 2016 Minerals Yearbook: Cement. U.S. Geological Survey. https://d9-wret.s3-us-west2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf.

Section 2.a.ii: U.S. market context

The U.S. is the fourth largest market for cement in the world. The U.S. consumed ~120M tonnes and produced ~95M tonnes of cement in 2022, with total sales worth an estimated $14.6B and an average price of $130 per tonne. [xvii] Domestic production is forecast to grow by ~31% to 124M tonnes in 2050 (~1% CAGR from 2023–50). [xviii]

The U.S. also imports ~24M tonnes of cement annually. 38% percent of cement imports come from nearby suppliers in Canada and Mexico, but 62% comes from countries like Turkey and Greece, typically where suppliers with access to water transport can take advantage of the low freight cost to ship cement by boat and barge. [xix]

Section 2.a.iii: U.S. cement production footprint

Today, the U.S. has 98 total cement plants that must be decarbonized to achieve net zero in the sector—96 in 34 states and two in Puerto Rico. [xx] Just four states (Texas, Missouri, California, and Florida) account for ~43% of shipped cement. [xxi] Plants are sited close to population centers and the markets they serve to minimize transport costs.

U.S. cement plants, excluding capacity in Puerto Rico, collectively operate 120 kilns with a mean age of 36 years, but the facilities are not homogenous. About two-thirds of capacity is provided by larger, more modern kilns (with ~0.75–1.5 MTPA of clinker output), while the remaining third is from smaller, older kilns (Figure 2.2). [xxii] This pattern reflects a decades-long trend of consolidating production in fewer, larger facilities. [xxiii] The last major wave of investment occurred from 2000–09 when 31 kilns representing ~41 MTPA of capacity were built or substantially overhauled (Figure 2.3), but the industry continues to invest in modernizing and expanding existing plants, as well as building new ones. [xxiv, xxv]

Figure 2.2: Current kiln footprint

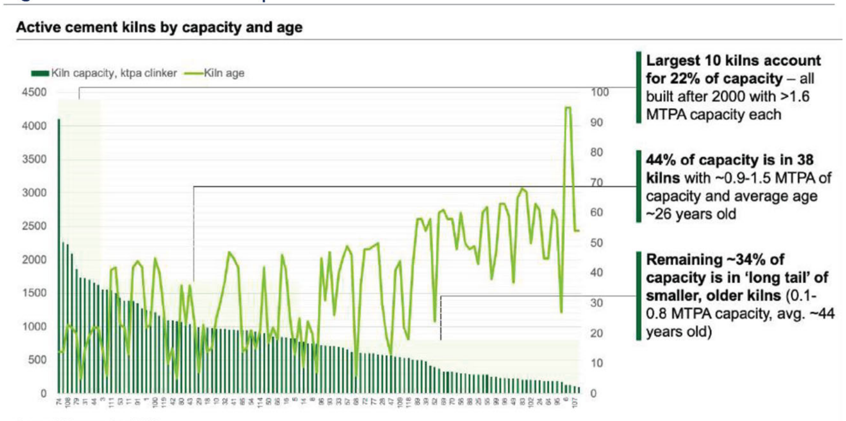

Figure 2.2. Current kiln footprint. X-axis shows each active cement kiln by capacity (in terms of clinker production) and age. 22% of capacity is concentrated in the largest 10 kilns, all built after 2000. Another 44% of capacity is in slightly older midsized kilns. The remaining 34% of capacity is in a 'long tail' of smaller, older kilns. Source: Portland Cement Association (2019, Dec. 31). U.S. Portland Cement Industry: Plant Information Summary.

Figure 2.3: Historical investment cycle for cement plants

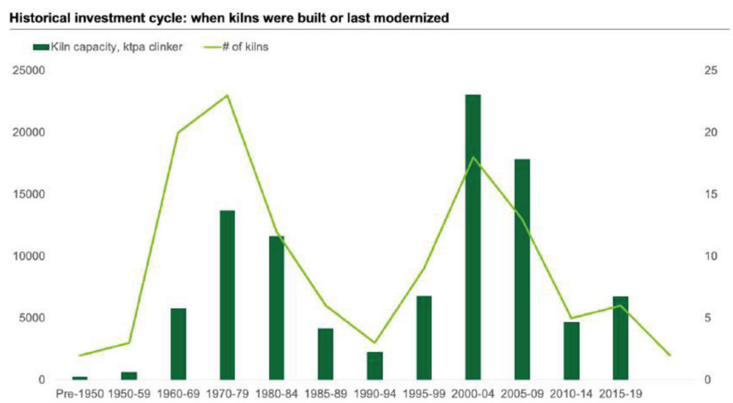

Figure 2.3. Historical investment cycle for cement plants. Number of kilns and capacity by period of construction or most recent modernization. The most recent surge in investment came in 2000–09 when 31 kilns representing ~41 MTPA of clinker-production capacity were built or modernized. Source: Portland Cement Association (2019, Dec. 31). U.S. Portland Cement Industry: Plant Information Summary.

Section 2.b: Technology landscape

Because emissions intrinsic to the production process or associated with high industrial heat drive ~85% of emissions, decarbonizing cement production will require innovative and sector-specific approaches, potentially including fundamental changes to the production process. A wide range of potential approaches are emerging, but they are at different stages of technological and adoption readiness (Figure 2.4).

Figure 2.4: Overview of representative approaches to cement decarbonization

NON-EXHAUSTIVE // REPRESENTATIVE MIX OF TECHNOLOGIES // FIGURES INTENDED TO BE BROADLY REPRESENTATIVE, NOT REFLECTIVE OF ANY INDIVIDUAL COMPANY OR PROPRIETARY TECHNOLOGY

High cost — Value accretive; Low — High

Emissions source	Potential approaches		Cost, $/t CO2	Cost, $/t cement	Unconstrained abatement potential,[5] (% to BAU)	ARL[6]	TRL[6]
Cross-cutting	Energy efficiency[1]		(35-40)	(0-5)	Up to 20%	5-9	9
	Clinker substitution	Portland limestone cement[2]	(75-80)	(5-10)	5-10%	7	7-9
		Fly ash blended cement[2]	(25-30)	(5-10)	30-50%	7	9
		Steel slag blended cement[2]	(15-20)	(5-10)	30-50%	7	9
		Natural pozzolans blended cement[2]	(70-75)	(15-20)	30-50%	2	7
		LC3 (Limestone Calcined Clay) blend[2]	(60-70)	(15-25)	30-50%	5	9
Heat	Alternative fuels	Biomass fuel[3]	30-35	0-5	1-8%	4	9
		Waste fuel[3]	(0-10)	(0-5)	1-4%	5	9
	Precalciner & kiln electrification		Emerging technologies		Up to 35%	1	5-6
Process	CCUS (with 45Q)[4]		35-75	25-55	85-99%	1	6-7.5
	Alternative production methods		Emerging technologies		25-100%	1	3-5
	Alternative binder chemistries		Emerging technologies		25-100%	1	3.5-9

Note: Approaches above are focused on primary production of cement. Additional approaches are available in downstream production of concrete (e.g., reduced cement consumption in concrete mixes, carbon curing of precast concrete products).

Figure 2.4. Overview of representative approaches to cement decarbonization. Not exhaustive—intended to illustrate the emerging mix of technologies and approaches. Not reflective of any individual company or proprietary technology. Approaches have different cost implications and are at different TRLs and ARLs. Energy efficiency, clinker substitution, and alternative fuel (waste and biomass) approaches are broadly at a high ARL and TRL today, with neutral to favorable economics and the potential to abate ~30–40% of emissions cumulatively (though all three areas also have opportunities for further R&D investment, including more novel substitute materials, expanded use of alternative fuels, and more dramatic efficiency measures). Getting to 100% abatement will require technologies at lower ARL and TRL and with more challenging economics like CCUS, alternative production methods, and alternative chemistries.

Notes: 1. A range of efficiency measures are available, but they are at different ARL and TRL today. Costs are estimated for measures that are deployable today, with more limited abatement potential. | 2. Clinker substitution economics estimated using blended cement composition ratios provided in Appendix A. | 3. Fuel abatement potential and economics estimated using fuel mixes and feedstock cost benchmarks provided in Appendix A. | 4. CCUS costs estimated using methodology discussed in Appendix B. Costs reported here are for CCS specifically and include $85/tonne 45Q tax credit. | 5. Unconstrained abatement potential is for a given tonne of cement produced, not estimated for the entire cement sector. It is estimated for each approach in isolation (i.e., not tied to a specific decarbonization pathway or sequence of approaches). | 6. ARL and TRL figures are representative estimates based on DOE and expert input. They do not reflect an assessment of any specific individual company or proprietary technology and should not be interpreted as such. For electrification, high end of range reflects potential for precalciner electrification, which is less technically challenging than kiln electrification because of the lower temperatures required.

The decarbonization approaches discussed in this report tie to the DOE's Industrial Decarbonization Roadmap pillars and prior Liftoff reports. Energy efficiency, industrial electrification, and carbon management have separate pillars in the Roadmap, although the Roadmap includes clinker substitution under energy efficiency. Alternative fuels, hydrogen, and several alternative production methods are counted in the Low Carbon Fuels, Feedstocks, and Energy Sources pillar.

Approaches can be broken out at a high level by emissions source.

Section 2.b.i: Cross-cutting measures

A set of cross-cutting measures can reduce overall emissions by reducing consumption of emissions-intensive clinker in cement mixes ("clinker substitution") and improving the efficiency of the production process.

Clinker substitution reduces the emissions associated with a given volume of cement by replacing part of the clinker in the cement mix with materials with lower embodied carbon. Clinker substitution measures are broadly at high TRLs and high ARLs today, with favorable economics: [12]

12 Detailed assumptions of cost analysis are provided in Appendix A.

- Traditional substitutes (e.g., ground limestone, fly ash, steel slag) are already commercially used, albeit at a limited but growing scale.
- Emerging substitutes (e.g., calcined clays, natural pozzolans) have demonstrated technical viability but are still deployed at a limited scale.
- More novel substitutes (e.g., engineered SCMs) are promising longer-term technologies but are in different states of readiness and will require continued R&D investment.

Different proportions of the clinker in a cement mix can be substituted with various materials to produce different lower-carbon blends. Cement blends currently in widespread use, like Portland Limestone Cements (PLCs), substitute up to 10–15% of clinker with materials such as ground limestone, driving 5–10% emissions reductions. [xxvi] More ambitious approaches, like ternary blends and calcined clay cements (e.g., Limestone Calcined Clay Cement, "LC3"), allow for substitution of ~30–50% of clinker in a cement mix by weight, driving emissions reductions of ~30–50%. Blends with steeper clinker substitution are technically proven and have strong economics but remain in limited use today.[xxvii, xxviii, xxix] Potential for scale-up of clinker substitution is discussed in greater detail in Section 3.a.

This report focuses on the primary production of cement, but the industry can further cut emissions by reducing material consumption downstream in the value chain. By reducing cement content in concrete and concrete use in construction, the broader construction sector can further reduce overall clinker consumption, compounding the decarbonization effects of clinker substitution in cement. [xxx]

Efficiency measures at the cement plant offer additional opportunities to reduce emissions by reducing energy consumption throughout production. A range of high-TRL and economically favorable efficiency measures are available. [xxxi] Modeling for this report considers 24 potential measures that could be adopted by a representative plant with neutral to positive economics, including process control, more efficient internal transport systems, high-efficiency coolers and grinders, and high-efficiency motors and fans (the full list is provided in the appendix). [xxxii] Other efficiency measures are at lower TRL and ARL and are farther from deployment readiness.

Section 2.b.ii: Heat measures

For heat-related emissions, alternative fuels like wastes and biomass are technologically and commercially mature today, while clean hydrogen, electrification, and other industrial heating alternatives remain further from deployment readiness: [13, xxxiii, xxxiv, xxxv]

- **Waste fuels and biomass** are technologically mature (some wastes like tires are already used as fuel for kilns today) and can generally be deployed without significant cost impact (potentially around -$1 to $1 of impact per tonne of cement in the absence of policy or other market incentives), but abatement potential is limited and deployment comes with supply and environmental constraints (discussed in Section 3.a).
- **Precalciner and kiln electrification** remain technologically nascent and have uncertain but likely challenging economics because of their high energy requirement and associated costs, particularly for high-heat applications like cement kilns.[xxxvi] Precalciner electrification could be closer to viability because of the lower heat required.
- **Clean hydrogen** is more challenging economically and is not currently on track to see significant uptake in the near term given available alternatives. Clean hydrogen can likely be used as up to ~5-20% of the fuel mix without a significant overhaul of plant infrastructure, but securing clean hydrogen at sufficiently low cost to compete with existing fuels is likely to be challenging. Even with subsidized production from the 45V tax credit, clean hydrogen may be prohibitively expensive for most cement

13 Detailed assumptions of cost analysis are provided in Appendix A.

plants, especially if significant investment in transportation and storage infrastructure is required. The available supply of clean hydrogen may also go first to sectors with higher willingness to pay, such as heavy-duty transportation.[xxxvii] Using hydrogen at higher rates in the fuel mix (e.g., up to 100%, consistent with complete decarbonization of kiln heat) will likely require more fundamental reconfiguration of existing plants or greenfield plant construction, with substantial associated CAPEX and opportunity cost from downtime. [14, 15, xxxviii]

- **Alternative industrial heating techniques** like thermal energy storage could also have applications for cement (discussed in detail in the Pathway to Commercial Liftoff: Industrial Decarbonization report), but these techniques similarly remain at early stages of technological and economic maturity. [xxxix, xl] See the Industrial Decarbonization report for a more detailed economics discussion.

Section 2.b.iii: Process measures

There are limited options to address emissions from calcination, and they are typically at lower levels of technological maturity and adoption readiness: [16]

- **Alternative production methods** for traditional cement products (e.g., alternative noncarbonate feedstocks, electrochemical production methods, and other alternatives to traditional rotary kiln plants) remain at the pre-commercial pilot or pre-pilot stage, and deployment economics and market accessibility remain unclear. [xli] Their potential pathway to commercial-scale deployment is considered in Section 3.c.
- **Alternative binder chemistries** shift away from traditional Portland-type cement clinker entirely. Alternative chemistries include belite, sulphoaluminate, and "MOMS" (magnesium oxide derived from magnesium silicates) clinkers and other engineered materials. Some materials are commercially available today at a small scale, but many remain far from technological maturity and are generally far from broad market adoption. [xlii] Their potential pathway to commercial-scale deployment is considered in Section 3D.
- **Carbon capture, utilization, and sequestration (CCUS)** may be employed to address emissions that cannot otherwise be cost-effectively abated from process (and potentially heat).[17] There are multiple potential approaches to carbon capture for cement plants. Post-combustion amine-solvent capture technology is at higher TRL today. However, the low CO2 concentration in post-combustion streams results in high CAPEX and OPEX that, when combined with the cost of CO2 transportation and storage infrastructure, drive extremely high costs (potentially ~$35–75 per tonne of CO2 including the 45Q tax credit, ~$120–160 per tonne without it). [18] Emerging technologies (e.g., capture with oxyfuel combustion, calcium looping, methods for capturing just the purer stream of process emissions) could have significant technical and economic advantages in the longer term but are at much lower TRLs today. [xliii, xliv, xlv, xlvi, xlvii]

14 The U.S. National Clean Hydrogen Strategy and Roadmap sees cement production as a "Third Wave" application for hydrogen that will become economically competitive "as clean hydrogen production scales significantly and as costs decline and infrastructure becomes available." U.S. Department of Energy (2023). U.S. National Clean Hydrogen Strategy and Roadmap. https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

15 Use of clean hydrogen may come with public and energy and environmental justice concerns that projects will have to address. Because hydrogen is currently positioned to play a more limited role in decarbonization of cement, justice implications of hydrogen projects are not considered extensively in this report, but detailed discussion can be found in the Pathway to Commercial Liftoff: Industrial Decarbonization and Pathway to Commercial Liftoff: Chemicals & refining reports.

16 Detailed assumptions of cost analysis are provided in Appendix A.

17 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

18 Cost estimates are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using CANSOLV amine-based post-combustion system. Capital costs are adjusted to reflect a 12-year payback period, consistent with what investors have said they would be willing to underwrite, using capital recovery factors from the Energy Futures Initiative. Transportation and storage costs of ~$10–40 per tonne of CO2 are assumed, consistent with the representative figures in the Carbon Management Liftoff report. The specific methodology is provided in Appendix B. Hughes, Sydney, and Patricia Cvetic. (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Microsoft Word - 17-4-1-2_Cement Plant Retrofit Capture_DFR_Rev7.docx (doe.gov). Brown, Jeffrey D., et al. (2023, Feb.). Turning CCS projects in heavy industry and power into blue chip financial investments. Energy Futures Initiative. EFI - CCS Report (energyfuturesinitiative.org).

Section 2.b.iv: Future technology landscape

To capitalize on opportunities for short and medium-term emissions reductions, it will be critical to improve the adoption readiness of the large number of technologies at high TRL but low ARL, especially the next generation of clinker-substitution and fuel-switching measures. But these measures will not be enough. Roughly 30-40% of emissions are addressable through currently deployable technologies, but full decarbonization of the sector will hinge on rapidly getting nascent technologies to technological maturity and bringing them into the market at scale.

Section 2.c: Market context: Structure, economics, and implications for deployment

The market context shapes the potential for deployment and eventual Liftoff of low-carbon cement technologies. The cement market has unique structural and economic attributes that create opportunities for and constraints on deployment.

Figure 2.5: Value chain map – cement, concrete, and construction

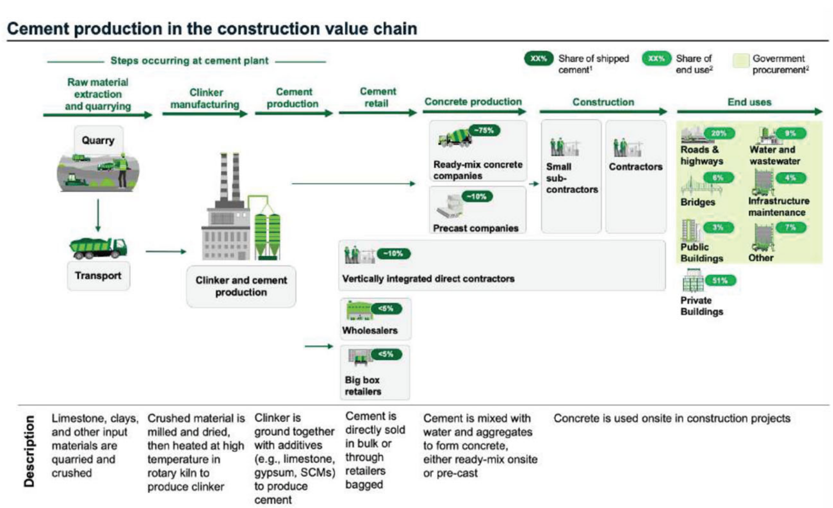

Figure 2.5. Overview of the cement-concrete-construction value chain. Cement production is upstream in the broader value chain. Government procurement accounts for roughly half of the end market for cement, but there are multiple layers of intermediaries (e.g., ready-mix companies, subcontractors, and construction contractors) between primary production and end uses. | 1. The share of shipped cement is estimated based on data from the Portland Cement Association's Survey of Portland Cement Consumption by User Group (2022). | 2. End-use share is estimated based on an analysis of data from the Portland Cement Association's U.S. Cement Industry Annual Yearbook (2022) by Breakthrough Energy Ventures.

Section 2.c.i: Cement market structure

Cement production is upstream in the broader construction value chain and represents a relatively small value pool within the construction industry. Total U.S. spending on cement was estimated at ~$14.6B in 2022, representing <1% of the ~$1.8T in total U.S. spending on construction, with cement being a typically small contributor to overall project costs (although this can vary based on project type). [xlviii, xlix]

The value chain is consolidated at either end but fragmented in the intermediate tiers. A few suppliers account for most production, and large buyers like government agencies for more than half of the demand, but between them are multiple layers of intermediaries:

- ***Supply side*. Production is increasingly consolidated in a small number of large companies, typically multinationals.** Twenty-four companies own all 96 active U.S. cement plants (excluding capacity in Puerto Rico), and the top 10 companies account for over 80% of installed production capacity. [l]
- ***Demand side.* Government procurement drives ~50% or more of U.S. cement consumption, giving the public sector an outsized role in shaping the market.** [19, li] Approximately 30% of total consumption—and two-thirds of government consumption—comes from roads, highways, bridges, and other infrastructure maintenance, with federal and state departments of transportation (DOTs) leading in setting requirements and allocating funding. [lii] The remaining third of government procurement is largely driven by water and wastewater infrastructure, utilities, and public buildings. The rest of the market is largely accounted for by private procurement for building construction (i.e., residential, commercial, and agricultural). [liii]
- ***Intermediaries.* There are multiple tiers of intermediaries in the value chain between primary production and end consumption, often with significant fragmentation**. Approximately 96% of all cement shipped goes through intermediaries (e.g., ready-mix concrete companies, concrete product manufacturers, contractors, and materials dealers) and there are typically multiple layers of ready-mix suppliers, subcontractors, and contractors between a cement plant and the end customer paying for a building or highway construction project. [liv] These intermediate tiers are often fragmented. For example, there are thousands of individual ready-mix concrete companies, which are often small businesses.

Section 2.c.ii: Product segmentation

Consumption of cement fits overwhelmingly into one of two concrete product segments, each with distinct attributes and requirements:

- **Ready-mix accounts for the largest share of the market but is a difficult segment for new materials to enter.** Approximately 70–75% of cement is used to make ready-mix concrete, which can be prepared onsite and used in various applications, including road paving and building construction. [lv] The ready-mix market has high barriers to entry, including more stringent product standards for structural applications like building construction. Additionally, because ready-mix concrete is prepared onsite in various environments and conditions, it is a challenging segment to break into for new cement products that may require tighter control of the concrete production process. However, because ready-mix accounts for such a large share of the market, deep decarbonization of the sector will require low-carbon technologies compatible with ready-mix applications.
- **Pre-cast is a smaller share of the overall market but can offer an initial foothold for new players.** Approximately 10–15% of cement is used in pre-cast applications where concrete is mixed,

19 ~49% before the Bipartisan Infrastructure Law and Inflation Reduction Act, which are assumed to increase the share of cement consumption driven by government procurement.

cast in a mold, and "cured" in a controlled environment before installation at a construction site. [lvi] Pre-cast products offer concrete suppliers more control over the production process and can be more amenable to new products, often providing an initial market niche.

The remaining ~10–20% of cement consumption is accounted for by bagged cement and specialty products.

Section 2.c.iii: Baseline economics

The baseline economics of cement production define the shape of the market. Four key factors are particularly important: [lvii]

- **High CAPEX and limited financing options for projects.** A new U.S. cement plant at 1+ MTPA scale can require $0.5–1.0B in CAPEX. [20] Major investments are typically financed on the balance sheet, either from existing assets and cash flow or by using traditional corporate finance: cement companies can have a high cost of capital due to their smaller size and the perceived risk of a merchant business model. [21] There is limited use of project finance for cement in the U.S. today; in conversations with numerous investors and large cement companies, no recent instance could be identified in which a project finance model was used. Moreover, large investment firms often have limited experience with cement projects and may not have analysts focused on cement companies, given their limited market capitalization. [lviii]
- **Long asset lives.** Facilities are expected to have asset lives of ~30–50+ years, with high CAPEX amortized over this extended period. [lix] In the current industrial base, 48 operational kilns were built before 1980; the oldest was built in 1928. [lx] Early retirement of plants represents a significant cost to cement companies.
- **High opportunity cost of downtime.** Similarly, plants are expected to operate with minimal downtime. They are taken offline for short periods on a roughly annual basis to be relined, but major overhauls are typically done on a decadal or multi-decadal timeline to minimize opportunity cost. Based on public data, one year of downtime at a representative 1-1.5 MTPA capacity cement plant could represent ~$100–200M of opportunity cost. [22] Interventions (e.g., retrofits with new technologies) that come with significant plant downtime will thus incur substantial additional costs.
- **OPEX driven by fuel and freight costs.** Production is optimized to minimize fuel costs, and any intervention that increases the cost of fuel is likely to have an outsized impact on overall production cost and margin. Both input materials and the finished product are also heavy and expensive to transport by land, and interventions that require longer-distance shipping of materials can quickly and significantly impact cost and margin.

Section 2.c.iv: Market attributes and implications for deployment

Four market attributes, shaped by the underlying economic dynamics of the sector, define the deployment model and viable business models for new technologies:

- **Regional fragmentation.** Because of high freight costs, the cement market is regionally fragmented. Cement is heavy. Freight cost typically makes it prohibitively expensive to ship cement far, and U.S. plants have limited access to lower-cost rail or waterborne transportation—71% of cement is shipped

20 Based on conversations with industry subject matter experts and large cement companies. Also see, e.g., Heidelberg's recent $600M investment in a new plant in Mitchell, IN. Heidelberg Materials (n.d.). "Mitchell K4." https://www.heidelbergmaterials.us/sites/mitchell.

21 This may be less relevant for large, integrated materials companies, typically international conglomerates, that have amassed a growing share of the U.S. cement market through recent acquisitions.

22 Assuming 1-1.5 MTPA of cement output at the $130/tonne average price estimated in 2022 by U.S. Geological Survey.

from the plant gate by truck, 19% by rail, and 10% by barge and boat. [lxi, 23] Plants are built close to customers and serve a local market, with their ability to realize economies of scale capped by the size of that serviceable demand pool. Decarbonization solutions must accordingly be tailorable to the unique conditions at each plant site.

- **Lack of long-term offtake agreements.** Cement procurement is typically a "handshake business" without long-term offtake. The ready-mix companies and contractors that are typically the immediate customers for cement producers buy on an as-needed basis for their construction jobs. Customers are reluctant to commit to longer-term offtake because of uncertainty about long-term demand amidst boom-and-bust construction market cycles. This model leaves cement plants with significant merchant risk and complicates efforts to create a credible long-term demand signal for the scale-up of new technologies.
- **Rigid industry standards and specifications tightly govern the deployment of cement and concrete**. An end user like a developer or construction company will set requirements for performance (e.g., consistency, strength, air content) and exposure conditions (e.g., proximity to water, exposure to chemicals), dictating the composition of the concrete mix and the type of cement that must be used. Industry associations like the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO, focused specifically on roads and highways) provide voluntary standards almost universally adhered to regarding defined cement types and compositions. These standards can either be prescriptive, detailing the specific composition of a cement blend, or performance-based, which require materials to meet certain performance benchmarks while offering more flexibility concerning precise composition. Large, high-profile customers like state DOTs play a major role in setting norms for an entire market and may do their own testing of materials. Specifications set by state DOTs are often taken as the authoritative model for other customers. To enter the market at scale, cement products must be compatible with standards and usually accepted by trusted authorities.
- **Risk-averse customers.** Customers are risk-averse and generally have a long adoption cycle for new approaches and products. Customers like ready-mix companies, contractors, and engineers are highly sensitive to the potential risks of adopting new technologies, which can range from cost/schedule overruns to life-safety risks. Particularly for structural use cases (e.g., construction of high-rise buildings, bridges, and other critical infrastructure), preventing performance issues is of paramount importance for cement and concrete users along the entire value chain (discussed in additional detail in Chapter 4).

Section 2.d: U.S. industry momentum

Over the last two decades, the U.S. has reduced the emissions intensity of cement, but further reductions are required to hit climate and decarbonization targets. Since 1995, the U.S. cement industry has reduced its emissions intensity per tonne of cement by ~10%, mostly by finding efficiencies in production and phasing in natural gas instead of coal and coke. [lxii] As of 2020, 92% of U.S. plants, accounting for 98% of production, were using the less energy-intensive dry kiln production method. [lxiii] About 73% of U.S. cement plants currently use some share of alternative fuels: the share of energy consumption accounted for by alternative fuels increased from 2% in 1996 to 16% in 2019. Since 1996, the share of thermal energy from coal and coke has fallen from 74% to 59%, while the share of natural gas has increased from 7% to 25%. [lxiv] More recently, the industry has phased in using Portland Limestone Cement (PLC), a blended cement that substitutes ground limestone for up to 15% of the mix to reduce clinker factor, typically yielding ~8% reduction in emissions intensity (see the following case study). However, the U.S. cement industry still has significant progress to make to reach net-zero targets.

23 ~97% of cement is shipped the 'last mile' to customers by truck. The phenomenon comes from cement that is shipped first by rail or water from the plant to a central terminal, then transported by truck to customers.

Today, the U.S. lags behind Europe and other parts of the world in adopting low-carbon approaches. The EU uses alternative fuels for ~50% of primary energy consumption in cement, compared to just ~15% in the U.S.[lxv] This higher share is enabled in large part by the comparatively high cost to landfill waste in the EU, which creates a strong economic case for the use of waste-based fuels.[lxvi]

The first commercial-scale demonstrations of deep decarbonization technologies are also largely happening outside of the U.S. [lxvii] Heidelberg Materials has broken ground on the first commercial-scale cement-carbon-capture facility at their Brevik plant in Norway and plans to begin operations by 2024. [lxviii] As of 2022, GCCA has identified more than 30 other projects worldwide, most concentrated in Europe. [lxix] Construction of the first commercial-scale cement CCUS deployment in North America is underway at Heidelberg's plant in Edmonton, Alberta, Canada. [lxx] Government support has been critical for project viability so far. For example, the Edmonton project has moved forward with significant support from the Canadian government, including direct financial support and carbon pricing. [lxxi, lxxii]

Though initial momentum has built overseas, interest in U.S. deployments is growing quickly post-IRA, and the U.S. could recapture global leadership with bold action.

Established cement companies are exploring the feasibility of deploying new technologies, including CCUS, at existing plants and more aggressive clinker substitution approaches like calcined clay cements. Clean Air Task Force counts five U.S.-based CCUS projects in the cement sector, all in early stages. [lxxiii] These projects include (1) a partnership between Holcim, Svante, Occidental, and Total Energies to explore the feasibility of carbon capture and sequestration at Holcim's Florence, CO plant, (2) DOE-funded feasibility and FEED studies for deployments at Holcim's Ste. Genevieve plant in Bloomsdale, MO, (3) CEMEX's Balcones, LA, plant (4) Heidelberg's new Mitchell, IN plant, and (5) a partnership between Heidelberg and the start-up Fortera to produce a supplementary cementitious material using captured CO2 from Heidelberg's Shasta, CA, cement plant. [lxxiv, lxxv, lxxvi, lxxvii, lxxviii]

Beyond incumbents, a robust startup ecosystem of 40+ new companies has developed to bring new production methods and novel products to market along the entire value chain.[lxxix]

Case study: Portland Limestone Cement (PLC) rollout – A model for adoption of low-carbon cement blends

The large-scale adoption of Portland Limestone Cements (PLCs) has been one of the most significant early steps toward cement decarbonization in the U.S. PLC blends replace up to 15% (typically ~10–11%) of clinker content with ground, uncalcined limestone and can achieve an ~8% average reduction in emissions compared to traditional Portland cement. [lxxx] PLCs were approved under the widely used ASTM C595 standard in 2012 and today account for roughly one-third of cement shipped in the U.S.

Figure 2.6: U.S. rollout of Portland Limestone Cements

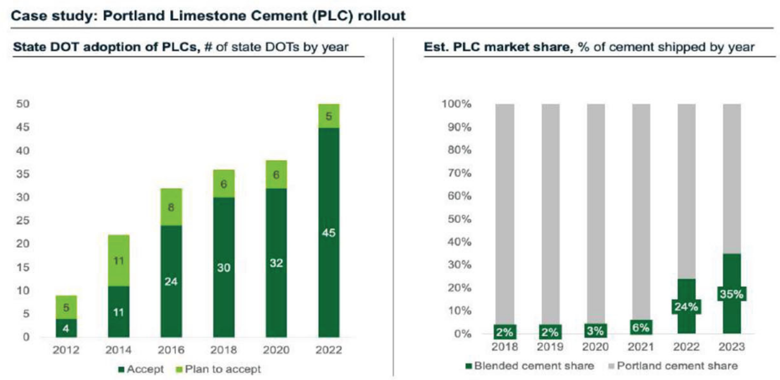

Figure 2.6. Key leading and lagging indicators from the PLC rollout: adoption by state DOTs and estimated market share. It took ten years for all 50 state DOTs to accept or have a plan to accept PLCs, and broader market uptake lagged state DOT uptake by several years. Source: State DOT adoption figures by year from Portland Cement Association. The established PLC market share is based on the share of blended cements reported in U.S. Geological Survey Mineral Industry Surveys. 2023 share estimated based on data through May 2023. The blended cements category includes other kinds of blended cement besides PLCs, but USGS estimates that 96% of total blended tonneage was driven by PLCs in 2023.

The PLC rollout provides valuable lessons for how other decarbonization approaches, particularly more aggressive clinker substitution in blended cements, could get to scale this decade:

- **Without intervention, the industry can have a 10+ year adoption cycle even for blends with well-established track records and a strong economic case—a timeline incompatible with rapid deployment**. Clinker substitution with ground limestone had a long track record and a strong value proposition. Cements with limestone content have been used in Europe and other countries since the 1960s, and blending limestone into Portland cement has been allowed under Canadian standards since 1983. In the U.S., up to 5% limestone has been used in Portland cements under ASTM C150 and AASHTO M85 since 2004 and 2007, respectively. [lxxxi] Because uncalcined limestone can be as much as ~$60 (~90%) cheaper per tonne than clinker, PLC blends also have a strong economic case, potentially enabling ~$5–10 of additional value capture per tonne of cement compared to OPC. [lxxxii] Yet it still took more than a decade after approval under industry standards for PLC to achieve substantial market share in the U.S.

- **As trusted first movers, state DOTs play a critical role in unlocking adoption by the wider market, but it can take ~5–10 years to reach a critical mass for adopting new materials.** Although ~5–10 first-mover states adopted PLCs within 1–2 years of initial acceptance under ASTM C595 in 2012, it took ~5 years for half and ~10 years for all 50 state DOTs to accept PLCs in their specifications. [lxxxiii]

- **Once tipping points are hit, however, market share can grow rapidly, potentially doubling year-over-year.** Even after most state DOTs had adopted PLCs, market share remained relatively stable at ~2–3% until 2021, when it began to grow rapidly, reaching ~35% of the market by 2023 (CAGR of 127% from 2020–23). [24]

The PLC rollout shows that rapid adoption of new lower-carbon cement blends is possible, but key barriers must be overcome to scale more aggressive clinker substitution methods (discussed in detail in Chapter 4).

24 Based on blended cement share of total shipped volume reported by the U.S. Geological Survey. USGS defines blended cements as products brought to market under ASTM C595, which will include PLC in addition to Portland-pozzolan and Portland blast-furnace slag cements.

Chapter 3: Pathway to commercial Liftoff

Key takeaways

- **Technologies could follow four distinct 'tracks' to commercial Liftoff** (outlined in Section 3.a.i below). In the short term, currently deployable measures could abate ~30% of emissions while delivering $1B+ in savings for industry by the early 2030s. In the longer term, achieving net zero by 2050 will require scaling technologies at lower TRL/ARL and with more challenging economics (CCUS, alternative production methods, and alternative binder chemistries).
- **Demand for low-carbon products will be the engine for Liftoff for all technologies.** Government procurement (state and federal) can play a decisive role in creating a strong demand signal for low-carbon cement.
- **The U.S. is positioned to lead internationally on decarbonizing cement production.** The U.S. can pioneer key technologies domestically, particularly low-cost CCUS and alternative production methods, then export them abroad to accelerate decarbonization of the ~7-8% of global CO_2 emissions driven by cement.
- **Scale-up will have to account thoughtfully for broader community impacts**. Scaling low-carbon cement technologies comes with powerful opportunities to benefit the economies, environmental quality, and health of fence-line communities, but some risks and concerns will also need to be addressed.

