S. HRG. 115–456

LEGISLATIVE HEARING ON S. 2602, THE UTILIZING SIGNIFICANT EMISSIONS WITH INNOVATIVE TECHNOLOGIES ACT, OR USE IT ACT

HEARING

BEFORE THE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS UNITED STATES SENATE

ONE HUNDRED FIFTEENTH CONGRESS

SECOND SESSION

APRIL 11, 2018

Printed for the use of the Committee on Environment and Public Works

Available via the World Wide Web: http://www.govinfo.gov

LEGISLATIVE HEARING ON S. 2602, THE UTILIZING SIGNIFICANT EMISSIONS WITH INNOVATIVE TECHNOLOGIES ACT, OR USE IT ACT

S. HRG. 115–456

LEGISLATIVE HEARING ON S. 2602, THE UTILIZING SIGNIFICANT EMISSIONS WITH INNOVATIVE TECHNOLOGIES ACT, OR USE IT ACT

HEARING

BEFORE THE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS UNITED STATES SENATE

ONE HUNDRED FIFTEENTH CONGRESS

SECOND SESSION

APRIL 11, 2018

Printed for the use of the Committee on Environment and Public Works

Available via the World Wide Web: http://www.govinfo.gov

U.S. GOVERNMENT PUBLISHING OFFICE

34–174 PDF WASHINGTON : 2019

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

ONE HUNDRED FIFTEENTH CONGRESS
SECOND SESSION

JOHN BARRASSO, Wyoming, *Chairman*

JAMES M. INHOFE, Oklahoma
SHELLEY MOORE CAPITO, West Virginia
JOHN BOOZMAN, Arkansas
ROGER WICKER, Mississippi
DEB FISCHER, Nebraska
JERRY MORAN, Kansas
MIKE ROUNDS, South Dakota
JONI ERNST, Iowa
DAN SULLIVAN, Alaska
RICHARD SHELBY, Alabama

THOMAS R. CARPER, Delaware, *Ranking Member*
BENJAMIN L. CARDIN, Maryland
BERNARD SANDERS, Vermont
SHELDON WHITEHOUSE, Rhode Island
JEFF MERKLEY, Oregon
KIRSTEN GILLIBRAND, New York
CORY A. BOOKER, New Jersey
EDWARD J. MARKEY, Massachusetts
TAMMY DUCKWORTH, Illinois
CHRIS VAN HOLLEN, Maryland

RICHARD M. RUSSELL, *Majority Staff Director*
GABRIELLE BATKIN, *Minority Staff Director*

C O N T E N T S

Page

APRIL 11, 2018

OPENING STATEMENTS

WITNESSES

ADDITIONAL MATERIAL

Page

—Continued

LEGISLATIVE HEARING ON S. 2602, THE UTILIZING SIGNIFICANT EMISSIONS WITH INNOVATIVE TECHNOLOGIES ACT, OR USE IT ACT

WEDNESDAY, APRIL 11, 2018

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

The Committee met, pursuant to notice, at 10:21 a.m. in room 406, Dirksen Senate Office Building, Hon. John Barrasso (Chairman of the Committee) presiding.

Present: Senators Barrasso, Carper, Inhofe, Capito, Fischer, Ernst, Sullivan, Cardin, Whitehouse, Gillibrand, Booker, Markey, and Van Hollen.

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

Senator BARRASSO. Good morning. I call this hearing to order.

Today we are here to discuss promising bipartisan legislation recently introduced by the Chairman, along with Senators Whitehouse, Capito, and Heitkamp.

The bill is called the Utilizing Significant Emissions with Innovative Technologies Act, or simply the USE IT Act. It is called the USE IT Act because the bill would encourage the commercial use of manmade carbon dioxide emissions. The bill supports the use of carbon capture technology and innovative research at sites with the captured CO_2. The legislation also facilitates permitting for carbon dioxide pipelines in order to move the carbon dioxide from where it is captured to where it is either stored or used.

The USE IT Act complements and builds off of recently passed legislation that was introduced by the same bipartisan group of Senators. That one was called the FUTURE Act, the Furthering Carbon Capture, Utilization, Technology, Underground Storage, and Reduced Emissions Act, simply, the FUTURE Act. It expanded and extended the 45Q tax credit for carbon capture. Carbon capture can and does work.

The Committee heard testimony from David Greeson of NRG Energy last year. Their Petra Nova project outside of Houston is the largest carbon capture project of its kind in the world. That project has now captured and used more than a million tons of carbon. The FUTURE Act is going to spur investment in more additional carbon capture projects like Petra Nova.

In developing both the FUTURE Act and the USE IT Act, Senators on both sides of the aisle have found areas of common ground. I appreciate Senator Whitehouse's leadership as we work together to develop the USE IT Act. I am going to continue to work with Senator Whitehouse to ensure any amendments to this bill are built on bipartisan consensus as we work to move it through the Committee and ultimately to the President's desk.

In my home State of Wyoming, we are blessed with an abundant supply of coal, oil, uranium, and natural gas. These tremendous resources fuel our State economy and employ people in well paying jobs; they provide affordable and reliable power to our Nation.

Coal, oil, uranium, and natural gas also make the United States more secure by making us less dependent on energy resources from other countries. We cannot afford to leave our resources stranded in the ground. That is why America must lead through innovation—and not regulation—as we continue to reduce emissions. This is the approach we take in the USE IT Act.

The bill will also allow coal plants in my home State of Wyoming to capture their CO_2 emissions and turn them into valuable products. It will encourage the use and permanent sequestration of CO_2. Greater use of these technologies, coupled with research support from the EPA, could lead to additional innovative technologies that will use CO_2 emissions.

This is a market driven approach. We are encouraging the development of markets for CO_2. All of these actions will result in less carbon dioxide in the atmosphere.

The USE IT Act is important for Wyoming. The Sheridan Press recently published a front page article titled Senate Bill Could Stimulate State Carbon Capture Projects. In the article Jason Begger, who is the Executive Director of the Wyoming Infrastructure Authority, who has testified before this Committee, endorsed the USE IT Act. He explained how the legislation will allow Wyoming to diversify the use of its energy resources, and I ask that this article be entered into the record.

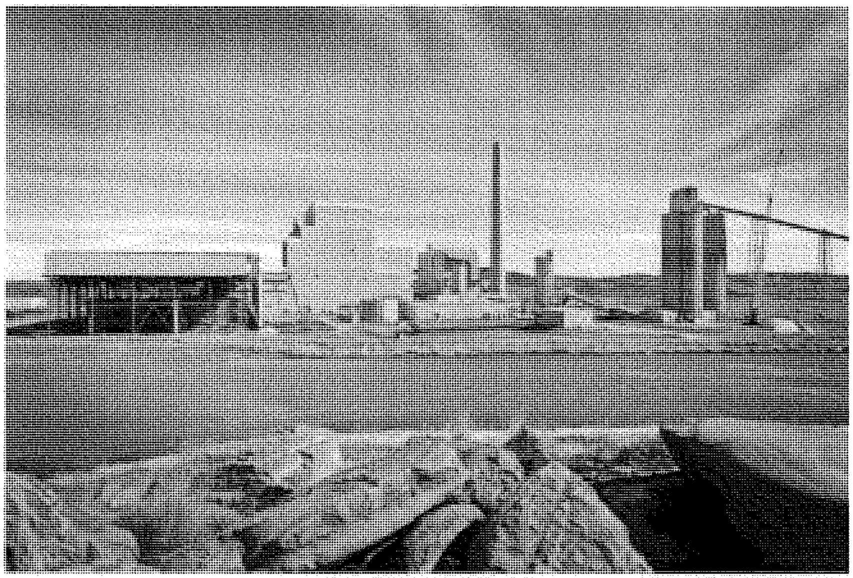
Without objection.

[The referenced information follows:]

The Sheridan Press

Senate bill could stimulate state carbon capture projects

By Michael Illiano|March 30th, 2018



Courtesy Photo | The Integrated Test Center is a facility attached to the Dry Fork power station in Campbell County that can divert up to 5 percent of the station's flue gas into research bays. Researchers can then connect small-scale carbon capture technologies to the bays and test them with the Dry Fork station's gas.

SHERIDAN — A bipartisan bill introduced to the Senate last week could energize clean-coal research in Wyoming.

The Utilizing Significant Emissions with Innovative Technologies Act, which was cosponsored by U.S. Sen. John Barrasso, R-Wyoming, would support carbon capture research and streamline federal processes to allow for faster development of carbon capture-research-related infrastructure.

Carbon capture processes aim to collect the carbon dioxide that is emitted by coal-fired plants in order to reduce pollution.

Jason Begger, the Wyoming Infrastructure Authority's executive director, said there are several proven methods for accomplishing this, but carbon capture research is focused primarily on developing cost effective ways for collectiong carbon dioxide emissions.

Begger said because society is beginning to demand cleaner energy, finding sustainable carbon capture technologies will be crucial to the future of Wyoming's energy resources.

"Almost two-thirds of our tax revenue comes from fossil energy resources, so in today's world where we are seeing a push towards lower-carbon sources of energy, that has a direct [effect] on our state's bottom line," Begger said. "Really, the benefit to these types of technologies moving forward is allowing Wyoming to continue developing its resources and keep its low tax base."

Begger added that the research the USE IT Act would enable could not only modernize Wyoming's energy resources, but it could help the state diversify uses for them. Once carbon dioxide is captured, it can be utilized in a number of processes to develop new products and materials.

"What if we can take this CO2, which right now is considered a waste product — some might consider it a liability — and turn it into an asset?" Begger asked.

Carbon dioxide can be used to manufacture carbon fibers, for instance, which are low-weight alternatives to metals like aluminum and can be used in products ranging from bicycles to airplanes.

Begger said the Wyoming Integrated Test Center, which the Wyoming Infrastructure Authority manages, would give the state an advantage in exploring carbon utilization techniques.

The Integrated Test Center is a facility attached to the Dry Fork power station in Gillette that can divert up to 5 percent of the station's flue gas into research bays. Researchers can then connect small-scale carbon capture technologies to the bays and test them with the Dry Fork station's gas, which Begger said is a rare opportunity.

"Currently, if researchers want to test a technology on a small scale, what they're doing is [creating] a flue-gas equivalent," Begger said. "What we can offer at the ITC is real flue gas with all the actual components and real world conditions — the right temperatures, the right pressures, something you can't get in a laboratory."

Dr. Mark Northam, the University of Wyoming's School of Energy Resources director, said the university is also engaged in researching methods to convert collected carbon dioxide into products, both through the ITC and on the UW campus. Northam added that the university's research is focused on converting carbon dioxide into physical products.

"There are some people who are looking at fuels – fuels aren't a very effective way to go about it because the only way to get value out of a fuel is to burn it and make more CO2," Northam said. "The more appropriate thing to do is to make something durable out of it. There is a lot of research going on around the world to try and make more durable products... The big challenge is how can you make them cost effectively."

The USE IT Act would also support the construction of carbon capture infrastructure, such as pipelines that transport carbon dioxide from the site where it is captured to the site where it can be utilized.

"That is important not in the form of dollars, but more in shortening the time limit between application and permit delivery by putting a cap of two years on it," Northam said. "That [makes it easier for] people who want to build pipelines...to get financing because right now it can take six or eight years to get a permit to put in a pipeline."

Northam added that Wyoming has previously explored paths for carbon dioxide pipes and the state would be well positioned if the bill becomes law.

Senator BARRASSO. The USE IT Act has two sections, one that promotes research and the other to facilitate development of carbon capture products and CO_2 pipelines.

The first title of the bill directs the EPA to conduct carbon dioxide research activities under existing authority in the Clean Air Act. Specifically, the EPA would provide technical and financial assistance to carbon dioxide utilization projects that use CO_2 generated from industrial facilities. EPA would also administer a competitive prize program to promote another innovative technology: direct air capture.