Figure 3.1: Pathway to Commercial Liftoff

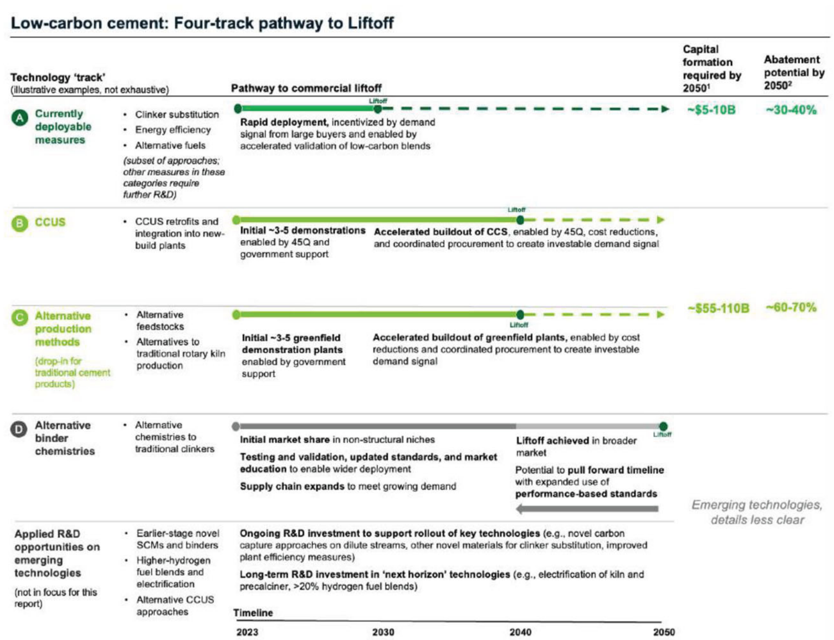

Figure 3.1: Liftoff pathway for the cement sector is split across technologies with varying TRLs/ARLs and distinct economic, market, and policy constraints and enablers. Four parallel 'tracks' are outlined for different technology types. Other technologies are on a longer timeline and require continuing R&D investment to achieve demonstration stage and deployment readiness.
Notes: 1. Capital formation opportunity was estimated according to methodology detailed in Appendix C (based on estimated CAPEX requirement to scale both currently deployable measures and CCUS or alternative production methods across the entire footprint of U.S. cement plants). 2. Abatement potential was estimated using methodology detailed in Appendix A (assuming the first 30–40% of emissions can be abated by a deployment-ready subset of clinker substitution, alternative fuels, and efficiency measures, with the remaining 60–70% addressed by CCUS and alternative production methods).

Section 3.a: Four-track pathway to Liftoff

Section 3.a.i: Four technology tracks

The pathways to commercial Liftoff for different low-carbon cement technologies will be shaped by their technology readiness, fundamental economics, and adoption cycles within the industry. This section identifies four parallel 'tracks' different technologies could follow to widespread commercial deployment and scale, all of which hinge on establishing a clear demand signal from end customers to cement producers:

A. **Currently deployable measures—clinker substitution, efficiency measures, and alternative fuels**—are compatible with existing standards, technologically ready, have a strong economic value proposition, and could achieve widespread adoption by the early 2030s. Aggressive deployment could drive ~30% emissions reduction by the early 2030s and ~40% by 2050.[25]

B. **CCUS** retrofits of existing plants and integration into new-build plants can scale from the 2030s, following initial demonstrations in the mid/late 2020s and supported by coordinated procurement, policy support, and cost reductions as deployments ramp.

C. **Alternative production methods** for traditional cement products can scale in the 2030s through greenfield plant deployments if they are demonstrated successfully and meet key performance and cost milestones in the late 2020s, with policy and demand support.

D. **Breakthrough alternative binder chemistries** can gain early footholds in niche, lower-risk applications, while passing through a longer-term adoption cycle to achieve full scale-up in the 2040s, with some potential to pull forward the timeline through broader adoption of performance-based standards.

Other emerging technologies are farther from commercialization and offer high-impact opportunities for applied R&D. These include transformative approaches like high-hydrogen fuel blends and kiln electrification, earlier-stage novel SCMs and binders and alternative approaches to carbon capture and utilization.

Section 3.a.ii: Demand as the engine for Liftoff

Establishing a strong demand signal out of coordinated procurement will be the first step for getting technologies to commercial Liftoff across all tracks. Credible demand for low-carbon cement products will incentivize companies to pursue decarbonization at the aggressive pace required to meet net-zero goals, unlock the business case for more expensive interventions, and allow capital-intensive projects to attract the investment they need. Coordinated procurement will need three components to shape the market effectively:

- **Procurement requirements for low-carbon products.** Large-scale buyers—particularly government agencies and the largest private-sector customers—are beginning to commit to procuring low-carbon materials at scale, and they can adopt requirements for their own purchases of these low-carbon materials (i.e., concretes using low-carbon cements) that are sufficiently aggressive to require suppliers to invest in new approaches.[lxxxiv, lxxxv] DOE's Industrial Decarbonization Roadmap projects that the U.S. cement industry could need to achieve a ~10% reduction in emissions by 2030, ~35% by 2035, and ~60% by 2040 to remain on track for net zero, and standards for low-carbon procurement could be correspondingly aggressive.[lxxxvi] Such requirements would also need to account for material performance to meet engineering requirements and to capture a material's full life cycle emissions impact.

  The federal government has already begun to set some requirements to these effects. EPA's Interim Determination for federal cement and concrete procurement requires materials purchased under IRA Sections 60503 and 60506 by GSA and DOT to be in the top 20% of the market based on emissions reduction, with adjustable requirements if materials are not available.[lxxxvii] GSA's low-carbon procurement pilot program sets specific emissions thresholds for cements and concretes.[lxxxviii]

- **Clear, credible quantification of embodied carbon.** Market actors in the public and private sectors can develop a shared set of credible metrics and standards for embodied carbon in cement and downstream products, supported by robust measurement and verification systems, data-sharing, and documentation (i.e., through standardized and widely available EPDs) to ensure purchased cement and concrete products meet low-carbon procurement standards (related challenges and potential solutions are considered in detail in Chapter 4).[lxxxix] EPA is currently leading an effort and providing grant funding to support improved market data for measurement, calculation, and verification of embodied carbon in materials, and future efforts can build on this foundation.[xc]

25 Based on modeling detailed in Appendix A.

- **Demand signal that reaches cement plants.** Large-scale buyers must develop ways to pass the demand signal for low-carbon cement through multiple layers of intermediaries in the value chain to cement plants. This could require more active management of construction supply chains and potentially using innovative contracting structures that allow for direct agreements between end customers and cement plants (related challenges and potential solutions are considered in detail in Chapter 4).

With their commanding share of the market and clear means of coordination, federal and state governments can play a particularly powerful role in implementing such a model.

To succeed in driving deep decarbonization, a coordinated procurement model must evolve to incentivize and economically enable ever-steeper reductions in embodied carbon. Initial investments to develop embodied carbon standards, the necessary data ecosystem and assessment methodologies, and deep supply-chain visibility will provide foundational capabilities for a long-term procurement regime. Longer term, large-scale buyers must raise standards for decarbonization and add new capabilities to support the deployment of technologies with more complex demand-side requirements.

The rest of this section considers how demand for low-carbon materials can pull technologies along each of the four tracks to Liftoff.

Section 3.a.iii: Commercial Liftoff by track

Track A: Currently deployable measures: Clinker substitution, efficiency measures, and alternative fuels

Key takeaways

- **Clinker substitution, efficiency measures, and alternative fuels are deployable today and could allow the industry to save ~$1B+ per year while abating ~30% of sector emissions by the early 2030s and ~40% by 2050.** Clinker substitution is the most powerful short-term lever, potentially abating ~25% of emissions and driving ~$5–20 of savings per tonne of cement.

- **Credible demand from large end customers, particularly requirements for low-carbon materials in project specifications, is needed to accelerate Liftoff** by incentivizing intermediaries in the value chain to use low-carbon cements and providing cement companies with the assurance that customers will buy low-carbon blends.

Clinker substitutes, efficiency measures, and alternative fuels are technologically proven, compliant with existing standards, and have strong economics today. Deployed aggressively, they could collectively abate ~30% of cement sector emissions and allow cement producers to capture an additional $1B+ of value per year by the early 2030s. With expanded deployment, they could abate ~40% of emissions by 2050. Each is considered in more detail below.

Clinker substitution

Clinker substitution has a strong positive economic case and will be the industry's most powerful abatement lever through the early 2030s. Deploying blended cements that are compliant with existing standards could yield an additional ~$1B of value per year industry-wide while abating ~20–25% of sector emissions by 2030.[26, 27]

Figure 3.2: Clinker substitutes – key attributes and economics

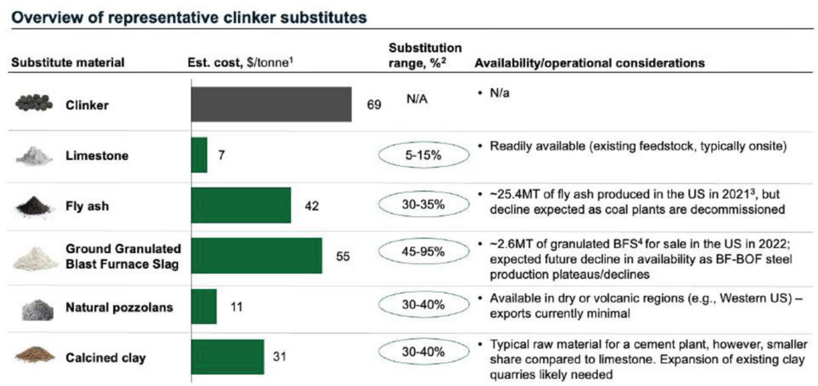

Figure 3.2: Overview of representative clinker substitutes with key attributes and economics. Clinker is energy-intensive and expensive to manufacture. Substitutes can be significantly cheaper per tonne, and substitution can thus drive significant reductions in cost. Materials can be substituted for ~5–15% of the mix by weight for limestone to up to 95% for slag. ~30–40% is more typical/feasible for most SCMs. Additional availability and operational considerations apply: fly ash and slag have limited supply; natural pozzolans are widely available in some regions; clays are already widely available at cement plants but may require expansion of existing quarries. Notes: 1. Cost for each substitute material is estimated on a per tonne basis using assumptions detailed in Appendix A. Clinker cost per tonne was estimated outside-in using representative fuel, energy, and material costs. | 2. High end of substitution range is given by ASTM C595. Increasing substitution past a certain level can change the viable end applications for a cement mix, such that the high end is not attainable in all use cases. Low end of substitution range reflects more common and feasible substitution levels based on expert input. | 3. Adams, Thomas H (2022). "Coal Ash Recycling Rate Increases Slightly in 2021; Use of Harvested Ash Grows Significantly." American Coal Ash Association. https://acaa-usa.org/wp-content/uploads/2022/12/News-Release-Coal-Ash-Production-and-Use-2021.pdf. | 4. U.S. Geological Survey (2021). Mineral Yearbook: Iron and Steel Slag. https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-slag-statistics-and-information.

Most substitute materials are cheaper than clinker, making substitution favorable economically. Clinker can cost ~$60–70 per tonne with typical fuel and power costs, while ground limestone costs $5–10 per tonne, although it is capped at 15% of a mix by current standards. Traditional SCMs like fly ash and steel slag cost $40–60 per tonne, and emerging SCMs like natural pozzolans and calcined clays could cost $10–35

26 Detailed calculations and underlying analysis are provided in Appendix A. The aggressive deployment scenario assumes cement producers can reduce clinker factor industry-wide to ~65% by the early 2030s by scaling a mix of substitutes and deploying low-clinker cements like calcined clay cements and other ternary blends. It should be noted that this level of substitution is significantly higher than targets set in both PCA's decarbonization roadmap (85% clinker factor by 2030) and DOE's Industrial Decarbonization Roadmap (84% by 2030, 66% by 2050). 35% substitution by the early 2030s is an ambitious target intended to reflect a high-end estimate of what industry could potentially achieve, driven by the powerful economic incentive from substantial cost savings and enabled by concerted effort (detailed in this chapter and Chapter 4).
The representative modeling exercise assumes the following shares by mass of materials in total U.S. cement production: 65% clinker, 15% limestone, 9% calcined clay, 5% gypsum, 3% fly ash, 2% natural pozzolans, <1% GGBFS, <1% other (does not sum to 100% because of rounding). Exact composition could vary. The modeling exercise makes some arbitrary assumptions informed by conversations with the industry and practical limitations on deployment (discussed in Appendix A).

27 ~25% emissions reduction for this level of deployment is roughly consistent with an RMI analysis suggesting that full-scale deployment of SCMs in the U.S. could abate ~38% of cement emissions. Esau, Rebecca, and Audrey Rempher (2022). "Low-Carbon Concrete in the Northeastern United States." RMI. Low-Carbon Concrete in the Northeastern United States - RMI.

per tonne (Figure 3.2). Representative low-carbon blended cements could deliver ~$5–20 of savings per tonne compared to high-clinker cements currently in use (Figure 3.3). At a representative 1.5 MTPA cement plant, this would equal $10–30M in annual savings or NPV of $75–230M with a 20–year investment lifetime.

Figure 3.3: Low-carbon cement blends

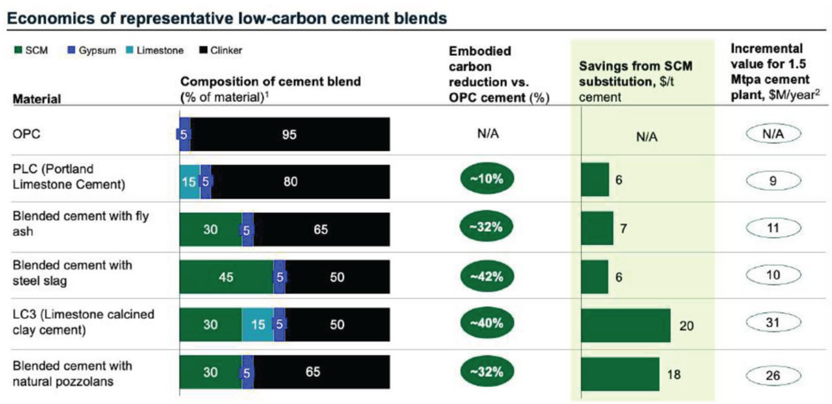

Figure 3.3: Representative low-carbon cement blends—composition, representative economics, and emissions reduction compared to ordinary Portland cement (OPC). Blends can achieve embodied carbon reductions of ~10% for PLCs to as much as ~40% for calcined clay and steel slag-based blends. Blends can also achieve savings of ~$5–20 per tonne, equivalent to ~$10–30M per year of additional value captured at a representative 1.5 MTPA cement plant. Detailed modeling assumptions are in Appendix A.
Notes: 1. ASTM C595 range; exact ratio chosen based on most likely given industry implementation/feasibility in the U.S. from conversations with industry experts. | 2. Based on a cement plant with 1.5MT of capacity per year.

While deployment costs will vary by site, the economics of clinker substitution are expected to be favorable under various circumstances. Plants must have a nearby source of substitute materials and may incur additional costs to make that source usable (e.g., investment to expand existing or develop new mines or quarries, investment in building out logistics infrastructure, and additional operating costs from transporting heavy materials). Public estimates suggest cement plants could produce calcined clay blends like LC3 with ~$15M of CAPEX investment, but conversations with industry suggest that some projects could require closer to $50–200M, with the discrepancy driven by the potential need to build new silos for material storage (at a cost of ~$50M each). [xci] Yet even if significantly higher CAPEX (e.g., $50–200M for new silos, storage facilities, and quarry redevelopment) and OPEX (e.g., from long-distance transportation of materials) are assumed, modeling suggests a wide range of projects could still be economically viable. [28]

The availability of raw materials constrains clinker substitution, but workarounds are available. Approximately 25 MT of fly ash and ~3 MT of steel slag suitable for cement production are available per

28 E.g., LC3 projects still deliver ~$5–20 of savings per tonne of cement even if $50–200M of CAPEX and substantial transport costs are assumed (assumes $50–200M of CAPEX (based on higher-end estimates provided in conversations with industry, driven by need to build additional silo capacity and infrastructure). Assumes $8-10 per tonne of cement of incremental OPEX, based on $29-31/tonne of clay cost to transport 200 km, estimated by Scrivener, et al. (2019), assuming LC3 mix is 30% calcined clay by weight. With $50-200M of CAPEX instead of ~$15M for LC3, excluding incremental transportation cost, plants save ~$14-19 per tonne. With cost to transport materials 200 km, savings fall to ~$4-11. Calculations made using assumptions given in K. Scrivener, et al. (2019). Financial Attractiveness of LC3. https://lc3.ch/wp-content/uploads/2020/10/2019-LC3FinancialAttractiveness-WEB.pdf.)

year as of 2021–22, theoretically just enough to replace ~30% of cement volume by weight. [29] However, fly ash supply is expected to decline precipitously as the power sector transitions away from coal, meaning the future supply of these conventional SCMs will not be available in sufficient quantities. Indeed, these inputs are already among the more expensive SCMs. Supply shortfalls could drive further price increases and create cost and schedule risk for projects if cement cannot be supplied in time, deterring use.

Scale-up can rely on a combination of approaches: [30]

- **Alternative sourcing of traditional substitutes**. Shortages of fly ash can be addressed by expanding ponded coal ash use, which is allowed under current ASTM standards. Extraction of ponded ash could be part of brownfield remediation programs for legacy coal infrastructure, though efforts must navigate environmental and health risks and the associated potential for liability. [xcii, xciii]
- **Expanded use of emerging substitutes**. Calcined clays and natural pozzolans are widely available in many regions and can accordingly replace substitutes that are likely to be in shorter supply in the future while potentially offering even more favorable economics. [xciv]

Efficiency measures

Efficiency measures could also scale by the early 2030s—they offer the potential to reduce emissions by up to 5% at minimal cost to the industry. A representative mix of 24 efficiency levers, including process control, more efficient internal transport systems, and high-efficiency motors and fans, could abate ~2–5% of emissions by 2030 without increasing the cost of production and potentially driving modest savings per tonne of cement. [31]

Steeper efficiency improvements will be more challenging. Because of the long lifetimes of existing plants, more radical reconfigurations of plants to improve efficiency are unlikely to be economical in many cases. [xcv] Interventions can involve technical tradeoffs (e.g., increasing the number of preheating stages can improve heat recovery but also increase electricity consumption) or encounter economic barriers (e.g., technologies like waste-heat recovery are commercially available but have not been adopted at scale because of their cost). [xcvi]

Alternative fuels

Alternative fuels also have near-breakeven economics and could abate ~5–10% of emissions by 2030 with aggressive deployment, but community impacts must be considered. [32] Waste-based fuels like tires, waste oils, and plastics are already widely used, and ~25% of waste tires in the U.S. may already be used in cement production. [xcvii] These fuels can offer modest economic advantages when burned in the kiln because of their high heat content relative to other fuels. With marginal economics at baseline, high tipping fees for waste disposal can create a strong economic incentive for using waste fuels in cement kilns and have been a key driver of the more rapid uptake of alternative fuels in Europe. Jurisdictions with high waste disposal costs will also offer favorable conditions for more rapid deployment in the U.S. [xcviii, xcix]

Biomass fuels also have marginal cost implications per tonne of cement and can thus enable emissions

29 ~25 MT of fly ash was produced in 2021, and ~3 MT of granulated blast-furnace slag was available for sale in 2021. Collectively, 28 MT of conventional SCMs could represent ~30% of the mass of cement produced annually in the U.S., assuming 100% utilization in cement. Competition from other sectors, which could drive up the price of fly ash beyond what can be economically used in cement mixes, means the upper bound for utilization is likely to be considerably lower. Fly ash availability estimated from Adams, Thomas H (2022). "Coal Ash Recycling Rate Increases Slightly in 2021; Use of Harvested Ash Grows Significantly." American Coal Ash Association. https://acaa-usa.org/wp-content/uploads/2022/12/News-Release-Coal-Ash-Production-and-Use-2021.pdf. GGBFS production from U.S. Geological Survey (2021). Mineral Yearbook: Iron and Steel Slag. https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-slag-statistics-and-information.

30 Scale-up of clinker substitutes could require expansion of quarries and mining facilities, with associated energy and environmental justice concerns. Potential EEJ implications are considered at a high level in Section 3.c, but this analysis was not scoped to assess these implications in detail.

31 These findings are consistent with other studies that suggest efficiency measures could abate ~5% of emissions by 2030 or 2040. See, e.g., Hasanbeigi, Ali, and Cecilia Springer (2019). Deep Decarbonization Roadmap for the Cement and Concrete Industries in California. Global Efficiency Intelligence. https://www.climateworks.org/wp-content/uploads/2019/09/Decarbonization-Roadmap-CA-Cement-Final.pdf.

32 Representative scenario finds potential for ~7% reduction in emissions by 2030, assuming alternative fuels share can expand to provide 35% of heat energy by 2030 on a trajectory to match the EU's 50% share by 2050. Detailed assumptions are provided in Appendix A.

reductions at minimal cost, though the availability of cheap biomass is limited and could be a constraint on deployment. [33] A recent study estimated that substituting biomass for 20% of coal content in kiln fuel mixes nationwide could reduce emissions by 4.3 MT CO_2 per year (~6% of annual emissions), but noted that the total U.S. supply of fruit stones and nut shells, the optimal biomass feedstocks given their high heat content, could offset just 2.7 MT CO_2 per year. [c]

Alternative fuels also come with air quality implications that need to be addressed. Combustion of tires, waste oils, and plastics has the potential to release additional air pollutants, potentially adversely affecting surrounding communities (discussed in Section 3.b). [ci, cii] This report does not estimate the cost of additional potential pollution-control equipment for fuel conversions, but these costs could be substantial. It should also be noted that a cement kiln that burns alternative fuels may be subject to different air emissions regulations, depending on the specific alternative fuels burned. As a result, the cost implications of thoughtful environmental stewardship may sometimes limit the uptake of alternative fuels.

Collectively, scaling clinker substitution, efficiency measures, and alternative fuels in line with an aggressive decarbonization pathway could require $25–60M of investment per plant—~$3–6B of total investment by the early 2030s. [34]

Liftoff for clinker substitution, efficiency measures, and alternative fuels

With clear demand from coordinated procurement, these currently deployable measures could rapidly achieve Liftoff. Large-scale buyers, particularly trusted government first movers like state DOTs, can lead with the initial adoption of lower-carbon blended cements, particularly ternary blends and blends using newer materials like calcined clays. Large buyers can incentivize uptake by ready-mix concrete suppliers and contractors by requiring low-carbon cement in project specifications and working with their lower-tier suppliers to facilitate adoption. An initial demand signal can be followed by rapid uptake in the rest of the market as customers follow the lead of first movers and cement plants convert production to lower-carbon blends, phasing out clinker-intensive products. (Key challenges and reasons why the market has not yet seen aggressive adoption are considered in Chapter 4.) If more aggressive blended cements follow the same trajectory as PLC, market share could double year-over-year once the critical tipping points are hit.

33 Analysis is based on economics for woody biomass (est. $41/ton). Detailed assumptions are in Appendix A. Other forms of biomass with higher heat content (e.g., stone fruits, nut shells) may be better suited to the fuel mix in cement kilns. Discussed in Pisciotta, Maxwell, et al. (2022, July). "Current state of industrial heating and opportunities for decarbonization." Progress in Energy and Combustion Science 91.

34 Assumes ~$10M of CAPEX required for a kiln bypass for alternative fuels and $15–50M of CAPEX for clinker substitution (based on estimated costs for mine or quarry expansion and additional storage and grinding equipment, both outside-in estimates and estimates provided in conversations with industry). There is significant potential for variability in CAPEX on a site-specific basis, depending on the local availability of materials and existing infrastructure. In outlier cases, $100–200M+ could be required. Sizing also assumes that cost per plant does not change with plant size, based on the assumption that similar equipment is required regardless of plant size. Detailed CAPEX assumptions are provided in Appendix A.

Track B: CCUS

Key takeaways

- **CCUS is a promising lever for cement decarbonization given the U.S. policy environment.** Industry believes CCUS will be critical for decarbonizing the ~60% of cement emissions intrinsic to the calcination process.
- **The economics are challenging today.** CCUS could come with ~$35–75 of incremental cost per tonne of CO2 and ~$25–55 per tonne of cement,[35] even with 45Q.
- **Liftoff will depend on coordinated procurement by large buyers to address challenging economics** by supporting necessary premiums and unlocking capital formation at the $0.5–1.0B per plant scale required.

The industry expects CCUS to play a key role in decarbonizing cement, but the technology is in the early stages of demonstration and deployment. Published industry and third-party roadmaps for the sector highlight CCUS, including retrofits of existing plants and incorporation into new builds, as a critical lever, potentially driving ~50–60% or more of cement decarbonization by 2050 (in the absence of alternative approaches).[ciii, civ, cv] But economics are challenging, and business models still need to be validated for plant operators and investors without experience with the technology. Liftoff is not assured in the absence of government financing, incentives, and demand for low-carbon materials.

Government financing, incentives, and demand will be critical in accelerating CCUS deployment in the cement industry. Public funding can help enable initial commercial-scale deployments in the U.S. The 45Q tax credit offers $85 per tonne of CO2 captured and permanently stored, improving the economic proposition of CCUS and helping to unlock the private sector business case for deployment. Large-scale procurement of low-carbon materials can create an enduring demand signal and potentially support cost premiums that may be needed for projects to be economically viable.

35 Based on analysis for CCS. Economic analysis was also performed for CCU and is discussed in the body of this section.

Figure 3.4: CCUS economics

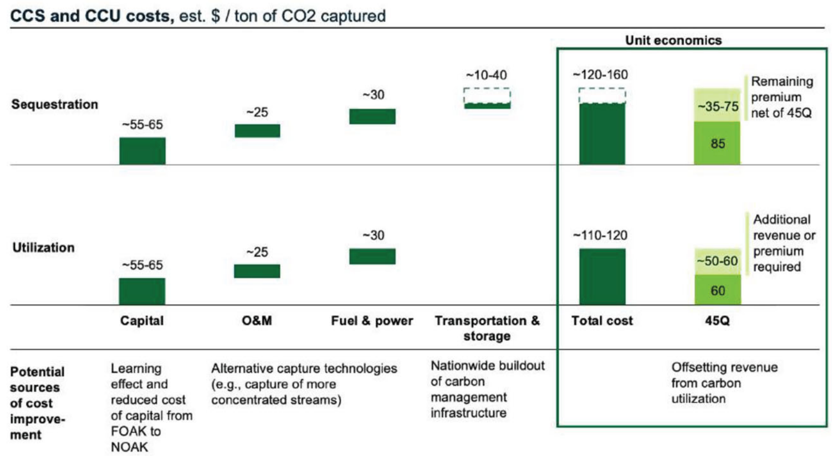

Figure 3.4. Illustrative economics for CCS and CCU deployments at a representative 1.5 MTPA cement plant. Figures for carbon capture are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using the CANSOLV amine-based post-combustion system. Capital costs are adjusted to reflect a 12-year payback period, consistent with what investors have said they will likely be willing to underwrite, using capital recovery factors provided by the Energy Futures Initiative. Transportation and storage cost of ~$10–40 per tonne of CO2 is assumed, consistent with the Carbon Management Liftoff report. Buildup yields a cost of ~$110–120/t CO2 without and ~$120–160 with transportation and storage. Assumes the project can capture the full value of the 45Q tax credit ($85/t CO2 for CCS and $60/t CO2 for CCU). In practice, the value of the tax credit that a CCU project can capture is contingent on a life cycle assessment of displaced emissions by NETL and FECM and could be a fraction of the full $60 potential credit. The figure for CCU is, therefore, a low-end estimate for the cost-revenue gap to bridge, as projects may require both additional transport infrastructure to transport captured carbon to another facility and likely will not be able to capture the full $60 value of the tax credit due to the volume mismatch between the CO2 captured and the CO2 that can be utilized with current technologies. Specific methodology is provided in the appendix. Sydney Hughes, and Patricia Cvetic. (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Energy Analysis | netl.doe.gov. Jeffrey D. Brown et al. (2023, Feb.). Turning CCS projects in heavy industry and power into blue-chip financial investments. Energy Futures Initiative. EFI – CCS Report (energyfuturesinitiative.org).

CCUS deployments necessarily drive incremental costs. Capturing and storing 95% of emissions at a representative 1.5 MTPA cement plant could cost ~$35–75 per tonne of CO2 and ~$25–55 per tonne of cement (equivalent to a ~20–40% premium on a $130 per tonne base price), even with the benefit of $85 per tonne of CO2 from the 45Q tax credit. CCS systems would thus need to achieve ~30–45% cost downs or corresponding revenue uplift for projects to break even with 45Q support. Without 45Q, capture and storage could cost ~$120–160 per tonne of CO2 and ~$85–120 per tonne of cement (~70–90% premium).[36, cvi, cvii]

High costs have three primary drivers:

- **Upfront capital costs**: A CCUS project can require $0.5–1B in CAPEX, and capital costs can account for ~50–55% of the total (excluding transportation and storage), driven by the cost of construction and the high cost to finance projects with a shorter payback period (e.g., 12 years required for projects to be economically viable with 45Q support). Total capital cost per tonne of CO2 is ~$55–65 with a 12-year payback period compared to ~$45–50 with a 30-year payback (~20–25% higher).[cviii]

36 See Figure 3.4 for a discussion of the methodology used for cost analysis. A detailed methodology is provided in Appendix B.

- **Operating costs from substantial fuel and power consumption**: Fuel and power needed for energy-intensive capture processes account for ~20–25% of levelized costs (excluding transportation and storage) and are particularly exposed to inflationary effects. [cix] In some cases, high energy demand could also drive additional costs not accounted for in the NETL modeling, such as the need to build a captive power plant if sufficient power cannot be drawn from the grid. [cx]

- **Potential for high CO2 transportation and storage costs**: Transportation and storage costs can vary widely based on site-specific conditions, such as whether the plant has access to an existing Class VI well for sequestration, how far away that well is, and how much additional pipeline and other supporting infrastructure needs to be built out. This analysis assumes $10–40 per tonne of CO2 in transportation and storage costs, consistent with prior NETL modeling and the Carbon Management Liftoff report, but the upper bound could be significantly higher for projects in less favorable geographies. [cxi, cxii]

However, industry is confident that CCUS systems can be deployed with minimal opportunity cost from plant downtime. Conversations with industry suggest CCUS systems can be built in parallel to operating plants and integrated during the planned ~2–3 weeks of annual downtime for relining of the kiln, which keeps opportunity cost from shutdowns to a minimum. [cxiii] If more substantial overhauls of the plant footprint are required, opportunity costs from lost operations could be significant, as discussed in Chapter 2.

Alternative CCUS technologies could eventually enable lower-cost deployments. Preliminary studies suggest that alternatives to traditional post-combustion amine-solvent systems like oxy-combustion and calcium-looping systems could be cheaper to build and operate, though these technologies remain at earlier stages of deployment readiness and public data on cost and performance remain limited. [37, cxiv]

Carbon utilization offers another potential route to improve project economics if high-value products can be produced. Using captured carbon to manufacture valuable products, CCU applications could generate additional revenue streams to help offset costs. Assuming it can capture the full $60 per tonne of CO2 45Q tax credit for carbon utilization projects, a CCU deployment would need to bridge a cost gap of ~$50–60 per tonne of CO2 and ~$35–45 per tonne of cement. However, this calculation is a low estimate: the value of the tax credit that CCU projects can capture is contingent on a life cycle assessment evaluated by NETL and FECM, and projects accordingly may not capture the full $60 value. CCU projects may also incur additional costs associated with the transportation of captured carbon to separate facilities and the operation of those facilities that will have to be offset by revenues.

The U.S. has a growing start-up ecosystem focused on using captured carbon to "cure" cement, concrete, and other construction products, though these are still typically pre-cast applications with a smaller accessible market and competition from low-cost alternatives. Many of these technologies remain nascent—largely pre-pilot or early pilot stage or are deployed at limited scale—but could also see additional demonstration and deployment in the mid-to-late-2020s, consistent with Liftoff in the 2030s.

CCUS Liftoff is contingent on the market finding ways to reduce, offset, and otherwise manage these high deployment costs, and government action can play a critical role.

- Initial demonstration projects could be completed in the mid-to-late-2020s, supported by grants and other forms of public funding in addition to 45Q. These demonstrations can validate the technology and business model for cement companies and investors and could drive initial cost reductions, unlocking follow-on deployments in the 2030s and 2040s.

- A next, larger wave of deployments will likely remain focused on sites in optimal geographies, where

37 Twenty studies of various technologies were reviewed in the DOE Industrial Decarbonization Roadmap (p. 148). Estimates come from 2006 to 2020 and are not adjusted to FY22 dollars or harmonized but broadly suggest that alternatives to post-combustion amine-solvent capture can be significantly cheaper, potentially closer to ~$40–60 per tonne of CO2.

projects can benefit from lower transportation and storage costs enabled by existing carbon pipelines, Class VI wells, and economies of scale from nearby CCUS project clusters. Among other regions, parts of PA, CA, the Gulf Coast, and the industrial Midwest could offer favorable conditions for large-scale deployment (Figure 3.5). [cxv] Coordinated procurement will be critical to support necessary premiums and unlock the investment case for capital-intensive projects.

- Deployment at remaining, less favorable sites will come last, benefitting from the cost reductions driven by learning effects, commercialization of new CCUS technologies, and buildout of shared carbon management infrastructure while relying on coordinated procurement to enable investment and economic viability.

Figure 3.5: U.S. cement plants and CCUS infrastructure

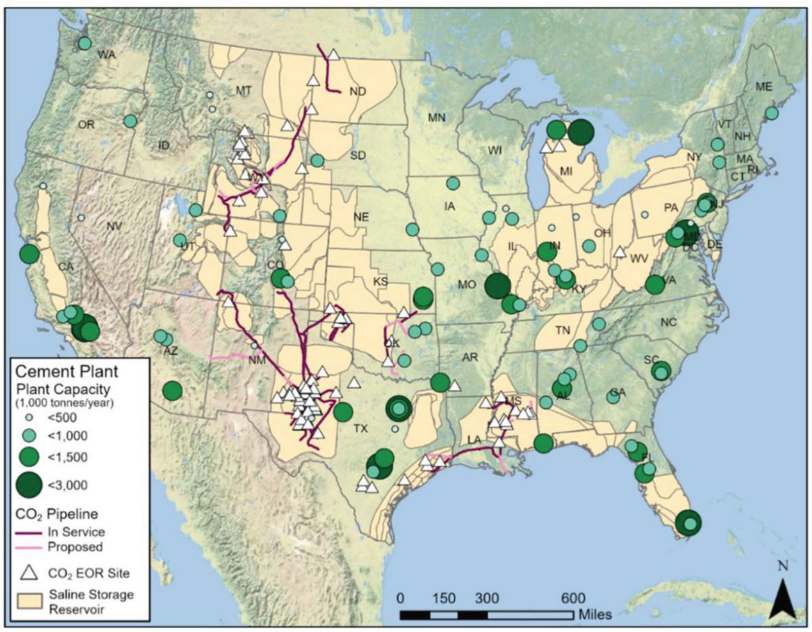

Figure 3.5. Map of U.S. cement plants overlaid with potential CCUS infrastructure, including saline storage reservoirs, current enhanced oil recovery (EOR) sites, and carbon pipelines. Note high-potential sites in CA, PA, the Gulf Coast, and the Midwest. Source: Sydney Hughes and Patricia Cvetic (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Energy Analysis | netl.doe.gov

Scaling CCUS across the entire industrial base could require ~$2–5B of investment by 2030 to support an initial 3–5 demonstrations, followed by up to an additional ~$55–100B of investment by 2050 for deployment at remaining and potential new-build plants (not accounting for potential reductions in capital costs or scale-up of alternative technologies in parallel).[38] Scale-up of CCUS could come with additional concerns from the public about environmental, health, and justice impacts, and projects will have to engage proactively with communities

38 Methodology for capital formation estimates provided in Appendix C.

and the public to ensure concerns are addressed (discussed in greater detail in Section 3.c and Chapter 4).

Track C: Alternative production methods for traditional cements

Key takeaways

- **Alternative production methods are still nascent, but could also scale in the 2030s.** To achieve Liftoff alongside CCUS, these technologies must demonstrate technological and economic viability commercially and prove they can enter the market under existing standards.
- **Greenfield plants will be capital-intensive—potentially ~$0.5–1.0B of CAPEX per deployment.** Coordinated procurement will again be critical to support premiums for FOAK deployments and enable capital formation.

Alternative production methods for traditional cement are emerging and could scale rapidly in the 2030s, provided they meet key milestones in the mid/late 2020s. These methods use fundamentally different approaches to produce drop-in replacements for traditional Portland or similar cements. They include alternative feedstocks, electrochemical production systems, and other alternatives to emissions-intensive rotary kilns (discussed in Chapter 2). [cxvi] Liftoff in the 2030s will require continued performance improvements, cost reductions, and significant public financial support.

Figure 3.6: Economics of alternative production methods

	Cost of traditional cement production	CAPEX premium for alternative method	OPEX premium for alternative method	Additional revenue streams	Potential cost for alternative method
Potential drivers of economics		CAPEX premium for FOAK plants (novel design) High cost of capital	More expensive parts of process (e.g., potentially from greater energy use)		If alternative methods can achieve sufficient cost-downs from FOAK to NOAK and/or generate sufficient offsetting revenue, **could achieve cost-parity or potentially improvement over traditional production**
Opportunities to improve economics		Learning effect and reduced cost of capital from FOAK to NOAK	Learning effect and supply chain maturation, enabling more efficient production	Selling byproducts of process (e.g., SCMs) to generate alternative revenue streams	

Figure 3.6. Illustrative economics and business model for alternative production methods. Alternative production methods could come with initial CAPEX and OPEX premiums compared to traditional production but can achieve parity by reducing these premiums and generating offsetting sources of revenue (e.g., production of SCMs and other valuable byproducts). Based on conversations with start-ups and investors pursuing alternative production methods. Figure does not reflect any one company or business model and is based on anonymized and aggregated information from multiple companies. Quantitative estimates are not provided due to limited performance history and public data.

Alternative production methods will have to meet key milestones with initial demonstrations in the mid/late-2020s to deploy on the timeline envisioned:

Performance: These technologies must demonstrate consistency with traditional cement products. They must work at commercial scale and yield products close enough to drop-in replacements for traditional Portland cements to enter the market under existing standards and with customers' trust. If this latter condition is not met, the timeline for broad market adoption could be pushed out significantly, as is the case with the alternative chemistries in Track D.

Competitive economics: Alternative production methods must achieve competitive economics with traditional production methods and CCUS. FOAK deployments will likely see a premium compared to traditional production, driven by a combination of high CAPEX (~$0.5–1B for a greenfield plant at commercial scale, potentially compounded by high financing costs) and an OPEX premium (e.g., from increased power consumption for energy-intensive processes). Business models generally assume some combination of the following:

- CAPEX premiums can be reduced from FOAK to NOAK by learning effects, improved financing conditions, and reduced cost of capital.
- OPEX premiums can be reduced by learning effects, economies of scale, and supply-chain maturation (in particular, the availability of process-optimized components that can improve plant efficiency).
- Remaining premium can be offset or more than offset by revenue from the sale of process byproducts (e.g., SCMs and other construction materials).

Coordinated low-carbon procurement will still be required to enable Liftoff by supporting the premium needed for initial deployments and providing a demand signal to attract capital at the multibillion-dollar scale required. These technologies could achieve Liftoff as follows:

- Initial commercial-scale demonstrations are launched in the mid-to-late-2020s, potentially with government funding and enabled by large-scale low-carbon procurement. ~3–5 technologies would demonstrate viability against key milestones, help achieve initial cost reductions, and prove competitiveness with traditional production methods and CCUS.
- If the economics prove viable and competitive, these technologies could scale with new-build plants in the 2030s and 2040s, either licensing the technology to incumbents or attempting to take market share themselves. The strong demand signal from coordinated government and private-sector procurement will again play a critical role in mobilizing required capital.

Liftoff could require ~$2–5B by the early 2030s for an initial ~3–5 demonstrations, with up to an additional ~$55–100B of investment by 2050 for new-build plants to decarbonize the full industrial base (trading off with CCUS deployments depending on whether site-specific conditions favor CCUS or an alternative production method).

Track D: Alternative chemistries

Key takeaways

- **Alternative binders to traditional clinker could have substantial abatement potential, but are far from widespread adoption.** Though they can build initial market share and scale in non-structural niches, these materials could face a ~10–20+ year adoption cycle to be accepted under widely used industry standards and achieve full-scale deployment in the broader market.
- **Accelerated customer adoption of performance-based standards like ASTM C1157 could significantly pull forward the adoption timeline.** Expanded use of performance-based standards in project specifications could allow novel materials to be deployed without developing new standards (potentially a 10+ year process).

Another set of technologies is similar to the alternative production methods following Track C, but, rather than produce drop-in replacements for cements currently in use, these technologies produce low-carbon cements with fundamentally different chemistries.

These alternative binder chemistries are generally nascent today, but could achieve Liftoff on a longer timeline after building initial momentum in niche applications and overcoming R&D, market adoption, and economic barriers.

Alternative chemistries are in different stages of technological maturity, market access, and economic viability, but all have significant progress to make before they can achieve large-scale deployment. Some materials, including magnesium oxides derived from magnesium silicates (MOMS) clinkers and certain bio-based and engineered clinkers, remain in the pre-pilot or pilot stage and will need additional R&D investment to progress. Others, including belite clinker, sulphoaluminate clinker, and alkali-activated binders, are commercially available, but only on a small scale. Performance is not yet well-characterized, and these materials are not approved for widespread use under existing industry standards, leaving them generally confined to a small subset of applications.

Alternative chemistries are on a longer track to Liftoff, and timelines will chiefly be determined by the industry standards process and adoption cycle:

- **In the short term, R&D investment—with government support—can facilitate the continuing development of alternative materials** that remain in the pilot or pre-pilot stage and conduct performance testing and validation of materials at higher levels of technological maturity.
- **When deployable, alternative chemistries can establish an initial market share in more accessible niches**, e.g., lower-risk, non-structural, pre-cast, and decorative applications (~15% of the market). This foothold can enable initial production scale and cost reductions, while allowing new materials to establish a track record of field performance.
- **In parallel, ASTM and AASHTO standards must be updated to allow alternative chemistries in a wider range of applications**, particularly building and transportation use cases accounting for >80% of demand. This process is expected to take 10+ years and will drive significant lead time for commercialization.
- **Even under optimistic assumptions about the timeline for approval, it could take until the 2040s for these materials to achieve a sizable market share**. Following approval under industry standards, customers can adopt alternative chemistries at a greater scale, potentially incentivized by demand for low-carbon construction and cases where alternative chemistries can offer economic or

performance improvements over traditional cement products. Rollout will likely be gradual, given the industry's slow adoption cycle, potentially taking another 10+ years.

Yet this timeline for full-scale adoption could be accelerated significantly by expanded use of performance-based standards, allowing alternative chemistries. Customers already have access to a performance-based standard, ASTM C1157, but it is not widely used. If customer education can convince a large share of the market to speed the adoption of ASTM C1157 and other performance-based standards, the timeline for broader adoption of alternative chemistries could be pulled forward significantly. Similarly, some large customers (e.g., large state DOTs like CalTrans) conduct their own testing and validation of materials independent of ASTM standards. Alternative chemistries that qualify under these supplemental testing regimes could grow their market share more rapidly.

Applied R&D opportunities on emerging technologies

There will be a continuing need for applied R&D across technologies and approaches. Some technologies like kiln electrification, expanded use of hydrogen, and some alternative SCMs and binder materials are at low TRL today and will require ongoing investment in basic R&D. Other critical technologies that are potentially closer to deployment, but still earlier stage, including CCUS, alternative production methods, and alternative binder chemistries, will require R&D investment both upfront and throughout the commercialization process to bring them to market and facilitate rapid deployment. Transformational technologies also have associated systems, facilities, and supply chains that will require their own R&D investment and improvement to ensure they can scale, integrate, and operate at maximal efficiency. Even technologies broadly or near-deployable today (e.g., clinker substitution, energy efficiency measures, alternative fuels) will require ongoing investment in applied R&D to improve performance and economics, maximize abatement potential, and speed commercialization by overcoming barriers encountered in the field.

DOE's Industrial Decarbonization Roadmap identifies key areas of focus for R&D investment across CCUS, low-carbon fuels and feedstocks, electrification, and efficiency levers, achieving impact on three time horizons:

- **"Near-term" (2020–25) needs**: support for low-capital measures (e.g., continued improvements in energy efficiency and waste-heat recovery), lower-carbon fuels and process heat (e.g., clean hydrogen, greater use of biofuels), and improvements to CCUS technology to enable more cost-effective capture on dilute emissions streams.
- **"Mid-term" (2025–30) needs**: development of increasingly ambitious low-carbon cement blends, routes for improved material-use efficiency and flexibility, process adaptations (e.g., precalciner electrification, alternative heating approaches, large-scale use of hydrogen), and advanced CCUS capabilities (e.g., oxy-combustion and indirect calcination, large-scale utilization).
- **"Longer-term" (2030–50) needs**: development of a circular approach for concrete, breakthrough heating approaches like kiln electrification and large-scale use of clean hydrogen, and innovative carbon capture and utilization approaches.

Although impacts will be felt on different timelines, early and sustained investment in all key areas will be critical to delivering technological improvements that can expedite deployment, improve economics and deployment-readiness of key levers, and unlock breakthrough approaches to accelerate decarbonization.

Section 3.b: U.S. leadership and technology export potential

With aggressive action, the U.S. can lead the world in cement decarbonization. Technologies developed, commercialized, and scaled domestically can be exported to address the ~7–8% of global carbon emissions from cement. Scaling low-carbon cement technologies worldwide will require business models that reflect other countries' economic and resource constraints, particularly in the developing world.

International cement decarbonization roadmaps lean heavily on technologies where the U.S. can play a key leadership role (examples reviewed in Figure 3.7). Published roadmaps suggest CCUS could abate ~35–50% of emissions, new processes ~5–15%, and material substitution ~5–15% (Figure 3.7).

Figure 3.7: International decarbonization pathways for cement

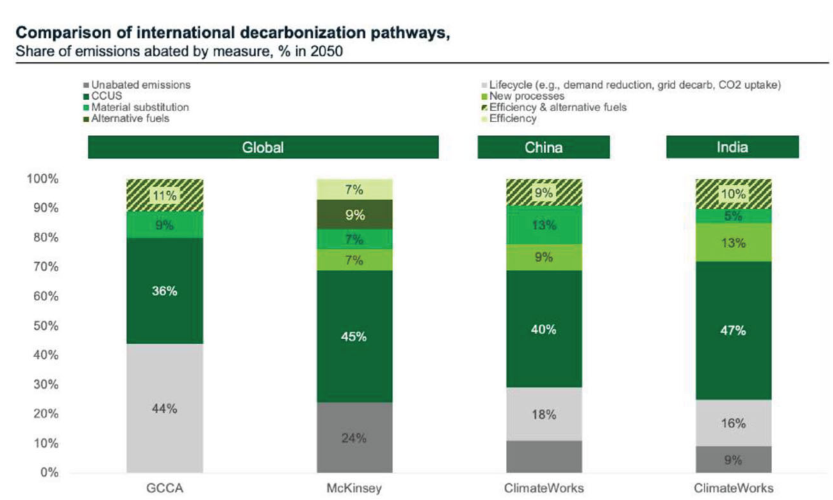

Figure 3.7. Comparison of modeled international and other-country decarbonization pathways for cement by 2050. CCUS is one of the largest drivers of emissions reductions in all cases, accounting for ~35–50% of abatement.
Sources: Global Cement and Concrete Association (2021). Concrete Futures: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf. Czigler, Thomas, et al. (2020). "Laying the foundation for zero-carbon cement." McKinsey and Company. https://www.mckinsey.com/~/media/McKinsey/Industries/Chemicals/Our%20Insights/Laying%20the%20foundation%20for%20zero%20carbon%20cement/Laying-the-foundation-for-zero-carbon-cement-v3.pdf. ClimateWorks Foundation (2021), "Decarbonizing concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China," https://www.climateworks.org/report/decarbonizing-concrete/.

In the short term, the U.S. can focus on commercializing and exporting the highest-impact measures that are currently deployable:

- **Clinker substitution**. The U.S. can help accelerate the global deployment of clinker substitutes by domestically validating and scaling more aggressive low-carbon blends and new SCMs like calcined clays, demonstrating technologies and business models for international use. Realizing the ~20–30% abatement potential of more aggressive clinker substitution worldwide could cut ~1.5–2.5% of all global CO2 emissions, using technologically proven measures with a strong economic case today. [39]

39 Based on 20-30% of ~7–8% of global emissions.

Longer term, the U.S. could have a transformative impact in accelerating global cement decarbonization by pioneering two deep decarbonization business models for export:

- **Low-cost CCUS**: A U.S.-developed business model for CCUS that does not require a substantial premium or cost support could be transformative for global cement decarbonization. The U.S. is positioned to lead the world in CCUS deployment across industries, with the potential to achieve key technological and economic breakthroughs domestically before exporting internationally. With its favorable policy and market environment for carbon management, the U.S. could de-risk, scale, and reduce the cost of capture systems, including serving as the global proving ground for new, lower-cost technologies that can be deployed worldwide. Because many countries lack the extensive carbon storage capacity of the U.S., developing and commercializing cost-effective forms of carbon utilization at scale, in addition to capture, could be particularly critical for unlocking wider global deployment.
- **Alternative production methods**: If alternative production methods achieve Liftoff, including reaching cost-competitiveness with traditional cement production, they could also have significant export potential. American companies that successfully commercialize new low-carbon production methods could capitalize on market growth to build greenfield plants overseas.

Section 3.c: Workforce and energy and environmental justice (EEJ) implications

Decarbonization of the cement sector must occur in a way that ensures the creation of quality jobs and addresses the concerns and protects the health and environmental quality of fenceline communities, both to meet the country's climate, economic, and EEJ imperatives and to ensure the success of projects in these communities. This report takes a broad look at workforce and energy and environmental justice concerns to highlight the key opportunities that can arise from cement decarbonization, as well as the risks that must be mitigated to protect communities from additional harms.

This report does not include a comprehensive analysis of non-GHG emissions from cement production (e.g., other criteria air pollutants), specific industry workforce considerations, or technical solutions for EEJ concerns. This qualitative analysis is the beginning of what must be a robust discussion of how actually to implement a just decarbonization strategy. Additional work from many stakeholders is needed to outline tactical solutions toward a shared goal of a prosperous, just net-zero economy.

Companies, investors, and public- and private-sector stakeholders across the entire value chain are critical in determining whether projects advance a just and equitable transition to net zero or exacerbate existing injustices. "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" covers key workforce and energy and environmental justice (EEJ) considerations, recommends specific actions, and provides online resources. Detailed discussion of workforce and EEJ considerations in the context of industrial decarbonization is provided in the Pathway to Commercial Liftoff: Industrial Decarbonization report. The section below covers EEJ considerations and impacts specific to the cement sector.

The EEJ impacts of low-carbon cement projects depend on the benefits and harms incurred, who experiences them, and how the impacts alleviate or compound existing burdens. Industrial facilities are disproportionately concentrated in geographic areas with higher shares of households with low incomes and residents who are not white, which have historically borne the brunt of adverse health and environmental impacts without corresponding access to the economic benefits of industrial activity. [cxvii] It will be vital to anticipate and mitigate potential adverse effects of industrial transformation. Large-scale projects must be undertaken in consultation with local communities and with community buy-in to protect often marginalized populations and ensure project success.

Broadly, decarbonization and transformation of the industrial base for cement is an opportunity to address historical environmental injustices and contribute to frontline communities' health, environmental quality, and economic vitality. Specific dimensions are considered below.

Section 3.c.i: Economic impacts

Workforce and economic benefits

Decarbonization can be a positive opportunity overall for the cement and concrete workforce. Buildout of retrofits and greenfield plants can create good-paying construction jobs. As the broader construction sector faces pressure to decarbonize, decarbonizing cement production can position cement and concrete producers to continue to compete and thrive, helping to protect the ~210,000 jobs currently in cement and concrete products manufacturing. [cxviii]

Constraints in the construction workforce, particularly shortages of workers in skilled trades, could impede the scale-up of low-carbon technologies. [cxix, cxx] It will be critical for U.S. to invest in job training (especially Registered Apprenticeships), intentional efforts to recruit and retain underrepresented populations, and other measures to build the workforce pipeline for these essential trades, not just for cement but for decarbonization of the economy and infrastructure buildout more broadly. Growing and maintaining the skilled workforce needed to achieve climate and industrial strategy goals will be contingent upon creating good-paying jobs with opportunities for professional development and career advancement, as well as high safety standards. Success will require effective collaboration between industry, labor and worker-serving organizations, and government. [cxxi]

It will also be vital to ensure that jobs and other economic benefits of sector transformation flow to frontline communities. Project developers can engage in community benefits agreements and develop community benefits plans to make commitments about the kinds of local benefits they will provide, as well as conditions of employment (including committing to wages, benefits, and health and safety standards) and job-training investments. [cxxii] Job training, such as registered apprenticeship programs, intentionally inclusive recruitment and retention strategies, such as financial and non-financial supportive services, and negotiated agreements between community stakeholders, are all critical tools to enable historically disadvantaged and underrepresented communities to participate in the economic benefits of local development. [cxxiii]

Cost of goods

Because cement is a critical upstream input for a wide array of critical goods (e.g., infrastructure, housing), impacts on cost can have far-reaching implications. Some interventions (e.g., clinker substitution and alternative production methods, provided they can achieve economic competitiveness compared to traditional production methods) could reduce the cost of cement production, with the potential for savings to eventually pass downstream to consumers. Though downstream cost implications may be limited (as cement typically accounts for a small share of overall project costs), in cases where structural cost increases may be incurred (e.g., CCUS), efforts must be made to protect consumers from cost increases, particularly those who are most economically vulnerable. In many cases, the 45Q credit, other tax incentives, and Infrastructure Investment and Jobs Act (IIJA)[40], also referred to as the Bipartisan Infrastructure Law (BIL) / IRA programs will help to defray costs and insulate consumers from cost increases.

Section 3.c.ii: Health and environmental quality impacts

Air quality

Cement production has historically been associated with significant air-quality concerns and harm to surrounding communities, including emission of SO_2, NO_x, and CO. [cxxiv] Decarbonization efforts can come with additional risks to be mitigated and opportunities to address air-quality concerns associated with cement production. Alternative fuels, particularly waste-based fuels like tires, plastics, and waste oils, can come with air pollution risks that must be mitigated. [cxxv, cxxvi, cxxvii] Carbon-capture retrofits and shifts away from kiln-based production methods also offer opportunities to improve local air quality by implementing new pollution-control and abatement measures (e.g., "scrubbing" of NO_X, SO_2, and particulate matter before carbon capture). [cxxviii, cxxix]

40 Infrastructure Investment and Jobs Act, Pub. L. 117-58, 135 Stat. 429 (2021)

Raw materials

Building out the supply chain for input materials also presents both risks and opportunities for the health and environmental quality of frontline communities. SCMs are disproportionately sourced in vulnerable communities, creating added risk and a particularly strong equity imperative to anticipate and address potential harms. Some SCMs and new feedstocks could require the development of new mining and quarry operations and supporting infrastructure, and any such redevelopment must be done in a manner that does not compromise the health and environmental quality of surrounding communities. [cxxx]

Using ponded coal ash as an SCM can contribute to the remediation of brownfield sites, improving the economics of costly remediation projects and providing a safer way of disposing of hazardous materials. [cxxxi] Efforts must be undertaken to ensure that ponded ash is handled safely and that redevelopment projects are undertaken consistent with the health and safety of surrounding communities.

Section 3.c.iii: Carbon management concerns

CCUS will likely be a major part of the decarbonization pathway for the cement sector. The public may have broader concerns about carbon management projects, including potential health and safety impacts of CO2 transport and storage infrastructure, the cumulative burden on local communities (e.g., extending the lifetime of emissions-intensive facilities), and potential financial support for companies with a poor track record on climate and environment. Successful delivery of CCUS projects will hinge on effective engagement with both local communities and the broader public to ensure risks and concerns are addressed. These potential risks, concerns, and approaches to public engagement and accountability are considered in detail in the Carbon Management Liftoff report. [cxxxii]

Chapter 4: Challenges and solutions

Key takeaways

- **Large-scale buyers, particularly government agencies, can develop shared standards for low-carbon materials** to enable informed and effective procurement.
- **Overall adoption cycle for new materials will have to be compressed from ~10–20 years to ~5–10** to meet aggressive deployment targets for the early 2030s**.** Accelerated adoption will require a combination of demand-side incentivization, market education, and technical assistance.
- **Capital-intensive deployments will require new procurement models with long-term offtake commitments to unlock required investment.** For example, a 10 to 12-year, ~$0.5–2.b offtake agreement could be at the scale needed to unlock investment to retrofit one representative 1–1.5 MTPA plant with CCUS or to support the construction of a greenfield plant using an alternative production technology.
- **Longer term, deep decarbonization technologies like CCUS could require initial government-backed interventions** to offset structural cost increases, including support from 45Q, premiums supported by low-carbon procurement, and updates to construction codes requiring low-carbon materials.

With concerted effort, the U.S. is positioned to recapture global leadership on low-carbon cement and lead on the commercialization of multiple key technologies. Stable policy support and favorable market and geological conditions make the U.S. the world's most attractive destination for CCUS today. In parallel, a vibrant U.S.-based startup ecosystem could bring revolutionary low-carbon cement technologies to market in the coming decades.

Rapid Liftoff of these technologies is possible, but contingent on overcoming six key challenges to compress adoption timelines for deployment-ready technologies and accelerate the commercialization of new approaches. Several additional challenges specific to CCUS are discussed in detail in the Carbon Management Liftoff report. These challenges include economic and commercial factors (e.g., cost uncertainty, demand uncertainty, lack of commercial standardization) and execution factors, (e.g., permitting lead times, limited transport and storage infrastructure, public concerns and opposition to projects).

Government action has a critical role in enabling solutions, leveraging both the power of government procurement and the government's ability to convene and coordinate key stakeholders across the value chain. Private-sector leadership will also be required to set ambitious goals and collaborate in overcoming barriers.

Figure 4: Challenges to Liftoff and potential solutions

Challenges	Potential solutions
1 **Lack of robust system to define low-carbon materials** makes it hard for large buyers to make informed procurement decisions	• **Establish shared standards and data infrastructure** to define and validate low-carbon cement and concrete products
2 **~10-20-year adoption cycle for new blends and materials** delays demand and corresponding investment in decarbonization	• **Invest in accelerated testing, validation, and demonstration** of low-carbon cements and concretes • Engage key end customers to **encourage requirement of low-carbon materials in project specifications**, including through adoption of performance-based standards • **Provide technical and financial assistance** to facilitate adoption in the broader value chain
3 **Informal, short-term procurement model** is not well-structured to attract long-term investment	• **Develop alternative procurement models** that provide direct offtake for projects
4 **Structural cost increases for CCUS and other approaches** may permanently increase cost to end users	• **Provide durable policy support** to address challenging economics • **Provide coordinated procurement** to support a long-term premium • **Update construction regulations** to require use of low-carbon materials in projects
5 **Technology, performance, and cost uncertainty** discourage deployment and investment	• **Provide support for early project development** and creation of archetypal business models and terms • **Provide continuing investment in R&D** for critical technology areas
6 **Lack of public support for projects,** driven by concerns about environmental and human health risks, EEJ and labor implications	• **Implement robust community benefits plans and agreements** that are responsive to public concerns, mitigate potential harms, and ensure accountability

Figure 4. Six key challenges and potential solutions highlighted in conversations with industry and key stakeholders across the value chain.

Challenge 1: The market lacks a robust system to define low-carbon materials, making it difficult for large buyers to make informed forward procurement decisions.

There is growing interest in the procurement of low-carbon cement and concrete products among government and private buyers, but markets broadly lack common, widely-scaled mechanisms for establishing and verifying which cement and concrete products qualify as sufficiently low embodied carbon. Without common standards and validation mechanisms, large buyers struggle to make informed procurement decisions and coordinate effectively to create a demand signal for industry.

Low-carbon procurement efforts rely on third-party "environmental product declarations" (EPDs), estimates of the embodied carbon of products (i.e., the emissions associated with their production, distribution, and use). [cxxxiii] Yet current EPDs come with key limitations, including:

- **Lack of standardization**. There is no single standard methodology to assess the embodied carbon of products in EPDs, making it challenging to compare cements and concretes during a competitive procurement process. The industry has expressed concerns that some EPDs are not effectively integrated with broader life cycle assessments, making it difficult to account accurately for the full life cycle impact of materials (e.g., the impact of durability and salvage or reuse potential). Challenges with standardization are compounded by fragmentation in the market, particularly in intermediate tiers of the value chain.
- **Limited data availability.** Data on emissions associated with specific inputs and production at specific facilities remains limited, making it difficult to produce accurate estimates of embodied carbon. Data may be available in many cases, but suppliers may not independently be incentivized or

resourced to make necessary investments in acquiring it. Without more robust data, some EPDs have historically relied on industry averages and have been unable to verify the true emissions content of products (though more recent efforts, e.g., GSA procurement standards, increasingly require facility-level data).

- **Limited accessibility for new products and facilities**. EPDs typically require a plant to have at least one year of operating history to provide needed data, which makes it challenging for technologies in the pilot stage or early deployment to receive EPDs and thus qualify for low-carbon procurement initiatives.

Solution 1: Establish shared standards and data infrastructure to define and validate low-carbon cement and concrete products for future procurement.

A shared standards regime to support low-carbon procurement will include three main elements outlined below, and federal efforts currently underway can provide a strong foundation for a long-term standards model.

- **Common definition of low-carbon cements.** Large government and industry buyers can convene to develop shared standards for what qualifies as low-carbon cement and concrete. Efforts can follow the lead of multiple actors, public and private, that have begun developing initial standards, including NIST, the First Movers Coalition (FMC) and GSA. FMC has already established a standard for low-carbon concretes used by its members in the construction and real estate industries, and GSA has set specific standards for "substantially lower embodied carbon materials" based on EPA's Interim Determination. [cxxxiv, cxxxv] It is important for standards to grow more stringent over time and set a sufficiently high bar to incentivize investment in deep decarbonization. A government-led or industry program after the model of EnergyStar could also provide voluntary certification of low-carbon materials that meet shared standards. [cxxxvi] With IRA funding, EPA is developing a carbon-labeling program for "substantially lower embodied carbon" construction materials. [cxxxvii]
- **Standardized approach and template for EPDs.** To implement these standards uniformly, the market must align on a common methodology for developing and validating EPDs. To capture the emissions impact of materials accurately, standard templates and methodologies should account for the impact of their full life cycle—including use in the field, potential reabsorption of CO2, and end of life, in addition to production—and incorporate digitized tracking for verification. A preliminary or provisional EPD mechanism will also be necessary to allow technologies at the pilot or early demonstration stage to qualify for low-carbon procurement.[cxxxviii] With IRA funding, EPA has led the initial work to establish standard practices for EPDs and can continue leading the market and shaping practices. [cxxxix] The Federal-State Buy Clean Partnership has convened 13 states and the federal government to harmonize procurement standards. [cxl, cxli]
- **Data collection and publication**. Development and widespread use of standardized EPDs will also require extensive collection and dissemination of data on emissions for various products. Large-scale government buyers can promote transparency by requiring the disclosure of emissions data as part of the procurement process. Efforts can build on existing EPD libraries like the Embodied Carbon in Construction Calculator (EC3) developed by Building Transparency and the federal LCA Commons to develop an industry-wide central, universally accepted repository. [cxlii, cxliii, cxliv]

Challenge 2: Historically, the industry has had a ~10 to 20-year adoption cycle for new blends and materials, which delays demand and subsequent investment in low-carbon production.

A multidecade adoption cycle will prevent the rapid deployment of clinker substitutes and delay the rollout of more novel materials. To realize maximal abatement potential and economic value by 2030, the adoption cycle for new blends and materials must be compressed from ~10–20 years to ~5–10 years.

The extended adoption cycle has three components:

- **Long lead times to update industry standards.** Updating ASTM and AASHTO standards is a lengthy process (historically 10+ years), imposing significant lead time for new materials to enter the market under prescriptive standards. [41] Standards are developed through a consensus-based process by committees composed of volunteer industry experts. Industry organizations are justifiably risk-averse about allowing the use of new materials, particularly where there are life-safety implications. Changing standards to accommodate new materials requires extensive testing, validation, and consensus-building with a range of stakeholders, which significantly pushes out the timeline for adoption.
- **Slow uptake by risk-averse end customers**. Even when new blends and materials are accepted under industry standards, end customers are risk-averse and typically slow to adopt new materials into project specifications because of potential risks to safety, performance, cost, and schedules. Large government buyers, particularly state DOTs, can play a critical role in bringing along customers and shifting the market, but they tend to be risk-averse given their need for materials to perform to high standards in the field and be durable under challenging environmental conditions. Private construction, engineering, and development companies are likewise often slow to adopt new materials that may come with performance and cost risk and have broadly been reluctant to adopt new standards (e.g., performance-based standards that could allow alternative chemistries) into their specifications.
- **Slow uptake by intermediaries (e.g., ready-mix concrete companies and contractors) for technical and risk reasons.** Ready-mix concrete companies and other contractors are often small businesses with little margin for error on projects, limited internal resources for testing and validation, and limited capacity and appetite to adapt to the technical requirements of new materials. Anecdotal evidence suggests this was a challenge even with the more modest changes to cement mixes under the PLC rollout: PLC blends were not always perfect drop-ins for existing practices, and using them successfully involved a learning curve, complicating deployment.

Solution 2: Pursue targeted interventions to compress the adoption timeline.

Three priority approaches could help increase confidence in new blends and materials, encourage end customers to accelerate adoption into specifications, including through the use of performance-based standards, and facilitate uptake by intermediaries:

Solution 2.a: Invest in accelerated testing, validation, and demonstration of low-carbon cements and concretes.

Government and industry can partner to expand and expedite testing, validation, and demonstration of more low-carbon cement blends and novel materials to speed acceptance under industry standards, build market confidence, and drive adoption. Accelerating this process will require a buildout of testing infrastructure, funding for additional large-scale material demonstrations, and more proactive engagement with industry standards organizations.

Minnesota DOT's "MnROAD" pavement test facility is a prime model for expanded testing. The facility includes segments of actively used roads and highways paved with different concrete and asphalt equipped with sensors to collect detailed data. These data can be used to evaluate material performance under a range of realistic deployment conditions. [cxlv] MnROAD is in the second year of a three-year effort to test concrete pavings made with several kinds of low-carbon cements, including PLC mixes with higher limestone content and blended cements with alternative SCMs (including some manufactured with sequestered CO2). Results will be published and used to inform and justify the adoption of new materials by state DOTs. [cxlvi]

41 See, for example, the extended timeline required to change and approve standards for Portland Limestone Cements.

Similar efforts on a larger scale will be needed to test additional blends in additional geographies. Testing and validating more materials would need to be done in parallel to enable rapid deployment. This could be unlocked via modest investments to build out parallel facilities and accelerate needed materials testing—for example, MnROAD's current operations are supported by ~$10M in grants. [cxlvii]

Government and industry organizations can engage more proactively with ASTM and AASHTO to ensure test results are rapidly incorporated into industry standards. NIST, DOT, or another relevant agency can lead outreach to socialize test results, identify gaps in testing, and prioritize future research accordingly. NIST's Low Carbon Cements and Concretes Consortium is already engaged in convening stakeholders for this kind of outreach.[cxlviii] Modest funding support for standards-setting organizations could also allow committees to meet more regularly and provide them with the resources to accelerate the review of new materials.

Once materials are validated, public funding can support demonstration projects for low-carbon cements and concretes in various use cases and conditions, with sites chosen for high public visibility and results widely publicized to build broader market confidence. Initial demonstrations could focus on horizontal applications like roads, highways, and pavers, then expand to lower-risk vertical construction like single-story buildings.

Solution 2.b: Engage key end customers to encourage the requirement of low-carbon materials in project specifications, including by adopting performance-based standards.

Concerted engagement with key customers and broader market education to encourage the inclusion of low-carbon cements in project specifications can shorten the adoption cycle. Industry organizations and key government agencies can lead outreach by forming a central clearinghouse for collecting and publishing technical and economic data, convening customers, and conducting active outreach to share information about new materials and build confidence. Efforts can focus first on the largest and most influential buyers of cement, particularly state DOTs, to have a maximal impact on the market. U.S. DOT and the Federal Highway Administration (FHWA) can lead in coordinating outreach to state DOTs and facilitating knowledge-sharing to raise ambitions, build comfort with new materials, and accelerate rollout.

Similar efforts could speed the uptake of performance-based standards to facilitate expanded market access for novel chemistries. Similar efforts could speed the uptake of performance-based standards like C1157 to facilitate expanded market access for novel chemistries. Again, U.S. DOT and FHWA can collaborate with NIST, other relevant agencies, and industry organizations to engage with state DOTs and encourage broader use of performance-based standards. A coordinated effort can facilitate information-sharing, quickly surface challenges, and quickly bring the full breadth of government and industry resources to bear to address them.

Solution 2.c: Provide technical and financial assistance to facilitate adoption in the broader value chain.

As the sector pursues more novel blends and materials, coordinated technical and financial support can help address the difficulties intermediate players in the value chain (e.g., small ready-mix companies and subcontractors) have with the rollout.

Industry organizations and governments can partner with small ready-mix companies and subcontractors to address the technical challenges of working with unfamiliar materials with distinct requirements. Local ready-mix, aggregate, and construction trade associations will be vital partners in any such effort. They can convene key players and serve as the central venues for training and outreach, proactively identify and address challenges, and collect and disseminate technical best practices.

Challenge 3: The procurement model for cement is not structured to attract the investment required for decarbonization.

Cement is traditionally purchased through "handshake" spot transactions, as the nature of the construction market disincentivizes long-term purchasing commitments (discussed in Chapter 2). According to investors, these kinds of short-term agreements are difficult to use as the basis for securing low-cost infrastructure financing.

Purchasing agreements are also adjudicated between intermediate steps along the value chain, where there is significant fragmentation. An end customer seeking to purchase cement for a project rarely, if ever, contracts directly with a cement producer, but instead with a construction firm that purchases cement through multiple layers of intermediaries, such as ready-mix companies and other subcontractors. As a result, it is difficult to establish bankable offtake commitments that directly link end customer willingness to pay for low-carbon cement to cement producers who need to invest to meet that demand.

Absent bankable offtake, the cement industry will struggle to attract investment at the scale needed for deep decarbonization projects. Therefore, establishing low-carbon procurement standards by large buyers is unlikely to be sufficient on its own. Coordinated procurement programs can address these challenges with an alternative purchasing model.

Solution 3: Develop alternative procurement models that provide direct offtake for projects.

To make the demand signal for low-carbon cement bankable for risk-averse investors and enable project finance at scale, large-end customers must develop a procurement model that provides greater offtake certainty for low-carbon cement plants. To de-risk projects sufficiently, such a model could need to have three main elements:

- **A direct, legally enforceable contract** between the cement plant and a creditworthy end customer (e.g., a government agency, large private customer, or large construction company);
- **Guaranteed offtake for most or all of a plant's output** for the investment period, with some guarantee regarding price; and
- **Active management of intermediaries in the supply chain** to ensure low-carbon cement products are used in the construction process, which could require off-takers to invest in improving visibility upstream in their project supply chains.

A range of options for such a model are available and actively explored by government and private-sector customers. Potential approaches include advance market commitments, direct procurement or structured offtake agreements, contracts for differences, contractual price guarantees, and advance purchase agreements for avoided carbon emissions.