The second title is all about creating a favorable environment for the permitting and development of the infrastructure needed to make carbon capture successful. In this title, the bill clarifies that carbon capture utilization and sequestration projects, as well as carbon dioxide pipelines, should be permitted in a timely and coordinated manner.

The bill will send an important signal to project developers that the Federal Government is committed to be a partner in the project development and in exploring new commercial uses for carbon dioxide.

The bill also establishes a process for stakeholders to work together to identify and develop models that facilitate the permitting and development of carbon capture projects and carbon dioxide pipelines.

So, I look forward to working with members of the Committee to advance this critical legislation.

I will now turn to the Ranking Member, my friend, Tom Carper, for his opening statement.

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

Senator CARPER. Thanks, Mr. Chairman.

Delighted to see our witness, our first witness, our lead-off hitter, who is actually quite a good hitter, as I recall, and to welcome our other witnesses who will follow Senator Heitkamp.

Mr. Chairman, I want to thank you for this hearing today, and I want to thank you, Senator Whitehouse, and others who have worked, along with our staffs, to craft this legislation for our consideration. It is really a pleasure to participate in a hearing that focuses on solutions to climate change, as opposed to a hearing that focuses and fuels the debate over the science of climate change.

Since the founding of our Union, our country has faced daunting challenges that at first seem impossible to overcome. With support from Federal, State, and local governments, Americans have found ways to innovate and craft solutions to overcome these challenges.

I believe the same can and must be true when it comes to addressing climate change. Smart policies at the Federal, State, and local levels have spurred a clean energy revolution in this country, and we have achieved real results. $507 billion have been invested in the clean energy sector over the past 10 years, and our country is the leader in exporting clean air and clean energy technology—— a leader.

Thanks in part to these investments in clean energy and energy efficiency, American consumers are paying less for energy today, not more; jobs—some 3 million of them, in fact—have been created here at home to produce these clean energy technologies.

However, if our country, and quite frankly, all countries, are going to address the challenge of climate change, we must do more to spur clean energy technology. That is why I have long believed that the Federal Government should foster and support the deployment of carbon capture, sequestration, and utilization technologies, and I have been, as a Congressman, as a Governor, and as a United States Senator, a strong advocate of doing just that.

Wide deployment of carbon capture, sequestration, and utilization could significantly reduce climate pollution emissions in this country and abroad, and could be a real win-win for coal communities, for manufacturing, and for our climate.

But just as with other coal related technologies, the barriers to carbon capture, utilization, and storage are largely financial—largely financial, not environmental. The reluctance of investors to invest in CCUS is not because we require these operations to meet other basic and important environmental requirements. Instead, investors have shied away from expensive, large scale carbon capture projects because energy prices are low. This country has struggled to put a price on carbon usage, and as a result, we are well on our way to ceding the economic opportunities of carbon capture technology to other countries, like China, which only hurt the very coal communities that our President says he wants to help. And a couple of us actually grew up in those coal communities.

American ingenuity has always been our best tool in meeting the challenges our country has faced, so it just makes sense that we would harness the same innovative spirit in order to find smart ways to spur CCUS in America.

Today we will hear, beginning with our lead-off witness, Senator Heitkamp, much about such innovative efforts occurring at the University of Delaware that, if successful, would make carbon capture a no-brainer—no-brainer—for businesses in the future.

This legislation before us, as the Chairman has said, is intended to spur more innovation in projects in CCUS like the one at the University of Delaware that we will hear about in just a moment. So, for that, I applaud the underlying effort and the Chairman and co-sponsors for your work.

Having said that, however, I do have one concern that I want to mention with the legislation which explains why I am not yet a co-sponsor. For one, I am concerned that the legislation may be handing over a program to an already burdened EPA to oversee what may be better suited for the Department of Energy to administer.

I am also a bit weary of discussing any additional streamlining provisions for this technology, when in the past two transportation bills we have established streamlining provisions to help these types of projects move through the permitting process more easily. I believe that before we consider a lot more streamlining measures, we ought to prioritize implementing the ones we have already put in place. Most importantly, I want to make sure that this effort is not connected with other efforts that may weaken the Clean Air Act.

In closing, let me reiterate that we don't need to scrap our environmental standards to provide a nurturing environment for American innovation and economic investment in carbon sequestration technologies; they are not mutually exclusive.

With that, we look forward to hearing from our lead-off witness and our other witnesses. Thank you all for being here with us today.

Thank you.

And for your leadership, thank you, Mr. Chairman.

Senator BARRASSO. Thank you, Senator Carper.

Senator Capito.

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

Senator CAPITO. Thank you, Mr. Chairman and Ranking Member. I am glad to see Senator Heitkamp here and Senator Whitehouse.

Senator Barrasso and I are the major authors of this bill. I said it is good to have the team back because we had a major victory at the end of last year with everybody's help; we passed the FUTURE Act, which Senator Barrasso referenced in his opening statement, which reauthorized and really improved the 45Q tax credit for CCUS. It was a huge milestone for all of us because we had a bipartisan group of Senators, a diverse coalition of coal and oil industry, environmental groups, and the labor organizations that were supporting us, so we are now looking to the second phase and making sure that this technology can make it out into the field.

Beyond the economics, we need to have adequate R&D into CCUS, some of that is being done at Nettle in Morgantown and at our universities, and that our regulatory structures aren't so onerous so as to prevent CCUS projects and carbon dioxide pipelines from being permitted.

I think there is an issue that we try to address in here, and that is on the carbon dioxide portion of the pipelining, which brings a different flavor to pipeline regulating than we have seen in the past. So, we are in the process of bringing together another coalition of stakeholders like the one that supported the FUTURE Act, and today's hearing is part of that process.

So, with all of us pulling together, I hope we can get another pro-CCUS bill. It is a win-win; it is an energy bill; it is a carbon emission reduction bill; and it will benefit all of us economically.

Thank you, Mr. Chairman.

Senator BARRASSO. Thank you, Senator Capito.

Senator Whitehouse.

OPENING STATEMENT OF HON. SHELDON WHITEHOUSE, U.S. SENATOR FROM THE STATE OF RHODE ISLAND

Senator WHITEHOUSE. Thank you, Chairman.

It is good to be working on this bill again and trying to advance the cause of carbon capture, utilization, and sequestration. Obviously, if you are going to capture and utilize carbon dioxide, it is helpful to have a way to distribute it to the ultimate users, and that is where the pipeline piece comes in; it is a very sensible adjunct to the bill that we got passed.

I would like to make two points. One is that pretty much everybody on the Republican side of the aisle who has thought the climate change problem through to a solution, whether it is former Senators, former Representatives, former Treasury secretaries, former EPA administrators, former presidential economic advisors, they all more or less come to the same place, which is that there needs to be a market price on carbon dioxide emissions.

I think we agree with that. There is usually the view that it ought to be revenue-neutral, it shouldn't be revenues used to build more government, we don't need to have that fight on this issue; and it needs to be border adjustable so a cement plant in Texas doesn't face unfair competition from the same cement plant across the border in Mexico.

All of that is very doable, but it is going to take a little bit more leadership from our friends in the fossil fuel industry before we get there.

I want to make it clear that, from my experience here in the Senate, when our oil majors say they understand that climate change is real, they understand that their product is causing it, and they support a price on carbon emissions, that that is not a truthful statement. At the end of the day, their entire political and electioneering apparatus remains fully dedicated to making sure that there is no price on carbon.

How they are going to explain to the future and to their shareholders why they say one thing publicly and direct their political and electioneering efforts in a completely different direction I leave up to them, but I am here as witness to the fact that there is zero political and electioneering support from those industries for the serious price on carbon they claim to support. So, in the meantime, we can do things to move things forward, and this is one of those ways to move things forward.

The second point I would like to make is that we need to be very careful about making sure that when we are talking about regulatory efficiencies, we are really talking about regulatory efficiencies. When that becomes a code for undoing environmental protections, I am out.

We have seen regulatory efficiencies pay off in big ways. Rhode Island has steel in the water and electrons flowing into the grid from the first offshore wind turbines in the United States because we designed a better regulatory process than Massachusetts did. Cape Wind in Massachusetts died over more than a decade of regulatory process. We did it faster, smarter, and right in Rhode Island, and the payoff is we got the first offshore wind in the country.

So, there in fact are ways to make regulation achieve its purpose in the most efficient way. We have to guard against that being a screen for undoing the underlying protections, and that is a principle that I am going to bring into this bill and into all of my oversight efforts on this Committee.

I appreciate the opportunity I have had to work with so many friends on this Committee on this and on the previous bill, and I am delighted to see my distinguished Dakotan colleague here.

Senator BARRASSO. Thank you very much, Senator Whitehouse.

Now to the distinguished Dakotan colleague, Senator Heitkamp.

Welcome to the Committee. Thank you for joining us and for your support of the bill.

STATEMENT OF HON. HEIDI HEITKAMP, U.S. SENATOR FROM THE STATE OF NORTH DAKOTA

Senator HEITKAMP. Thank you, Mr. Chairman, and hello to all my friends on the Environment and Public Works Committee.

I think Sheldon occasionally says that because he can't remember if it is North or South Dakota.

[Laughter.]

Senator WHITEHOUSE. It is not East or West?

[Laughter.]

Senator HEITKAMP. Good morning, Chairman Barrasso.

Senator BARRASSO: If it is a road or if it is an island, yes.

[Laughter.]

Senator HEITKAMP. Or soon to be.

Good morning, Chairman Barrasso.

Senator WHITEHOUSE. No fair, all you westerners ganging up on me.

[Laughter.]

Senator HEITKAMP. I am going to start over now.

[Laughter.]

Senator HEITKAMP. Good morning, Chairman Barrasso, Ranking Member Carper, and all of my friends and colleagues on this Committee. I want to thank you so much for the invitation to testify on this USE IT Act, Utilizing Significant Emissions with Innovative Technologies Act.

I just want to make a point that for generation after generation we have seen CO_2 as a pollutant, and the efforts that this Committee, in a very bipartisan way and our group of four have really tried to turn the page and start looking at CO_2 as an opportunity and as a legitimate and valuable by-product.

So, Senator Barrasso, I want to thank you so much, and your staff, for your incredible work on this and making it a priority of your office, and inviting me and allowing me to be part of that work.

Senators Whitehouse and Capito, your continued work and partnership in these efforts on carbon capture, utilization, and storage initiatives, that leadership continues beyond the work that we did on our FUTURE Act, and we know that these new policies can create an environment in which innovation and implementation of CCUS technologies and processes are allowed to thrive and grow.

Much has already been said about the FUTURE Act. It was one cog in that wheel, and we know that we need to make sure that we can commercialize the work that is being done that we can continue to drive the technology in ways that will amaze and astonish people out in the country.

When we talk about the challenges of how to implement the policies that would encourage CCUS in this country, it was clear that closing the financing gap through the FUTURE Act was critical, but merely doing that one piece wasn't enough.

It was before this very same Committee last year where the FUTURE Act was being discussed during a hearing on expanding and accelerating the deployment and use of CCUS, and questions were posed to the witnesses about what additional challenges existed and what further policies we needed to promote CCUS. The response was clear: there needed to be a comprehensive approach that looked across the entire Federal and State regulatory policies to better coordinate and establish an environment where CCUS projects are not burdened by long lead times or duplicative and unnecessary regulations, and that we needed to build out the infrastructure necessary to move the CO_2 from the source to those areas that are best able to utilize it as a by-product.

As a result of that hearing, Chairman Barrasso took the lead on addressing some of those very concerns, and I happily joined him and my colleagues, Senators Whitehouse and Capito, in that effort.

The USE IT Act directs EPA and CEQ to prioritize and take lead roles at the Federal level in supporting CCUS and direct air capture research, and establishing guidance for project developers and operators that will allow better coordination and facilitation of these projects. It also clarified that existing policies facilitating the build out of infrastructure projects are applicable to CCUS projects and CO_2 pipelines.