Providing this guaranteed offtake with government procurement could require adopting alternative contracting models. Procurement experts at several federal and state agencies expressed concern that long-term offtake commitments could be at odds with acquisition requirements, but alternative contracting structures currently in use (e.g., Multiple Award Task Order Contracts and Indefinite Duration, Indefinite Quantity contracts already used by agencies to manage complex, long-term acquisition programs), could offer an alternative model. More complicated procurement mechanisms could require additional investment in the contracting shops at state DOTs and key federal agencies with less experience with these vehicles. [cxlix] Private buyers could have more flexibility in implementing new approaches but require greater coordination to build buyers' coalitions and collectively implement new procurement models (e.g., through forums like the First Movers Coalition). [cl]

A 10–12-year commitment worth \$0.5–2.0B total could provide sufficient offtake assurance to enable a project finance model for a commercial-scale retrofit or greenfield plant using novel decarbonization approaches. For a CCUS retrofit of a representative 1.5 MTPA cement plant, a $0.5–1.0B total commitment over 12 years could cover the total cost of the premium beyond 45Q. [42] Over ten years, a ~$1.3–2.0B commitment could provide 100% offtake coverage for NOAK greenfield plants using alternative production methods or novel chemistries. [43] Guaranteeing offtake from FOAK plants could require a larger commitment to cover the cost premium of early deployments.

Challenge 4: Deep decarbonization technologies, particularly carbon capture, may involve permanent structural cost increases.

If cost declines do not bring costs of key technologies below expected revenues, projects will struggle to achieve long-term economic viability. As discussed in Chapter 3, CCS deployments could involve a structural cost increase of $35–75 per tonne of CO2 with 45Q (equivalent to ~20–40% premium per tonne of cement) and $120–160 per tonne of CO2 without 45Q (equivalent to ~70–90% premium per tonne of cement). Adding incremental and permanent cost increases to cement can create ongoing challenges to the economic viability of business models and deter investment in scale-up depending on the policy environment.

Solution 4: Establish policy and market models that offset structural cost increases.

Additional revenue streams or incentives may be required to enable the long-term economic viability of deep decarbonization technologies that come with these structural cost increases. Government and industry can work in tandem to pursue policy, regulatory, and market mechanisms that help address the structural costs associated with CCUS and other decarbonization measures. Three priority actions are detailed below.

Solution 4a: Provide durable policy support to address challenging economics.

Policy support can help bridge remaining cost gaps after long-term cost declines. Approaches could include an extension of 45Q or other market-based mechanisms. Policy support can stack with other measures, such as revenues from other products and premiums (discussed in Solution 4b), which may be particularly important if cost declines are more limited.

Solution 4b: Provide coordinated procurement to support a long-term premium.

Government procurement programs can set aggressive standards for low-carbon materials and provide additional funding to support premiums. At the federal level, the Biden-Harris Administration's Buy Clean Initiative seeks to leverage the government's purchasing power to spur expanded manufacturing of low-carbon materials, pursuant to the Administration's goal of achieving net zero in federal procurement by 2050. [cli] The Inflation Reduction Act provides $4.5B to support the procurement of low-carbon materials by GSA and U.S. DOT. [clii] At the state level, New Jersey's Low Embodied Carbon Concrete Leadership Act (LECCLA) provides a tax credit to concrete suppliers on government projects that provide quantifiable reductions in embodied carbon, while other states are phasing in similar programs. [cliii] Large private-sector buyers could adopt a parallel approach consistent with their decarbonization mandates.

However, passing a premium through multiple layers of intermediaries in the value chain will come with additional challenges. Intermediaries could impose additional premiums in each tier, diluting the effect of coordinated procurement. Success will likely hinge on the capacity of end customers to manage their supply chains more actively, which may require capacity-building in their procurement and contracting organizations.

42 Calculations are provided in Appendix B. Analysis assumes an offtake agreement would cover the remaining premium per tonne of cement after 45Q on cement sold by an existing plant.

43 Assumes alternative production methods can achieve parity with the current cement price of ~$130 per tonne, with a 10-year offtake to cover 100% of output for a 1–1.5 MTPA plant.

Solution 4c: Update construction regulations to require using low-carbon materials in projects.

State and local building codes and other construction regulations offer an opportunity to overcome cost barriers to decarbonized materials by prescribing their use in projects. [cliv] Building and construction codes already require certain materials, typically for safety reasons, and could set similar requirements for low-carbon cements and concretes.

Some jurisdictions have already begun to implement such a model. Portland, OR, requires Portland cement concretes used in city-owned construction projects to have embodied carbon below a maximum value for a given strength class, verified by a third-party EPD. [clv] Marin County, CA, adopted a building code that requires all concrete placed in the county to meet either a limit on cement or embodied carbon that scales with the specified compressive strength of the material. [clvi]

Because building and construction codes are generally defined at the state or local level, the change would likely be a slower process, working locality-by-locality. Efforts could start in large jurisdictions with the most construction activity to build market share and momentum, then try to achieve wider adoption nationwide. Under BIL and IRA, DOE has ~$1.2.b in funding to accelerate the adoption at the state and local level of traditional and innovative building energy codes, including zero energy codes and building performance standards.[clvii, clviii]

Challenge 5: Critical emerging technologies face performance and cost uncertainty. Others remain at low TRL.

Measures like CCUS, alternative production methods, and alternative materials as applied to low-carbon cement remain untested at commercial project scale in the U.S.; cement companies and investors will need to see technologies and business models de-risked before they pursue the substantial capital investments required for deployment. Cement companies are also unfamiliar with these technologies and will need to build comfort operating CCUS systems or new kinds of plants before they can deploy at scale. Other critical technologies are at low TRLs or will need further progress on applied R&D to achieve necessary cost and performance improvements for widespread deployment.

Solution 5a: Support early project development and create archetypal business models and terms.

Support for early deployments in CCUS, alternative production methods, and alternative chemistries will be needed to reduce technology and execution risks. Three to five commercial-scale projects could be needed for each technology to prove it can be operationally and commercially viable at scale. Billions of dollars are potentially available through BIL and IRA to support these initial deployments, helping offset high costs and improve the economic viability of FOAK projects. To ensure initial deployments have their maximal effect in de-risking business models for investors and unlocking follow-on deployments, it will be important to collect and publish technical and economic data from initial demonstrations to inform future investment decisions.

Similarly, developing standardized project and financing structures for these technologies can accelerate long-term buildout. Publication of project execution best practices, lessons learned, and project terms—particularly from projects that receive government support—can provide a replicable template for future deployments. [44]

Solution 5b: Provide ongoing R&D investment to advance transformative lower-TRL technologies and accelerate adoption across technologies.

Where critical breakthrough technologies remain at lower TRL, continuing R&D investment can accelerate progress towards technological maturity and ultimate commercial-scale adoption. Start-ups, academic research organizations, and relevant parts of the DOE and other federal agencies, including IEDO and

44 Also discussed in the Carbon Management Liftoff report in the context of carbon management projects.

ARPA-E, can help catalyze and drive breakthrough R&D efforts. Non-profit organizations can also play a role by continuing to highlight the importance of research into cement decarbonization, particularly the next wave of deep decarbonization technologies, and fostering collaborative partnerships between research institutions, industry, and government agencies. More detailed discussion of potential R&D priorities is provided in Chapter 3 of this report and in DOE's Industrial Decarbonization Roadmap. Additional discussion of challenges and solutions related to R&D is provided in the Pathway to Commercial Liftoff: Industrial Decarbonization report.

Challenge 6: Lack of public support for projects, driven by concerns about environmental and human health risks and EEJ and labor implications.

Fenceline communities and the public are often wary of industrial projects because of the history of adverse environmental, health, EEJ, and labor impacts they may bring. Ensuring community buy-in and addressing public concerns is not just an ethical imperative for developers–failure to build trust with the public can stymie project development, increasing costs by delaying progress and potentially leading to projects being non-viable altogether.[clix]

For cement decarbonization, this challenge is particularly pronounced in the context of CCUS projects, which can require substantial buildout of infrastructure (including pipelines), are perceived as allowing continued use of fossil fuels, and may come with additional environmental impacts that have to be abated. [45]

Solution 6: Implement robust community benefits plans and agreements that are responsive to public concerns, mitigate potential harms, and ensure accountability.

Community benefits agreements (CBA) are signed between developers and community groups that negotiate community support for a project in return for benefits from the developer.[clx] CBA negotiations are avenues for developers to engage with communities to understand how their project can meet with their goals while ensuring that community needs are met. These CBAs can incorporate mechanisms designed to mitigate the impacts from project development that the community is concerned about. Selected examples include requiring the usage of state-of-the-art scrubbers for facilities that may come with air pollution concerns, investments in local infrastructure, job training and local hiring requirements, and implementation of GHG reduction programs.

45 Discussed in detail in the Carbon Management Liftoff report.

Chapter 5: Metrics and milestones

The DOE will track two types of key performance indicators to understand the progress needed for successful decarbonization of the cement sector.

- **Leading indicators** are signs to evaluate the present status of technology readiness, market adoption readiness, and penetration of key technologies.
- **Lagging indicators** are retroactive verification of the successful or unsuccessful scaling and adopting of decarbonizing technologies (e.g., evaluations of progress toward net-zero targets).

The indicators outlined below can be used to track industry milestones and evaluate decarbonization progress. These metrics allow the integrated tracking of leading and lagging indicators, which can be updated and shared regularly. These milestones do not represent DOE targets but are important progress markers to create confidence across the ecosystem.

'Track'	Leading indicators / milestones	Lagging indicators / milestones
Overall	• Total investment in low-carbon cement	• Volume of low-carbon cement produced • Emissions intensity per tonne of cement industry-wide
Coordinated procurement model to unlock demand-pull across tracks	• Common methodology and standards for embodied carbon in cement and concrete (e.g., standard LCA methodology, EPD template) established and accepted by governments and the private sector • 'Library' of EPDs for low-carbon cement and concrete products established and made widely available • Commitments by large government and private-sector customers to buy low-carbon materials	• Share of government-driven cement procurement covered by low-carbon materials standards • Overall emissions intensity of government-purchased cement and concrete • Share of private-sector cement procurement covered by low-carbon materials standards
Clinker substitution, energy efficiency, and alternative fuels	• Successful demonstrations of LC3-type and ternary blends in key applications (e.g., road and highway pavings) by 2025 • Adoption or planned adoption of LC3-type and ternary blends by all 50 state DOTs	• Clinker factor (clinker share of cement mix by weight) industry-wide • Energy efficiency improvement relative to baseline • Alternative fuels share of industry energy consumption

CCUS	• 3–5 commercial-scale demonstrations by 2030, including demonstration of alternative capture technologies • Project finance model for CCUS established by 2030	• CCUS retrofits of existing plants, integration into new-build plants, associated capital formation
Alternative production methods	• 3–5 commercial-scale demonstrations by 2030 • Demonstrated technological success at commercial scale by 2030 • Initial cost reductions from FOAK to NOAK by 2030, consistent with commercial competitiveness with traditional production and CCUS • Products accepted under existing standards and adopted by large customers • Project finance model for greenfield deployments established by 2030	• Number of greenfield plant builds with alternative production methods and associated capital formation
Alternative binder chemistries	• Entry into the approval process and approval by industry standards organizations (timing will vary by material based on current TRL)	• Market share, starting in non-structural applications

Appendices

Appendix A: Modeling assumptions for Track A measures – clinker substitution, alternative fuels, and efficiency measures

Appendix A.1: Abatement potential and economic impact

Representative decarbonization pathways were modeled to estimate the economic and emissions impact of the currently deployable measures considered under Track A (clinker substitution, alternative fuels, and efficiency measures). Three representative scenarios were developed in consultation with industry experts to estimate the abatement potential and economic opportunity associated with deployment of these levers:

- **2030 Scenario 1: Moderate deployment.** More moderate but still ambitious deployment of key technologies, representing a slightly more ambitious set of deployment targets than the 2021 PCA roadmap. Modeling suggests the measures considered could abate 23% of sector emissions by 2030 if deployed consistent with Scenario 1 (22% from economically positive measures).
- **2030 Scenario 2: Aggressive deployment**. More aggressive deployment of key technologies by 2030, assuming targeted interventions can unlock accelerated scale-up. It presents a particularly ambitious, but achievable set of high-end targets. Modeling suggests the measures considered could abate 36% of sector emissions by 2030 if deployed consistent with Scenario 2 (32% from economically positive measures).
- **2050 Scenario**: Potential scale-up of key technologies in 2050. Modeling suggests the measures considered could abate up to 48% of sector emissions by 2050 if deployed consistent with this scenario (44% from economically positive measures).

These scenarios should be taken as directional estimates and are intended to be representative of feasible outcomes, not predictive or prescriptive. The report focuses on Scenario 2 to highlight an achievable upper-bound potential for deployable technologies, but, as noted in the report, industry is not presently on track to deploy at this scale. Significant intervention will be required to achieve deployment milestones consistent with Scenario 2.

Scenarios may overstate the potential impact from clinker substitution because they do not account for use of SCMs already taking place at ready-mix concrete plants, rather than cement plants. Scenarios may also overstate deployment potential of biomass fuels, which are in limited supply (discussed in Chapter 3).

Detailed assumptions and outputs are given for each scenario below. Note: for clinker substitution in all scenarios, “proportion in cement” refers to a weighted average across all modeled U.S. cement production, not the share of the material in a specific cement blend or at an individual cement plant.

2030 Scenario 1: Moderate deployment

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement in 2030	% energy savings	5%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 5-7%.
Energy Efficiency	Implied impact on emissions in 2030	% reduction in CO2e per tonne cement	5%	Assumed 5% reduction in energy emissions based on 5% energy emissions decrease.
Alternative fuels - biomass	Assumed % of total fuel needs in 2030	% of total fuel need	5%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~5% of fuel mix in 2030. Used assumption given high costs and supply constraints.
Alternative fuels - waste	Assumed % of total fuel needs in 2030	% of total fuel need	35%	PCA 2021 US roadmap (p 29) documents aspiration to use waste based alternative fuels for ~25% of fuel mix in 2030. Assumed 10% higher share in scenario given cost effectiveness of waste based alternative fuels.
Alternative fuels - waste	Tires as share of overall fuel mix 2030	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2030	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content.
Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2030	%	5%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximum substitution limits.
Clinker substitution	Clinker proportion in cement 2030	%	75%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050 with 0.85 target for 2030. Have assumed 0.75 target for 2030 could be met by using calcined clay and shifts of fly ash from concrete to cement production step.
Clinker substitution	Limestone proportion in cement 2030	%	10%	In-line with ASTM C595 range of 5-15%; exact ratio most likely given industry implementation/feasibility (Industry expert input).
Clinker substitution	Gypsum proportion in cement 2030	%	5%	Assumed share does not change in 2030.
Clinker substitution	Other proportion in cement 2030	%	0.7%	Assumed share does not change in 2030.
Clinker substitution	Calcined clay proportion in cement 2030	%	6%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics
Clinker substitution	Fly ash proportion to be mixed with clinker in 2030	%	2.0%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)

Clinker substitution	GGBFS proportion to be mixed with clinker in 2030	%	0.5%	Assumed no change given limited additional volumes likely going forward
Clinker substitution	Natural pozzolans proportion to be mixed with clinker in 2030	%	1.0%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2030		
Levers	Abatement cost (USD/tCO2)	Abatement potential (MtCO2)	% of BAU emissions abated
Energy efficiency	-31.1	1.5	2%
Alternative fuels - biomass	161.5	0.6	1%
Alternative fuels - waste	-4.6	6.4	7%
Clinker substitution	-54.0	11.4	13%

Annual savings to industry ($M)	(691.59)

2030 Scenario 2: Aggressive deployment

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement in 2030	% energy savings	5%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 5-7%
Energy Efficiency	Implied impact on emissions in 2030	% reduction in CO2e per tonne cement	5%	Assumed 5% reduction in energy emissions based on 5% energy emissions decrease
Alternative fuels - biomass	Assumed % of total fuel needs in 2030	% of total fuel need	15%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~5% of fuel mix in 2030. Used assumption given high costs and supply constraints
Alternative fuels - waste	Assumed % of total fuel needs in 2030	% of total fuel need	35%	PCA 2021 US roadmap (p 29) documents aspiration to use waste based alternative fuels for ~25% of fuel mix in 2030. Assumed 10% higher share in scenario given cost effectiveness of waste based alternative fuels
Alternative fuels - waste	Tires as share of overall fuel mix 2030	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2030	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content

Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2030	%	5%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximum substitution limits
Clinker substitution	Clinker proportion in cement 2030	%	65%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050 with 0.85 target for 2030. Have assumed 0.65 target for 2030 could be met by using calcined clay and shifts of fly ash from concrete to cement production step
Clinker substitution	Limestone proportion in cement 2030	%	15.0%	High-end of range of ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitution	Gypsum proportion in cement 2030	%	5%	Assumed share does not change in 2030
Clinker substitution	Other proportion in cement 2030	%	0.5%	Assumed share does not change in 2030
Clinker substitution	Calcined clay proportion in cement 2030	%	9%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics
Clinker substitution	Fly ash proportion to be mixed with clinker in 2030	%	3.0%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input). Assumed slight increase in fly-ash given economics and emission intensity, though potentially limited supply going forward
Clinker substitution	GGBFS proportion to be mixed with clinker in 2030	%	0.5%	Assumed no change given limited additional volumes likely going forward
Clinker substitution	Natural pozzolans proportion to be mixed with clinker in 2030	%	1.5%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2030		
Levers	**Abatement cost (USD/tCO2)**	**Abatement potential (MtCO2)**	**% of BAU emissions abated**
Energy efficiency	(31.1)	1.5	2%
Alternative fuels - biomass	34.2	3.4	4%
Alternative fuels - waste	(4.6)	6.4	7%
Clinker substitution	(59.4)	19.7	23%

Annual savings to industry ($M)	(1,246.47)

2050 Scenario

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement 2050	% energy savings	20%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 20-30%
Energy Efficiency	Implied impact on emissions in 2050	% reduction in CO2e per tonne cement	20%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 20-30%
Alternative fuels - biomass	Assumed % of total fuel needs in 2050	% of total fuel need	20%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~15% of fuel mix in 2050. Assumed slightly higher %
Alternative fuels - waste	Assumed % of total fuel needs in 2050	% of total fuel need	50%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~45% of fuel mix in 2050. Assumed slightly higher %
Alternative fuels - waste	Tires as share of overall fuel mix 2050	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2050	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content
Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2050	%	20%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximium substitution limits
Clinker substitution	% clinker in 2050	% of total cement	60%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050. Have assumed 0.6 target for 2050 could be met by using limestone, calcined clay, natural pozzolans, and innovative SCMs
Clinker substitution	Limestone proportion in cement 2050	%	13%	In-line with ASTM C595 range of 5-15%; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitution	Gypsum proportion in cement 2050	%	5%	Assumed share does not change in 2050
Clinker substitution	Other proportion in cement 2050	%	5.00%	Assumed mix of concrete waste and innovative SCMs.
Clinker substitution	Calcined clay proportion in cement 2050	%	15%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics

Clinker substitution	Pozzolans proportion in cement 2050	%	2%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2050		
Levers	**Abatement cost (USD/tCO2)**	**Abatement potential (MtCO2)**	**% of BAU emissions abated**
Energy efficiency	(31.1)	6.7	7%
Alternative fuels - biomass	30.1	4.5	5%
Alternative fuels - waste	(9.7)	10.1	10%
Clinker substitution	(59.9)	26.0	27%

Annual savings to industry ($M)	(1,866.14)

Appendix A.2: Economic deep dives

Economic deep dives were performed for select clinker substitutes and alternative fuels. General assumptions used for these deep dives are given below:

Category	Assumption	Unit	Value	Source / notes
Baseline - all	Capacity	Million tonnes/yr	1.5	Assumption, consistent with NETL 2023 modeling
Baseline - all	Utilization	Percent	100%	Assumption
Baseline - all	Lifecycle	years	20.0	Assumption
Baseline - alternative fuels	Coal cost	$/tonne of coal	60.0	US EIA
Baseline - alternative fuels	Coal emission intensity	kg CO2/ GJ of coal	96.1	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix
Baseline - alternative fuels	Coal heat value	GJ/tonne of coal	28.5	https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s01.pdf. Took mid-point of values between 24,400 and 32,500. Also: https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
Baseline - alternative fuels	Fossil fuel share of combined fuel	%	85%	GNR (2020 average)
Baseline - alternative fuels	Coal % of fossil fuel share	%	68%	GNR (2020 average)
Baseline - alternative fuels	Coal % of combined fuel	%	58%	Calculated
Baseline - alternative fuels	Petcoke % of fossil fuel share	%	21%	GNR (2020 average)
Baseline - alternative fuels	Petcoke % of combined fuel	%	18%	Calculated
Baseline - alternative fuels	Petcoke cost	$/ tonne of petcoke	163.8	Average 2022 price USGC Argus fob USGC 6.5pc sulphur coke index
Baseline - alternative fuels	Petcoke heat value	GJ/tonne petcoke	32.0	GNR (2020 average)
Baseline - alternative fuels	Petcoke emissions intensity	kgCO2/ GJ of petcoke	97.5	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix
Baseline - alternative fuels	Natural gas cost	$/GJ of natural gas	7.23	Calculated from below
Baseline - alternative fuels	Natural gas cost	$/MMBTU of natural gas	7.6	EIA average US industrial price 2022 - https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PIN_DMcf_a.htm
Baseline - alternative fuels	MMBtu to GJ conversion	GJ	1.1	
Baseline - alternative fuels	Natural gas % of fossil fuel share	%	11%	GNR (2020 average)

Baseline - alternative fuels	Natural gas % of combined fuel	%	9%	Calculated
Baseline - alternative fuels	Natural gas emission intensity	kg CO2/ GJ natural gas	56.1	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix.
Baseline - alternative fuels	Natural gas heat value	GJ/ton	48.5	midpoint, https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
Baseline - alternative fuels	Secondary fuel % of combined fuel	%	15%	GNR (2020 average).
Baseline - alternative fuels	Secondary fuel heat value	*GJ/tonne of fuel*	35.0	Assumption similar to waste tire.
Baseline - alternative fuels	Secondary fuel emission intensity	kg CO2/ tonne of fuel	85.0	Waste (tire) as proxy.
Baseline - alternative fuels	Secondary fuel cost	$/tonne of fuel	30.0	Assumption - 50% of coal value
Baseline - alternative fuels	Combined fuel emission intensity	kgCO2/ tonne combined fuel	90.9	Calculated
Baseline - SCM	Clinker proportion in cement	%	95%	GNR (2020 average)
Baseline - alternative fuels	Heat consumption	kJ per kg clinker	3875.0	GNR (2020 average)
Baseline - alternative fuels	Heat consumption	GJ per t cement	3.7	Calculation from above
Baseline - SCM	All in clinker cost	$/tonne of clinker	69.3	Clinker cost calculated in separate tab (see back up bottoms up build up). Adding in heuristic to account for additional processing etc., involved with clinker in cement production
Baseline - SCM	Clinker to cement heuristic	%	0.8	Heuristic to convert clinker cost to cost of clinker used for cement due to additional energy requirements
Baseline - SCM	Gypsum proportion in cement	%	5%	GNR (2020 average)
Baseline - SCM	Clinker emission intensity	kg CO2/ tonne of cement	790.0	Bottom-up analysis + median range from EPA, https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf
Baseline - SCM	Clinker emission intensity	kg CO2/ tonne of clinker	828.0	Chemical emissions from clinker (525kgCO2/tonne clinker) + fuel needed for kiln (303 kgCO2/tonne clinker)
Baseline - SCM	Gypsum emission intensity	kgCO2/ tonne gypsum	0.0	Assumed purchase of gypsum, resulting in scope 3 emissions
Baseline - SCM	Gypsum cost	$/tonne of cement	1.0	18 USD in 2018 for uncalcined gypsum in the US (Source: USGS); assuming 20 USD in 2020 and 5% per tonne of cement

Baseline - SCM	Gypsum cost	$/ tonne of gypsum	20.0	Calculated using gypsum proportion in cement
Alternative fuels - biomass	Capex for kiln bypass, storage	$M/plant	10.0	Industry expert input assumption, assumes multi-fuel burner (common in the US); equity financed 100%
Alternative fuels - biomass	Capex amortization period	years	2.0	To fully implement (equity financed 100%)
Alternative fuels - biomass	Biomass cost	$/tonne of wood	41.0	Average of Jan, Feb, March 2023 cost per tonne of manufacturing densified biomass products (EIA); https://www.eia.gov/biofuels/biomass/#table_data
Alternative fuels - biomass	Biomass heat value	GJ/tonne of wood	14.7	https://ens.dk/sites/ens.dk/files/Statistik/metode_traeaffald.pdf
Alternative fuels - biomass	Biomass emission intensity	kg CO2/ GJ of biomass	0.0	Industry expert input
Alternative fuels - biomass	Biomass % of total fuel	%	60%	Maximum potential given lower heat value of wood (combined fuel heat value should be 22GJ/ton+
Alternative fuels - waste	Capex for kiln bypass, storage	$M/plant	10.0	Industry expert input assumption, assumes multi-fuel burner (common in the US)
Alternative fuels - waste	Capex amortization period	years	2.0	To fully implement (equity financed)
Alternative fuels - waste	Tire cost	$/tonne tire chips	15.3	Calculated from below
Alternative fuels - waste	Opex cost of co-processing scrap tires	$/tonne of tires	10.0	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Assumed tires are pre-processed off-site before arriving at plant. Page 43 provides co-processing estimates from (GIZ/Holcim 2020, ICF 2017). Used low-end of estimates
Alternative fuels - waste	Cost of energy from tires	$/GJ	5.3	Proxy cost for sourcing tires (nominal cost of energy x heat value)
Alternative fuels - waste	Nominal price of energy from tires	$/GJ	0.2	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Page 44 provides estimates ($0.15/GJ, US tires 2021). Used mid-points of estimates and calculated $/tonne by multiplying by heat value
Alternative fuels - waste	Capex cost of scrap tires	$M/plant	1.0	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Page 43 provides pre- and co-processing estimates from (GIZ/Holcim 2020, ICF 2017). Used low end of estimate. Assumed pre-processing occurs offsite before arriving at plant
Alternative fuels - waste	Tire emission intensity	kg CO2/ GJ tire	85.0	https://www.eia.gov/environment/emissions/co2_vol_mass.php
Alternative fuels - waste	Tire heat value	GJ/kg tire	35.0	Used midpoint from Thermogravimetric and Kinetic Analysis of Co-Combustion of Waste Tires and Coal Blends (2021), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7931440/#:~:text=The%20calorific%20value%20of%20the,coal%20and%20other%20solid%20fuels

Alternative fuels - waste	Tire % of total fuel	%	20%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Alternative fuels - waste	Other waste cost	$/tonne other waste	11.38	Calculated using average of tire and waste plastics
Alternative fuels - waste	Capex cost for other waste	$M/plant	1.3	Calculated using average capex of waste tire and waste plastics
Alternative fuels - waste	Other waste emission intensity	kg CO2/ GJ other waste	80.0	Calculated using average of tire and waste plastics
Alternative fuels - waste	Other waste heat value	GJ/kg other waste	35.0	Calculated using average of tire and waste plastics
Alternative fuels - waste	Other waste % of total fuel	%	70%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Alternative fuels - waste	Waste plastic cost	$/tonne waste plastic	7.5	Calculated from below
Alternative fuels - waste	Cost of co-processing waste plastics	$/tonne of waste plastic	7.5	IFC 2017 report: INCREASING THE USE OF ALTERNATIVE FUELS AT CEMENT PLANTS: INTERNATIONAL BEST PRACTICE. Page 67 appendix table. Used mid-points of estimates for small facility given 5% production. Assumed pre-processing occurs offsite before arriving at plant
Alternative fuels - waste	Cost of energy from waste plastics	$/GJ waste plastic	0.0	Assumed cement plants receive this for free instead of being paid for it to go to landfills.
Alternative fuels - waste	Capex cost of waste plastics	$M/plant	1.6	IFC 2017 report: INCREASING THE USE OF ALTERNATIVE FUELS AT CEMENT PLANTS: INTERNATIONAL BEST PRACTICE. Page 67 appendix table. Used mid-points of estimates for small facility given 5% production. Assumed pre-processing occurs offsite before arriving at plant.
Alternative fuels - waste	Waste plastic emission intensity	kg CO2/ GJ waste plastic	75.00	Morgan Stanley Research Report - Cement decarbonization (Energy efficiency and alternative fuels)
Alternative fuels - waste	Waste plastic heat value	GJ/kg waste plastic	35.0	ECRA 2016; EPA 2020b
Alternative fuels - waste	Waste plastic % of total fuel	%	10%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Clinker substitutes - Fly ash	Fly ash to be mixed with clinker	%	30%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - Fly ash	Emission intensity fly ash	kg CO2/ tonne fly ash	0.1	MPA Fact Sheet 18, CO2e of UK cement, additions and cementitious material
Clinker substitutes - Fly ash	Fly ash cost	$/tonne fly ash	45.0	Industry expert input

Clinker substitutes - all	Proportion gypsum to be mixed with clinker	%	5%	Global Cement and Concrete Association, 2020 (US numbers)
Clinker substitutes - all	Gypsum cost	$/ tonne of gypsum	20.0	Calculated using gypsum proportion in cement and USGS $/tonne gypsum
Clinker substitutes - GGBFS	Proportion to be mixed with clinker	%	0.5	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - GGBFS	Emission intensity	kg CO2/ tonne GGBFS	79.6	MPA Fact Sheet 18, CO2e of UK cement, additions and cementitious material, assuming transport costs and grinding at plant)
Clinker substitutes - GGBFS	GGBFS cost	$/tonne GGBFS	55.0	https://www.chemanalyst.com/Pricing-data/ggbfs-1307#services
Clinker substitutes - natural pozzolans	Natural pozzolan cost	$/tonne pozzolans	11.0	USGS Mineral Yearbook 2022 Summary, construction sand cost as a proxy (incl extraction, transport and margin of the seller)
Clinker substitutes - natural pozzolans	Proportion to be mixed with clinker	%	0.3	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - natural pozzolans	Emission intensity	kg CO2/ tonne pozzolans	0.1	Similar to fly ash, assuming no additional treatment needed
Clinker substitutes - calcined clay	CC % to be mixed with clinker	%	30%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - calcined clay	Proportion limestone to be mixed with clinker	%	15%	Industry expert input
Clinker substitutes - calcined clay	CC emission intensity	kg CO2/ tonne of CC	187.3	Refer to emission intensity of CC tab
Clinker substitutes - calcined clay	Limestone emission intensity	kgCO2/ tonne limestone	8.0	Limestone fines, MPA Fact sheet 18 CO2e of UK cement, additions and cementitious material
Clinker substitutes - calcined clay	Calcined clay cost	$/tonne CC	7.0	Assumed similar raw material opex cost as limestone given similarity of processes (e.g., extraction) and abundance as clay
Clinker substitutes - calcined clay	Limestone cost	$/ tonne of limestone	7.0	USGS Mineral Yearbook Summary for crushed stone (incl. limestone), selling price (2022) at $14/ton, deducting transportation costs (50 km at 0.1 USD/t/km = 5 USD) and margin of 20% gives proxy for production costs at ~$7/ tonne
Clinker substitutes - calcined clay	Capex for additional rotary kiln	$M/plant	6.6	Financial Attractiveness of LC3, K. Scrivener, A. Dekeukelaere, F. Avet, L. Grimmeissen (assuming rotary kiln at plant at capacity, no available one for use given US demand. Assuming rotary kiln instead of flash calciner, given current commercial availability constraint of latter

Clinker substitutes - calcined clay	Capex for silo from other types of cement	$M/plant	8.0	Industry expert input and cross-checked with press clippings on project announcements for cement silos (e.g., Tokyo Cement announced a Cement terminal with 3 cement silos costing total of $12M in 2021). https://www.globalcement.com/news/item/13440-tokyo-cement-commissions-colombo-cement-terminal. Assumed higher cost per terminal
Clinker substitutes - calcined clay	Capex for raw material storage	$M/plant	1.0	Industry expert input
Clinker substitutes - calcined clay	Amortization period	years	2.0	
Clinker substitutes - calcined clay	Heat consumption of calcined clay	TJ/ton	2.2	THAA Cemtech 2021
Clinker substitutes - calcined clay	Electricity for grinding	kwh/ton	20.0	Loesche
Clinker substitutes - calcined clay	Electricity	USD/ MWh	73	US EIA
Clinker substitutes - calcined clay	Maintenance cost for new equipment	$/tonne calcined clay	5	Assumption: 50% of cement maintenance costs
Clinker substitutes - calcined clay	Labor costs for new equipment	$/tonne calcined clay	12.13	65% of labor costs for baseline (lower production volume)
Baseline - all	WACC	%	10%	Assumption

Appendix A.3: Representative efficiency measures

The modeling exercise assumes adoption of representative efficiency measures outlined below, identified based on input from industry experts:[46]

Initiative	Electrical saving (kwh/t)	Thermal saving (GJ/t)	Investing cost ($/t)
Efficient transport systems (elevator instead of air conveyor)	3.4	0	3
Process control vertical mill	1.55	0	1
Energy management and process control	4	0	1
High efficiency classifiers in cement (product) mill	3.95	0	2
Improved grinding media in ball mills	4	0	0.5
High efficiency motors (applying variable speed drive)	3	0	0.2
Efficient fans with variable speed drive	7	0	1.3
Optimization of compressed air systems	3	0	0.2
Efficient lighting (led)	0.3	0	0.3
Production of low alkali cement	0	0.44	0
Convert to reciprocating grate cooler	-3	0.27	2.9
Kiln combustion system improvements	0	0.3	1
Optimize heat recovery/upgrade clinker cooler	-2	0.105	0.2
Seal replacement in the kiln process	0	0.011	0.1
Low pressure drop cyclones	2.55	0	3
Efficient kiln drives motors	0	0	0.3
Improved refractories material	0	0.5	0.3
Kiln shell heat loss reduction	6.1	0.365	0.3
Adjustable speed drive for kiln fan	0.1	0	0.2
Selecting raw material with lower friction coefficient	0	0	0.1
Selecting raw material with lower humidity	0.1	0.1	0.1
Selecting raw material with lower dimension	0	0.1	0.1

46 Energy savings and costs estimated based on Mokhtar, Nasooti (2020), "A decision support tool for cement industry to select energy efficiency measures." *Energy Strategy Reviews*.

Appendix B: CCUS economics assumptions

Figures for carbon capture are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using a CANSOLV amine-best post-combustion system, on a 1.5 MTPA cement plant.[47] Capital costs are adjusted to reflect a 12-year payback period using capital recovery factors from the Energy Futures Initiative.[48] Transportation and storage costs of ~$10–40 per tonne of captured CO2 are assumed, consistent with Carbon Management Liftoff report.[49]

This estimate does not include other owner's costs such as pre-production costs associated with start-up and performance evaluation and inventory of chemicals and spare parts for ongoing operations. These costs are assumed to be limited and not to materially alter project economics.

Detailed calculations for storage (CCS) and utilization (CCU) cases are provided in Table B.1 and Table B.2, respectively.

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Table B.1: CCS economics

Assumption	Low	High	Sources / notes
Case used	CM95-B	CM95-B	PH/PC kiln with coal/coke
Capital costs			
Total capex, $M	$ 544,376,000.00	$ 544,376,000.00	From NETL study for CM95-B
Capital recovery factor	0.11	0.13	CRF used by EFI for 12-year payback (compare to NETL CRF for 30-year payback of 4.63%)
Amortized capital cost, $ p.a.	$ 59,881,360.00	$ 70,768,880.00	
Operating costs			
Fixed O&M, $ p.a.	$16,575,809.00	$16,575,809.00	From NETL study for CM95-B
Variable O&M, $ p.a.	$11,335,656.00	$11,335,656.00	From NETL study for CM95-B
Total O&M, $ p.a.	$27,911,465.00	$27,911,465.00	From NETL study for CM95-B
Fuel + Power, $ p.a.	$33,649,342.00	$33,649,342.00	From NETL study for CM95-B
OPEX, $ p.a.	$61,560,807.00	$61,560,807.00	From NETL study for CM95-B
Total cost p.a.	$121,442,167.00	$132,329,687.00	
CO2 captured, tonnes p.a.	1,104,478	1,104,478	Assumes 95% capture of 1,162,608 tonnes CO2 emitted from kiln p.a. for dry PH/PC kiln
Cement output, tonnes p.a.	1,500,000	1,500,000	Assumption of NETL study

Model outputs	Low	High
Cost of capture, $ / tonne of CO2	$109.95	$119.81
Total capital cost, $ / tonne of CO2	$ 54.22	$ 64.07
Total O&M cost, $ / tonne of CO2	$25.27	$25.27
Fuel + power cost, $ / tonne of CO2	$30.47	$30.47
Cost of capture, $ / tonne of cement	$80.96	$88.22
Total capital cost, $ / tonne of cement	$ 39.92	$ 47.18
Total O&M cost, $ / tonne of cement	$18.61	$18.61
Fuel + power cost, $ / tonne of cement	$22.43	$22.43
With T&S		
Transport & storage cost, $ per tonne of CO2	$10	$40
Transport & storage cost, $ per tonne of cement	$7.36	$29.45
Cost of capture + T&S, $ / tonne of CO2	$119.95	$159.81
Cost of capture + T&S, $ / tonne of cement	$88.32	$117.67
Premium on $130 base price per tonne of cement	68%	91%
Net of 45Q		
45Q, $ per tonne of CO2	$85	$85
45Q, $ per tonne of cement	$62.59	$62.59
Cost of capture + T&S net of 45Q, $ / tonne of CO2	$34.95	$74.81
Cost of capture + T&S net of 45Q, $ / tonne of cement	$25.74	$55.09
Premium on $130 base price per tonne of cement	20%	42%
Cost reduction to breakeven with 45Q	29%	47%
Offtake commitment contract sizing		
Offtake commitment p.a.	$38,606,317.00	$82,628,177.00
Total offtake commitment (12 yrs)	$463,275,804.00	$991,538,124.00

Table B.2: CCU economics

Assumption	Low	High	Sources / notes
Case used	CM95-B	CM95-B	PH/PC kiln with coal/coke
Capital costs			
Total capex, $M	$ 544,376,000.00	$ 544,376,000.00	From NETL study for CM95-B
Capital recovery factor	0.11	0.13	CRF used by EFI for 12-year payback (compare to NETL CRF for 30-year payback of 4.63%)
Amortized capital cost, $ p.a.	$ 59,881,360.00	$ 70,768,880.00	
Operating costs			
Fixed O&M, $ p.a.	$16,575,809.00	$16,575,809.00	From NETL study for CM95-B
Variable O&M, $ p.a.	$11,335,656.00	$11,335,656.00	From NETL study for CM95-B
Total O&M, $ p.a.	$27,911,465.00	$27,911,465.00	From NETL study for CM95-B
Fuel + Power, $ p.a.	$33,649,342.00	$33,649,342.00	From NETL study for CM95-B
OPEX, $ p.a.	$61,560,807.00	$61,560,807.00	From NETL study for CM95-B
Total cost p.a.	$121,442,167.00	$132,329,687.00	
CO2 captured, tonnes p.a.	1,104,478	1,104,478	Assumes 95% capture of 1,162,608 tonnes CO2 emitted from kiln p.a. for dry PH/PC kiln
Cement output, tonnes p.a.	1,500,000	1,500,000	Assumption of NETL study

Model outputs	Low	High
Cost of capture, $ / tonne of CO2	$109.95	$119.81
Total capital cost, $ / tonne of CO2	$ 54.22	$ 64.07
Total O&M cost, $ / tonne of CO2	$25.27	$25.27
Fuel + power cost, $ / tonne of CO2	$30.47	$30.47
Cost of capture, $ / tonne of cement	$80.96	$88.22
Total capital cost, $ / tonne of cement	$ 39.92	$ 47.18
Total O&M cost, $ / tonne of cement	$18.61	$18.61
Fuel + power cost, $ / tonne of cement	$22.43	$22.43
With T&S		
Transport & storage cost, $ per tonne of CO2	$10	$40
Transport & storage cost, $ per tonne of cement	$7.36	$29.45
Cost of capture + T&S, $ / tonne of CO2	$119.95	$159.81
Cost of capture + T&S, $ / tonne of cement	$88.32	$117.67
Premium on $130 base price per tonne of cement	68%	91%
Net of 45Q		
45Q, $ per tonne of CO2	$85	$85
45Q, $ per tonne of cement	$62.59	$62.59
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Cost of capture + T&S net of 45Q, $ / tonne of cement	$25.74	$55.09
Premium on $130 base price per tonne of cement	20%	42%
Cost reduction to breakeven with 45Q	29%	47%
Offtake commitment contract sizing		
Offtake commitment p.a.	$38,606,317.00	$82,628,177.00
Total offtake commitment (12 yrs)	$463,275,804.00	$991,538,124.00

Appendix C: Capital formation sizing

The capital formation opportunity for cement is estimated roughly and directionally for 2030, 2050, and cumulatively, assuming two kinds of deployments:

- Scale-up of currently deployable measures (e.g., clinker substitution and alternative fuels) at all plants excluding grinding-only plants, including active plants and potential additions by 2030 and 2050. [50, 51] Efficiency measures are not included because of data limitations.
- Scale-up of CCUS and alternative production measures—assumed to have roughly the same CAPEX requirement based on industry conversations—at all plants excluding grinding-only plants, including currently active plants and potential additions by 2030 and 2050.

For the 2030 horizon, it is assumed that currently deployable measures are fielded at the entire footprint of cement plants, while CCUS and alternative production methods see ~3–5 initial deployments each, consistent with their Pathways to Liftoff.

For the 2050 horizon, it is assumed that the remaining plant sites (those not covered by demonstrations) see deployment either of a CCUS retrofit or greenfield build using an alternative production method or potentially a novel chemistry.

This approach may overstate CAPEX requirements in two ways:

- It assumes CAPEX for all measures will remain roughly consistent regardless of plant size. For CCUS, greenfield plants, and in many cases of the currently deployable measures, CAPEX is unlikely to vary with plant size, given that similar equipment is required regardless of production capacity. In other cases, plant size may have more of an impact on CAPEX.
- It does not assume CAPEX reductions from FOAK to NOAK.

A detailed CAPEX buildup is given in Table C.

50 Excluding five current plants that are grinding-only.

51 Number of potential new-build plants is estimated by calculating the 1.5 MTPA plants required to meet incremental demand by 2030 and 2050. Potential new-build plant capacity may be overstated if incremental demand is met with latent capacity at existing plants rather than new construction.

Table C: Capital formation sizing

	By 2030		Incremental by 2050		Cumulative by 2050	
	Low	High	Low	High	Low	High
Est. plant footprint						
Baseline plant footprint, excluding 5 grinding-only plants, #	93	93	93	93		
Baseline production (2022), Mtpa	95	95	95	95		
Production in outyear (2030 or 2050), Mtpa	109	109	124	124		
Est. capacity per new build plant, Mtpa	1.5	1.5	1.5	1.5		
Implied new build plants, #	9	9	19	19		
Implied total plants, excluding grinding-only, #	102	102	112	112		
CAPITAL FORMATION						
Demonstrations						
CCUS						
Assumed CCUS demo CAPEX, $M	500	1,000	500	1,000		
CCUS demos, #	3	5				
Total CCUS demo CAPEX	1,500	5,000				
Alt production methods						
Assumed alt production method demo CAPEX, $M	500	1,000	500	1,000		
Alt production method demos, #	3	5				
Total alt production method demo CAPEX	1,500	5,000				
Total demo CAPEX	3,000	10,000			3,000	10,000
Deployments						
Currently deployable measures						
Alternative fuels and efficiency CAPEX per plant, $M	10	10	10	10		
Clinker substitution CAPEX per plant, $M	16	60	16	60		
Total CAPEX per plant, $M	26	70	26	70		
Total plants deployed, #	102	102	10	10		
Total CAPEX for deployment	2,652	7,140	260	700	2,912	7,840
CCUS or alt production methods						
CAPEX per deployment, $M	500	1,000	500	1,000		
Total plants deployed, # (excluding demos)	0	0	106	102		
Total CAPEX for deployment	0	0	53,000	102,000	53,000	102,000
TOTAL CAPITAL FORMATION Incremental by outyear, $M	5,652	17,140	53,260	102,700	58,912	119,840

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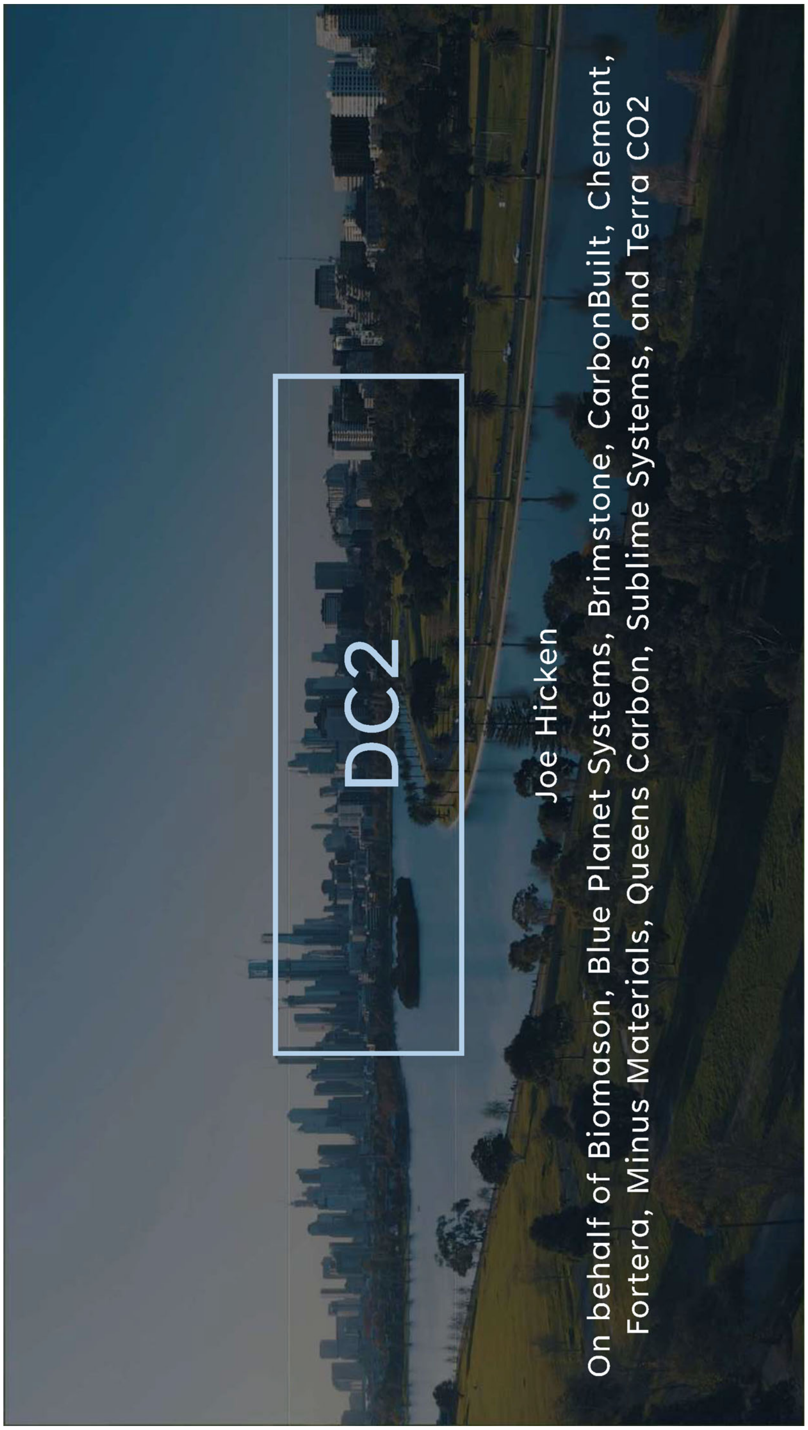
Sublime Systems

APPENDIX 4


DC2
Joe Hicken
On behalf of Biomason, Blue Planet Systems, Brimstone, CarbonBuilt, Chement,
Fortera, Minus Materials, Queens Carbon, Sublime Systems, and Terra CO2

ABOUT US

DC_2 is a coalition of innovative companies at the forefront of the global effort to reduce carbon emissions from cement and concrete. Our ten current members—Biomason, Blue Planet Systems, Brimstone, CarbonBuilt, Chement, Fortera, Minus Materials, Queens Carbon, Sublime Systems, and Terra CO2—are pioneering North American venture- and private-sector-backed climate technology companies dedicated to delivering ultra-low carbon, carbon-neutral, and carbon-negative cement and concrete solutions. Collectively, our technologies rethink production processes and feedstocks, introduce novel materials, and utilize or sequester CO_2 directly in concrete—all with a goal of decarbonizing the cement and concrete sector.

SHARED OBJECTIVES

LOW-CARBON FUTURE

To build future infrastructure with low-carbon cement & concrete

LOCAL JOBS, LOCAL SUPPLY

To create new American jobs, bolster US competitiveness and reinforce local economies and local supply chains

INDUSTRIAL BASE CAPACITY

To scale up the low-carbon cement and concrete industrial *manufacturing* base

ENVIRONMENTAL JUSTICE

To promote co-benefit generation and environmental justice in designing the future of manufacturing

SHARED POLICY LEVERS

PRODUCTION TAX CREDITS

Per dollar per kg of CO_2 abated, low-carbon cement and concrete is one of the most efficient taxpayer investments in avoiding CO2.

DEMAND SUPPORT

A well-constructed demand-side support strategy will unlock additional private financing to commercialize transformational solutions

EARLY ADOPTER PLATFORMS

We will seek to use the power of the public sector to convene sandbox testing to build confidence

LOW-CARBON GLOBAL STANDARDS

Ecolabeling is fraught with non-standard accounting.

TRANSFORMATIONAL PROCUREMENT POLICIES

Procurement policies that are attempting to buy clean and accelerate innovation are blunted by incrementalist, or supply-limited product offerings

THE GWP OF THE FINAL CONCRETE DRIVES EVERYTHING.

Collectively, we are technology agnostic. More shots on goal = greater probability of success in avoiding, abating, capturing and storing carbon to net-zero success.

TECHNOLOGY

We have distinct technologies that will drive down GWP of the critical materials that comprise our modern society

DEPLOYMENT

We are innovating, from displacing high GWP binders, to net-negative feedstocks, to alternative manufacturing, to mineralization of CO_2 (alone or in combination)

ADOPTION

We live in a world built to suit. We have customers that prefer prescription, performance, and customer-determined applications

IMPACT

Our success is not driven by innovation alone, but by the combination of adoption and net carbon reduction

BIOMASON

biomason.com

TECH	Biocement® grows in ambient temperatures, building with carbon to create controlled, structural cement for products or applied services
DEPLOY	A bacterial process that enables concrete manufacturers to decouple from cement-based manufacturing for block plants and precast products
IMPACT	Uses carbon as an input, enabling carbon-negative pathways through the production of construction materials

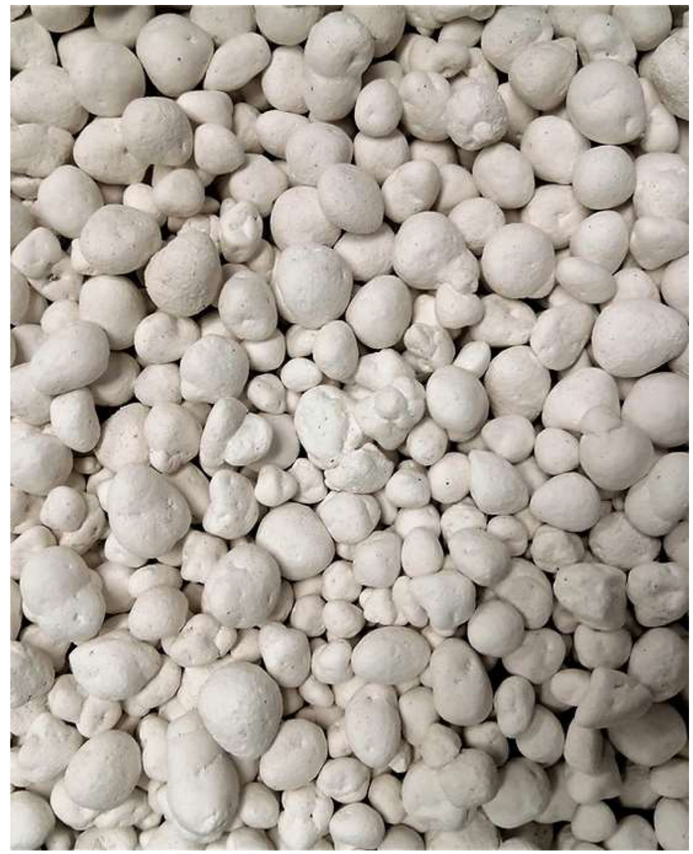
2023

BLUE PLANET SYSTEMS

blueplanetsystems.com

TECH	Geomimetic mineralization technology uses CO2 from any source as a feedstock to create ultra-low/carbon negative aggregative
DEPLOY	Commercial demonstration plant operating in CA to produce carbon-sequestering aggregate to be utilized in concrete as a replacement for virgin aggregate
IMPACT	Potential to store up to 1,120 lbs of CO2 per cubic yard of concrete

2023



BRIMSTONE

brimstone.com

TECH

Carbon-negative process that produces portland cement from a carbon-free calcium silicate rock instead of limestone

DEPLOY

Portland cement from the Brimstone process is physically and chemically identical to conventional portland cement

IMPACT

As reflected in a third-party LCA, the Brimstone process is carbon-*negative* across a range of energy-use scenarios.

2023

CARBONBUILT

carbonbuilt.com

TECH

Retrofits of existing concrete masonry facilities with off-the-shelf equipment to enable ultra-low carbon concrete technology, including utilization of low-carbon raw materials and waste CO2.

DEPLOY

Commercially available concrete masonry units at CarbonBuilt's flagship retrofit in Alabama, with additional retrofits underway

IMPACT

70-100% carbon footprint reduction, through both avoidance and mineralization, compared to facility baseline

2023

CHEMENT

chement.co

TECH	Renewable electricity + CaO3 to perform the chemical reaction with less energy and less CO2 emitted + cheaper carbon capture
DEPLOY	Cement for cast in place concrete deployed via ready-mix concrete producers
IMPACT	• More efficient production • No energy emissions • Easier carbon capture

2023

FORTERA

forterausa.com

TECH

The Fortera ReCarb™ process re-carbonates Calcium Oxide without losing its cementitious properties, resulting in a cementitious mineral that is rich in CO_2.

DEPLOY

- SCM blend up to 35%
- 100% OPC substitute

IMPACT

- 70-100% Reduction in CO_2 per ton of cement
- Commercial Plant in Redding, CA

2023

MINUS MATERIALS

minusmaterials.com

TECH	Producing carbon-negative, biorenewable limestone powder using microalgae, sunlight, seawater and CO_2
DEPLOY	Minus Materials limestone is "plug and play" as a raw material for portland cement production or a filler for portland limestone cement
IMPACT	Elimination of process (calcination) emissions during portland cement manufacturing, and permanent CO2 storage as a filler or SCM.

QUEENS CARBON

queenscarbon.com

TECH	Breakthrough ultra-low CO2 manufacturing technology to produce cementitious materials from industry-standard raw materials
DEPLOY	Modular & scalable reactors that produce decarbonized SCM's at the cement plant
IMPACT	• Limitless, cost-competitive SCM supply • 20-50% cement decarbonization

SUBLIME SYSTEMS

sublime-systems.com

TECH

Clean, all-electric extraction of calcium and reactive silica from zero-carbon raw materials resulting in cement that exceeds performance and durability standards (ASTM C1157)

DEPLOY

Currently manufacturing by the ton: ultra-low-carbon cement for ready-mix concrete producers building cast in place structures

IMPACT

Independent third-party LCA (preliminary EPD) indicating >93% reduction in CO_2

2023

TERRA CO2

terraco2.com

TECH	Conversion of inexpensive, abundant, and local feedstocks from existing aggregate mines to high-performing and cost-competitive cementitious materials
DEPLOY	Supplement, blend, or replace Portland cement
GEO	Headquarters and pilot plant located in Golden, Colorado.

2023

POINTS OF CONTACT

CONNOR WOODRICH
cwoodrich@forterausa.com
>

MICHELE BLACKBURN
mblackburn@terraco2.com

TROY HOTTLE
troy.hottle@biomason.com

SAL BRZOZOWSKI
sbrzozowski@carbonbuilt.com

SIMON G. BRANDLER
simon@brimstone.com

SARAH WILLIAMS
sarah.williams@minusmaterials.com

LAURA BERLAND-SHANE
laura@blueplanetsystems.com

DANIEL KOPP
daniel@queenscarbon.com

POINTS OF CONTACT

GREG HOUCHINS
greg@chement.co

JOE HICKEN
joe@sublime-systems.com

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NO CRYSTAL BALL

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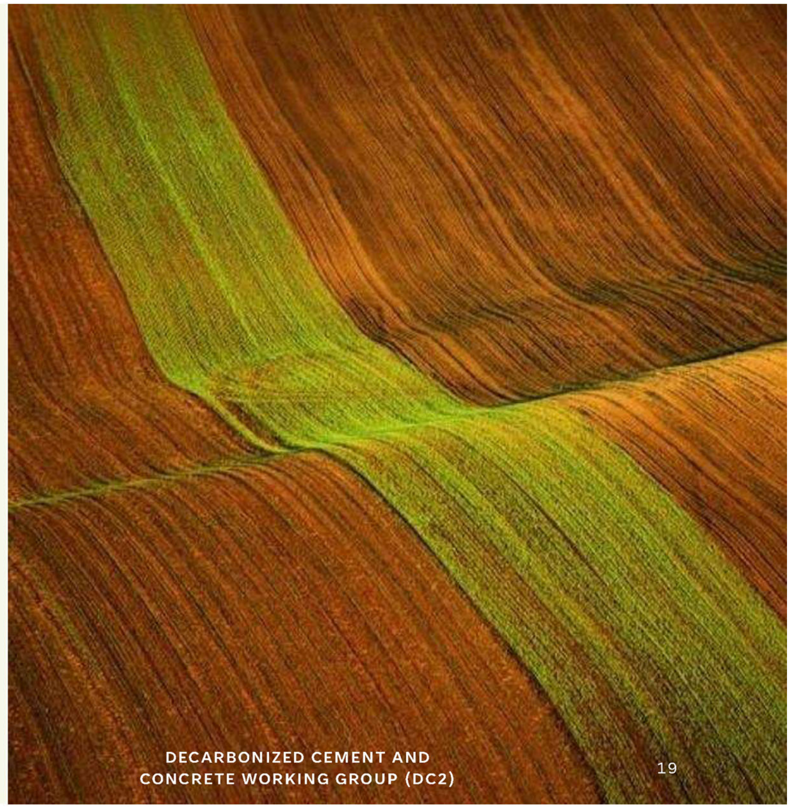

Senate Committee on Environment and Public Works
Hearing Entitled *"Opportunities in Industrial Decarbonization: Delivering Benefits for the Economy and the Climate"*
November 15, 2023
Questions for the Record for Dr. Ellis

Senator Sullivan:

1. The cement industry is responsible for about 8% of global carbon emissions. Natural pozzolans are a domestically sourced material used as a replacement ingredient for fly ash and calcined limestone in the manufacture of cement and concrete. Replacing up to 40%, and potentially up to 50% in some circumstances, of the cement in concrete with natural pozzolans could reduce the carbon content of the replaced cement by approximately 90%. As evidenced by ancient Greek and Roman concrete structures still standing today, natural pozzolans are durable. Beyond any particular grant opportunity, what can we do to help advance the vision of companies and entrepreneurs that want to advance the incorporation of natural pozzolans in cement manufacturing?

Dr. Ellis:

Sublime Systems is exceedingly supportive of natural pozzolan as a method to reduce the amount of carbon-intensive portland cement required in today's concrete. In fact, Sublime's cement cures through a similar chemical reaction – we cite the durability of Roman concrete as the evidence and justification for our more efficient cement manufacturing process.

As CR Minerals, a company that specializes in the production of natural pozzolans, describes: concrete formulations using portland cement can take advantage of the Roman process of converting Calcium Hydroxide (CH) into Calcium-Silicate-Hydrate (CSH), the binder in concrete, by doing what they did: adding sufficient natural pozzolan to consume all the available CH in the concrete. In doing so, a potentially destructive by-product in modern day concrete (the CH) is converted into performance and endurance-enhancing CSH. When CH, a by-product of the hydraulic reaction of portland cement and water, is left to its own devices, it creates porosity in concrete. The porosity allows for the ingress of deleterious chemicals and water, which then leads to harmful reactions within the concrete - such as Alkali Silica Reactivity (ASR), Sulfate attack, Chloride attack on reinforcement, efflorescence, and freeze-thaw damage. The by-product CH can help fortify concrete – when natural pozzolan is added to the concrete mix, or when left alone it can initiate destructive processes in the concrete that can lead to concrete failure.

Sublime eagerly supports manufacturers of materials that reduce the overall global warming potential of the final cast-in-place concrete. In fact, one of our key advisors is Jeff Whidden, the President of CR Minerals. Their product is already commercially available, and would be categorized in the DOE cement Liftoff report as a supplementary cementitious material that is a "currently deployable measure." CR Minerals and other distributors of natural pozzolans face the same treatment as Sublime Systems – carbon avoidance technologies are not rewarded by tax incentives like the 45Q which rewards producers of carbon dioxide that subsequently capture it and store it. A new Production Tax Credit or a modification of the 45Q credit should reward all technologies that reduce the embodied carbon of concrete. Today, the 45Q credit picks winners in a way that doesn't support free market innovation." Additionally, like Sublime, natural pozzolans would benefit from a broader embrace of performance-based standards, which do not dictate a specific composition or recipe but a material's performance across durability and strength parameters. This will be required for many natural pozzolans to take up 40-50% of the cement blend, and a wider endorsement of these by public sector agencies will help clear that path.

Senator CAPITO. Thank you.
Ms. ANGIELSKI.

STATEMENT OF SHANNON ANGIELSKI, PRESIDENT, CLEAN HYDROGEN FUTURE COALITION

Ms. ANGIELSKI. Thank you, Ranking Member Capito, also to the Chairman and members of the committee for this opportunity to discuss the role that clean hydrogen can play in industrial decarbonization.

As the President of the Clean Hydrogen Future Coalition, I represent a diverse set of stakeholders that came together to promote clean hydrogen as a critical pathway to achieve global decarbonization objectives. Our foundational principle is to decarbonize the economy through technology neutral and resource agnostic, or, as we call it, color-blind policy, that will enable clean hydrogen to be a scalable decarbonization solution.

Obviously, we know the international climate authorities have identified clean hydrogen as a pathway for meeting global climate targets, and that is really because clean hydrogen is a game changer. It has the ability to accelerate decarbonization across all sectors as well as transition existing and create new skilled, high-paying jobs that underpin the clean energy transition.

There is a thriving hydrogen market today that operates. It is mainly used in petroleum refining and ammonia production, which represents approximately 90 percent of total domestic hydrogen production in use. Other hydrogen applications are used in smaller quantities for synthetic fuels, chemicals and plastics or other niche applications. However, we currently produce hydrogen almost totally from natural gas, and that is because we have low cost, abundant supplies that supported by a vast network of infrastructure.

As Senator Capito already pointed out, there are alternative methods to lower the carbon intensity of these hydrogen production methods such as electrolytic hydrogen using zero emitting electricity, as well as reforming of fossil fuels with carbon capture and storage.

If the domestic refining industry were to convert their existing production methods to produce clean hydrogen, that process in and of itself would reduce industrial sector greenhouse gas emissions by 5.5 percent. That is really not an insignificant number, particularly after what Leah has already said. There are other industries that do not currently use hydrogen, as already has been mentioned, steel, concrete and others, so we have several ways to decarbonize those industries using clean hydrogen.

I really want to thank Congress for the work that has already been done, both bipartisan and through the IRA. Many of these programs Senator Capito already mentioned, and the witnesses, so I will not talk about the hydrogen hubs, which are critical at this point, as well as the Section 45E tax credits and the industrial decarbonization funding. But there has also been other legislation introduced by Senators Coons and Cornyn that I want to raise that would enable clean hydrogen to decarbonize the industrial sector and port operations.

In the last Congress, Representatives Tonko and McKinley introduced a bill that would establish a pilot program at DOE to enter into contracts for differences to offset what are the increased costs associated with the production or purchase of clean hydrogen in industrial applications.

The Coalition is also recommending that Congress consider funding a new program in the farm bill. This would provide grants for the production and use of ammonia that is produced with clean hydrogen as a feedstock for domestic fertilizer production and as a tool to lower, obviously, greenhouse gas emissions in the industrial sector. There are a couple of hydrogen hubs that are looking at that sector to provide their clean hydrogen to offset those fertilizer production methods.

While groundbreaking and necessary investments made by Congress will serve as a significant down payment to expand the clean hydrogen economy, it is important to recognize that additional policies will be needed to achieve economies of scale and stimulate the use of clean hydrogen, particularly in those industries where hydrogen is not currently used as the incumbent fuel or feedstock.

DOE suggests that securing long term off-take agreements for clean hydrogen is one of the key near-term challenges, as well as the associated infrastructure buildout. The long term off-take agreement is really due to the significant cost gap between the cost of clean hydrogen and the incumbent fuels, which are much cheaper, as I have already mentioned, as well as the volumes of hydrogen that are needed to decarbonize these industrial processes.

DOE has also indicated that in order to achieve their goal of 50 million tons of clean hydrogen per year by 2050, the entire clean hydrogen supply chain must scale rapidly. That will only occur if new policy is adopted that incentivizes the private sector investments that are needed.

There is precedent for Congress to enact policy support to stimulate the creation of new markets when it deems it is necessary to do so. Clearly the existing domestic clean hydrogen market will need similar policy treatment. We look forward to working with Congress to develop and design some of those new demand use policies that will enable capital creation.

As the Administration considers how to implement an indirect booking claim accounting system for implementing the 45E tax credit, the Coalition wants to caution against adopting principles such as additionality or hourly time matching as those measures would delay investment and make clean hydrogen unnecessarily costly.

The Coalition is pleased that Chairman Carper, along with Senator Cantwell and ten of her Senate Democratic colleagues, submitted letters to the Administration urging against adopting overly prescriptive regulations that would make the use of the 45E tax credits largely inaccessible, and have the negative impact of little private sector investment, and really delay the ability of clean hydrogen to be an industrial decarbonization tool.

I want to conclude my remarks by sharing the significant benefits that have already been discussed through industrial decarbonization and that clean hydrogen can bring. It can bring a lot of benefits to communities across the Country in jobs, as well as health impacts and reduction in environmental emissions, and creating a new clean hydrogen commodity market carries significant economic value and positions the U.S. to be a global leader in the export of hydrogen.

Thank you again and we appreciate the opportunity to be here.

The prepared statement of Ms. Angielski follows:]

Clean Hydrogen Future Coalition

Written Testimony of Shannon Angielski

President

Clean Hydrogen Future Coalition (CHFC)

Before the

Senate Environment and Public Works Committee

Hearing on "Opportunities in Industrial Decarbonization: Delivering Benefits for the Economy and the Climate"

CHFC Testimony:

The Role of Clean Hydrogen in Industrial Decarbonization

Washington, D.C.

November 15, 2023

CHFC Clean Hydrogen Future Coalition

Introduction and Background on the Clean Hydrogen Future Coalition

Thank you, Chairman Carper, Ranking Member Capito, and members of the committee for this opportunity to discuss opportunities for industrial decarbonization, and how it can deliver benefits for the economy and climate.

Modeling by the Intergovernmental Panel on Climate Change (IPCC) and others predicts that global climate change mitigation efforts will fall short of the 2°C target unless the world's energy system — from power generation to all end-use sectors — undertakes substantial technological changes. One of the most viable technology pathways that international climate modeling authorities have identified for meeting those climate targets is clean hydrogen.

Clean hydrogen is a game changer and has the ability to accelerate decarbonization across all sectors of the U.S. economy, as well as transition existing — and create new — skilled, high paying jobs needed to support the clean energy transition. Multiple domestic industries have identified clean hydrogen as a critical component of their strategy for achieving net-zero greenhouse gas (GHG) emission targets.

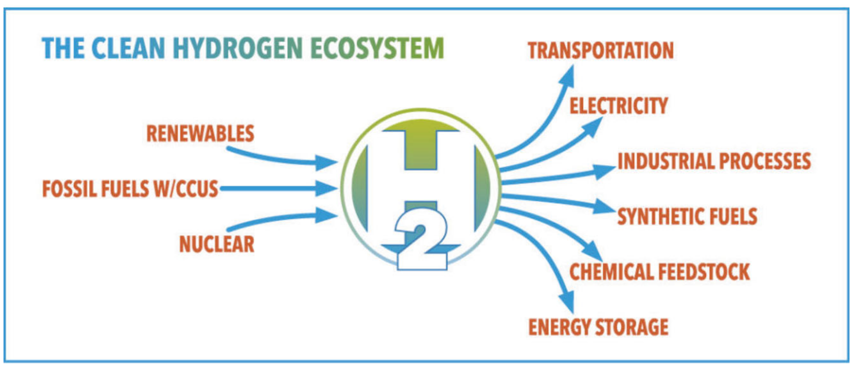

Figure 1: The Clean Hydrogen Ecosystem

The CHFC was founded to bring together a diverse set of stakeholders to promote clean hydrogen as a critical pathway to achieve global decarbonization objectives while also increasing U.S. global competitiveness. The coalition came together around the foundational principle to decarbonize the economy through the advancement of technology neutral and resource agnostic policy needed for clean hydrogen to be able to be widely used throughout our energy system.

The CHFC membership reflects the full clean hydrogen ecosystem, including energy companies, labor unions, utilities, NGOs, equipment suppliers and project developers who are committed to the advancement of a net zero GHG economy that is supported by new and existing infrastructure across the supply chain to fully scale clean hydrogen production and use in the U.S. Success in reaching our decarbonization goals will require a robust and sustained set of policies to incentivize investments in clean hydrogen production, distribution, and use throughout the economy. Several of our members represent a variety of sectors that already use hydrogen, or that can use hydrogen as a replacement fuel or feedstock, and new users of hydrogen, including those industries that currently produce and use hydrogen in the U.S., and which will be the focus of this testimony.

Existing Industrial Markets for Hydrogen and its Potential to Decarbonize Industry

Clean – or low-carbon – hydrogen has significant potential to decarbonize the industrial sector in both existing market applications that typically use fossil-derived hydrogen as well as in new industrial applications that do not currently use hydrogen. In industrial processes where hydrogen is combusted, it does not emit carbon dioxide (CO_2). In processes where hydrogen is used as a feedstock, replacing it with clean hydrogen will lower the GHG emissions profile of those products.

Existing Industrial Hydrogen Uses

Today, the primary demand for fossil-derived hydrogen is as a chemical feedstock in petroleum refining to remove sulfur and upgrade heavy oil into more refined fuels (55% of total U.S. hydrogen use) and ammonia for fertilizer production (35%).[1] Other existing industrial applications use hydrogen in smaller quantities including combining hydrogen and CO_2 to produce methanol and which serves as a feedstock to produce other fuels and chemicals such as plastics.

Approximately 10 million metric tons (MMT) of hydrogen are domestically produced annually for these end uses, almost totally from natural gas.[2] The reason for this is because of the low-cost and abundant supplies of natural gas, which also reflects the existing infrastructure available to transport and distribute natural gas at low cost to industrial facilities.

The largest share of hydrogen produced and used domestically is in the refining and ammonia sectors. Clean hydrogen can serve as a replacement for the carbon-intensive hydrogen currently used in those sectors and result in lower CO_2 emissions. If the current hydrogen production, nearly all of which is produced with natural gas using steam methane reforming, utilized 90% CO_2 capture and storage, emissions would be reduced by more than 80 MMT per year, and that amount would increase if some of the clean hydrogen is produced by electrolysis using electricity from non-emitting sources. By comparison, current direct industrial sector emissions are 1490 MMT annually, which means current hydrogen production, if decarbonized, could reduce industrial emissions by 5.5% annually.[3] Replacing the fossil-derived hydrogen with clean hydrogen represents an immediate opportunity to decarbonize these industrial uses of hydrogen.