While I will admit I am biased when it comes to advancing this bill and these policies, North Dakota is at the forefront of developing CCUS projects if the right conditions are met. As of yesterday, we are the first State in the country that has been authorized by EPA to regulate Class 5 injection wells. We have three CCUS projects at various stages of planning. Red Trail Energy in Richardton is looking to capture and store CO_2 from an ethanol plant. Project Tundra is looking to add carbon capture equipment to the back end of an existing coal fired power plant in the Allam cycle project that could be fueled by synthetic gas produced at our great lignite coal resource in our State. It is really quite amazing.

All of these projects are not what we called in the old days vaporware. They are real, they are being developed every day, they are being invested in by the State and by private entities in the State of North Dakota, so we are ready to go. We are ready to go if the conditions are right.

To that point, I would like to submit several records or several letters in support of the USE IT Act. I want to make this point because I think sometimes we talk a lot about saving jobs and doing what we can to make sure people stay working. These employers represent thousands of jobs in my State, and even more jobs if we look at the indirect benefit of this value-added industry to my State. So, I would like to submit these letters in support.

Senator BARRASSO. Without objection.

Senator HEITKAMP. Thank you.

[The referenced information follows:]

BPC Action

FOR IMMEDIATE RELEASE
April 9, 2018
Contact: Kimberly Dean
(202) 218-6774
kdean@bpcaction.org

BPC Action commends Sens. **John Barrasso** (R-WY), **Sheldon Whitehouse** (D-RI), **Shelley Moore Capito** (R-WV) and **Heidi Heitkamp** (D-ND) for introducing S. 2602, the *Utilizing Significant Emissions with Innovative Technologies (USE IT) Act*. This bill will facilitate the development of carbon capture technologies, reduce emissions and maintain America's energy independence.

We must build on recently enacted investments in carbon capture to continue innovating in this space. Cutting-edge and commercially viable technologies are needed to mitigate carbon emissions and best utilize our critical natural resources. The USE IT Act's carbon utilization and direct air capture research are important to developing these technology breakthroughs. Collaboration among federal, state and non-government partners will also spur the development of carbon capture facilities and CO2 pipelines – infrastructure that is crucial in maximizing opportunities promoted by the USE IT Act.

BPC Action applauds the bipartisan action of these senators and looks forward to working with Congress to pass legislation that secures our energy future and economy.

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

April 10, 2018

Senator John Barrasso
307 Dirksen Senate Office Building
Washington, DC 20510

Senator Sheldon Whitehouse
530 Hart Senate Office Building
Washington, DC 20510

Senator Shelley Moore Capito
172 Russell Senate Office Building
Washington, DC 20510

Senator Heidi Heitkamp
516 Hart Senate Office Building
Washington, DC 20510

Re: Encouraging American Innovation in Advanced Low-Carbon Technologies

Dear Senators Barrasso, Whitehouse, Capito, and Heitkamp:

As a former Deputy Administrator of the U.S. Environmental Protection Agency and recognizing that the sponsors agree to continue with bipartisan consensus going forward, I thank you for your leadership in introducing the Utilizing Significant Emissions with Innovative Technologies Act (USE IT) Act. American innovation in advanced low-carbon technologies from carbon capture use and storage to nuclear energy to renewable energy is critically important to boost our economic growth and to prevent the worst impacts of climate change. From a business perspective, there will be markets for American advanced low-carbon technologies across the globe as other countries continue to expand their efforts to reduce carbon emissions to address climate change.

The USE IT Act supports research on carbon utilization. I believe that transforming captured carbon emissions from a liability into a valuable commodity will be a powerful way to align our economic incentives with our environmental goals. Federal support for research on carbon utilization should focus on three areas: reducing technology costs and increasing the number of technology options; conducting lifecycle analysis to ensure that over time the focus is on permanently storing more of the carbon; and identifying how to scale up these options to meet climate goals. The legislation would also support research on direct air capture; this important technology has the potential to result in "negative emissions" and may help us achieve the goals of the Paris

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

Agreement which include net zero emissions in the second half of this century. Reducing the costs of direct air capture technology and developing business models for its deployment are important research priorities.

On behalf of the Center for Climate and Energy Solutions, I thank you again for your leadership and I encourage you and your colleagues to enact the USE IT Act — and its research and development incentives for carbon capture technology — to open the door that can accelerate American innovation.

Sincerely,

Bob Perciasepe

Bob Perciasepe
President
Center for Climate and Energy Solutions

2101 WILSON BLVD. SUITE 550 ARLINGTON, VA 22201 P: 703-516-4146 F: 703-516-9551

NRECA
America's Electric Cooperatives

CURC CARBON UTILIZATION RESEARCH COUNCIL
ADVANCING FOSSIL ENERGY SOLUTIONS

The Honorable Senator John Barrasso
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Senator Shelley Moore Capito
172 Russell Senate Office Building
Washington, DC 20510

The Honorable Senator Sheldon Whitehouse
530 Hart Senate Office Building
Washington, DC 20510

The Honorable Senator Heidi Heitkamp
516 Hart Senate Office Building
Washington, DC 20510

Dear Senators Barrasso, Whitehouse, Capito, and Heitkamp:

The Carbon Utilization Research Council (CURC) and the National Rural Electric Cooperative Association (NRECA) are pleased to support the "Utilizing Significant Emissions with Innovative Technologies" Act (USE IT Act). The USE IT Act demonstrates a growing bipartisan leadership effort for advancing carbon capture, utilization, and sequestration (CCUS) technologies that will improve our nation's economic and energy security objectives, while also mitigating emissions of CO_2 from the use of fossil fuels. This legislation demonstrates a federal commitment to continue to work with industry to find collaborative pathways for funding and deploying CCUS.

As organizations that are committed to developing technology solutions for the responsible use of our coal and fossil fuel resources, we are pleased to see Congress share a view that technologies like those that are supported by the USE IT Act will enhance the value of our country's vast domestic resources while also supporting our national – and global – need for reliable, secure, clean and affordable energy.

Currently, the Clean Air Act does not direct the Environmental Protection Agency to use its existing authority to support carbon utilization or innovative carbon capture research. More development is needed for these important technologies to match those advancements seen in solar and wind generation technologies. Implementation of the USE IT Act will ultimately lead to solutions that will help bring down the costs of commercial-scale CCUS projects integrated with power generation. These efforts will complement and enhance work already being done through public-private partnerships such as the Wyoming Integrated Test Center and the National Carbon Capture Center.

Building on the FUTURE Act, legislation championed by this same group of Senators, the USE IT Act will go a step further by improving the permitting of carbon capture, utilization, and sequestration projects and CO2 pipelines, which will provide necessary certainty to power generators and other industrial sources and will incentivize the build-out of CCUS projects.

We thank you for your leadership and look forward to supporting your efforts to advance this important legislation.

Sincerely,

Jim Matheson
CEO, NRECA

Shannon Angielski
Shannon Angielski
Executive Director, CURC

Senator HEITKAMP. The impressive panel of witnesses that you have assembled to follow me are in a much better position to get further into the details of why this bill addresses some of those challenges laid out in the September hearing. What I can tell you is that I am certain that these efforts will lead to breakthroughs that provide for economic and employment benefits to our country and provide long term technological solutions that will allow for the continuation of an all of the above energy policy, all while addressing climate challenges by greatly reducing carbon emissions.

I want to make one final statement. I think that when we are looking back at our legislative careers, and we are thinking how did we do, did we just stand in our corners and shout across the void and across the divide? Occasionally something will come up where we will say we walked across, we sat down, we figured it out, and we did something that actually made a difference in the U.S. Congress.

I think this effort is exactly that, and I think all of us who have worked on this, especially the four of us who have been particularly engaged, will have something to talk about. We will have an example of the kind of leadership that we have exhibited while we are here, and I think this not only has been a wonderful piece of policy, it has been a wonderful example of how friends and colleagues can get together to actually move important policy for the people of this country.

So, I proudly join and support all of my co-sponsors, and I encourage a quick resolution out of this Committee and hard work on the floor of the Senate to get this thing passed in the U.S. Senate.

Thank you, Mr. Chairman, for this opportunity.

Senator BARRASSO. Thank you very much, Senator Heitkamp. Glad you could join us today. Appreciate it.

Senator HEITKAMP. Thank you.

Senator BARRASSO. At this time, I would like to call our four witnesses to the table.

We will now hear from our witnesses, and I am pleased to introduce Dr. Mark Northam, who is the Director of the University of Wyoming's School of Energy Resources. Prior to his service at the university, he has had extensive research experience in the private sector. Additionally, he has worked as a research science consultant in the areas of carbon management and technical intelligence at the Research and Development Center at Saudi Aramco. Dr. Northam also worked at Mobil and ExxonMobil for over 20 years, where he held a variety of research operations and managerial positions.

I want to thank you for your willingness to testify today.

Additionally to Dr. Northam we have Dr. Julio Friedmann, who is the CEO of Carbon Wrangler, LLC.

It is good to see you again. Welcome back to the Committee. We appreciate your insightful testimony at the hearing last September on carbon capture, and we look forward to hearing your insights today.

Next is Noah Deich, who is the Executive Director of the Center for Carbon Removal; and Dr. Feng Jiao from Senator Carper's home State of Delaware.

Senator Carper, would you like to add any few words of introduction?

Senator CARPER. Isn't that a great name, Feng Jiao? It means common sense. No, it doesn't really, but it could, because this is very much a common sense approach, I think.

After finishing his post-doctoral research at the Lawrence Berkeley National Laboratory, Dr. Jiao joined the faculty at the University of Delaware, I think in 2010. Was it 2010?

Mr. JIAO. Yes, 2010.

Senator CARPER. Chemical & Biomolecular Engineering Department. Today he is still at that department at the University of Delaware, serves as an Associate Professor. He is also the Associate Director for the Center for Catalytic Science & Technology. His current research focuses primarily on converting carbon dioxide into valuable chemicals.

Dr. Jiao has published more than 50 articles.

Is that true?

Mr. JIAO. Yes, that is true.

Senator CARPER. OK. More than 50 articles in leading scientific journals, such as the Journal of American Chemical Society, regarding his work in electrochemistry and nanomaterials. Just last year he was awarded $1 million by the Department of Energy to further his work on carbon capture and utilization. In addition, Dr. Jiao started a company called CO_2 Energy LLC specializing in carbon capture and utilization.

We welcome you, Dr. Jiao. It is great to see you. Happy that the First State is represented on both sides of the dais. Thank you.

Senator BARRASSO. I want to remind the witnesses that your full testimony will be made part of the record of the official hearing today, so we please ask you to keep your statements to 5 minutes so that we have time for questions. Look forward to hearing your testimony.

Dr. Northam, please begin.

STATEMENT OF MARK A. NORTHAM, EXECUTIVE DIRECTOR, SCHOOL OF ENERGY RESOURCES, UNIVERSITY OF WYOMING

Mr. NORTHAM. Thank you.

Chairman Barrasso, Ranking Member Carper, and members of the Senate Committee on Environment and Public Works, thank you for inviting me to testify on the Utilizing Significant Emissions with Innovative Technologies Act, or USE IT Act.

Senator Barrasso, thank you for the introduction. You took away the first 10 minutes of my testimony.

For those of you who are here to see the other Mark, I think he was here today, and he is over in the House today, so sorry if you are disappointed.

I came to the university following 26 years in the oil and gas industry. I have had the privilege of working on carbon dioxide utilization and storage issues, technologies and policies for the bulk of my career.

For example, I was a technology leader with the Sleipner CO_2 Storage Project in the Norwegian offshore from its inception. Sleipner CO_2 Storage Facility was the first in the world to inject CO_2 into a dedicated subsurface reservoir for the purpose of storage. The Sleipner facility has captured CO_2 at the Sleipner area gas development since 1996. The captured CO_2 is directly injected into the offshore sandstone reservoir. Nearly a million tons of CO_2 is injected per annum, and over 17 million tons has been injected since inception.

My work with carbon capture, utilization, and storage continues through the present day at SER, the School of Energy Resources. We continue to conduct important research related to the geologic storage of CO_2 in saline aquifers, and to improve carbon dioxide-motivated enhanced oil recovery operations.

The State of Wyoming is an ideal jurisdiction to advance research and projects related to capturing and utilizing emissions of CO_2. For example, the Wyoming legislature provided for the development of an integrated test center to serve as an operational test site for CO_2 capture and utilization technology developers. The Wyoming Infrastructure Authority led the development of the site with the support of many private and public sector entities in Wyoming.

The ITC will soon host five semifinalists of the coal track of the $20 million NRG COSIA Carbon XPRIZE, a global competition to develop breakthrough technologies that convert CO_2 emissions from fossil fuel combustion into products with the highest net value. Competitors in this program are developing processes that utilize CO_2 in the production of, for example, enhanced concrete, biofuels, nanotubes, and fertilizers. In fact, the Carbon XPRIZE finalists were announced Monday evening in New York City, and five of these finalists will be operating by the end of this calendar year in Wyoming.

Wyoming is also one of a handful of States with existing CO_2 pipeline infrastructure to serve an active enhanced oil recovery industry. The State has also planned for future expansion of the network through ongoing efforts of the Wyoming Pipeline Corridor Initiative, primarily for providing CO_2 to parts of the State with significant demand for supply.

I am pleased to testify today in support of the USE IT Act. My testimony focuses on carbon dioxide utilization section of Title I, which amends section 103 of the Clean Air Act to authorize the U.S. Environmental Protection Agency to support certain CCUS related research and development activities by the States, institutions of higher education, and others.

Title I of the USE IT Act, in part, authorizes the EPA to carry out a research and development program for carbon dioxide utilization to promote technologies that transform carbon dioxide generated by industrial processes into a product of commercial value, or as an input to products of commercial value. The bill defines carbon dioxide utilization as technologies or approaches that lead to the use of carbon dioxide through fixation of CO_2 through photosynthesis or chemosynthesis, such as through the growing of algae or bacteria; the chemical conversion of CO_2 to a material or chemical compound in which the CO_2 is securely stored; and the use of CO_2 for any other purpose for which a commercial market exists.

The EPA is to provide technical and financial assistance to certain eligible CO_2 utilization projects, with the eligibility criteria including access to an emissions stream from a U.S. based stationary source that is capable of providing not less than 250 metric tons of CO_2 per day.

I support these provisions. Not only do they create another source of critically needed funding for the CCUS related research and technologies, but also they apply to a broad swath of potential CCUS technologies. Eligible technologies include the use of CO_2 for any other purpose for which commercial markets exist, which I interpret to include CO_2-EOR.

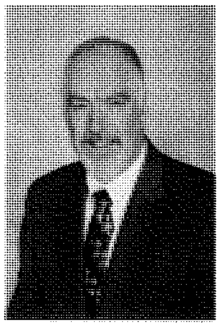
Moving to Title II, the USE IT Act first explicitly makes certain CCUS related projects, including CO_2 pipelines, subject to the 2015 Fixing America's Surface Transportation Act, or FAST Act. The FAST Act seeks to streamline Federal environmental review and permitting, reducing bureaucratic redundancies for certain large infrastructure projects, and second, directs the Chair of the White House Council on Environmental Quality, in consultation with EPA, DOE, and others, to prepare guidance to facilitate reviews associated with the deployment of CCUS projects and CO_2 pipelines.

I support these provisions as well. In addition to financial challenges, CCUS projects face unfortunate headwinds caused by well intended, but nonetheless, arguably, counterproductive Federal policies. These policies include time consuming reviews under NEPA, which is a specific challenge for States such as Wyoming that have significant areas of Federal lands. The Underground Injection Code under the Safe Drinking Water Act also arguably stands as an impediment to CCUS projects due to aspects of the Class VI CO_2 injection storage regulations that are difficult, if not impossible, for the private sector to utilize. Title II of the USE IT Act should go some way toward ameliorating these and related challenges facing CCUS projects and technologies.

This concludes my testimony. I am pleased to testify today in support of the USE IT Act. The ongoing Federal role in supporting CCUS research at institutions of higher education is imperative.

Mr. Chairman, Ranking Member Carper, and members of the Committee, I would be pleased to answer any questions that you may have. Thank you.

[The prepared statement of Mr. Northam follows:]



Dr. Mark A. Northam
Founding Director of the School of Energy Resources University of Wyoming

Dr. Mark Northam is the Founding Director of the School of Energy Resources at the University of Wyoming. He came to the university in 2007 after 25 years of domestic and international experience in the upstream oil and gas industry with Mobil, ExxonMobil and Saudi Aramco. Dr. Northam held a variety of research, operations and management positions during that time in Texas, Louisiana, Virginia, Norway, and Saudi Arabia before joining the University of Wyoming in Laramie, Wyoming.

Mark earned a Ph.D. degree in Organic Geochemistry from the University of Texas at Austin and a Bachelor of Science degree in Chemistry from Wake Forest University. He is originally from Virginia.

STATEMENT OF DR. MARK NORTHAM

EXECUTIVE DIRECTOR

of the

SCHOOL OF ENERGY RESOURCES, UNIVERSITY OF WYOMING

before the

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

concerning the

"UTILIZING SIGNIFICANT EMISSIONS WITH INNOVATIVE TECHNOLOGIES ACT"

APRIL 11, 2018

Introduction

Chairman Barrasso, Ranking Member Carper, and Members of the Senate Committee on Environment and Public Works, I am Mark Northam and I serve as the Executive Director of the School of Energy Resources at the University of Wyoming. Thank you for inviting me to testify on S. 2602, The Utilizing Significant Emissions with Innovative Technologies Act (USE IT). I came to university following 26 years in the oil and gas industry. Immediately prior to accepting my current position, I was employed by Saudi Aramco in Dhahran, Saudi Arabia, where I worked as a Research Science Consultant in the areas of Carbon Management and Technical Intelligence. Prior to joining Saudi Aramco, I worked for over twenty years at Mobil and ExxonMobil, holding a variety of research, operations, and management positions in the US and Europe.

I have had the privilege of working on carbon dioxide (CO_2) utilization and storage issues, technologies and policies for the bulk of my career. For example, I was a technology leader with the Sleipner CO_2 Storage Project in the Norwegian offshore from its inception. The Sleipner CO_2 Storage Facility was the first in the world to inject CO_2 into a dedicated subsurface reservoir for the purpose of storage. The Sleipner facility has captured CO_2 as part of the Sleipner area gas development since 1996. The captured CO_2 is directly injected into an offshore sandstone reservoir. Nearly 1 million tonnes of CO_2 is injected per annum and over 17 million tonnes has been injected since inception to date.

My work with Carbon Capture, Utilization and Storage (CCUS) continues through the present day at SER. We continue to conduct important research related to the geologic storage of CO_2 in saline aquifers, and to improve carbon dioxide-motivated enhanced oil recovery operations (CO_2-EOR). For example, SER is advancing two project sites in Wyoming under Phase I of the

U.S. Department of Energy's Carbon Storage Assurance and Facility Enterprise (CarbonSAFE) program, which has the aspiration of siting one or more large-scale integrated CCUS facilities throughout the United States by 2025. Our current work builds upon UW's prior CCUS research under the Wyoming Carbon Underground Storage Project, a pioneering three-year research project that thoroughly characterized two potential CO_2 storage reservoirs (the Weber Sandstone and Madison Limestone) on the Rock Springs Uplift in the southwestern corner of Wyoming.

Separately, and in conjunction with colleagues at West Virginia University, University of Kentucky and elsewhere, UW is pleased to play an integral role in DOE's Joint US/China Clean Energy Research Consortium (CERC) program. CERC is a multi-year DOE effort to foster collaborative research and development of CCUS and other clean coal technologies between the U.S. and China.

SER's work on ensuring a sustainable future for fossil fuels extends well beyond CCUS to fields such as carbon engineering. UW is well along in developing and advancing novel and innovative technologies related to the extraction and production of valuable non-Btu products from coal. The primary focus of this research is to advance coal utilization as a feedstock to manufacture and generate valuable non-Btu coal-based products such as carbon fiber and carbon-rich chemicals, agricultural supplements and building products. The manufacture of some of these coal-based products has the potential to be deployed as a pre-treatment before coal is combusted to offset the typically high costs associated with post-combustion carbon capture solutions. And some of these products – e.g., graphite and carbon fiber -- are predicted to be in short supply as the demand for lightweight materials, renewable energy and the like grows in the years ahead.

The State of Wyoming is an ideal jurisdiction to advance research and projects related to capturing and utilizing emissions of CO_2. For example, the Wyoming Legislature provided for the development of an Integrated Test Center (ITC) to serve as an operational test site for CO_2 capture and utilization technology developers. The Wyoming Infrastructure Authority led development of the site with the support of many private- and public-sector entities in Wyoming. The Gillette-based Integrated Test Center (ITC) will be inaugurated in May of this year. When operations commence later this year, it will deliver 20 MW-equivalent emissions stream from the coal-fired Dry Fork Station to test bays that will accommodate up to seven technology developers. The ITC will soon host five semifinalists of the coal-track of the $20M NRG COSIA Carbon XPRIZE, a global competition to develop breakthrough technologies that convert CO_2 emissions from fossil-fuel combustion into products with the highest net value. Competitors in this program are developing processes that utilize CO_2 in the production of, for example, enhanced concrete, biofuels, nanotubes and fertilizers. In fact, the Carbon XPRIZE finalists will be announced Monday in New York City.

Wyoming is one of a handful of states with existing CO_2 pipeline infrastructure to serve an active CO_2-EOR industry. The state has also planned for future expansion of the network through ongoing efforts of the Wyoming Pipeline Corridor Initiative, primarily for providing CO_2 to parts of the state with significant demand but no supply.

Finally, Wyoming has enacted a body of laws and regulations to encourage and sustain the environmentally responsible siting and operation of CCUS-related projects in the State.

Testimony

I am pleased to testify today in support of the USE IT Act. My testimony focuses on the "Carbon Dioxide Utilization" section of Title I, which amends section 103(g) of the Clean Air Act to authorize the U.S. Environmental Project Agency (EPA) to support certain CCUS-related research and development activities by the States, institutions of higher education and others. I conclude with some brief remarks regarding Title II that, in part, seeks to coordinate and simplify the federal and state requirements that apply to CCUS projects and CO_2 pipelines thereby facilitating and enabling development of needed facilities and infrastructure.

Title I, Carbon Dioxide Utilization. Title I of the USE It Act in part authorizes the EPA Administrator to "carry out a research and development program for carbon dioxide utilization to promote technologies that transform carbon dioxide generated by industrial processes into a product of commercial value, or as an input to products of commercial value" (*USE IT Act, § 101*). The bill defines "carbon dioxide utilization" as "technologies or approaches that lead to the use of carbon dioxide" through: (1) the fixation of CO_2 through "photosynthesis or chemosynthesis, such as through the growing of algae or bacteria"; (2) the chemical conversion of CO_2 "to a material or chemical compound in which the [CO_2] is securely stored"; or (3) the "use of [CO_2] for any other purpose for which a commercial market exists" (*id.*). The EPA is to provide technical and financial assistance to certain eligible CO_2 utilization projects, with the eligibility criteria including access to an emissions stream from a U.S.-based stationary source that is capable of providing not less than 250 metric tons per day of CO_2.

I support these provisions. Not only do they create another source of critically needed federal funding for CCUS-related research and technologies, but also they potential apply to a broad swath of potential CCUS technologies. Eligible CCUS technologies include the "use of [CO_2] for any other purpose for which a commercial market exists", which I interpret to include CO_2-EOR. CO_2-EOR remains the dominant customer of captured CO_2 in the United States, as recently confirmed by the National Coal Council.[1] Active CO_2-EOR projects exist in Wyoming, Texas, New Mexico, Colorado, Idaho, Montana, Kansas, Louisiana, Mississippi and Michigan. The Rocky Mountain region – Wyoming, Idaho, Colorado and Montana – contains an estimated four billion barrels of technically recoverable oil using CO_2-EOR.[2] Carbon dioxide remains in high demand for EOR throughout Wyoming, so the USE IT Act holds promise in leveraging this commercial demand to advance CCUS technologies and projects. The existence of a "shovel-ready" use for captured CO_2 can serve as a bridge to other markets for those early-adopters of carbon capture technologies.