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[1] U.S. Department of Energy, "Pathways to Commercial Liftoff: Clean Hydrogen", March 2023
[2] U.S. Department of Energy, "Pathways to Commercial Liftoff: Clean Hydrogen", March 2023
[3] U.S. Environmental Protection Agency Greenhouse Gas Inventory, April 2023.

In addition, utilizing or repurposing existing infrastructure that already serves carbon-intensive industries that cannot be electrified will be a cost-effective way to immediately move toward industrial decarbonization. America's existing pipeline infrastructure serves many of the identified existing industrial sectors and can be used to transport blends of hydrogen and immediately begin reducing the GHG emissions of those industries.

Clean Hydrogen Production

There are two main pathways to produce clean hydrogen:

1. Electrolytic hydrogen, which uses zero-emissions energy such as nuclear or renewable energy, to power an electrolyzer that passes an electric current through water, splitting it into hydrogen and oxygen.
2. Reforming fossil fuels with carbon capture and storage (CCS), which uses fossil fuels to create hydrogen and then captures and stores the CO2 emissions produced in the process.

New Industrial Uses of Clean Hydrogen

There are other industrial processes that do not currently use hydrogen, but can, or even may need to, use clean hydrogen to reduce GHG emissions.

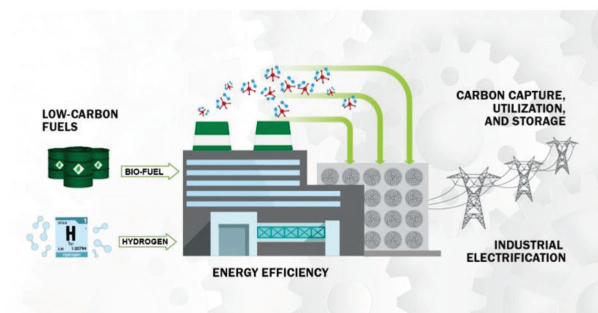

Figure 2: Role of Clean Hydrogen in Industrial Decarbonization[4]

The U.S. steel industry heavily relies on fossil fuels as a reducing agent with the iron ore to produce steel products. A blast furnace heats purified coal or coke, limestone, and iron ore, then injects it with oxygen to remove impurities. An alternative process for processing iron ore is the direct reduced iron (DRI) method, which removes oxygen from iron ore in the solid state, without melting it. The reducing agents are typically reformed natural gas or coal. Given domestic steelmaking represents approximately 8% of total domestic industrial GHG emissions,

[4] Source: U.S. Department of Energy

replacing the fossil fuels with clean hydrogen can significantly contribute to reduced industrial GHG emissions and the steelmaking process.[5]

Other industries that require high-heat intensity processes, such as cement, can use clean hydrogen to produce the high heat energies required. New uses of clean hydrogen that can substantially reduce emissions include the production of sustainable aviation fuel (SAF) which utilizes captured CO_2 emissions and clean hydrogen to make fuel.

Federal Policy Support for Industrial Decarbonization and Clean Hydrogen

Congress has embraced the role clean hydrogen can play in our country's industrial decarbonization goals through enactment of major federal programs, including providing funding for industrial decarbonization grants in both the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA); the Clean Hydrogen Hub program created in BIL; and the Section 45V clean hydrogen production tax credit program established in the IRA.

Nearly $6 billion in funding appropriated by Congress in both the BIL and IRA recognized the contributions that clean hydrogen can make to decarbonize the U.S. industrial sector. Currently, the Department of Energy (DOE) is reviewing applications for which it solicited proposals for using clean hydrogen in some of the highest emitting, hardest-to-abate industries where rapidly deployed decarbonization technologies can have the greatest impact, including iron, steel production, and steel mill products. In this funding opportunity, hydrogen and carbon capture-specific projects should be transformative and specific to the Department's industrial decarbonization objectives. Hydrogen-based, direct reduced iron making facilities; hybrid glass furnace approaches such as hydrogen fueling with electrification; the development of new ironmaking or steelmaking technologies using hydrogen integration; or the conversion of existing iron and steelmaking thermal processes using hydrogen integration are just some examples of how hydrogen will be used in this program and others to help decarbonize the U.S. industrial sector.

The Regional Clean Hydrogen Hub program administered by DOE seeks to create interconnected networks of clean hydrogen infrastructure, producers, and consumers, promoting clean hydrogen as an energy carrier and energy storage solution while facilitating the commercial-scale adoption of clean hydrogen. Congress appropriated $8 billion for this program to establish a minimum of four regional clean hydrogen hubs with at least two regional clean hydrogen hubs to be located in the regions of the United States with the greatest natural gas resources. The other two can be located in any region of the United States as long as they meet the criteria of feedstock diversity, end-use diversity and employment opportunities. DOE has allocated up to $7 billion in funding to establish the regional hubs, and in October announced the selection of seven hub awardees that will enter negotiations as part of this program. DOE is proposing to use the remaining $1 billion in funding to create a program to address the challenge of building demand for clean hydrogen by designing support mechanisms for end uses. DOE is exploring

[5] Oak Ridge National Laboratory (US DOE), "Potential Decarbonization Strategies and Challenges for the U.S. Iron & Steel Industry", Sachin Nimbalkar, PhD.

options such as pay-for difference contracts and reverse auctions to assist buyers in securing financing. The program will aim to overcome financing hurdles for potential hydrogen buyers, provide transparency market prices and contract terms to accelerate the adoption of clean hydrogen.

The 45V clean hydrogen production tax credit was enacted in the IRA with the goal of promoting clean hydrogen production within the U.S. This incentive offers a tax credit for each kilogram of clean hydrogen produced to projects that commence construction prior to 2033 and provides that tax credit for a period of ten years. The credit amount is determined based on the lifecycle GHG emissions intensity of the hydrogen. Congress designed the credit to provide a higher tax credit value for producing low to zero GHG emissions intensity clean hydrogen production, with a maximum credit of $3 per kilogram of clean hydrogen.

In addition to BIL and IRA, federal legislation has been introduced in the House and Senate that recognizes the need for stimulating industrial demand of clean hydrogen and designed to help reduce the costs of adopting clean hydrogen:

- The **Hydrogen for Industry Act**, introduced by Senator Coons and Senator Cornyn, directs the Secretary of Energy to establish a "Hydrogen Technologies for Heavy Industry Demonstration Program." Under this program, the Secretary will provide grants for commercial-scale demonstration projects for end-use applications of hydrogen; construction of new commercial-scale facilities that will use hydrogen as a fuel or feedstock; or retrofits or expansion of an existing facility determined to be qualified to enable use of hydrogen as a fuel in the industrial application of hydrogen. The bill also directs the Department of Transportation (DOT), DOE, and Department of Commerce (DOC) to jointly conduct a study to examine the potential for emissions reductions at industrial facilities through hydrogen applications.

- The **Clean Hydrogen Deployment Act of 2021**, introduced by Congressman Paul Tonko and Congressman David McKinley in the 117th Congress, establishes a pilot program at the DOE to enter into contracts on a competitive basis with entities for payment of increased costs associated with the production or purchase of eligible hydrogen for use in projects. The goal is to support clean hydrogen users by offsetting increased costs associated with using hydrogen. When selecting entities, the Secretary shall pick projects that use eligible hydrogen as a feedstock in an industrial application such as ammonia; use hydrogen as a fuel in an industrial application; use hydrogen as a fuel in a transportation application; use hydrogen in a power application; and use hydrogen produced using electricity generated from zero-emission energy sources.

Recognizing the need for domestic market stimulation, the coalition is recommending that Congress consider a new program and amendments to existing programs in the Farm bill. CHFC is recommending Congress include incentives for the production and use of ammonia produced with clean hydrogen for the production and use of domestic fertilizer. This would lower GHG emissions in the agricultural sector and reduce dependence on imports of fertilizer from foreign adversaries. CHFC's proposal would authorize the U.S. Department of Agriculture (USDA) to provide grants for producing and using ammonia made with decarbonized hydrogen by expanding the USDA's mission under last year's Fertilizer Production Expansion Program. Some of the selected hydrogen hubs are already targeting decarbonized fertilizer as one of their major end-uses in their hubs to expand the production and use of clean hydrogen in those regions.

The CHFC is also recommending that Congress embrace the use of decarbonized hydrogen in other programs authorized in the Farm bill including: (1) modifying the definition of "renewable energy systems" under the Rural Energy for America Program to include decarbonized hydrogen; (2) amending the definition of eligible technologies" under USDA's Section 9003 loan program to include decarbonized hydrogen produced from biogas or agricultural waste; and (3) embracing the energy storage benefits of decarbonized hydrogen in the implementation of the Rural Energy Savings Program.

Challenges and Drivers for Scaling Commercial Clean Hydrogen Investment in Industrial Decarbonization

While groundbreaking and necessary investments made by Congress in the BIL and IRA will serve as a significant downpayment to expand the clean hydrogen economy and decarbonize the U.S. industrial sector, it is important to recognize additional federal policies will be needed to achieve economies of scale, lower the cost of hydrogen production and stimulate the use of clean hydrogen within the industrial sector. Particularly in industries where hydrogen is not an incumbent fuel or feedstock, such as steel, chemicals or those in which it is a replacement for heat-intensive uses, additional policy will be critical to reducing costs and stimulating market adoption.

45V will be a key driver to catalyzing a domestic clean hydrogen market. The policy is designed to significantly reduce the cost of clean hydrogen production so it can compete with traditionally produced hydrogen. About $1/kg is the estimated average cost for current hydrogen production using natural gas without CO_2 capture. This equates to roughly $7.50 per mmBtu of natural gas on a heat content basis. However, the $1 per kg cost does not include any additional costs to compress, transport and store clean hydrogen, which means the $1 per kg cost will be higher for industrial users. Those industrial users will be facing the equivalent of more than $7.50 per mmBtu in replacement fuel or feedstock prices. However, today's price of natural gas is roughly $3 per mmBtu. The delivered cost of the clean hydrogen – not including the need for the industrial user to potentially modify or add new infrastructure at the industrial site and the potential added investment costs of the delivery infrastructure – is too expensive to adopt in these industries as a replacement fuel or feedstock.

In a recent International Energy Agency (IEA) report, the IEA indicates that "*efforts to stimulate (clean) hydrogen demand are lagging behind what is needed to meet climate ambitions*."[6] In the U.S., DOE's "Commercial Liftoff Report: Clean Hydrogen" identifies one of the near-term challenges to "clean hydrogen liftoff" is securing long-term offtake for clean hydrogen, which is due to the significant cost gap between the cost of clean hydrogen and the incumbent fuel or feedstock. DOE also recognized this challenge for the Regional Clean Hydrogen Hub program by

[6] International Energy Agency, "Global Hydrogen Review 2023".

reserving $1 billion in hub funding to create a program to address the challenge of building demand for clean hydrogen. Lack of demand is a critical gap as viewed by CHFC members and filling it is key to the success of scaling a domestic – and global – clean hydrogen industry.

Long-term demand for clean hydrogen is needed to catalyze capital investment in the domestic supply chain necessary to lower costs and allow the market to mature. The IEA states that "*without robust demand, producers of low-emission hydrogen will not secure sufficient off-takers to underpin large-scale investments, jeopardising the viability of the entire (clean) hydrogen industry*."[7] This includes investments in equipment manufacturing such as electrolyzers to produce clean hydrogen, additional infrastructure such as new pipelines or modifications to existing pipelines needed to distribute clean hydrogen, or modifications at existing industrial facilities in order to use clean hydrogen. Corporations will not make investments in any aspect of the supply chain until there are demonstrated market end-uses through long-term offtake agreements that will drive the return on the full supply chain of investments. Policies designed to close this gap would help to secure long-term offtake agreements and accelerate the ability of clean hydrogen to decarbonize the industrial sector.

DOE recognizes that "*to scale the clean hydrogen market from less than 1 million tons per year today to DOE's target of 50 million tons per year by 2050, **the entire clean hydrogen supply chain must scale rapidly**…*"[8] The IEA indicates that globally, clean hydrogen is being "*taken up very slowly in existing applications, accounting for just 0.7% of total hydrogen demand. The report suggests that hydrogen production and use in 2022 was linked to more than 900 Mt of CO_2 emissions.*"[9] Rapid scaling of the clean hydrogen supply chain will only occur if there is new policy that incentivizes the investments needed.

<u>Policy Needs for Accelerated Adoption of Clean Hydrogen in the Industrial Sector</u>

The IEA has called for global government action by stating "*governments need stronger policy action on multiple fronts to tap into the opportunity that low-emission hydrogen offers*", and to "*take bolder action to stimulate demand creation for (clean) hydrogen, particularly in existing hydrogen uses.*"[10] CHFC members are evaluating a suite of policy tools that could be considered by Congress to incentivize the use of clean hydrogen in industrial applications, including those proposed for the Farm bill as well as legislation that has already been introduced in Congress to address this need.

There is precedent for Congressional support for the creation of new markets where it deems policy is necessary to do so – such as the renewable energy and carbon capture and storage industries – by enacting policies in the form of tax credits, research and development funding to reduce costs, streamlined infrastructure permitting through the FAST21 Act, and loan guarantees. The existing domestic clean hydrogen market will need similar policy treatment.

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[7] International Energy Agency, "Global Hydrogen Review 2023".
[8] U.S. Department of Energy, "Pathways to Commercial Liftoff: Clean Hydrogen", March 2023
[9] International Energy Agency, "Global Hydrogen Review 2023".
[10] International Energy Agency, "Global Hydrogen Review 2023".

CHFC urges Congress to develop new demand-use policies that will enable capital creation for clean hydrogen investment.

As Congress and the Administration continue to work to implement policies to promote the production and use of clean hydrogen, care must be taken not impose policies that will restrict or preclude innovation and the ability of a clean hydrogen industry to scale. CHFC supports policy designs that stimulate the production and use of low-cost, clean hydrogen with a fully transparent lifecycle GHG accounting system applied consistently across the value chain. To that end, CHFC has been very engaged on the implementation of the 45V clean hydrogen production tax credit and DOE's proposed clean hydrogen production standard (CHPS) to ensure that this policy delivers on the intent of stimulating the clean hydrogen economy in the U.S.

As stated by DOE in its *Liftoff* report, clean hydrogen will only be a climate change mitigation solution if policies are adopted to accelerate its ability to be used by industry. The coalition wishes to reinforce the colloquy on 45V between Chairmen Wyden and Carper on the Senate floor during consideration of the IRA, in which they agreed that the use of indirect book and claim accounting should be used to determine the carbon intensity of the clean hydrogen production methods:

> "*It is also my understanding of the intent of section 13204, is that in determining 'lifecycle greenhouse gas emissions' for this section, the Secretary shall recognize and incorporate indirect book accounting factors, also known as a book and claim system, that reduce effective greenhouse gas emissions, which includes, but is not limited to, renewable energy credits, renewable thermal credits, renewable identification numbers, or biogas credits*.
>
> *Is that the chairman's understanding as well?*
>
> *Mr. WYDEN. Yes.*"

Indirect book and claim accounting will be critically important to accelerate the ability of clean hydrogen to be adopted and enable it to decarbonize industry. Treasury should adopt the use of such indirect book and claim accounting. As Treasury considers how to implement an indirect book and claim accounting system, policies such as additionality, prescriptive time matching, or limiting the use of book and claim accounting will significantly delay investments in clean hydrogen production, make the use of clean hydrogen in the industrial sector unnecessarily costly, and delay the intended impact of decarbonizing hard to abate industrial sectors, and should be avoided.

- *Additionality*: The CHFC does not recommend strict additionality requirements, including requiring clean hydrogen producers to utilize only newly built clean resources, be included in the 45V guidance. The CHFC values the importance of decarbonizing the grid and ensuring that clean energy resources are available for that purpose. Nationwide, there are many renewable energy projects in interconnection queues. In many cases these projects have waited 5+ years to break ground. Guidance on the 45V tax credit should recognize that these resources and associated transmission interconnections will take time to construct. As renewables are added to the grid and transmission capacity increases, time-matching and regional requirements should become more restrictive, but additionality should not be a requirement.

- *Time-matching*: Currently, there is both a lack of sufficient zero-emitting resources and a nationwide administrative system for accounting for renewable energy certificates (REC) and energy attribute certificates (EAC) on hourly time scales. As new renewable sources of power are developed, driven by other IRA incentives, and accounting systems improve, more restrictive time matching can be implemented. The CHFC recommends annual matching until 2030 before adopting more frequent time matching.
- *Regional Matching*: There are only certain regions of the country that have sufficient zero-emissions resources that enable co-locating electrolyzers with those resources. Restrictive regional matching will limit the investment in clean hydrogen produced from zero-emissions resources. As additional zero-emitting resources are added over time, so too should regional restrictions evolve in parallel.

The CHFC is pleased that Chairman Carper, along with Senator Cantwell and 10 of her Senate Democratic colleagues, submitted letters to the U.S. Treasury Department, the DOE and the White House on this issue, urging caution that the Administration not adopt overly prescriptive implementing regulations that would make use of the tax credit inaccessible and have the devastating consequence of little private sector investment in the clean hydrogen industry – which will only delay the ability of clean hydrogen to be an industrial decarbonization tool. Importantly, as the Chairman well knows, as the lead Senate sponsor of the 45V tax credit bill, Senator Carper's colloquy's message on the book and claim accounting factors for the 45V program reflects the Congressional intent of how the 45V tax credit program should be implemented by the Administration. In addition, a half dozen labor unions submitted similar letters with similar precautionary messages, urging the Administration to consider the job impact potential of the tax credit program in addition to balancing the important, expected environmental benefits of the program. All of those letters, as well as the CHFC letters, are attached as appendices to my testimony.

<u>Benefits of Clean Hydrogen in Industrial Decarbonization</u>

Growth of a clean hydrogen industry presents an opportunity to provide benefits to communities across the country, including transitioning and creating jobs, climate benefits, and decreased air pollution. It also presents opportunities to expand economic growth and provide domestic energy security benefits.

Community, Health, Environmental and Climate Benefits

As stated throughout this testimony, using clean hydrogen in the industrial sector will enable the U.S. to accelerate its decarbonization goals and reduce other emissions associated with the use of fossil fuels across the industrial sector that have significant local and regional beneficial impacts. Using clean hydrogen in the industrial sector will improve air quality in many areas of the country, which will have direct benefits for local communities. In addition, environmental and health benefits are also seen at the source of clean hydrogen production if derived from low- or zero-emission sources.

Domestic Job Transition and Creation

Companies that have existing expertise in hydrogen production and operations, such as industrial gas, chemicals, oil and natural gas, as well as labor unions with the skilled workforce, will support the transition and help to expand the workforce needed for the clean hydrogen economy to grow.

In 2030, DOE reports that the hydrogen economy could create approximately 100,000 net new direct and indirect jobs related to the build-out of new capital projects and new clean hydrogen infrastructure, which represents roughly 450,000 cumulative job-years through 2030. Direct jobs include employment in fields such as engineering and construction. Indirect jobs include roles in industrial-scale manufacturing and the raw materials supply chain. In addition, new job skills such as electrolyzer and electrolyzer component manufacturing, expanding fuel cell expertise, and electrolysis facility engineering, procurement, and construction (EPC) expertise will be created.[11]

Analysis conducted by Rhodium identifies job creation at an individual facility level, which suggests that jobs at clean hydrogen production facilities will range from 330 to 520 jobs during construction, and ongoing maintenance and operations jobs at the facility will range from 45 to 65 jobs. The construction jobs include construction trades, metal workers and assemblers, legal workers, engineers,) executive and business operations, production occupations, and machinery installers, maintenance, and repairers. The operations jobs include installers, maintenance, and repairers, production occupations, executive and business operations, engineers, and plant system operators.[12]

Economic and Energy Security Benefits

The economic benefits of a domestic clean hydrogen industry extend beyond the economic impact of the jobs it will create. Creating a new clean hydrogen commodity market carries significant economic value and positions the U.S. to be a global leader in the production, use and export of clean hydrogen. Doing so will increase U.S. balance of trade and enable the U.S. to maintain energy security by being a domestic producer and user.

Conclusion

Industrial decarbonization represents the most immediate and clear opportunity to achieve our decarbonization goals, and clean hydrogen has a significant role to play in decarbonizing hard to abate industrial sectors. An-all-of-the-above approach to clean hydrogen production will accelerate the ability to scale and leverage investments in both new and existing infrastructure needed for clean hydrogen to be adopted by the industrial sector. The CHFC applauds Congress

[11] U.S. Department of Energy, "Pathways to Commercial Liftoff: Clean Hydrogen", March 2023

[12] Rhodium Group, "Clean Hydrogen Workforce Development: Opportunities by Occupation", Galen Hiltbrand, Whitney Jones, Ben King, and Nathan Pastorek, September 27, 2023

CH2FC

for recognizing the value of this approach and looks forward to working with members of this Committee and in the Senate to design and adopt policies that will aid in the expansion of the clean hydrogen industry and its ability to rapidly decarbonize our industrial base.

CHFC

Appendix A – 45V Letters to Treasury

1. Letter to Administration from Chairman Carper
2. Senate Letter to Administration on 45V Hydrogen Production Tax Credit
3. Trade Union letters
    - United Association
    - NABTU
    - LiUNA
    - United Brotherhood of Carpenters and Joiners of America
    - International Brotherhood of Electrical Workers
4. CHFC Comments on Credits for Clean Hydrogen and Clean Fuel Production (Notice 2022-58)
5. CHFC Supplemental Comments on the Credit for Clean Hydrogen Production (Notice 2022-58)

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Ranking Member Capito:

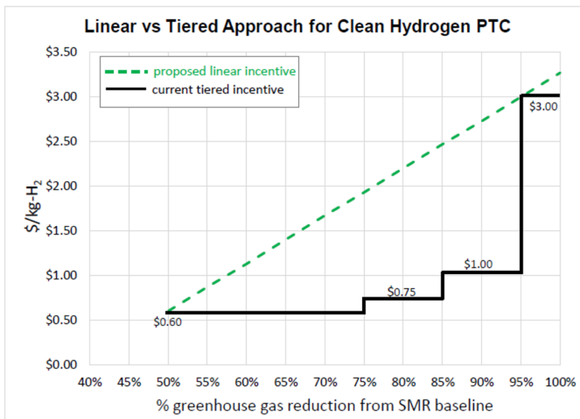
1. *I did not vote for the so-called Inflation Reduction Act (IRA) and was not involved in its drafting, but that law established the 45V clean hydrogen production tax credit. I have heard concerns from stakeholders that the IRA explicitly prohibits the stacking of the 45V tax credit and the 45Q carbon capture tax credit, while there is no similar prohibition on stacking 45V with either the 48E renewable investment or 45Y renewable production tax credits. Do you believe that the IRA authors' decision not to allow 45Q and 45V credits to "stack" is detrimental to blue hydrogen?*

RESPONSE:

Yes, the decision to not allow 45Q credits to stack with 45V is detrimental to blue hydrogen. Prior to enactment of the 45V tax credits, CHFC advocated to increase the credit values of the lower three tiers of the tax credit in order to attract private investment for the production of blue hydrogen. As one way to achieve that, CHFC suggested the ability to stack 45V and 45Q the same way 45V can be stacked with renewable and nuclear electricity incentives. CHFC believes this will be critical as the current credit values will not be sufficient to attract the scale of investments needed for blue hydrogen. It will be difficult to accelerate the scale of a clean hydrogen industry without the contributions that blue hydrogen must make – we need the scale of the infrastructure that blue hydrogen will bring to produce and move the volumes of clean hydrogen for it to be an effective decarbonization technology.

Instead of using the four-tiered approach included in 45V, the clean hydrogen PTC, the CHFC also advocated using a linear method to set the value of the tax credit. The linear method avoids the extreme step-changes in the PTC values and instead utilizes a straight-line approach, using the same values for the end points as the current tiered method (see Appendix A). This would best incentivize clean hydrogen (H_2) production based on its CO_2 intensity. This method will also provide better financing terms for all project developers by avoiding extreme changes in the value of the credit due to small fluctuations in the operations of a facility.

Both the tiered and linear approaches would rely on the results of the required lifecycle analyses (LCAs) for the conventional steam methane reforming baseline as well as for new, clean hydrogen production methods. This creates uncertainty for project developers that is significantly compounded by the steep drops in the value of the tax credit in the tiered approach. For example, when considering hydrogen produced from solar electricity, depending on how the CO_2 intensity is calculated, it may not be able to achieve the top tier of credit values, and could drop to levels insufficient to incentivize clean hydrogen production using solar. With the linear approach, changes in the CO_2 intensity values are proportional to changes in the tax credit values. Given the operations of a hydrogen production facility can vary, a project that achieves a CO_2 intensity of 0.42 in one year may only achieve a CO_2 intensity of 0.48 in another and, under the tiered approach, would drop to the lower value of the tax credit from \$3 to \$1/kg H_2 for that year of operation. This creates significant uncertainty for financial investment.



a. *Do you have any further comment on how the structure of 45V or the "stackability" with renewable investment tax credits and production tax credits is meant to maximize returns for green hydrogen and not for blue hydrogen using CCUS?*

RESPONSE:

As you will see in the table below, the stacking of renewable electricity credits with 45V for electrolytic clean hydrogen production greatly increases the total value of tax credit benefits for clean hydrogen projects utilizing electrolysis. The table also shows the total value of tax credit benefits if 45Q were allowed to be stacked with the value of the 45V credit. So, in response to this question, yes, the ability to stack the renewable tax credits with 45V does maximize returns for green hydrogen and not for blue hydrogen. Note that two projects with the same CO_2 intensity (see the second tier) receive vastly different levels of tax benefits. An electrolysis project using 95% renewable and 5% grid average electricity would be eligible for a combined \$2.33/kg H_2 from 45V and the renewable electricity production tax credit. Whereas a project using natural gas and CO_2 capture and storage would be eligible for \$1.00/kg H_2 without stacking with 45Q and \$1.73/kg H_2 if stackability were allowed.

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CO_2 intensity[1] kg CO_2e/kg H_2	45V credit	Sec.45 RE credit[2]	total 45V + RE credit	45Q credit CO_2 capture[3]	total 45V + 45Q credit
<0.45	\$3.00	\$1.40	\$4.40	NA	NA
0.45 to <1.5	\$1.00	\$1.33	\$2.33	\$0.73	\$1.73
1.5 to <2.5	\$0.75	NA	NA	\$0.71	\$1.46
2.5 to 4	\$0.60	NA	NA	\$0.69	\$1.29

[1]includes emissions from electricity use (100% and 95% RE), reforming, and upstream methane
[2]assume 50 kWh/kg H_2 for electrolyzer; 2023 value of renewable energy (RE) PTC =\$0.28/kWh
[3]CO_2 capture and sequestration rates of 90 – 95% and upstream CI of 0.6 to 2.7 kg CO_2e/kg H_2

2. *What concerns do you have over the proposed additionality requirements and do you believe this could stifle the growth of all types of hydrogen, due to additional costs and the potential for permitting delays? What would a strict additionality requirement mean for this nascent industry?*

RESPONSE:

The CHFC rejects additionality requirements and supports allowing clean hydrogen producers to use existing clean power sources. Additionality would significantly delay investments in clean hydrogen projects by forcing them to wait until new clean energy projects come into service. It takes on average seven years for a new renewable project to come online once an interconnection agreement is filed. That means a renewable project that is entering into the interconnection queue in April 2023 would not become operational until April 2030 at the earliest, which is nearly at the end of the 45V tax credit program. Project development delays would not only undermine the ability of projects to use this tax credit but delay our nation's ability to decarbonize.

Nor are additionality requirements included in 45V statutory language, demonstrating lack of Congressional intent to require additionality requirements in 45V implementation. In fact, Congressional intent that additionality is not required is demonstrated by the fact that the tax credits established in Section 45U of the Code for existing nuclear facilities can be stacked with 45V tax credits. Strict additionality would be incredibly restrictive on a budding industry and the federal government should enact rules that enable the hydrogen industry to get off the ground.

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Senator Mullin:

1. *Can you speak to the importance of permitting reform for utilizing existing natural gas infrastructure to blend hydrogen for industrial carbonization?*

RESPONSE:

In a letter to Senator Martin Heinrich dated October 26, 2021, then Federal Energy Regulatory Commission Chairman Richard Glick indicated that the Commission has "broad authority under the Natural Gas Act to regulate the terms and conditions for interstate natural gas pipeline transportation service" and that the Commission would "maintain jurisdiction over an interstate natural gas pipeline if that pipeline were to blend some amount of hydrogen into gas stream."[1] However, clear statutory authority to blend hydrogen with natural gas would provide more certainty and avoid questions of interpretation of that authority under the NGA.

Permitting reform will be needed for the buildout of additional pipeline infrastructure which will be needed to transport natural gas and hydrogen blends. Ensuring that industrial centers are able to site and permit pipelines to transport and receive hydrogen or blends of hydrogen and natural gas will ensure that the buildout of a clean hydrogen economy is not slowed by outdated and inefficient permitting processes.

2. *Can direct use of low-carbon fuels offer better solutions than electrification?*

RESPONSE:

Not all industrial energy uses can be electrified. For these applications, low-carbon fuels – particularly clean hydrogen – can offer better solutions. To decarbonize the U.S. economy, it will be critical to enact policies and regulations that foster innovation and growth in the low-carbon fuel sector.

3. *How can growing a domestic hydrogen market complement the important role of natural gas in America's energy security?*

RESPONSE:

Expanded domestic natural gas production has enabled the U.S. to become less reliant on foreign markets to meet domestic energy consumption needs. Increased self-reliance has bolstered energy security as the U.S. no longer has to rely on countries with volatile and unstable political systems, resulting in increased economic competitiveness. Hydrogen can play a similar role in promoting America's energy security and complement the vital role natural gas has come to play in America's energy supply mix. Hydrogen can be produced domestically using various resources like wind, natural gas, and biomass; lower greenhouse gas emissions; create

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jobs; and bolster the U.S. economy. It is critical that federal regulations foster the nascent hydrogen industry as it, too, can play a vital role in meeting U.S. energy consumption needs and eliminate dependence on foreign suppliers.

In particular, the important role natural gas can play in complementing and building the clean hydrogen market is to produce clean hydrogen using natural gas with CO_2 capture. Add on to this that the natural gas industry will be needed for moving and distributing molecules and there will be opportunities for adapting existing infrastructure to carry clean hydrogen and high hydrogen natural gas blends.

Senator CAPITO. Thank you. Thank you, all three of you.

We are going to go to Senator Markey first.

Senator MARKEY. Thank you, Madam Chair.

Environmental justice cannot be an afterthought of industrial decarbonization. It must be front of mind. For far too long fenceline and frontline communities have borne the brunt of industrial pollution, wreaking havoc on the health and economic wellness of Black, Brown and low wealth individuals in our Country, and creating environmental sacrifice zones in the name of economic growth for others.

When it comes to industrial innovation, we need to be better than before, not continuing with business as usual, which created the climate crisis and environmental injustices. That is why industrial decarbonization that depends on green hydrogen needs guardrails and strong standards.

Ms. Angielski, will you commit to advocating for the three guardrails of green hydrogen, additionality, deliverability and hourly time matching, to help us deliver the greenest hydrogen possible?

Ms. ANGIELSKI. Thank you for the question and I recognize the issues that you are raising, Senator.

The Coalition is proposing that we adopt more restrictive policies, as you are suggesting, these three guardrails of additionality, restrictive or hourly matching, and regional matching over time. Our recommendation is to begin to adopt more restrictive measures beginning in 2030, which is a similar approach to what the European Union has adopted.

The reason for that is we want to see significant investments in the supply chain that is necessary to support the scale of that industry and the growth of the industry in order for clean hydrogen to deliver on that decarbonization solution for industrial decarbonization.

Senator MARKEY. I would say that I am just going to urge you to understand that we want your ambitions to be high for innovation, but we also want ambitions to be high to ensure that we are not perpetuating injustice and obscuring pollution, which is what these industries have done historically.

That is a long timeframe and that is why guardrails for hydrogen created with targeted new and renewable energy, as well as continuous inclusive community engagement, will be what spurs truly clean energy technologies.

Dr. Ellis, thank you for joining us from Somerville, Massachusetts. You said in your testimony that Sublime Systems tried to keep community needs in mind when selecting the site of its first commercial plant in the Commonwealth, including using tools like the Climate and Economic Justice Screening tool, which is based on my Environmental Justice Mapping and Data Collection Act.

Dr. Ellis, do you agree that it is important for deployed clean tech solutions to provide strong benefits to the surrounding communities through a transparent and robust community benefits agreement process?

Ms. ELLIS. Thank you, Senator Markey.

I agree. I believe that the energy transition can be a just transition.

In the case of Sublime Systems, we have used the Justice40 Tool to look at where we might site our first commercial plant. What struck me is that many of these disadvantaged communities are the site of old manufacturing towns. In fact, what makes these towns, what makes them left behind and disadvantaged is the same reason why new manufacturing will come to these towns. These are places where permitting is already sighted industrial. There is already access to railroads. In many cases, these sites already have access to hydroelectricity that has been built decades and even hundreds of years ago.

We believe that coming back to the city is right for us, but it is also right for the community. We hope to bring not only jobs and training, but also to really integrate with the community and be a good neighbor to the people who are welcoming us into their community.

Senator MARKEY. Thank you. As you said, after China and the United States, cement is third in terms of emissions. It is responsible for 8 percent of all global carbon emissions. Even once new technologies get developed to try to tackle that problem, it can take two decades for the market to catch up.

How can the Federal Government further drive demand for low carbon construction materials like cement?

Ms. ELLIS. Thank you, Senator Markey. The U.S. Government buys 60 percent of the cement that consumed in the United States.

Senator MARKEY. Say that again. That is a crazy number.

Ms. ELLIS. It is, in fact, a crazy number. The U.S. Government buys 60 percent of the cement in the United States, and that is a combination of the GSA, the Federal Highway Administration, the Army, DOT, both at the State and Federal level.

If there are no advance market commitments, if there is no commitment to buy low carbon cement from the Government, this makes my job, as an innovator in this sector, more than twice as difficult as it should be. I believe the Government has a responsibility to make these commitments to create bankable contracts that will allow us to get project finance to build these plants.

Moreover, that 8 percent of global CO2 emissions, it is not mostly in the United States. It is global. These countries that are going to be building more because of growing and urbanizing populations, are undergoing a period of dirty growth. They are going to be building cement plants that are based on legacy fossil fuel technology unless we can move quickly to develop American-made electrochemical technology, deploy this internationally and export our technologies.

Senator MARKEY. So the faster we innovate, and that can be driven by robust Federal procurement policies, because the Federal Government consumes 60 percent of all cement. Then we can export that new technology that gets developed because the Federal Government had strong procurement policies around the rest of the world.

I thank you. I know my time has expired. Thank you, Madam Chair.

Senator CAPITO. Senator Cramer.

Senator CRAMER. Thank you, Madam Chair.

Thanks to all of our witnesses for being here. I will try not to jump around too terribly much. So much has already been said that is intriguing to me.

I want to start with you, Ms. Regitsky. your testimony referred to the United States' comparative carbon advantage. I appreciate that terminology. It also points out appropriately that the United States imported more than 1.2 gigatons of embodied emissions, mostly from China.

I appreciate, Dr. Ellis, your referencing this is a global issue. We tend to look inward and sort of beat ourselves up a little bit, in my view, too much. By the way, I love the idea of being the innovators and then exporting the innovation. We sometimes forget that most of what we export is brainpower and innovation as well as products.

That said, according to data that was compiled by the CRC, goods manufactured in the United States are 40 percent more carbon efficient than the world's average. But the U.S. imports 75 percent of its goods from less carbon efficient countries.

Again, getting back to this global issue, getting back to trade policy as much as anything, is why I often say that so much of our energy and environmental policy is inward. It is punitive, rather than recognizing the global nature of all of this.

I want to get to the PROVE IT Act, that is where I am leading. I appreciated Ms. Regitsky bringing it up, because without good solid data to demonstrate the statistics I just used, I don't know that we can move forward as easily until we start proving that we really are more carbon efficient than the rest of the world.