Title II, Improvement of Permitting Process for CO_2 Capture and Infrastructure Projects. Title II of the USE IT Act –

✓ *First*, explicitly makes certain CCUS-related projects, including CO_2 pipelines, subject to the 2015 "Fixing America's Surface Transportation Act or "FAST Act" (*Pub. L. No. 114-94*). The FAST Act seeks to streamline federal environmental review and permitting, and reduce bureaucratic redundancies for certain large infrastructure projects. For example, the FAST Act tightened the requirements that project opponents must follow under the National Environmental Policy Act, or NEPA, when bringing challenges; and

[1] "CO_2 Building Blocks: Assessing CO_2 Utilization Options" (NCC, August 2016).
[2] Jones, N., Cook, B., Whitaker, S. "CO_2-EOR in Wyoming: Project Review and Forecast of Potential" (Enhanced Oil Recovery Institute) (draft; available from author).

✓ *Second,* directs the Chair (Chair) of the White House Council on Environmental Quality (CEQ), in consultation with EPA, DOE and others, to prepare guidance: (1) to facilitate reviews associated with the deployment of [CCUS] projects and [CO_2] pipelines"; and (2) that identifies "current or emerging activities that transform captured [CO_2] into a product of commercial value, or as an input to products of commercial value" (*USE IT Act, § 202*). The guidance must address the panoply of federal laws that apply to such projects – including but not limited to NEPA, the Clean Air Act and the Safe Drinking Water Act (SDWA) – and must include the development of NEPA programmatic environmental reviews for CO_2 pipeline networks. The USE IT Act also directs the chair to form at least two task forces to perform various tasks, such as the development of common models for State-level CO_2 pipeline regulation.

I support these provisions, as well. In addition to financial challenges, CCUS projects face unfortunate headwinds caused by well-intended, but nonetheless, arguably, counterproductive federal policies. These policies include time-consuming reviews under NEPA, which is a specific challenge for states such as Wyoming that have significant areas of federal lands. The Underground Injection Code under the SDWA also arguably stands as an impediment to CCUS projects due to aspects of the Class VI CO_2 injection storage regulations that are difficult if not impossible for the private sector to utilize. Title II of the USE IT Act should go some way towards ameliorating these and related challenges facing CCUS projects and technologies.

<u>Conclusion</u>

This concludes my testimony. I am pleased to testify today in support of the USE IT Act. The ongoing federal role in supporting CCUS research at institutions of higher education is imperative. Mr. Chairman and Members of the Committee, I would be pleased to answer any questions that you may have.

Senate Committee on Environment and Public Works
Hearing entitled, *"Legislative Hearing on S. 2602, the Utilizing Significant Emissions with Innovative Technologies Act, or USE IT Act."*
April 11, 2018
Questions for the Record for Mr. Northam

Chairman Barrasso:

1. Dr. Northam, Section 201 of S. 2602 clarifies that carbon capture projects and carbon dioxide pipelines are eligible for coordinated and timely permitting.

   Why is this type of regulatory certainty critical to developers of potential projects?

Answer by Dr. Northam: Thank you for this question Chairman Barrasso. The simple answer is that uncertainty is a primary barrier to securing financing for any project of the magnitude required to deliver a new carbon dioxide capture project or for a pipeline. By ensuring a defined limit for the timing of decisions on permitting for these projects, all parties gain certainty about the timing for the need for funds to be available based on the commencement of various stages of delivering the project (final engineering, construction, commencement of operations, etc.). Knowledge that permitting will be delivered within the defined time frame reduces the overall risk for delivering the project.

Senator BARRASSO. Thank you so much, Dr. Northam, for being here today.

Dr. Friedmann.

STATEMENT OF S. JULIO FRIEDMANN, CHIEF EXECUTIVE OFFICER, CARBON WRANGLER, LLC

Mr. FRIEDMANN. Mr. Chairman, Ranking Member Carper, all the distinguished members of the Committee, thank you so much for inviting my testimony. I am honored to return. I believe last time I was here I was pleased and proud to serve as a minority witness. Today I am pleased and proud to serve as a majority witness.

My name is Julio. Until recently, I served as the Senior Advisor for Energy Innovation at the Lawrence Livermore National Laboratory. Prior to that, for about 2 and a half years, I was the Principal Deputy Assistant Secretary at the Office of Fossil Energy and happy to serve under Secretary Moniz there. I have spent 17 years working on clean energy technology and development, most of that focused on CCUS, and mostly from Lawrence Livermore National Lab.

My testimony last September focused on CCUS as a technology set. Since then, a sea change has occurred regarding this critical and important technology. Much of this is the result of the passage of the FUTURE Act. In my own travels around the world, we are the talk of the town, and carbon is the new black.

The Act will greatly enhance the ability of commercial CCUS projects. It will attract financing, and it has already reaffirmed the United States unambiguously as the leader worldwide in CCUS development, deployment, and policy.

Because of that financial support for the FUTURE Act, the rate of CCUS deployment is now limited by a different set of issues. Some of those issues are associated with the cost of technology; some of them are associated with the use of carbon dioxide itself; some of them are associated with regulatory issues and permitting issues.

As such, I am pleased to see the USE IT Act bill. I am pleased to testify in support of it. I believe that the USE IT Act will ultimately lower hurdles to investment; it will lower barriers to deployment; and ultimately it will serve the development, deployment, and export of this important clean energy technology.

I just want to speak very briefly about direct air capture. This is something I have spent a lot of time working on and believe that this is an underserved and important technology option.

There are simply some sources of carbon dioxide that mankind emits that are hard to manage, and in doing so, dealing with those will prove to be very expensive. Direct air capture technology today already beats the cost of many of those options, and those costs are coming down fast. There are at least three companies that are developing and deploying this technology worldwide, and I have been very impressed by the rate of progress. That said, there remains substantial technical challenges, which is part of the reason to have substantial focus on the research and development of them.

The same thing can be said about the use of carbon dioxide and conversion to valuable products. We are seeing, again, a lot of interesting technologies developed and a lot of interesting companies out there. The venture community, the equity companies, the banks that are looking at these companies have uniformly said, gosh, these are cool; wish we had 100 more like them behind it. There are simply not enough shots on net, there are not enough companies being fielded and deployed, and there needs to be a larger innovation thrust in order to get those technologies to market.

In that context, Title I of this bill I think provides a pathway to doing so. In my own experience at the Department of Energy, we fielded a solicitation in this arena. We would love to see more work of that kind. It would be my hope that if the EPA has this research program and begins it, that they would actually partner with the Department of Energy in thinking about a good way to structure and execute such a program.

With respect to CO_2 infrastructure otherwise, in many ways the United States has already demonstrated its prowess in fielding and managing CCUS infrastructure. The current network of about 5,000 miles of CO_2 pipelines, the creation of class II and class VI statutes under the EPA and under the Safe Water Drinking Act, and in fact, programs like the long lived regional Carbon Sequestration Partnerships have all been important to actually get this infrastructure up and running.

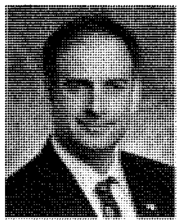
However, there are still shortcomings to these programs. The infrastructure elements that are out there limit deployment in the market in many ways. These are in my written testimony, and I ask for you to review those.

Many groups have acknowledged that there is a shortage in this infrastructure and that they prevent a limitation. These pipelines, these storage sites are going to be anchors for commercial development; they are going to be anchors for future manufacturing in a new carbon economy; they are going to be anchors for communities who want to preserve jobs or have growth.

Among other things, the Department of Energy's Quadrennial Energy Review volume 1.1, the work from the Global CO_2 Initiative, the State CO_2-EOR Working Group have all identified the critical issue of pipeline permitting and pipeline deployment in order to get this technology up and running. The most important of these pipelines will actually have to be built in States that don't have an EOR opportunity, which are unused to the permitting and deployment of these. So, having pathways that will make it faster and easier for investors to look at the risks and say, yes, we understand that we want to build this thing and that the risks and the costs associated with it are realistic and manageable is an important outcome of a bill like the USE IT Act.

I could go on, but the punchline here is if we want to get beyond 10 million or 20 million tons of deployment, if we want to get to 50 million to 100 million tons of deployment of CCUS, we will need to get this kind of infrastructure up and running.

[The prepared statement of Mr. Friedmann follows:]



Dr. Julio Friedmann
Principal Deputy Assistant, Office of Fossil Energy
U.S. Department of Energy

Dr. Julio Friedmann is the Principal Deputy Assistant Secretary for the Office of Fossil Energy, at the U.S. Department of Energy. His portfolio includes R&D and programs in Clean Coal and Carbon Management, Oil and Gas systems, international engagements in clean fossil energy, and inter-agency engagements within the US government. His earlier appointment as Deputy Assistant Secretary for Clean Coal and Carbon Management focused on clean coal and carbon capture, utilization, and storage.

In his prior appointment as Chief Energy Technologist for Lawrence Livermore National Laboratory, Dr. Friedmann's research included smart grid and energy systems analysis, conventional and unconventional hydrocarbons, CCS, geothermal power, renewable power prediction and integration, and supercomputing applications to energy. Earlier, he worked for five years as a senior research scientist at ExxonMobil and as faculty at the University of Maryland. Dr. Friedmann has a Bachelor of Science and Master of Science from the Massachusetts Institute of Technology and a Ph.D. in Geology from the University of Southern California.

Senate Environment & Public Works Committee
The USE IT Act and CCUS Deployment

Dr. S. Julio Friedmann, CarbonWrangler LLC
Written Testimony

Thank you for inviting my testimony – I'm honored to return to this committee. My name is Julio Friedmann, the CEO of Carbon Wrangler. Until recently, I served as the Senior Advisor for Energy Innovation at the Lawrence Livermore National Laboratory. From 2013 to early 2016, I served as the Principal Deputy Assistant Secretary for the Office of Fossil Energy at the US Department of Energy. I have worked for 17 years on clean energy technology development and deployment focusing my work on CCUS, mostly from my positions at Lawrence Livermore National Laboratory.

My last testimony in September focused on carbon capture, use and storage (CCUS). Since then, a sea-change has occurred regarding this critically important sector of the clean energy industry. Much of this is the result of the FUTURE Act, passed into law Feb 9th 2018, which provides substantial incentive to avoid greenhouse gas emissions through the storage and use of CO_2. The act will greatly enhance the ability of commercial CCUS projects to attract financing, and has already re-affirmed the US as the global leader in CCUS technology and policy. Recently, the IEA estimated that the passage of the act will yield projects that capture, use, and store roughly 10-30M tons CO_2 each year in the US.[1]

Because of the financing support the FUTURE Act provided, the rate of CCUS deployment is now limited by a different set of issues. Improvements in conventional carbon capture technology will help position US companies for domestic use and export, although much of this is currently well supported (and managed) by the US Dept. of Energy. However, scrubbing CO_2 from the air (sometimes called direct-air capture (DAC) or "sky mining"), is underrepresented and presents strong opportunities for development. The same can be said for CO_2 conversion and use (CCU, CO2U, or carbon-to-value (C2V)), which present new opportunities for US manufacturing. These technical areas would benefit from new programs to develop and improve their performance and bring technology to the field. NOTE: Many studies have concluded that CCUS is necessary to reach global 2030 climate targets[2] and that greatly expanded CO2U and carbon removal (including DAC) are necessary for the world to reach its climate targets beyond 2050.[3]

Although more technology development would help, the greater barriers to uptake and use of CCUS are uncertainties in policy and regulation. Often, the permitting of pipelines, CO_2 injection wells and certification of storage sites present substantial financial commitments, and may take many years to complete. This adds risk to commercial projects, and ultimately limits investment. Changes to current statute and policy could lead to better coordination between state and federal authorities, and reduce real or perceived barriers to founding projects and deploying this emissions reduction technology. In making changes, care should be taken to ensure that all relevant agencies and stakeholders have a voice and that existing

[1] https://www.iea.org/newsroom/news/2018/march/commentary-us-budget-bill-may-help-carbon-capture-get-back-on-track.html
[2] https://wedocs.unep.org/bitstream/handle/20.500.11822/22101/EGR_2017_ES.pdf?sequence=1&isAllowed=y
[3] Peters, G. & Geden, O., 2017: *Catalysing a shift from low to negative carbon.* In: Nature Climate Change, doi:10.1038/nclimate3369

protections are not weakened in a way that is counterproductive to the shared goals of improved environmental stewardship and economic growth.

Direct Air Capture and CO2 Use technology

Exactly one year ago, there were exactly zero commercial projects that separated CO_2 from the air for commercial gain. Today there are three, with additional projects mounting. Several of these were mentioned in my last testimony before this committee,[4] including the Climeworks Direct Air Capture plant in Zurich (Figure 1) and the Regeneration Engine in Reykjavik Iceland. New projects include the Carbon Engineering Air-to-Fuels project in British Columbia, and a US project slated to begin operation this fall, featuring Global Thermostat's DAC technology (Figure 1).

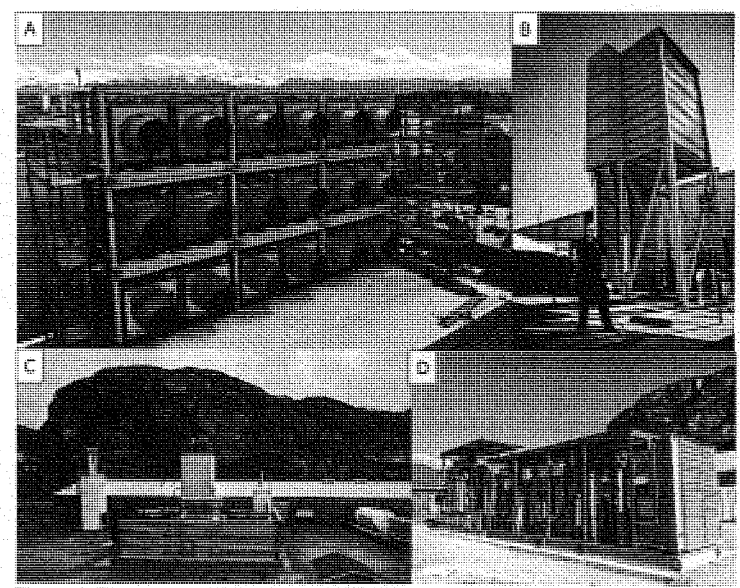


Figure 1: Direct-air capture projects. (A) Climeworks 1000 ton/y project in Hinwil, Switzerland, May 2017 (B) Global Thermostat's pilot plant in Palo Alto, CA, 2014. (C) Carbon Engineering's DAC plant in Squamish, British Columbia 2015. (D) The Greyrock air-to-fuels plant in Squamish at the Carbon Engineering site,

Unlike conventional CO_2 capture, DAC starts with a highly dilute gas stream (400 ppm, or 0.04%. This means that unconventional technologies are needed to separate CO_2 from the air, and that incremental improvements on existing technology will not deliver CO_2 at a competitive price.[5,6] While at the DOE, I was pleased to launch the first solicitation world-wide for capture from streams less than 1% CO_2. However, to make progress in this arena a

---

4 https://www.epw.senate.gov/public/_cache/files/e/a/eae08931-a714-434e-84f0-6a2edcebfc0e/BAC13A21C743DCE907756A4A3EFA9C49.friedmann-testimony-09.13.2017.pdf

5 https://www.aps.org/policy/reports/assessments/upload/dac2011.pdf

6 http://iopscience.iop.org/article/10.1088/1748-9326/aa6de5/meta

long-lived direct-air capture program with substantial core funding and continued funding is needed. Other countries are getting into the game. Just last year, the UK launched a government program that supports DAC research, as well as other kinds of carbon dioxide removal.[7]

It is reasonable to see DAC in two contexts. First, DAC is an engineered form of pollution clean-up. Based on the Paris Accord, which seeks to achieve "a balance between sources and sinks of greenhouse gases in the second half of this century ", CO_2 removal is required, and DAC is one pathway to achieve that balance. Additionally, it is reasonable to see DAC as a pathway to providing CO_2 to consumers which lack concentrated sources or pipeline infrastructure. Today, these include the food and beverage industry which uses CO_2, but also stranded opportunities for CO_2 storage or EOR, where geological CO_2 storage resources could be used if supplied. In the future, however, customers for DAC-supplied CO_2 will include a new manufacturing and commercial enterprise converting CO_2 to products.

Current and future markets for CO_2-based products include cements and concrete, fuels and chemicals, and solid carbon products like carbon black or carbon nanotubes.[8] Many US companies have started and grown over the past decade in each of these markets, and some will begin to generate revenues this year. This is part of the basis for the NRG/Cosia XPrize in CO_2 capture and use[9] and the basis for the Integrated Test Center in Gillette, WY[10] (and its counterpart in Alberta). Combining DAC with carbon-to-value (C2V) manufacturing can create a distributed manufacturing new carbon economy based on clean power, heat, and CO_2 restored from the air and oceans.[11]

However, many of the key CO_2 conversion and use technologies are at an early stage. The existing DOE programs in this area, both at the Office of Fossil Energy and the Office of Energy Efficiency and Renewable Energy, are relatively small and new. Given the economic and environmental opportunity represented by C2V, additional funding and expanded programs would help achieve important outcomes for economic growth and environmental remediation.

Improving permitting of projects and CO2 infrastructure.

In many ways, the US has demonstrated prowess in fielding and managing CCUS infrastructure. The current network of ~5000 miles of CO_2 pipelines, the class II and class VI statutes at the EPA under the Safe Water Drinking Act, and the long-lived Regional Carbon Sequestration Partnerships program at DOE all exemplify this prowess. However, substantial shortcomings to these programs and infrastructure elements limit the market for greater uptake.

- Most of the CO_2 pipelines were built before 2003. Only a few built since then have crossed state lines. Almost all were built for EOR and do not serve key US saline formation storage resources. Almost all the pipelines are at full capacity.
- Key mid-continent states (IA, IL, IN, OH, WV, PA, and MI) have little or no access to CO_2 pipeline networks.

[7] https://nerc.ukri.org/press/releases/2017/09-greenhousegas/
[8] http://www.icef-forum.org/platform/upload/CO2U_Roadmap_ICEF2017.pdf
[9] https://carbon.xprize.org
[10] http://www.wyomingitc.org
[11] https://static1.squarespace.com/static/54a2e4c1e4b043bf83114773/t/59cc06aa017db287c38e47d2/1506543286676/New+Carbon+Economy+Consortium+Workshop+Report.pdf

- Many recent CO_2 pipelines were partly financed by the US government for single-point CCUS projects funded by the DOE.
- Only one class VI well (designed for CO_2 storage) has been permitted by the EPA. The process took 54 months. No additional permit proposals are pending.

Many groups have acknowledged that current pipeline infrastructure limits the potential for CCUS deployment in the US today, including the DOE's Quadrennial Energy Review vol. 1.1,[12] the Global CO_2 Initiative,[13] and the State CO_2-EOR Working Group.[14] These groups have recognized a role for governments to support the development of this key environmental infrastructure. They also recognized that improved state and federal coordination would help speed the permitting and development of pipelines and CO_2 storage sites safely and well. Pacific Northwest National Lab estimated that ~10,000-30,000 miles of new pipelines would be needed by 2030 to achieve large-scale deployment of CCUS in the 48 contiguous states.[15]

Often, the permitting, construction, and operational readiness of pipelines and storage sites determines the timeline for commercial projects, and the total project cost is sensitive to the time taken for these steps. Concern about ambiguities in process or delays in permitting directly affect the financial viability of projects and their ability to attract investors – in other words, those concerns are substantial barriers to financing. Policies that would help clarify the timelines, requirements and roles for those involved and limit the burden or risk to potential CCUS project developers will help maximize deployment and minimize waste.

Many other clean energy technologies (such as wind or solar) rightly benefit from policy support for infrastructure and finance risk management. Today, this includes preferred access to existing transmission likes (i.e., loading order or portfolio standards), FAST act support for transmission line permitting, and net metering programs. Programs like DOI's "Smart from the Start" for offshore wind also help, and show how coordinated State and Federal efforts can provide clarity, avoid conflicts among potential stakeholders, and speed permitting.

For CCUS to achieve high deployment rates (50-100M tons/y), more policy clarity, support and program investments are required. For example, the CarbonSAFE program[16] at DOE helps potential project developers and regional interests gather new geological and geophysical data to support new projects in new areas. However, that new data cannot serve to bring projects to market if investors remain confused or concerned about how to build, access, or develop key CCUS infrastructure. Ultimately, additional regulatory clarity, potential streamlining or acceleration of permitting, and additional policy measures will greatly improve the chances of commercial development. Ideally, many stakeholders including industry, state and federal government, NGOs, and public representatives would be involved to seek opportunities to improve current law and statute.

[12] https://www.energy.gov/policy/downloads/quadrennial-energy-review-first-installment
[13] https://assets.contentful.com/xg0gv1arhdr3/5VPLtRFY3YAIasum6oYkaU/48b0f48e32d6f468d71cd80dbd451a3a/CBPI_Roadmap_Executive_Summary_Nov_2016_web.pdf
[14] http://www.betterenergy.org/wp-content/uploads/2018/02/White_Paper_21st_Century_Infrastructure_CO2_Pipelines_0.pdf
[15] https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-17381.pdf
[16] https://www.energy.gov/under-secretary-science-and-energy/articles/energy-department-announces-more-44-million-co2-storage

Final thoughts

We are at the edge of a new carbon economy – one that harnesses innovation and entrepreneurship to create new products, companies, and wealth through capturing and converting fugitive carbon into value-added products. US leadership has already stimulated new interest in expanding CCUS projects, including DAC and C2V projects, but major hurdles still persist that will prevent wider uptake. Those hurdles include insufficient support for domestic innovation in DAC and C2V, and lack of clarity and ease in permitting CO_2 infrastructure in a way that is both economically viable and serves multiple important environmental goals. US companies' competitiveness suffer and are limited in their ability to create export products and technologies in a carbon-constrained global market.

New policies would help create markets for projects, vendors, operators, and energy services in a new carbon economy - ones that can be supported through conventional financial investors that would accelerate the development and deployment of these novel technologies and industries.

An Internal Email Contradicts Scott Pruitt's Account of Controversial Raises
The EPA administrator has said he "didn't know" about unusual salary bumps given to a pair of trusted aides, but a message from one of those staffers claims otherwise.
The Atlantic
April 9, 2018
https://www.theatlantic.com/news/archive/2018/04/pruitt-epa-raises/557561/

An email that suggests Environmental Protection Agency Administrator Scott Pruitt personally signed off on a controversial pay raise for a favored aide last month is roiling the agency.

In the last few days, top staffers became aware of an email exchange between one of two aides who received such a raise and the agency's human resources division. In mid-March, Sarah Greenwalt, senior counsel to the administrator, wrote to HR in an attempt to confirm that her pay raise of $56,765 was being processed. Greenwalt "definitively stated that Pruitt approves and was supportive of her getting a raise," according to an administration official who has seen the email chain.

A second administration official confirmed the exchange. The email "essentially says, 'The administrator said that I should get this raise,'" the official told me. Both spoke on condition of anonymity in order to discuss the private correspondence. A request for comment sent to an EPA spokesman was not immediately returned.