We have actually done a lot to bring down CO2 emissions in the United States. We really have been innovative. Rather than buying more steel from China, how about more steel from West Virginia, or Indiana or how about proving that a Bakken barrel of oil is cleaner than a Venezuelan barrel of oil? In the cement sector, especially, this probably is as obvious as it is anywhere.

I am not saying we shouldn't always strive to improve. It is not that. I think we beat ourselves up too much. What is my point? I guess I would just like, Ms. Regitsky, if you would talk a little bit more about the PROVE IT Act and what value that could bring to the discussion.

I might ask you, Dr. Ellis and Ms. Angielski, on the same topic of data collection, while we try to forward lean into the production. Ms. Regitsky?

Ms. REGITSKY. Thank you, Senator Cramer, for the question and for your bipartisan introduction of the PROVE IT Act.

As you have mentioned already and I mentioned in my testimony, data is really kind of the first piece of the puzzle to start, as you said, proving that indeed much of U.S. production is already more emissions efficient than other countries, especially countries that we are importing our goods from.

What the data allows us to really have this transparent reporting of this emissions intensity and the competitive advantage, the carbon advantage, of U.S. production. The other thing it enables us to do is respond to when other countries are starting to think about their own policies. For example, the EU, as you probably know, is starting to implement their own carbon border adjustment mechanism.

By folks looking at the existing carbon advantage of the U.S., such as CLC, they noted that because of the U.S.'s carbon advantage, looking at the U.S. imports into Europe, into the EU, versus, say, China's imports to the EU, which are going to be more carbon intensive, the U.S. actually stands to gain market share in the EU market with the EUC ban in place.

Having things like PROVE IT will enable us to make sure that when those types of policies that other countries put in place come into fruition, we can really make sure that they are fair and are accurately representing the low emissions intensity of the U.S. market.

Senator CRAMER. Very well said. Dr. Ellis, anything more?

Ms. ELLIS. Yes, I would like to echo that. The Europe Carbon Border Adjustment Rule is very important for protecting against dirty imports.

I would also say that in the EU and in America, there is a proliferation of EPDs, environmental product declarations. That is the nutritional label for cement materials that list not only the embodied carbon of that material, but also the embodied energy. Many of the other pollutants that Senator Markey mentioned affect the local communities in which these materials are made.

Ms. ANGIELSKI. I can speak to you with respect to clean hydrogen. Right now, the lifecycle analysis and accounting methodology is already built into Federal policy to qualify for clean hydrogen, whether it is tax credits or DOE grant funding. That accounting system for tracking the emissions associated with production and use is already built into Federal policy that will catalyze this industry.

It is really important to recognize that if there are industries that want to use clean hydrogen and that will purchase it at a premium price, for example, the carbon intensity value of that hydrogen is going to be the critical aspect of that. Because there are industries that are going to want to be able to say, look, I am using decarbonized hydrogen and it is reducing my product emissions by X amount. That is the selling point and the value add, I will just say for clean hydrogen.

Senator CRAMER. This looks to me like the PROVE IT Act is at is sort of the low-hanging fruit in this group.

Ms. Angielski, I wanted to ask you, of course, about the Heartland Hydrogen Hub. Thank you for your work on that.

Thank you, Madam Chair.

Senator CAPITO. Thank you. Senator Whitehouse.

Senator WHITEHOUSE.

[Presiding.] Thank you. Thanks to Senator Cramer for his interest in carbon border work and I look forward to making more progress in that area.

Dr. Regitsky, we have a number of things on the horizon. The first is the European Union's CBAM, Carbon Border Adjustment Mechanism, which will begin counting carbon emissions shortly and begin tariffing carbon emissions in 2026. The United Kingdom, it has just been reported, will be joining the EU on a similar schedule with a similar carbon border tariff to neutralize any tariff obligations between the UK and the European Union.

What effect will that have on decarbonizing America's industrial sector?

Ms. REGITSKY. Thank you, Senator Whitehouse, for the question and the opportunity to build on my response to Senator Cramer's question as well.

Yes, the new CBAM policies that the EU and the UK are planning to put in place, already in motion, will certainly have an impact globally and on U.S. manufacturing as well. As we have already been discussing, U.S. manufacturers are often already much more carbon efficient and energy efficient than manufacturers in other countries. So they stand to gain actually from being able to access more of these European and UK markets because they have a carbon advantage to some of the other countries that are importing into those places.

If we couple that with further investments in decarbonization in our domestic industry, then that carbon advantage is just going to keep growing and growing and creating even more opportunity to take that global market share. As other countries beyond the European continent are thinking about border adjustments as well, then that just furthers the opportunity even more.

Senator WHITEHOUSE. The economic experts who advised the EU and the CBAM note that there will be some economic headwinds for America by virtue of having to pay a carbon tariff to the EU, because we are more carbon intensive than the EU, but that headwind will be more than offset by a massive tailwind as manufacturing now taking place in China and supply chains now beginning in China move to the United States because the relative difference between the tariff that China would have to pay and the tariff that the U.S. would have to pay would actually be a huge economic value.

If we were to step up our own participation in the EU and now potentially UK CBAM, we could reduce the tariff headwind while also enjoying the tailwind. Is that not correct?

Ms. REGITSKY. Yes, that is exactly right, Senator.

Senator WHITEHOUSE. Then one other thing that I would mention that is coming at us is the Administration's decision, the Office of Management and Budget's decision, which I very strongly applaud, to take the social cost of carbon that is shortly to emerge from the Environmental Protection Agency's, EPA rulemaking process and make sure that it is applied across the board. We have heard testimony about buying cement. Into that cement calculation would now have to fit $190 per ton social cost of carbon.

I expect, Dr. Regitsky, that you also see that as a positive influence on industrial decarbonization in America?

Ms. REGITSKY. Certainly, having some kind of mechanism to differentiate the emissions intensity of the products that the Federal Government is buying will be able to advantage those who are producing the more efficient product, as well as create those markets for innovators like Sublime and others to really see the potential of the market for the investments that they are making into their net zero technologies. It will certainly be able to increase the amount of innovation in really being able to get to net zero in industry.

Senator WHITEHOUSE. It is a fairly elementary proposition of market economics that polluters should pay the cost of their pollution rather than socialize the costs of their pollution onto other innocent parties. Without that, the whole principle of market economics, which is the principle of price signals, is warped and degraded and doesn't work any longer.

Do you believe it is consistent with traditional economic policies to have the social cost of carbon and the CBAM, and other tariffs reflect the fact that there are harms from carbon emissions?

Ms. REGITSKY. I would say that I am certainly not an economist, but my understanding is generally being able to price in these negative externalities where the costs are being brought on to somewhere in society and putting those in the places that are causing the actual harm and the cost does align with the idea of negative externalities in economics.

Senator WHITEHOUSE. You may not be an economist, but you know what negative externalities are. That is a pretty good first step. I will take it.

Thank you, Chairman.

Senator CAPITO.

[Presiding.] Thank you.

Ms. Angielski, in my opening statement, I talked about ARCH2, the Hydrogen Hub, and how excited we are to have that coming to our region, particularly my State. But each hub has selected different mixes of pathways for producing, and I think that was written into the bill.

When it comes to build-out of our Nation's hydrogen infrastructure, where do you think the initial demand will come from and what will the associated emission benefits be?

Ms. ANGIELSKI. Thank you, Senator Capito.

I am familiar with the hub in West Virginia and the ARCH2 hub. The important attribute, I would say, about the hydrogen hubs generally is that they will enhance that sort of network effect that is needed by aggregating both the production, the transport and use demand, and enable that infrastructure to be shared, and the lower cost, at least initially, as the industry grows.

One significant benefit of what the ARCH2 hub is looking at is that they have a variety of end use sectors that exist within the hub that can take advantage of it. If you think about the existing markets, those are probably the lowest hanging fruit in terms of emissions reductions and targets where hydrogen can be adopted in those sectors. That is because they already need hydrogen and use hydrogen.

But the other sectors as in the industrial, for plastics, chemicals, whether we are talking about transportation fuels outside of the industrial sector, or even in other industrial end uses like cement or concrete, that is where hydrogen can grow and expand. However, to do that we will need some additional policy and price support, likely.

The industrial sector is the third largest emitting sector. The sooner we actually use hydrogen in those sectors, the sooner we will see those emissions benefits.

Senator CAPITO. I mentioned permitting and how there have been some bureaucratic headwinds to getting these projects approved. How concerned are you about the permitting process that we are seeing on the Class VI wells? And then there is the issue of permitting the transport of hydrogen as well. Could you speak a little bit about that?

Ms. ANGIELSKI. As it relates to the Class VI permits, you mentioned it in your opening remarks. I think there are almost 60 applications pending before EPA. One has a provisional permit out of the 60. Many of these applications were filed years ago.

You all obviously provided funding to EPA and the regional offices to really try to help expedite the processing of applications. The hope is that once EPA is able to staff up and get the expertise, I think there is also a lack of expertise at the moment to provide that resource and to serve the resource needs throughout the Country.

Hopefully, those funds will catalyze that and really help to accelerate processing of those applications. But it is a concern because obviously, as you know, the longer permitting takes, that is the time value of money for project developers.

The same is true when we are talking about any infrastructure component of a project, including pipelines, as you mentioned. I think probably the biggest concern is with respect to siting of pipelines and the time it takes to site. That is a permitting issue. It is also a local landowner and other regional or community set of issues.

I think appropriate engagement in the communities but then also a streamlined siting authority among the Federal agencies, in particular, would be really critical to go a long way in accelerating or processing those more quickly.

Senator CAPITO. Dr. Ellis, you mentioned that you are going to site your first manufacturing facility in Massachusetts. How far along are you on that project? Have you gotten into the permitting parts of that yet?

Ms. ELLIS. Yes, we have already gotten into permitting. We were lucky to find a plot of land that was already zoned industrial.

Senator CAPITO. Was it a brownfield?

Ms. ELLIS. It was a brownfield site. However, I would share your concern about permitting timelines. It is something where you can be a startup to pool all these resources, but at a certain point, you have to hurry up and wait if you are being held back by permitting.

Especially with the enhanced scrutiny that comes with taking government funding from the IPA, for example, from the Office of Clean Energy Demonstration, if we were to win that funding, we would be subject to NEPA. That could very much create a situation in which we hurry up and then wait.

Senator CAPITO. So your permits now are just through Massachusetts, your State permitting?

Ms. ELLIS. That is right.

Senator CAPITO. Generally they go faster. All right. Thank you.

Senator Merkley is going to question, but Senator Whitehouse, I believe you are going to take the gavel from me. I will pass it along.

Senator WHITEHOUSE. {Presiding] I will gladly do so. Thank you so much.

Senator MERKLEY. Thank you very much, Mr. Chairman.

Dr. Regitsky, I unfortunately was at a foreign policy gathering, so I missed some of your presentation. As I understand it, Breakthrough Energy is a network Bill Gates helped set up, trying to find the innovative technologies that are necessary to bring to scale to meet the goal of net zero in 2050. Is that a fair summary?

Ms. REGITSKY. Thank you, Senator. Yes, that is a very good summary.

Senator MERKLEY. In this process, building materials are obviously a key piece of this challenge. Could you comment a little bit about the role of mass timber as a substitute for buildings that are, say, 1 to 14 stories high and the comparison to traditional concrete and steel buildings?

Ms. REGITSKY. Yes. Thank you for that question.

I will start by saying I am not a structural engineering architect, a technical expert or anything like that. I have really focused on, how do you reduce emissions from heavy industrial producers.

That said, I think it is widely recognized that using alternative materials such as mass timber could be one of the solutions to be able to help decrease some of the current usage of things like concrete and steel in places, in buildings and structures where it makes sense.

But I believe it is also true that mass timber buildings still use some amount of those traditional materials as well. With the development that we expect globally, we still anticipate needing quite a bit of those traditional materials in order to really be able to develop these structures.

But yes, mass timber can certainly play a role in the buildings where it makes sense and where it can perform.

Senator MERKLEY. Where it can, and there may well be much taller buildings that are part of our world that require concrete and steel, both of which consume a lot of energy.

I was intrigued when I first came to the Senate by a company that presented me with a paperweight which was essentially cement made in a different strategy in order to capture carbon. Essentially, when this is put into a building, you have locked up carbon forever.

The downside was that the energy required to produce it and the massive amount of water required to produce it meant that if you were looking at kind of the whole lifecycle of it, it wasn't a solution. There were very few places you could use that tremendous amount of water and of course the energy required to make it meant that you were producing carbon into the air to begin with.

But in terms of the investments that Breakthrough Energy is making, do you see a pathway where there are significant opportunities to greatly reduce the amount of energy that goes into concrete and steel buildings?

Ms. REGITSKY. Yes. I think there are multiple companies within the Breakthrough Energy investment portfolio that are trying to solve this exact problem. For one example, there is a company called Brimstone. They are actually looking to be a drop in replacement for current cement production today, so no need to change the standards or the way that construction currently occurs.

But the process that they use can entirely eliminate the emissions from the cement manufacturing. It is an entirely different process than the way cement is manufactured today. They also create a byproduct that will capture carbon as well. So if everything, depending on the types of energy they end up using in their process, which they are compatible with clean electricity, they could come up with a potentially carbon negative cement alternative that is a drop-in replacement.

There are many other companies as well that are finding new materials that substitute for cement as a binder so that you can use less cement in concrete since cement is the most carbon intensive part of concrete. There are many strategies out there today within the investment portfolio as well as other companies such as Sublime.

Senator MERKLEY. I think that is really important.

I am using that as a pivot to turn to you, Dr. Ellis, and your company. I love the name Sublime, given that you have a process to convert limestone to cement that consumes far less energy, and I think that is at the heart of it.

Have you, in your kind of analysis, really looked at kind of the whole cycle of the products so that you are including, kind of apples to apples comparisons with other products in terms of transportation, use of whatever source of energy is engaged and so forth?

Ms. ELLIS. Yes, that is right. We have recently done an environmental product declaration with the industry's leading provider of these lifecycle analyses, both on the production of these materials.

I think what you say is very important, especially as it relates to mass timber. There is not only CO2 emissions in the production of these materials, but we also have to look at the life cycle, the durability and the end use of these materials to make sure that carbon is avoided throughout the lifecycle and also that energy consumption is reduced in the production of these materials. For example, today, without Sublime's technology, the cement industry would have to decarbonize with post combustion carbon capture, which would double the cost and double the electricity consumption of cement making.

As it relates to cement versus timber, mass timber is a great material. As the other witness said, it can be used in many applications, especially in low-lying buildings.

But cement is unique in that it is very durable and strong. I think a material like this will be needed more than ever, especially in a changing climate where robustness and durability is important and the lifecycle that you can get from a building made with cement is unparalleled.

Senator WHITEHOUSE. Senator Ricketts.

Senator RICKETTS. Thank you very much.

I want to also thank Chairman Carper and Ranking Member Capito for putting this hearing together and our witnesses for sharing your perspectives with us here today.

We have talked a lot about carbon. One of the things I think often gets overlooked in these conversations when we talk about emissions and so forth, is that actually carbon is valuable beyond just kind of the obvious that you need carbon dioxide in the air for plants to be able to grow. There are many uses for carbon that we need in our society. In fact, what many people don't realize is that actually in Nebraska, with our renewable fuels industry, specifically ethanol plants, we create some of the cleanest carbon in the industry.

It has many critical uses across our economy. For example, in our meat processing industry in Nebraska, carbon is used to rapidly chill meat, to be able to use it in transportation, to transport it, because we want to keep that food frozen as we are moving it around the Country.

We also use it in water treatment. Carbon is used to be able to take out, for the removal of organic chemicals during the treatment process. Of course in medical applications, carbon is used to sterilize medical supplies and development of pharmaceuticals and so forth.

Ms. Angielski, how can we continue to promote innovative uses of carbon which add value to our supply chain?

Ms. ANGIELSKI. I can speak at least to how carbon and hydrogen could be used together. If you look at the sustainable aviation fuels today, they need large amounts of carbon dioxide. If you capture that carbon dioxide, even better and they need hydrogen. So if you decarbonize the hydrogen, you can produce fuels that can really help to decarbonize industries like the aviation industry or some of these other maritime sort of applications of what fossil fuels are using today. That is certainly one way to use it.

There are a number of CO2 conversion pathways. Obviously, putting it into processes like concrete is another way that has already been discussed, but I think the innovation needs to continue. Clearly, companies like Sublime and others that are trying to find innovative ways to decarbonize, but also funding provided by DOE to fund CO2 innovation and use is really critical to continuing to find markets for the product.

Senator RICKETTS. You mentioned hydrogen. Let's talk about that for just a moment.

Nebraska has a long history of being an innovator when it comes to the agricultural industry. We have a company you may be familiar with, Monolith Materials, that has a patenting process, a unique process, to be able to take natural gas and crack it into hydrogen and carbon black. Carbon black goes into things like mascara, your tires, and cases for cell phones.

Typically, it is a very dirty process to make it from petroleum, but this is a clean process. Of course then we can have that carbon black to be able to make these products we just talked about that we need in everyday life. But also, you get hydrogen out of that. One of the uses for that is to be able to make clean anhydrous ammonia that then goes back into agriculture. We also have another company, Project Meadowlark, that is doing the same thing with regard to taking hydrogen and so forth.

Can you talk a little bit about how hydrogen can make agriculture and other industries more efficient, cleaner, and promote economic development? What are some of the other things we can do as we have some of these opportunities to be able to use hydrogen in conjunction with carbon?

Ms. ANGIELSKI. Thank you for the question. You hit on a key industry or sector that, for a State like Nebraska, could really help contribute to decarbonization objectives for an industry and the agricultural sector that really doesn't have what I would say are very targeted solutions today that they have available to reduce their emissions from their processes.

Even in the agricultural sector, you mentioned at least Monolith and what they are looking at is to use decarbonized hydrogen as one of the feedstocks to produce ammonia and fertilizer. When you apply that, you could have agricultural products that are now decarbonized. You could also use hydrogen in many of the pieces of farm equipment that are needed to run and obviously farm the land.

Obviously, that is another area where that sector can really decarbonize from what they are currently using today, which is fossil fuels typically. Water irrigation systems need power. You can use hydrogen to power those. There is a lot of opportunity, I think, for hydrogen to really help in the agricultural sector and decarbonize those emissions.

Senator RICKETTS. Have you seen some of these applications for hydrogen being used in some of the hydrogen hub projects people are talking about?

Ms. ANGIELSKI. There are at least two hydrogen hubs that are looking at fertilizer uses and using the decarbonized hydrogen that would be produced in that hub as the feedstock to produce ammonia and fertilizer, so yes, definitely. I think ARCH2 is looking at that. If it is not ARCH, it might be the Midwest one, I believe.

Existing use cases for hydrogen are really what I consider to be the low hanging fruit for adopting decarbonized hydrogen in those sectors. It can really go a long way to helping create and stimulate the demand that clean hydrogen really needs to grow an industry in this Country.

Senator RICKETTS. Great. Thank you very much.

Ms. ANGIELSKI. Thank you.

Senator WHITEHOUSE. The gavel reverts to you.

Senator CARPER.

[Presiding.] Thank you so much.

Senator RICKETTS. Chairman Carper, as I promised, I did get a chance to mention our ethanol industry in Nebraska in this hearing.

[Laughter.]

Senator CARPER. I knew we could count on you.

Thanks so much. It is a good morning, a full morning. This hearing is off to a good start. I have asked people on both sides of the aisle and they are very complimentary of the witnesses and the tone you are helping us to set. I have a couple questions and will jump right in. I appreciate Senator Whitehouse filling in for me.

Dr. Regitsky, in the Fifth National Climate Assessment that was released yesterday, I mentioned it earlier in my opening statement, some 14 Federal agencies and hundreds of our Nation's top scientists explained the urgency of cutting greenhouse gas emissions. We know that Federal actions are key to unlocking swift and sharp emission reductions from industry. That is why the EPW Committee provided funding through the Bipartisan Infrastructure Law and the Inflation Reduction Act to support near-term actions and transformative technologies to reduce emissions from heavy industry.

With that as a backdrop, let me ask this question of Dr. Regitsky. Would you please describe ways in which the programs enacted under the Bipartisan Infrastructure Law and the Inflation Reduction Act are supporting our efforts to decarbonize heavy industry?

Ms. REGITSKY. Thank you, Senator, for the question.

What you relayed in your opening statement and has been discussed by other witnesses as well, there are many programs within the Infrastructure Law and Inflation Reduction Act that are going to help industry progress on its way to industrial decarbonization. Just to name a few that I think are really important and to just highlight a key piece that the two bills do together is really match supply support with demand support, which is really important.

So on the supply side, as I mentioned in my testimony, over $6 billion at the Department of Energy to support industrial decarbonization demonstration projects. This is historical. There has not been this amount of funding to industrial decarbonization ever from the U.S. Government.

The fact that it is for commercial scale demonstrations, first of a kind facilities, is really critical because that is really going to be able to support the transformative technologies that we really need to get to net zero, as well as the incremental emissions reductions that we need as well.

This is a program that I am personally very excited about. We are waiting now for DOE to make the selections, which I believe will come out early next year.

I already mentioned, too, that the industry appetite for this program has been immense. There were ten times the amount of requests for funding than the $6.3 billion, which just shows how much it means.

Senator CARPER. Did that surprise you?

Ms. REGITSKY. Maybe I was a little surprised, though maybe I should not have been, because the investments that will be required to truly decarbonize all of heavy industry is going to be massive. Six billion dollars sounds like a lot, but it is really just a fraction.

I think that the ten times initial need for this first program to come out just gives us a glimpse of what industry is really looking for. Then just to say, there are many other pieces that witnesses and members have already mentioned. The hydrogen hubs, of course, will be critical to using clean hydrogen to decarbonize industry.

Also very many tax incentives in the Inflation Reduction Act that will be relevant for industry; 48C, an investment tax credit for reducing industrial emissions in existing facilities; 45D for clean hydrogen, 45X could be really game changing for thermal storage, which I mentioned in my testimony, to really unlock the ability of those thermal batteries to decarbonize industrial heat, and many more.

On the demand side, it is really great that these investments were paired with the almost $5 billion to Federal agencies for procuring low carbon materials. So the government is helping companies invest to make their materials cleaner and then creating the markets for those clean materials to really match that supply and demand and show the industry that there is a buyer for the clean goods that they are going to be making.

Senator CARPER. Thanks very much for that.

I have a followup question, then I am going to turn to Senator Padilla for his questions.

You have already responded to this question in part, but I am going to ask it again more directly to see if there is anything you want to add. What role does public investment play in the technology development life cycle? How can we, as policymakers, ensure that technology developers can continue to overcome the barriers to deployment?

Ms. REGITSKY. I am happy to elaborate on that followup question. The government support all across the innovation cycle is going to be critical, definitely in the early stages where really this isn't where private capital comes in at all, where folks are still discovering their technologies in the lab, and really kind of fine tuning these technologies.

The government really has a place to step in throughout the development. So taking that lab technology to a pilot scale, to then a larger scale demonstration, to then financing for even further deployment. A big part of technology development is risk. So where the government can come in is to really help de-risk these technologies and accelerate their ability to go through development and get to scale.

One quick thing to mention is just, innovation is messy. It is a feedback loop. You make progress, you fail, you learn, and then you eventually succeed. You can't really skip any of those steps. So what the government support helps to do is de-risk at every one of those steps, make sure that learnings are able to be shared between entrepreneurs. It just accelerates the process.

Senator CARPER. Thanks for that response.

Senator Padilla, it is good to see you this morning. Welcome.

Senator PADILLA. Thank you, Mr. Chairman. Kudos to you for having multiple witnesses today with affiliation with the Massachusetts Institute of Technology, a brilliant move. You can tell when there is 120 pages of testimony submitted, MIT folks who are involved.

[Laughter.]

Senator PADILLA. California prides itself in having one of the lowest emitting cement factories in the Country located in Redding, California. We also helped to forge startups in a network of ten companies referred to as DC2 that are committed to going even further by making cement and concrete with no, or very low, emissions. However, as I have discussed at previous hearings, most current tax credits reward companies that first emit and then capture their emissions, but not as much for companies that are lowering or eliminating their emissions altogether.

My first question is for Dr. Ellis. As a member of the DC2 Alliance, can you speak to your company's experience with the current tax incentives like Sections 45Q, which I think has been raised already, and 48C, and the agencies that developed and oversee them?

Ms. ELLIS. Thank you so much. This is a really important question.

Right now there is no tax credit available for technologies that avoid the manufacture of carbon. Sublime Systems submitted a concept paper for 48C and we were discouraged from the full application.

And 45Q creates perverse incentives. Sublime Systems could manufacture carbon and monetize it by using limestone as an input material from our cement. But we believe that is wrong to do. That is not very forward looking and it is the wrong use of this tax credit.

Instead, the Congress and the Treasury should consider technology agnostic tax incentives to reward the avoidance of carbon as much as it does for carbon production, capture and storage.

Senator PADILLA. An ounce of prevention is worth a pound of cure. That is my translation.

The second question is for Dr. Regitsky. You were involved in the Sierra Club study of cement factories in California and other States. What lessons did you learn regarding innovations in decarbonizing cement and concrete at factory scale?

Ms. REGITSKY. Thank you for the question, Senator.

This was a really groundbreaking study that was conducted because of the facility level data that it provides. Of course, these are just estimates. These are actually very difficult numbers to get, to have production data from facilities.

But what these estimates are providing us is to really have a granular view of the performance of different facilities, so we can get an idea of what the average performance is, how well the top performing facilities are doing, and how well the bottom performing facilities are doing. These are all existing facilities.

So by looking at that difference, you can see what is already possible, even just using the best available technology today and where those kind of near-term emission reductions are possible. The study has really been able to showcase this in cement as well as a handful of other sectors. It really showcases the usefulness of this type of data.

To bring this back to a conversation we had earlier in the hearing, I mentioned this is difficult data to come by. The U.S. Government actually has all of the data to come up with these numbers in existing reporting. The Census has these production numbers from these facilities, but of course, it is kept very confidential for good reasons. But the PROVE IT Act discussed earlier would actually start enabling the sharing of this type of data between government agencies so that the government can start seeing what these emissions are, get the averages, and all of that as well.

Senator PADILLA. Thank you. One more question, Mr. Chair. This builds on an item that Senator Whitehouse raised earlier in the hearing.

Looking ahead to COP28 this month, it is important to consider the global scale needed for industrial decarbonization as countries around the world increase their demand for concrete and other building materials.

Dr. Ellis, Sublime has a goal of producing a million tons of concrete by 2028. That is very laudable, but in the United States alone, our demand exceeds 100 million tons. How can we help scale up low-and no-carbon emission concrete companies to the level needed to effectively supply the national and global market?

Ms. ELLIS. Thank you, Senator.

The Office of Clean Energy Demonstration, combined with the Low Programs Office, is an excellent first start. If we are successful in applying these two programs, it will support us through a phase of growth where we can achieve economies of scale and reduce costs so we can compete on cost with today's carbon intensive Portland cement. These programs need robust support beyond these initial appropriations.

Also, as Senator Markey said earlier, if we move quickly to create government advance market commitments, since the government buys 60 percent of the concrete used in the United States, if we move quickly with these advance market commitments to bring these clean technologies to scale, we can move to export these technologies to the rest of the world where new greenfield cement plants will be built in a period of dirty growth in India, Africa and places where the world's population is growing and becoming more urban. We have an opportunity to act now to prevent decades more CO2 emissions from these carbon intensive industries.

Senator PADILLA. Thank you so much. I appreciate your leadership.

Thank you, Mr. Chair.

Senator CARPER. Thank you, Senator Padilla.

We have been joined by Senator Fetterman, my neighbor across the line in Pennsylvania.

Senator FETTERMAN. Thank you, Mr. Chairman.

Senator CARPER. You are welcome. You are recognized.

Senator FETTERMAN. Thank you, everybody.

I am sure you probably don't know this, and it is probably not very interesting as a fact, but I live right across the street from a steel mill. Literally, it is the last functional steel mill in all of western Pennsylvania, which is a remarkable statement because that is where more than half the world's steel was actually manufactured back in the middle of the 20th century.

I have been in conversations with the leadership of U.S. Steel over the years. One of the things now that just came onto their screen about now is, we have a mandate to do decarbonize our industry. I was like, wow, that is remarkable.

How can you possibly decarbonize steel? If anyone has seen a video of it or is familiar with it, it is a very violent and explosive kind of a process. It is very, very dirty. I know that very well because you have to scrape it off the windows and things at our home.

I asked the leadership, and said, to me decarbonizing the steel industry would be like having a steak house that you don't have a dead cow. It seems kind of incompatible. How is that possible? Then they started saying, well, you know, hydrogen with that as well.

Then I asked, where do we get the hydrogen from? Because my understanding is that it comes from natural gas. Is that accurate, to any experts? Is that accurate?

Ms. ANGIELSKI. I am happy to answer that question, Senator Fetterman. Today, the majority of hydrogen that is produced comes from reforming natural gas. You are correct. You can lower the carbon emissions of that process by capturing and storing the CO2. So you can still use natural gas, decarbonize it and reform it so that way it can be used in the steelmaking process. That is certainly one way to decarbonize the steel industry.

Senator FETTERMAN. Of course, obviously, you are experts and again, much smarter than I am, but I know natural gas is a fossil fuel. It does have carbon involved. Of course fracking is often very controversial, certainly within the Democratic Party and in Pennsylvania as well.

My next question is, if it is coming from natural gas and is turned into hydrogen or where it is made the way, it is currently under the most stringent kind of environmental requirements, is that really what is happening? Are we decarbonizing steel or are we green washing that? What does that mean to the average union worker who might be thinking, I am going to lose my job because we are not able to meet some of these standards.

Politically, those are the ones that are going to run to the Republican side and the steel is going to go to the industries all across the world that make steel without any labor unions, without any kind of environmental kind of restraints, or all these other kinds of things.

I would very much like to decarbonize steel, but these are the kinds of industries that have I think a very truth that you can't really make it without having carbon involved unless there is some kind of super, next kind of a paradigm shift.

How is that possible? What can be really meaningful having that conversation in industries like that which are a part of the western Pennsylvania legacy? Is there a path forward on that? I would open that to anybody.

Ms. ANGIELSKI. I would be happy to start, Senator. I want to touch on your jobs component of this because I think the unions and job market writ large, whether we are looking at just the fossil fuel industry or a clean energy industry, I think existing jobs are going to be the underpinning for the transition. If we are going to transition to these clean jobs, we will continue to need that union labor.

Again, I would say Congress and what they did in enacting the IIJA and of course the IRA, all of these requirements to make sure that we have apprenticeship programs to train and skill workers in these new industries will be critical for that.

But we will need that labor, as it relates to natural gas and the use of natural gas to produce hydrogen and or to replace the fossil fuels that are used in the steelmaking process. As we drive toward zero emissions, a hydrogen profile or an emissions profile, I should say, I think we are going to need the natural gas industry with carbon capture and storage to really help build out the infrastructure that is going to be needed to get to that net zero emitting carbon intensity hydrogen production method, so that way it can be used in decarbonizing these industries, whether it is steel or other industries.

Senator FETTERMAN. Mr. Chairman, 30 seconds?

Senator CARPER. At least 35.

Senator FETTERMAN. Thank you.

I guess the final question on this is that perhaps you are aware of how controversial natural gas and fracking is now. Despite all that and the realities that are a part of that, and I do support natural gas, are we being honest about decarbonizing an industry like that? Is it meaningful? Is it genuinely meaningful and all that? Is that dangerous because if we just say we are not going to even make these in America anymore, now we are running right into the arms of a foreign kind of steel manufacturers?

Ms. REGITSKY. If I may I take on this question, Senator, I think that is a very fair question.

There are other ways of making steel, even primary steel, that is being developed now that would altogether remove fossil fuels from the process and still deliver that primary, high quality steel we need in several industries today, and that actually have the potential to grow the U.S. domestic steel market share.

BCG came out with a study that the global clean steel demand in 2050 is something like $1 trillion. The U.S. has the ability, if we make investments now in a variety of technologies, to be able to capitalize on that. So, things that use clean electricity, and bypass fossil fuels altogether.

And just a comment on the natural gas pathway. While natural gas and using carbon capture to create hydrogen is certainly one way to create a form of low emissions hydrogen that could go into steel making, the process that would use is a direct reduction process that actually in Toledo, Cleveland Cliffs had the direct reduction iron process with natural gas already.

The way that you would introduce hydrogen into the steel making process is through the same type of process. If you are thinking about efficiency and energy efficiency, where the more efficient you can be, the fewer your costs, the more product you are making, the more revenue a company is generating. If you actually start with natural gas, then make hydrogen, and then put it into a DRI facility, you are adding an extra step rather than just going straight from hydrogen in the facility itself without that step.

I think that is where the importance of things like the hydrogen hubs trying to stimulate the supply of clean hydrogen from a variety of sources beyond just the natural gas dry hydrogen, but clean hydrogen from electricity as well, can really be what unlocks that ability for clean hydrogen to be used in the steel industry to provide truly clean primary steel.

Senator FETTERMAN. I genuinely apologize. I am sorry this has gone so far. Thank you for the opportunity. Thank you, everyone, for answering all my questions.

Ms. ELLIS. Mr. Chairman, may I weigh in as well on Senator Fetterman's prompt?

Senator CARPER. OK.

Ms. ELLIS. I want to commend you, Senator Fetterman, on your point about using natural gas as a stopgap solution for decarbonizing steel. This is something that we think of as well.

Sublime Systems has a true zero, not a net zero, way of making cement. We don't emit CO2 in the first place. I think that is very important.

The witness from Breakthrough Energy mentioned that there are innovative technologies that are avoiding CO2 emissions in the first place, both for cement and steel. I also want to add that we have signed an agreement with the United Steelworkers Union for labor for our first commercial plant to make this true zero cement. The United Steelworkers Union employs 50 percent of the cement workers in the United States. We believe it is very important for these workers to bring their skills.

We bring this new innovation and this electrochemical manufacturing. They bring the knowledge, skill, expertise and the safety skills to build this new plant. I do think that together with our innovation and with the workers from the old manufacturing, we can bring American manufacturing into a clean energy future.

Senator FETTERMAN. I sure hope that is true, because the union workers that I live next to and talk to see that as, well, it might be the end of our career in making steel in the Mon Valley.

I have gone way, way, way too long. I apologize. Thank you.

Senator CARPER. Thanks so much for being here. Thanks very much for your questions and for sparking a pretty darned good discussion.

We may have another colleague or two to join us. More than half of the committees are meeting right now. So people are trying to be in several places at once.

I have a question I want to ask Dr. Regitsky. We do not mean to be picking on you, ma'am. You are good to join us even remotely.

I would like to talk a little bit with you about near-term technology solutions. Many of the transformative technologies that will enable deep decarbonization, such as entirely new ways to produce clean materials, will require time to reach commercial scale. I think we realize that.

As the just-released Fifth National Climate Assessment makes all too clear, we don't have time to wait for these solutions to come to market as the climate crisis progresses. While those new technologies develop, many tools are already available to make meaningful emissions reductions today. That is good news.

Dr. Regitsky, in your written testimony, you discussed various methods that can be deployed in facilities today to achieve meaningful emissions reductions. Would you just take a few minutes and share with us some specific examples of existing methods that can deliver immediate results?

Ms. REGITSKY. Thank you for the question, Senator.

There are definitely a host of available technologies today that can be used to start reducing emissions now. I would say at the top of the list is energy efficiency. In any sector, that is always your go-to solution. Any time you are able to become more energy efficient, you are saving costs. So really, it is a win-win.

With new technologies like smart manufacturing, where you can go in and add smart sensors to your different equipment, really monitor the performance of equipment, and really optimize that energy usage is really increasing the opportunity for energy efficiency even more.

On electrification, especially of low temperature heating process, for example, the food and beverage industry is one big user of low temperature heat. Rather than using natural gas to create that heat, electric heat pumps are a viable option today to be able to generate that low temperature heat and reduce a significant portion of those types of emissions across industrial sectors. Of course, electrification will also require infrastructure for that clean electricity and continued cooling of the grid as well.

As a final example in the cement and concrete space, it is really great to see the innovative technologies, the transformative technologies like Sublime is developing. But in the near-term, there are things called supplementary cementitious materials, SCMs, that can be used to reduce the cement content within concrete, so you are reducing the emissions of your concrete mix.

Right now, a lot of these are sourced from current industrial wastes, fly ash from coal, slag from steel production, but we know that these things are not going to always be in supply as those industrial processes start decreasing.

So there are companies who are actually creating synthetic SCMs from widely abundant sources near already existing concrete infrastructure that can start supplying more of these materials to reduce that amount of cement per unit of concrete. That is something that can be done today.

Senator CARPER. Good. Thanks a lot.

My next question I would like to direct to Dr. Ellis. This question deals with keys to adopting clean cement.

We rely on a variety of materials that must meet our rigorous standards in order to ensure safety and longevity. The steel that reinforces our buildings and the concrete that supports the transport of people and goods functions under a variety of scenarios.

National standards organizations play a role in setting performance standards for all kinds of materials, but local entities are often responsible for enforcing those standards, as in the case with building codes.

Dr. Ellis, my question is, how does the performance of cement made from new processes compare to the traditional cement production?

Ms. ELLIS. That is a fantastic question. Thank you.

For many years, cement was defined by its chemistry and not just the stoichiometry, the items and the elements present, but the crystal structure of the cement. Today's Portland cement is made in a large kiln and that crystal structure can only be made in a kiln.

So if we want to decarbonize cement, if we want to employ the supplementary cementitious materials, they can be swiftly and massively deployed as the witness from Breakthrough Energy just mentioned, it means we have to change the definition of cement to be from a prescriptive-based standard, which specifies the crystal structure of the cement, to a performance-based standard.

The good news is that this change from a prescriptive to a performance-based standard happened decades ago. In 1992, ASTM International, the standards-making body, created this performance-based standard. This is a standard that Sublime cement applies to and we meet and, if not, exceed this performance-based standard. This means that our cement reacts with water, gel sets and hardens to make the same durable concrete that we have been using for decades and millennia. It is very important that the infrastructure that we are building, especially with public funds, is durable and safe.

Senator CARPER. Thanks.

I think you partly answered this question, but I am going to ask it anyway and see if you would like to add any other thoughts. This is for Dr. Regitsky.

Would you comment on the need to update specifications and standards to help improve the marketability of clean products? Also, what are some other examples of clean materials other than cement that will require such updates? Dr. Regitsky?

Ms. REGITSKY. Thanks for the question, Senator.

I can certainly build off of Dr. Ellis' response previously that these performance-based standards exist today. The standard-making bodies have created them and there are products that meet these standards.

But the issue is that the standards and specifications need to be adopted by the people in charge of creating whatever the project is, infrastructure or buildings. For example, State DOTs are one player that is really important in a regional market. If a State DOT adopts a specific specification, then most suppliers in that market will want to meet that specification in order to be able to access the State DOT infrastructure projects.

We saw that this change happened with a type of blended cement called Portland Limestone Cement, PLC. It blends about 10 percent limestone into a cement mix, so can reduce emissions largely that way. Now that is already accepted in a majority of State DOTs today and has really impacted the adoption of this new cement blend.

We are able to do that same kind of State DOT adoption to just performance-based standards, as Dr. Ellis mentioned. That will be a game changer for innovative technologies that don't necessarily meet the strict definition of what cement is today, but can meet the performance requirements of these structures.

Being able to partner with organizations like State DOTs, with private sector and public sector building projects in order to make people comfortable with these types of performance specifications is going to be really critical.

Senator CARPER. Thanks for that response.

I want to talk a bit about hydrogen and industrial decarbonization. Ms. Angielski, how is the existing industrial infrastructure adapting to incorporate hydrogen technologies? Again, how is the existing industrial infrastructure adapting to incorporate hydrogen technologies?

I understand that the industrial processes that are used in the production of things like steel, cement, glass, and chemicals all require high temperature heat. Currently, this heat is produced by burning fossil fuels. For these processes, hydrogen can play an important role in helping us reach net zero goals.

How easily can hydrogen be integrated into existing industrial processes without major modifications and how is the existing industrial infrastructure adapting to incorporate hydrogen technologies?

Ms. ANGIELSKI. Thank you for the question, Chairman.

I would say that at least in the industrial or the existing industries that use hydrogen, they are looking at ways to produce low carbon hydrogen at a cost that would be equivalent to how they produce or use at the same cost of what is called gray hydrogen produced from natural gas today. The industries that you mentioned that are potential users of hydrogen are waiting for hydrogen production costs to come down in price in order for them to begin to adopt using hydrogen in those processes.

The important thing to understand is that the cost of hydrogen today is, on average, roughly about $1 per kilogram and that is how it is measured. That equates to about $7.50 per MMBTu of natural gas on an energy content basis.

So if you are looking at a price point of a dollar as a replacement for natural gas as the incumbent fuel in many of these processes, the price of hydrogen will also need to go down in order for that natural gas to be substituted using hydrogen.

Some industries, some steel-making industries here in the U.S. are looking at becoming like hydrogen ready, is what they call it, to make sure that they have the ability to adopt hydrogen when the price comes down or there are sufficient volumes to be able to use hydrogen.

Other industries are looking at utilizing, as I mentioned, existing infrastructure, so there are some producers on the Gulf Coast where there is a pretty thriving hydrogen industry already. They are looking to produce hydrogen and try to do so in a way that would be able to be cost effective for their already existing industrial customers to be able to adopt the hydrogen in those industries.

So everybody is moving toward or moving in a good direction. Let's put it that way. We are waiting for the tax credit policies and the guidance coming from Treasury that will be really helpful in stimulating that activity and behavior.

Senator CARPER. In terms of bringing down the cost of hydrogen, what have we done in terms of policy, tax policy, the legislation that we enacted, what have we done that is actually going to help with respect to bringing down the cost of hydrogen? What more could the government do or academia do, or are there other ways that could help bring down the price of hydrogen?

Ms. ANGIELSKI. Absolutely. I know Abigail and others, as witnesses, can speak to this as well. I am happy to do that. Senator, you led on the Section 45E tax credits, these production tax credits. They are going to go a long way in stimulating production of clean hydrogen.

I think if there are policies that can be implemented to help offset that cost differential that I was just describing in terms of the replacement cost of using hydrogen in those sectors, that would go a long way toward stimulating the demand in those industries and help really drive adoption of decarbonized hydrogen in those processes.

Senator CARPER. Do any other witnesses want to comment on that with respect to bringing down the cost of hydrogen?

Ms. REGITSKY. I am happy to add to that question, Senator. I certainly think the policies that the government has already put in place which Congress passed in the Infrastructure Law and Inflation Reduction Act, as Ms. Angielski already mentioned, will certainly help on that supply side in bringing the costs down.

The Department of Energy certainly has this in its sights with its Hydrogen Earthshot and really bringing down the price of clean hydrogen to that $1 a kilogram figure. So these policies are already in place.

A big important thing is getting them implemented. So on the 45B tax credit, just to make sure that guidance is out quickly. The lack of the guidance is really kind of stalling investor investing into new clean hydrogen projects and electrolyzers. That is definitely going to be a key piece of ensuring that the policy is meant to do what it is supposed to do and is able to bring those costs down.

Senator CARPER. Thank you.

I am going to ask a couple of open-ended questions here and ask you to think about them. I like baseball. There is a saying in baseball about the pitcher telegraphing his or her pitch. It means the batter, whoever is watching the pitcher or the way the pitcher holds the ball, releases the ball and throws it to the plate, the pitcher gives away what kind of pitch it is going to be, fastball, curveball, or whatever.

We are going to turn to Senator Sullivan when he gets settled.

The last question I will be asking you is to think about out loud is where you agree. I think sometimes we have witnesses that don't agree on almost anything. I try to look for a couple of things where we can agree. I think there is a fair amount of agreement here amongst the three of you. So before we wrap it up, we will come back and ask, where do you agree?

With that, Senator Sullivan. It is good to see you.

Senator SULLIVAN. Thank you, Mr. Chairman. Thanks for waiting. Thank you to our witnesses. Appreciate you guys being here.

I show this chart a lot. It is actually really relevant for today because President Biden is meeting with President Xi Jinping. There is a lot of talk about emissions globally since 2005 to 2020. This has been fact checked and everything.

The emissions of China, we all know, are kind of through the roof. Nobody disputes that. Our emissions have actually declined pretty dramatically. The reason is we had a dramatic revolution in the production of natural gas. I think very few people argue with the reason why that went down.

So my question for you, my question for the witnesses is, to what extend do you think mandating, and very little of that was mandated, it was the private sector that innovated on the issue of hydraulic fracking and then kind of the extended reach drilling, which we do in Alaska, which shrinks the surface footprint and makes it much more environmentally sustainable.

To what degree do you think, in the industrial sector, the Federal Government should be mandating issues? There is an article I would like to submit for the record, from the New York Times. Mr. Chairman, I don't normally submit articles from The New York Times. The title is Biden to Target Industrial Pollution in Second Term, If He Gets One.

Senator CARPER. Without objection.
[The referenced information follows:]

Biden to Target Industrial Pollution in a 2nd Term, if He Gets One

nytimes.com/2023/09/16/climate/biden-climate-second-term.html

Coral Davenport September 16, 2023

If President Biden wins a second term, his climate policies would take aim at steel and cement plants, factories and oil refineries — heavily polluting industries that have never before had to rein in their heat-trapping greenhouse gases.

New controls on industrial facilities, which his advisers have begun to map out and described in recent interviews, could combine with actions taken on power plants and vehicles during his first term to help meet the president's goal of eliminating fossil fuel pollution by 2050, analysts said. Industrialized nations must hit that target if the world has any hope to avoid the most catastrophic impacts from climate change, according to scientists.

"If people look at what this administration has done on climate and say 'This is enough,' this country is not going to get to our goals," said John Larsen, a partner at Rhodium Group, a nonpartisan energy research firm whose analyses are regularly consulted by the White House.

But talking about more regulations at the start of what promises to be a bruising election cycle is perilous, strategists said. In particular, the prospect of new mandates from Washington regarding steel and cement, the bedrock materials of American construction, could sour the swing-state union workers courted by Mr. Biden.

"If you are seen as imposing debilitating regulations on heavy industry that employs large numbers of people, you're not only going to get a backlash from manufacturing, but labor as well," said David Axelrod, the Democratic strategist who ran former President Barack Obama's campaigns. "How to do that without looking like you are stabbing these industries in the back, or in the front for that matter, is a real political challenge."

Still, the urgency of global warming requires action, Mr. Larsen said. "Most other problems in America aren't going to be 10 times worse in 10 years if we don't do something right now," he said. "Climate's not like that. If this year has shown us anything, with the extreme weather and fires, it's that it won't just stay at this level — it's going to break all the records we've just broken."

Republicans are eager to seize on the suggestion of additional regulations at a time when many Americans think the economy is in a downturn.

“Apparently skyrocketing gas and energy prices weren’t enough for Biden, he wants to raise the prices on building and infrastructure costs and put hard working Americans further into debt,” said Emma Vaughn, a spokeswoman for the Republican National Committee. “Biden will not be elected to a second term — American families can’t afford it.”

But Collin O’Mara, chief executive of the National Wildlife Federation, and others believe that after Americans have sweltered through a summer of the hottest temperatures in recorded history, watched the nation’s deadliest wildfire in over a century decimate a Hawaiian island, inhaled wildfire smoke from Detroit to Atlanta, and experienced hot-tub ocean temperatures off the Florida coast, at least some voters will be ready to embrace more climate action.

A second-term Biden climate agenda would come after the president has already delivered transformative policies to reduce greenhouse gases generated by the United States, the country that has pumped the most carbon dioxide into the atmosphere since the Industrial Revolution.

Last year, Mr. Biden signed into law the Inflation Reduction Act, a landmark climate law, which will provide at least $370 billion over the next decade for incentives to ramp up sales of electric vehicles and expand wind, solar and other renewable energy. Under Mr. Biden, the Environmental Protection Agency has proposed regulations, expected to be finalized next year, designed to compel the phaseout of gasoline-powered cars and coal-fired power plants.

Together, those policies could help cut the nation’s emissions nearly in half over the next decade, analysts say.

The United States and nearly 200 other countries agreed in 2015 to try to limit the rise in average global temperatures to 1.5 degrees Celsius (2.7 degrees Fahrenheit) by 2100, compared with preindustrial levels. Beyond that point, scientists say, the effects of deadly heat waves, flooding, drought, crop failures and species extinction would become significantly harder for humanity to handle. But the planet has already warmed by an average of about 1.2 degrees Celsius and the United States and other nations are far from meeting their goals.

As emissions in the United States decline from energy and transportation, the country’s two biggest sources of greenhouse gases, industry would become the most polluting sector of the economy. That makes businesses like steel and cement manufacturing — among the most difficult to clean up — the obvious target for the next round of climate regulation.

At the White House, Mr. Biden’s climate team has already envisioned a multi-step plan to cut industrial pollution if he wins re-election.

The first step would use carrots, steering incentives from the 2022 Inflation Reduction Act toward nascent technologies to help factories to reduce their carbon footprint.

For example, green hydrogen, a fuel produced by using wind and solar power, is muscular enough to run a steel mill but emits only water vapor as a byproduct. And cement production involves heating limestone and releasing large amounts of carbon dioxide, but several companies have been developing cement that does not emit carbon and may even absorb it.

The second step would be to try to compel global competitors to clean up their operations through a "carbon tariff" — a fee added to imported goods like steel, cement and aluminum based on their carbon emissions.

Congress would need to approve such a tax, which has support from Democrats and some Republicans. The European Union imposed a similar carbon border tax earlier this year.

To justify a carbon tariff to the World Trade Organization, the United States would likely have to impose the same type of taxes on industrial pollution at home. While efforts to impose a carbon tax have long been seen as dead on arrival in Congress, the administration could instead use its executive authority to impose new top-down regulations on industrial pollution by using the 1970 Clean Air Act, which formed the basis for its proposed regulations on cars and power plants.

But those policies are already under fire.

Candidates seeking the Republican presidential nomination have argued that Mr. Biden's promotion of electric vehicles and solar energy makes the United States more reliant on its chief economic rival, China, for necessary components and that cutting emissions at home does not matter when other countries continue to pollute.

"If you want to go and really change the environment, then we need to start telling China and India that they have to lower their emissions," said former South Carolina Gov. Nikki Haley at the first Republican debate last month.

Mr. O' Mara, an informal adviser to the Biden re-election campaign, said that the United States needs to push other nations to act before Mr. Biden can build support for new domestic climate measures.

"If we don't hold polluters in India and China accountable first, the politics are almost impossible," Mr. O'Mara said.

Perhaps even worse for Mr. Biden, unionized autoworkers are uneasy about his regulations designed to pivot the American market away from gasoline-powered cars and toward electric vehicles. Concerned that electric vehicles require fewer workers and a transition could cost jobs, the United Auto Workers has so far declined to endorse Mr. Biden. The union went on strike Thursday against the nation's largest carmakers, in part over demands that workers at electric vehicle battery factories be covered by the U.A.W. contract.

That discontent could spread to workers in the steel and cement industries if new regulations mean fewer jobs.

Sean O'Neill the senior vice president of government affairs at the Portland Cement Association, which represents the majority of the nation's 20 cement manufacturers, said his industry would welcome federal help to decarbonize and would consider supporting some form of a carbon tariff, under certain circumstances. But it would oppose regulations that could limit the availability of materials to build and repair buildings and bridges, he said.

"Any policy that could hamper the domestic production of cement could be problematic to the downstream industries — concrete, construction," he said.

At the Biden campaign headquarters in Wilmington, the messaging strategy steers away from regulations and instead highlights the impacts of extreme weather and climate denial on the part of Republicans.

Mr. Biden leaned into those themes at a Sept. 10 news conference, saying, "The only existential threat humanity faces even more frightening than a nuclear war is global warming going above 1.5 degrees in the next 20 — 10 years. That'd be real trouble. There's no way back from that."

Recent surveys show that Americans are concerned about climate change and think the government and large corporations should do more to fight it, but opinion is mixed when it comes to specific policies.

In surveys by the Pew Research Center this year, 66 percent of adults said the government should encourage wind and solar energy while just 31 percent want the country to phase out fossil fuels. Respondents were divided on the question of whether the government should encourage the use of electric vehicles, with 43 percent saying it should, 14 percent saying it should not and 43 percent saying it should neither encourage or discourage.

While 54 percent of adults polled by Pew said climate change was a major threat to the country's well-being, respondents ranked it 17th out of 21 national issues in a January survey. "Even for Democrats, who say it's important, it's not the top issue," said Alec Tyson, a researcher who helped conduct the survey.

The Biden campaign is betting that the real-time damage from weather disasters made worse by climate change will turn out one demographic the president especially needs — young voters in high numbers.

"Climate is one of the biggest issues for us — and as we get older it will continue to be," said Representative Maxwell Frost, 26, Democrat of Florida, who serves on the Biden campaign's advisory board and is the only member of Congress from Generation Z.

“Climate is paramount across the South, especially here in Florida where we are on the front lines of the climate crisis, with hot-tub temperatures in the surrounding ocean,” said Mr. Frost, speaking by telephone from his Orlando district soon after it was flooded by Hurricane Idalia. “The ocean water, the record heat post-hurricane, the record temperatures in the water — these are things we know and feel.”

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Portland Cement Association
200 Massachusetts Ave NW, Suite 200
Washington D.C., 20001
202.408.9494 Fax: 202.408.0877
www.cement.org

The Honorable Tom Carper
Chairman
Environment and Public Works Committee
Washington, D.C. 20510

The Honorable Shelly Moore Capito
Ranking Member
Environment and Public Works Committee
Washington, D.C. 20510

Dear Chairman Carper and Ranking Member Capito:

The Portland Cement Association (PCA)[1] appreciates you holding the hearing titled, *Opportunities in Industrial Decarbonization: Delivering Benefits for the Economy and the Climate*. This hearing is essential, as an opportunity to share our progress and challenges with Congress, as the cement industry decarbonizes. We encourage the Committee to use this hearing to evaluate future federal permitting and regulatory reform along with the investments needed to reduce manufacturing emissions. Additionally, as the Committee considers public policies for infrastructure and government procurement, it should consider the availability of the materials, its resilience, and its ability to protect life.

PCA and its members are appreciative of the Environment and Public Works Committee's support of the industry in recent years, particularly in the Infrastructure Investment & Jobs Act and Inflation Reduction Act.

PCA's members represent the majority of cement production capacity in the United States and serve nearly every congressional district. The cement and concrete industry contribute over $100 billion to the U.S. economy and employs over 600,000 people.

Cement – the principal ingredient in concrete – makes civilization possible. The mixture of portland cement, aggregate, and water makes the building material concrete. Concrete is essential to the modern world. It is used in the pipes and facilities that deliver clean water, to build the ports essential to world trade, to construct mass transit systems connecting people, and in the buildings we work and live in.

Our industry has pledged to become carbon neutral across the cement and concrete value chain by 2050.[2] By way of brief background, cement manufacturers face a unique chemical fact of life. The chemical process required to convert limestone and other raw materials into clinker, the primary ingredient in cement, generates carbon dioxide (CO2) as an unavoidable byproduct during pyro-processing. Currently, roughly 60 percent of all emissions from the cement sector come from these manufacturing process emissions, separate and distinct from energy-related emissions. While the industry expects to make great strides in reducing carbon emissions through measures like using carbon-free fuel/heating technologies and low-carbon/carbon-free raw materials, the full elimination of CO2 generated from raw materials during pyro-processing is

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[1] PCA conducts market development, engineering, research, education, technical assistance, and public affairs programs on behalf of its member companies. Our mission focuses on improving and expanding the quality and uses of cement and concrete, raising the quality of construction, and contributing to a better environment.

[2] https://www.cement.org/docs/default-source/roadmap1/pca-roadmap-to-carbon-neutrality_final.pdf

not possible. Given this chemical fact of life, the cement industry requires expansive tools and technologies to achieve deep decarbonization.

Cement Blends

Other than water, concrete is the most-used material on the planet, representing about 50% of all manmade materials by mass. The United States uses over 120 million tons of cement each year. Because society produces so much concrete each year, even small changes to its formulation can have dramatic effects on the construction industry's annual carbon footprint—and benefit everyone on the planet.

In the near term, cement manufacturers have developed a modified formula: portland-limestone cement (PLC), a blended cement with a higher limestone content, which results in a product that works the same, measures the same, and performs the same but with a reduction in carbon footprint of 10% on average. Modifying a concrete mix design to replace higher carbon materials with lower carbon ingredients is an effective strategy to reduce its environmental footprint. Whereas the U.S. standard for portland cement allows for up to 5% of clinker to be replaced by limestone, the standard for blended cement allows for 5% to 15% limestone replacement in PLC (Type IL). The same clinker is used to make portland cement and portland-limestone cement, but there is less of it in PLC. And concrete mixes designed with PLCs are compatible with all supplementary cementing materials (SCMs), so when you substitute PLC for ordinary portland cement, you can continue to use all the other materials you use to make concrete for an even greater reduction in carbon footprint. If all cement used in the U.S. in 2019 had been converted to PLC, it would have reduced CO2 emissions by 8.1 million metric tons, which the U.S. EPA says is the equivalent of taking 1.75 million cars off the road for an entire year.

It should be noted that cement, like other building materials, must meet rigorous standards to ensure the safety of the building or infrastructure being constructed. PLC is extensively tested, has proven technology, is readily available through the same supply chain that already successfully serves developers, builders, and contractors.

Alternative Fuels

Regulatory and technical barriers exist for cement plants to use alternative fuels, such as industrial byproducts that otherwise would end up in landfills, including plastics, fabrics/fibers, non-recycled paper and cardboard, tires, and other valuable non-hazardous secondary materials, that will help the industry reach its carbon neutrality goal by 2050. Cement kilns provide an effective and environmentally sound solution that avoids landfilling these materials, benefiting the cement industry and society at large. Since 1990, the industry has reduced its use of traditional fossil fuels by over 15% by using these alternative fuels. Reducing legal barriers to allow kilns to increase usage of these lower-carbon alternative fuels to replace traditional fossil fuels, such as coal and pet coke, can help reduce kiln CO2 combustion emissions.

The U.S. lags well behind the European Union (EU) in its adoption of alternative fuels, which reflects fundamental differences in the regulation of industrial manufacturing, its approach to conserving, recovering, and using secondary materials, and the EU's use of available levers to discourage landfilling and drive carbon reduction.

We see a tremendous opportunity in the U.S. to reduce emissions, via the use of alternative fuels, with the right policies. In the Department of Energy's (DOE) Industrial Decarbonization Roadmap. The agency identified alternative fuels as a pathway for cement manufacturers to reduce their greenhouse gas (GHG) emissions, and the DOE identified needed research on the subject. Among the research it requested for alternative fuels is research on emissions, heating values, carbon content, and contaminant profiles associated with alternative fuels. In the DOE's Industrial Decarbonization Roadmap, DOE also identified the need to catalog fuel mixtures and evaluate economic & GHG reduction benefits and opportunities for economic scale-up of alternative fuels.

The federal government can facilitate additional technical research to analyze the waste and non-hazardous secondary materials streams to confirm that alternative fuels have similar heating values and lower CO2 emissions profiles when compared to traditional fossil fuels. Following such research, we hope that Congress will make pragmatic changes to federal environmental policies that will provide for increased alternative fuel usage while responsibly protecting the environment and enhancing America's energy security.

Carbon Capture Utilization and Storage

The cement industry is facing significant obstacles to implementing carbon capture utilization and storage (CCUS) technologies at its plants. Currently, there are no commercial-scale CCUS installations at any cement plant within the U.S. CCUS cannot be widely implemented at cement plants until there is a clear path to siting and permitting these technologies. Additionally, significant infrastructure investments are required for the capture, compression, storage, and transportation of CO2. Part of that infrastructure will need to supply water and energy for carbon-capture units and associated auxiliary equipment, as well as the energy required for the ultimate delivery of the captured CO2 to its final end-use.

While many promising technologies are under development domestically and overseas, significantly more research and federal funding is needed for CCUS technologies to reach the commercial development stage for the industrial sector, including cement. The cement industry is conducting research on capture technologies, including a variety of solvent, sorbent, and membrane technologies, carbonation, mineralization, calcium (or carbonate) looping, oxyfuel combustion and calcination, cryogenic capture, and algae capture as carbon reduction and removal technologies to hasten the industry's decarbonization efforts. The cement industry is pursuing various potential technologies because each cement plant and cement kiln is different. Their differences include numerous variables, including plant design, emission control requirements, space constraints, water availability, energy availability, and process parameters, each of which will influence the viability of specific carbon removal and reduction technologies. No single off-the-shelf CCUS commercial design or technology will work for every cement plant, and many plants will likely require a combination of capture technologies. It is essential that federal research and funding be directed at multiple technologies so CCUS can feasibly be implemented for the cement industry promptly.

Provided a CCUS technologies can be proven or demonstrated at scale, with substantial research and the implementation of appropriate federal and state policies, CCUS technologies could become scalable within the next ten years.

Given the challenges in decarbonizing the entire cement and concrete value chain, the cement industry will be unable to reach its carbon neutrality goal by 2050 alone. We can only achieve this goal with significant policy support from the federal government to assist with eliminating regulatory hurdles once carbon technologies are commercialized. Needed policy support includes measures to modernize the permitting programs that cover the installation of carbon capture and energy efficiency technologies, carbon transmission infrastructure, and electricity generation. Federal permitting remains an obstacle to the planning, construction, and installation of carbon capture technologies and the infrastructure needed to sequester or utilize the captured carbon. First, there are regulatory obstacles to installing new energy-intensive carbon capture equipment at cement plants and other facilities. The New Source Review (NSR) Program, established under the Clean Air Act Amendments of 1977, presents regulatory barriers for cement facilities to make GHG reduction and energy efficiency improvements. Under the NSR Program, installing CCUS, investing in significant energy efficiency projects, or other major capital investments to reduce GHG emissions at cement facilities result in extended and costly permitting processes and potentially unrealistic emissions and monitoring requirements. The federal government will need to enact policy reforms to reduce these barriers under the NSR Program to ensure that cement plants can install major GHG reduction and energy efficiency technologies, including CCUS technologies, without unnecessary impediments.

Conclusion

All the above-mentioned needs are currently regulated by numerous federal environmental laws with inconsistent guidance, permitting processes, and agency interpretations.

We encourage the Committee to use this hearing to evaluate future federal permitting and regulatory reform along with the investments needed to reduce manufacturing emissions. Such action is necessary to enable the industry to reach its goal of carbon neutrality across the concrete supply chain by 2050. We look forward to working with the Committee on legislation and agency oversight as it considers its next steps. If you have any further questions, please contact me at soneill@cement.org or 202.719.1974.

Sincerely,

Sean O'Neill
Senior Vice President, Government Affairs
Portland Cement Association

Senator SULLIVAN. A lot of this article focuses on mandates to industry, you have to do this and you have to do that, to industry. One of the challenges of that, of course, is that sometimes you miss innovation. Again, nobody argues that we are actually the leader in the reduction of greenhouse gas emissions. China is the dirty polluter. I hope the President brings that up in his meetings with Xi Jinping today.

That wouldn't have happened, in my view, which benefits everybody, let alone jobs and the environment, had there been a heavy-handed approach from the Federal Government saying, here is exactly how you need to do this. That revolution in the production of natural gas, nobody believed that could happen. The story is quite remarkable, but it really is essentially a lesson in the innovative capacity of the American private sector.

So I am curious, for both the witnesses, this is kind of an open-ended question for all the witnesses. When you go for certain goals, if the feds come in and say X, Y, and Z has to happen, a lot of times you miss the opportunity for the innovation that can make things even better. Do either of you have an opinion on that?

Ms. ELLIS. I do, Senator Sullivan. I would like to thank you for sharing that graph. That graph actually made me very proud to be American and to see the leadership that we have taken in adopting new technologies quickly and having an impact.

I believe that what I am doing at Sublime Systems, developing a new technology to make cement that is true zero, not net zero, which means that we won't have to add additional cost, additional energy, additional labor into decarbonizing cement production, I think that is very important for us.

Senator SULLIVAN. Sorry to interrupt, but it is a great point. Are you doing that because the feds or the Congress said to do this or are you just saying, hey, this can be great for my company, great for my community, great for my State, great for the Country, and help the environment?

Yes, we are a capitalist society. Make some money. There is nothing wrong with that. Why are you doing it?

Ms. ELLIS. I am doing it because I think it is important. I think it is important to move quickly. I see it as a tremendous opportunity to develop new technology, and I think history has shown that the U.S. Government has had a role in catalyzing the development of new technology, be it through NASA or the internet.

I know there are countless other monumental technologies that have just had that partnership with the government to bring new ideas that are made in America and to export them globally. The U.S. produces 100 million tons of cement per year, but we also import about 20 percent of our cement from overseas.

Senator SULLIVAN. From where?

Ms. ELLIS. From Turkey, Greece, Vietnam, Canada, really from all over. I think this is a great opportunity to export made in America technology to India, Africa, China, to these places that have these incredibly polluting heavy industrial assets, because we know that climate change affects all of us, in the U.S. and elsewhere.

Senator SULLIVAN. That is one reason I am a big fan of exporting American, clean, burning American LNG. It is the same analogy. Thank you for that.

I know we have a witness virtually. Mr. Chairman, I would like to hear from that witness.

Ms. ANGIELSKI. Thank you, Senator. Thank you for the question.

I would say that many of our members right now are already committed to innovative approaches to decarbonizing their operations. Many of them are industrial sector producers and users of their products.

Senator SULLIVAN. Do you worry about that article I just cited?

Ms. ANGIELSKI. I haven't had a chance to look at it. What I can say is that absent mandates at the moment, these companies are committing and investing. They are looking at other policy tools and levers, of course. We were very much advocates of the clean hydrogen hubs and for the Section 45B tax credits.

Part of my testimony has also called for action on helping to reduce the costs for adopting hydrogen as a replacement fuel in many of these industrial sectors. That is not a call for a mandate, but there will be a need for policy tools and levers to continue to both produce and use decarbonized hydrogen.

Senator SULLIVAN. So more flexibility with tools versus strict mandates. In Alaska, we always say, particularly with regard to the feds, the one-size-fits-all approach just did not work for our State. When D.C. is making rules, oh, we are going to apply that to all of America, inevitably that does not work in my State. So, flexibility and tools, but maybe not so strict mandates? Is that kind of what you are saying?

Ms. ANGIELSKI. We haven't taken a position as a coalition on mandates because there hasn't been a discussion about industrial decarbonization and mandates for it. I hold the fact that our members are already investing and looking toward a future that is decarbonizing and making those investments today. Then partnering with the Department of Energy in innovative approaches to do that is going to be critical to making sure that we are successful.

Senator SULLIVAN. Great. To the online witness, do you want to take a crack at that if you are still online?

Ms. REGITSKY. Yes, Senator. Thanks for the opportunity.

Certainly mandates are one type of policy that can reduce emissions, but certainly not the only one. What is important, which I think has already been discussed by the other witnesses, is that what we care about is emissions and in industry, a lot of time emissions intensity. How many emissions are being produced every time you make a ton of cement or a ton of steel?

That is really the factor that we care about. Policies that are smart, that can target that kind of data point, emissions intensity, but then allow industry to innovate and use whatever tools are necessary to meet that target is really what is going to help innovation the most.

It will help create this level playing field so that innovators who are aiming for the most emissions intensity savings stand to benefit the most because those are the technologies that we are going to really need to transform the heavy industry. Thinking about smart policies that incentivize innovation is certainly helpful.

Senator SULLIVAN. Great. Those are great answers.

Mr. Chairman, thank you. I do think to the witnesses' point, it is a great strategic advantage of America, particularly relative to China. We can be doing that in a much less carbon intensive way here and then exporting and beating them at their own game.

Thank you, Mr. Chairman.

Senator CARPER. Thanks so much for joining us and for your questions. It will be interesting to hear what comes out of the meeting today between President Biden and President Xi. We are all ears.

We are about to wrap it up. Areas of agreement, a lot of times folks in Washington, even in the Senate, focus on disagreement. In this committee, we actually focus a lot more on, where do we agree, or how can we find common ground and build on that.

Let me start, if I could, with Dr. Ellis. What are some major areas of agreement that you think you would like to just emphasize for us in closing?

Ms. ELLIS. Thank you. I think we can all agree that our solutions are urgently needed and that they are very important. This is also a massive opportunity for us to work together and to really surmount this challenge and to create more jobs in America, to reduce imports, to increase exports, and bring high quality jobs back to old manufacturing towns with new technology that is also clean and benefits the community more.

Senator CARPER. Thank you.

Ms. Angielski.

Ms. ANGIELSKI. Thank you, Senator. I think what I would like to say is that the time is now, especially as we think about clean hydrogen. This industry needs to grow and it needs to grow very rapidly if it is going to be able to play the role that it needs to play as a decarbonization solution.

This is a very large, complex ecosystem. The industrial sector is a very large, complex ecosystem. Clean hydrogen is only one aspect of that, but it touches many industries and many sectors.

For the solution to be able to be used and achieve decarbonization objectives, I think much of the policy that we have in place, thanks to you and others in Congress, that will be a great starting point. We need to continue to work together in looking at policy for making sure that ecosystem can grow and enable clean hydrogen to serve the role that it is supposed to.

Senator CARPER. Good. Thank you.

Batting cleanup, Ms. Regitsky.

Ms. REGITSKY. Thank you, Senator. I would certainly agree with what Dr. Ellis and Ms. Angielski have already mentioned on the opportunity that industrial decarbonization brings for American workers, for the American economy, for really the competitiveness of American industry internationally, as well as all the community and health benefits as well that will come along.

The time certainly is now, we have policies in place, thanks to Congress, that are really getting the ball rolling but we will need much more. This is really going to be a collaboration between the private sector and the public sector. Innovation is really at the center of it all and really being able to propel that innovation for these technologies to get us to a net zero industry.

Senator CARPER. Good. Thank you.

In closing, I want to thank each of you, all three of you, two in person and one remotely. Thank you for joining us today. Thank you even more for sharing your insights and your perspectives on what I think we all realize is a hugely important topic for not just the Congress, but for our Country and for our planet.

To put it simply, we are all experiencing climate change now through and increasingly devastating extreme weather events throughout our planet. To slow climate change, we need to slash greenhouse gas emissions and one third of the solution lies in our industrial sector, one third.

Today, we have heard some good news. We do not always share good news here, but today there is some good news. By investing in clean, low, and zero carbon manufacturing, we are growing back good paying jobs, American competitiveness and our economy, as well as cleaning up local air pollution and fighting the climate crisis. Today's hearing gives us a game plan for what we must do going forward.

Before we adjourn, we have a little bit of housekeeping. Senators who were here or not here are welcome to submit additional questions for the record until the close of business on Wednesday, December 6th. We will compile those questions, we will send them over to each of our witnesses and we will be asking the three of you to reply to us by Wednesday afternoon, December 6th. No, not really. You will have you have until Wednesday, December 20th, two full weeks for some really good answers. You have given us some really good answers already and we applaud each you very much.

Thanksgiving is coming up. It is one of my favorite holidays. I think it is one of our favorite holidays in America.

I hear a lot of people say, it has never been this bad, it has never been this bad on our planet, in our Country, or whatever. I always remind them that things have been a lot worse. We had a civil war. We lost a million men. We followed that up with two world wars, the Great Depression, when one out of every four people didn't have a job that wanted a job. We took on communism. We have been through worse than this.

To the extent that we can pull together, share ideas, find ways to harness technology, and really create economic opportunity out of the technology that we are talking about here with clean hydrogen, there is a lot to be happy about and to look forward to.

So we will compile the questions and send them to you and look forward to your responses to them by December the 20th.

With that, a very happy Thanksgiving coming up and I look forward to seeing you on the other side. Thanks much.

With that, this hearing is adjourned.

[Whereupon, at 12:07 p.m., the hearing was adjourned.]

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