The email began floating around the agency's top ranks after the EPA's Inspector General expanded its inquiry into Pruitt's hiring practices to include the raises, according to the two administration officials. In early March, as first reported by The Atlantic, Pruitt requested hefty salary bumps for Greenwalt and his director of scheduling, Millan Hupp.

When the White House refused to sign off on the raises—$56,765 and $28,130, respectively–Pruitt used an obscure hiring authority under the Safe Drinking Water Act to grant them anyway. The provision, which allows the EPA's administrator to appoint up to 30 staffers without White House or congressional approval, was intended to help the agency bring on experts and staff up especially-stressed offices. Greenwalt and Hupp's raises went into effect on April 1, according to HR documents obtained by The Atlantic.

Now, the agency's IG is probing whether Pruitt abused that hiring authority. On Wednesday, Pruitt was pressed by Fox News's Ed Henry to respond to The Atlantic's report, but denied any knowledge of the episode. "You didn't know they got these pay raises?" Henry asked. "I didn't know they got the pay raises until yesterday," Pruitt responded.

"My jaw dropped when he said that," said the first administration official. The perception that Pruitt had gone on TV and lied, the official said, was what really scared people inside the agency.

After the interview, top aides, including Pruitt's chief of staff, Ryan Jackson, began corralling files that appeared to contradict Pruitt's statements. Both administration officials described it as a way of "getting ahead" of the IG's investigation. Greenwalt's email, however, has proved the most troubling, according to the two administration officials. "It's an 'oh, shit' moment that they're trying to figure out before the IG finds the email," said one. "Because it'll be damn near impossible to have Sarah explain her way out of it."

Senate Committee on Environment and Public Works
Hearing entitled, *"Legislative Hearing on S. 2602, the Utilizing Significant Emissions with Innovative Technologies Act, or USE IT Act."*
April 11, 2018
Questions for the Record for Dr. Friedmann

<u>Chairman Barrasso:</u>

1. Dr. Friedmann, Section 201 of S. 2602 clarifies that carbon capture projects and carbon dioxide pipelines are eligible for coordinated and timely permitting.

   Why is this type of regulatory certainty critical to developers of potential projects?

   Regulatory clarity and the associated certainty are important to obtaining project financing. This is true at the earliest stage of project development, when securing the risk capital needed to execute the front-end engineering and design (FEED). It is also true for the final investment decision, especially for debt financing. For the FEED study capital investors, they want certainty that there is a viable path forward on the project. For equity financers, they are concerned about construction time and delay, which add substantial cost to a project from interest on debt.

<u>Ranking Member Carper:</u>

Please provide a response to each question, ***including each sub-part.***

2. Title II of the USE IT Act attempts to try to address some of the frustrations expressed by industry and states with the carbon dioxide pipeline permitting process.
   a. Please explain further the difficulties that industry and states are having with the process.
   b. In your view, what are the top issues that the federal government should address to remedy these difficulties?
   c. In your view, are environmental regulations, such as Clean Air Act regulations, a limiting factor for CCUS?

A) There are multiple issues that companies, financiers, and states face regarding CO_2 pipeline permitting and approval today:
   - *Many states that would benefit the most from CO_2 pipelines (IO, IN, IL, NE, SD, OH, WV) have never permitted a CO_2 pipeline, which is likely to result in delays and uncertainty. Such delays and uncertainty will limit the ability to finance projects dramatically.*
   - *Pipelines must run to potential injection and storage sites. If these are conventional CO_2-EOR operations, permitting of class II wells under the Safe Water Drinking Act is straightforward. However, wells that have might be permitted for CO_2 storage are not straightforward.*
     i. *The EPA developed and promulgated a new rule for CO_2 injection wells (Class VI) in 2010. Only one Class VI well has been permitted in the US,*

and it took 54 months to permit. If a pipeline project is dependent on this process, uncertainty and delay could very well stop financing and development.

ii. *Only North Dakota has primacy for Class VI well permitting, leaving all permitting to regional EPA jurisdictions. Only one of those jurisdictions (EPA regional office 5) has ever issued a class VI permit. Lack of familiarity and experience will limit states and companies' progress in achieving injection permits, which will in turn limit pipelines.*

iii. *Uncertainties remain regarding the degree of monitoring for CO_2 injection. These uncertainties are manifested in subparts RR and UU of the Clean Air Act. Potential project developers and operators have little understanding regarding the implementation of these two rules. To date, the EPA has received only two proposed submissions under subpart RR and by only one company (Occidental Petroleum).*

- *There are very few companies who develop or operate CO_2 pipelines today – in essence, only three (Kinder-Morgan, Denbury, and Burlington). One of these is uncertain as to whether or not it will accept any man-made CO_2, which could further limit the pool of potential actors. Uncertainties in permitting within or across state borders will prevent new companies from entering this business and competing, which will likely lead to increase costs and delays of implementation.*

NOTE: CO_2 is a fairly benign and inert gas. It is made by human bodies and put into our food and beverages. The regulatory stringency applied to storage is substantially higher than that applied to non-hazardous and hazardous waste water injection (Class I wells), mining waste operations (Class III wells), and similar to oil and gas for pipeline permitting (PHMSA). Given the low risk associated with accidental leakage of CO_2 (both low probability and low consequence), it is worth considering whether application of current regulations is disproportionate to the risks.

B) *While there are likely other important concerns, these are the top issues the Federal government should consider to accelerate the financing and permitting of CO_2 transportation and storage projects:*

- ***Dedicated rights-of-way**: In areas without CO_2 pipelines, there are no dedicated rights-of-way that a company or developer might use to accelerate permitting and construction while assuring minimal environmental impact. For example, power or existing natural gas transmission corridors could serve as pathways for accelerated CO_2 pipeline permitting. In situations or jurisdictions where no credible right-of-way is apparent, the Federal government should consider what conditions and characteristics could enable fast-path creation of a CO_2 right-of-way.*
- ***Revision of Class VI wells**: Every 8 years, the EPA Class VI well rules are subject to review. However, this well class was created without a scientific record of human health or environmental impacts, contrary to most EPA processes. This is precisely why a Federal advisory task force would be useful. It is also worth considering whether a more frequent review period is warranted over the next 20 years so as to converge more rapidly on a robust and appropriate Class VI environmental protection standard.*

- ***Review of RR and UU (Clean Air Act)**: Even in circumstances where the physics and chemistry of CO2 injection into the subsurface is identical or highly similar, subparts RR and UU require very different regulatory treatment. The lack of a scientific basis for this difference is problematic, and may lead to legal challenges and litigation. There is a Federal role in reviewing these standards and creating a more robust science-based standard for the promulgation of these rules.*

C) *YES, some environmental regulations, like the Clean Air Act and the Safe Water Drinking Act, act as barriers to the deployment of CCUS projects. NOTE: The vast majority of the provisions of these acts do not create barriers. Rather, real and potential barriers to CCUS are limited to very specific and restricted aspects of these Acts and their associated rule making. For example, as mentioned above, subparts RR and UU under the Clean Air Act prescribe oversight and compliance for CO_2 injection. Class VI wells under the Safe Water Drinking Act prescribe oversight and compliance for CO_2 injection. It is possible to focus narrowly on these limited and particular components of these important environmental protection laws that deal with CO_2 and leave the remaining protections elsewhere in the laws untouched.*

3. As I mention in my statement during the hearing, in the past two transportation bills we've established streamlining provisions to help infrastructure projects – like CCUS projects - go through the permitting process easier. Many of these provisions have yet to be implemented, are underfunded or are not being staffed. Before layering additional streamlining measures, I believe we should prioritize implementing the ones already in place. It is my understanding that, just recently, a carbon dioxide pipeline in Wyoming is taking advantage of the existing streamlining provisions, such as the Federal Permitting Improvement Steering Council. Is that your understanding and if that is the case, why do we need to add carbon dioxide pipelines to the Council's authority as the USE IT Act attempts to do?

Until passage of the FUTURE Act provisions in the enrolled 2018 Bipartisan Budget Act, there was no financial incentive to develop and deploy CCUS projects. This means commercial interest in building pipelines of this kind are largely less than 5 months old. As such, very few states had planned CO_2 pipelines, and even fewer interstate pipeline project were commercially viable.

Since the FUTURE Act provisions sunset at the end of 2023, just 5 years from now, waiting for the development of problems in permitting would likely condemn many projects from completion, and avoiding explicit access to streamlined provisions would likely chill potential investment. Recent studies by the International Energy Agency and by the Univ. of Texas concluded that the scale of CCUS deployment following passage of the FUTURE Act provisions would be limited entirely by access to pipelines and storage options which were not enhanced oil recovery.

I would certainly agree that increased funding and staffing for existing provisions would increase the likelihood that states and companies would make better use of the existing provisions. I would submit that the benefit to local communities, a national manufacturing base, and ability to rapidly reduce GHG emissions merit additional measures to maximize the deployment of CCUS.

4. Often whenever there is an attempt to build-out a new technology, like CCUS, it sometimes takes the federal government some time to react and know how to respond. We had some hiccups with the permitting process for offshore wind, and the Department of Interior was able to address those through the Smart from the Start program. This was implemented through current authorities. Do you think a program similar to Smart from the Start implemented at the agency level could help with some of the permitting concerns?

   The Smart from the Start program did indeed serve the community developing offshore wind. It made good use of a decade of prior attempts to deploy offshore wind projects. This experience suggests several points:
   - *If one were to pursue a similar pathway of learning and interagency coordination, almost certainly the FUTURES Act provisions would expire before key conclusions and learnings could be adopted.*
   - *The experience of offshore wind development highlighted the need for new and dedicated infrastructure to commercialize (i.e., offshore transmission trunk lines). This is true for CO_2 pipelines as well.*
   - *Almost all offshore wind projects are on Federal lands. This made it appropriate for Dept. of. The Interior to lead Smart from the Start. In contrast, most CO_2 pipelines and dedicated storage projects are privately held or leased from private land owners. This makes the equities of participants different, including Federal agencies.*
   - *There is enormous merit in considering a parallel process like Smart from the Start for CCUS projects. Once could imagine Dept. of Transportation, Dept. of Energy, and EPA working together with industry, NGOs, and academic leaders. However, I do not see that as a sufficient substitute for the proposed provisions of the USE IT Act.*

5. In the hearing, I asked you how the USE IT Act could be improved. Would you please provide further details on how this bill could be improved?

   There remain several potential barriers to the deployment of CCS. The most important barrier, finance, has been substantially lowered for many projects through the 45Q amendments of the 2018 Bipartisan Budget Act (FUTURE Act provisions). Other financial proposals, such as Master Limited Partnerships for clean energy projects proposed by Senator Coons (including CCS) and private activity bonds for CCS proposed by Senators Bennett and Portman. Both are under current consideration and would help.

   Given the focus of Title II of the USE IT Act on regulatory and permitting barriers, there are several amendments worthy of consideration:
   - ***Assessment of CO2 storage utilities**: One potential means to reduce implementation barriers for CCUS projects would be the creation of dedicated CO_2 utilities. Like a waste management utility or natural gas distribution utility, a CO_2 utility could provide a public service (disposal of CO_2), raise funds (through bonds or customer fees), assess CO_2 storage resources, pursue infrastructure and regulatory permits, and aggregate risk (e.g, manage long-term liabilities and manage post-injection obligations). One could amend the USE IT*

Act to create a small granting program (~\$6-10) for a handful of groups (3-5), tasked with the job of assessing the viability of a CO_2 storage utility for a key geological storage resource (e.g., saline formations in the Gulf of Mexico region, Illinois Basin, or intermountain west). These groups should compete for the proposed programmatic funds through an open and transparent solicitation process. One potential model: the DOE Regional Carbon Sequestration Partnerships, phase I. The grantees would be tasked with 2-years to deliver a proposal for a CO_2 utility for their region and resource, for consideration of the EPA and FERC.

- ***Reassessment and revision of Class VI, RR, and UU injection well provisions.*** *Currently, Section 202 of the USE IT Act casts a broad net around potential pathways to reduce regulatory and permitting barriers. One potential amendment would include a narrowing of focus to permitting of CO_2 injection wells. The newest CCUS regulatory provisions (Class VI, and monitoring under subsections RR and UU) would benefit from an open and transparent process to review current industrial practice, experience from permitting, and scientific work. The goal should be a scientific, performance-based standard that would help to ensure both public safeguards and to avoid unnecessary regulatory burden.*
- ***Alternative compliance mechanisms for post-injection site care.*** *Some potential operators and some public stakeholders are concerned about the appropriate management of CO_2 storage sites after injection, commonly called post-injection site care (PISC). Many proposals for PISC have been proposed. Examples include:*
    - *A fund raised from tipping-fee for storage injection.*
    - *A pooled industrial fund, similar to the oil-spill management fund*
    - *Transfer of liability to a third-party company who will accept the long-term risks, obligations, and liabilities*
    - *Transfer of liability to State or Federal authorities, with costs and risks fully or partially offset by posting of private bonds.*

  A USE IT Act amendment could include directing the EPA to convene a working group to assess alternative approaches to PISC as a function of cost, risk, and efficacy. The EPA Administrator could be directed to provide a report within 2 years of enactment, and to ensure that the working group is diverse, expert, and clearly tasked.

Senator Duckworth:

6. Direct air capture is one of many negative emissions technologies (NETs) that have the capacity to help the international community meet the climate change commitments made under the landmark Paris Climate Accord. That is why the Federal Government should invest in NET research and development initiatives, such as the work being conducted by Archer Daniels Midland in Illinois. This Illinois company is in the early stages of developing net-negative bio-energy with carbon capture and storage (BECCS)

technology, which was the most common NET used in the Intergovernmental Panel on Climate Change's modeling of mitigation scenarios on how global temperature goals could be achieved.

In light of the significant potential of BECCS to reduce carbon pollution, would you agree that funding research to better understand lifecycle greenhouse gas emissions of bio-energy based net-negative emission pathways is key to achieving the carbon dioxide removal goals of this bill?

Absolutely. Research and life-cycle analysis on the system carbon footprint are essential to ensure that investment and risk supported by public funds lead to public benefits, in this case from understanding the carbon reductions gained (in short, a carbon dividend). Such information will also help future investment, policy, and regulatory decisions and avoid waste & uncertainty.

7. The Illinois Basin has the capacity to store billions of tons of CO_2 safely and permanently, and the Federal Government should continue investing in this area. Since there are practical limits to how much carbon can be utilized, we must sequester excess carbon to achieve the benefits of carbon capture to reduce emissions.

   In light of the importance of effectively sequestering excess carbon, would you agree that there would be significant benefits in amending S. 2602 to address long-term sequestration challenges? What additions to the USE IT Act would you suggest to do so?

   There remain several potential barriers to the deployment of CCS. The most important barrier, finance, has been substantially lowered for many projects through the 45Q amendments of the 2018 Bipartisan Budget Act (FUTURE Act provisions). Other financial proposals, such as Master Limited Partnerships for clean energy projects proposed by Senator Coons (including CCS) and private activity bonds for CCS proposed by Senators Bennett and Portman. Both are under current consideration and would help.

   Given the focus of Title II of the USE IT Act on regulatory and permitting barriers, there are several amendments worthy of consideration:
   - ***Assessment of CO_2 storage utilities**: One potential means to reduce implementation barriers for CCUS projects would be the creation of dedicated CO_2 utilities. Like a waste management utility or natural gas distribution utility, a CO_2 utility could provide a public service (disposal of CO_2), raise funds (through bonds or customer fees), assess CO_2 storage resources, pursue infrastructure and regulatory permits, and aggregate risk (e.g, manage long-term liabilities and manage post-injection obligations). One could amend the USE IT Act to create a small granting program (~\$6-10) for a handful of groups (3-5), tasked with the job of assessing the viability of a CO_2 storage utility for a key geological storage resource (e.g., saline formations in the Gulf of Mexico region, Illinois Basin, or intermountain west). These groups should compete for the proposed programmatic funds through an open and transparent solicitation process. One potential model: the DOE Regional Carbon Sequestration*

Partnerships, phase I. The grantees would be tasked with 2-years to deliver a proposal for a CO_2 utility for their region and resource, for consideration of the EPA and FERC.

- ***Reassessment and revision of Class VI, RR, and UU injection well provisions.*** *Currently, Section 202 of the USE IT Act casts a broad net around potential pathways to reduce regulatory and permitting barriers. One potential amendment would include a narrowing of focus to permitting of CO_2 injection wells. The newest CCUS regulatory provisions (Class VI, and monitoring under subsections RR and UU) would benefit from an open and transparent process to review current industrial practice, experience from permitting, and scientific work. The goal should be a scientific, performance-based standard that would help to ensure both public safeguards and to avoid unnecessary regulatory burden.*
- ***Alternative compliance mechanisms for post-injection site care.*** *Some potential operators and some public stakeholders are concerned about the appropriate management of CO_2 storage sites after injection, commonly called post-injection site care (PISC). Many proposals for PISC have been proposed. Examples include:*
    - *A fund raised from tipping-fee for storage injection.*
    - *A pooled industrial fund, similar to the oil-spill management fund*
    - *Transfer of liability to a third-party company who will accept the long-term risks, obligations, and liabilities*
    - *Transfer of liability to State or Federal authorities, with costs and risks fully or partially offset by posting of private bonds.*

  A USE IT Act amendment could include directing the EPA to convene a working group to assess alternative approaches to PISC as a function of cost, risk, and efficacy. The EPA Administrator could be directed to provide a report within 2 years of enactment, and to ensure that the working group is diverse, expert, and clearly tasked.
- ***Dedicated rights-of-way:*** *In areas without CO_2 pipelines, there are no dedicated rights-of-way that a company or developer might use to accelerate permitting and construction while assuring minimal environmental impact. For example, power or existing natural gas transmission corridors could serve as pathways for accelerated CO_2 pipeline permitting. In situations or jurisdictions where no credible right-of-way is apparent, the Federal government should consider what conditions and characteristics could enable fast-path creation of a CO_2 right-of-way*

<u>Senator Whitehouse:</u>

8. Both the Center for Carbon Removal and Carbon Wrangler are engaged with the various carbon utilization and direct air capture (DAC) companies around the United States and the world.

    a. What is the general state of these two industries today?
    b. Are there examples of companies doing promising work in this space today? If yes, please describe some of this work.

c. Do you think there is scaling feasibility for ocean direct air capture technologies to pull CO_2 from the ocean to precipitate carbonate-building materials like limestone bricks or sand? Could the act of pulling CO_2 from seawater indirectly aid in our solutions for ocean acidification?

A) *The DAC industry is very much in its infancy – only a handful of companies with their first commercial products. In this way, it is like lithium-ion batteries 20-30 years ago. The carbon-to-value industry (C2V) is in some ways more mature, especially in applications that make cement and concrete from CO_2. For other value products (e.g., CO_2-to-fuel or CO_2-to-carbon black) they are still in early stages, mostly testing in University high bays.*

B) *There are three DAC companies who have commercial offering, all powered by 100% renewable power. Each has started in a distinct market.*
   a. ***Climeworks** (Zurich, Switzerland) is selling 1000 tons CO_2/y to a greenhouse, and has contracted carbon removal services for permanent storage in an operating facility in Iceland.*
   b. ***Carbon Engineering** (Squamish, British Columbia) is producing diesel and gasoline from CO_2 captured from the air, and has an operating 3-4 barrel a day facility.*
   c. ***Global Thermostat** (Princeton, NJ) is commissioning a large facility (several thousand tons/y) in the US to provide CO_2 to a food and beverage company. The plant is under construction, should be operating within Q2 2018, and fully operational by Q3 2018.*

   There are many carbon-to-value companies. The few described here represent ones of particular impact and potential in their sectors
   d. ***Cement and concrete: Solidia** (Piskataway, NJ) and **CarbonCure** (Nova Scotia) both user CO_2 to cure a novel formulation of cement. In this, they appear to be making cement with higher strength and higher corrosion resistance that conventional cement. It also cures ~30x faster, and does not require water to process. Their commercial plants (in New Jersey and Alabama, respectively) are making concrete forms and selling them. They appear to be able to produce low-carbon-footprint cement and concrete at market parity prices. Both have attracted major investment for capital plants and major partners (e.g., BP, Southern Co., LaFargeHolcim, Total)*
   e. ***CO_2-to-fuels and CO_2-to-chemicals**: This applications set supports dozens of companies. The largest is **Carbon Recycling International** (Reykjavik, Iceland) which converts 4000 tons/y CO_2 into 6000 tons/y methanol for sale as a fuel in northern Europe. Their technology is based on Nobel Prize winning chemist George Olah (Univ. So. California). All companies require substantial energy to upgrade CO_2 into a fuel. Some use power (e.g., **Opus 12**, Berkeley CA) and others use heat (**Greyrock**, Sacramento CA). These companies range from fully commercial and established to bench-top processes.*
   f. ***Durable carbon products**: These companies convert CO_2 to long-lived products like plastics (**Novomer,** Boston MA; **New Light**, Huntington*

*Beach CA), carbon black (**Monolith**, Palo Alto CA), carbon nanotubes (**Solid Carbon Products**, Provo UT; C2CNT, Ashburn Virginia) and even diamond (**ADA Diamonds**, San Francisco CA). Most of these companies are relatively new with no production facilities. However, Novomer and New Light are both producing products for testing, and Monolith is building a pilot production facility in Hallam, Nebraska)*

C) *YES, it is feasible to scale direct-ocean capture of CO_2. Most of the technologies that separate CO_2 from seawater today are either mature (e.g., reverse-osmosis membranes) or readily scalable (e.g., novel hollow-fiber membranes, micro-encapsulated solvents). NOTE: Some of the key work on this technology was done by Google X, the US Navy (Naval Research Lab) and key DOE National Laboratories (Lawrence Livermore and Sandia).*
YES, these technologies can and do directly reduce ocean acidification where they operate.
YES, these approaches also can (and do) precipitate fine-grained carbonate minerals, which could serve as a construction material. This may particularly help vulnerable ocean communities (and US military installations like the Marshall Islands or Midway) obtain materials to harden local infrastructure (ports, seawalls).

9. The recently passed CCUS bill will provide \$35/ton for avoided carbon emissions that is utilized and \$50/ton if the CO_2 is stored permanently. The USE IT Act would direct EPA to coordinate with other agencies and stakeholders to create a DAC technology advisory board that would create a competitive prize, aimed at reducing the cost to build these technologies.

   a. Do these bills put the right incentives on the table to help drive down the cost of capture for DAC projects and move this technology closer to commercialization?
   b. What other forms of federal investments can we make to further develop utilization and carbon removal technologies?

A) *YES, the recently passed CCUS provisions under section 45Q of the tax code provide the right incentives to mote this technology closer to commercialization. The could be amended to make the transfer of tax credits more flexible or to make them refundable.*
B) *There are many additional potential Federal investments to further support CO_2 utilization and carbon removal technologies*
   - *An expanded **innovation agenda**, including EPA, DOE, and NSF. I have provided some detailed examples as an appendix to this testimony (see below)*
   - *Additional **financial incentives**, such as Master Limited Partnerships for clean energy projects proposed by Senator Coons (including CCS) and private activity bonds for CCS proposed by Senators Bennett and Portman.*
   - ***Procurement authorities for carbon removal services** (e.g., an annual direct government purchase of DAC + CCS to a minimum of three bidding companies)*
   - ***Procurement authorities** to government agencies **for low-carbon materials** used in construction (e.g., low-carbon cement or low-carbon plastics). This would be*

particularly useful for Dept. of Transportation, Dept. of Defense, and the Army Corps of Engineers

- ***Matching grants** (through DOE or Dept. of Transportation) **for CO_2 pipeline** construction. These grants could match either State or private investments.*
- ***Investment in regional accelerators** to support entrepreneurs in developing and commercializing C removal and CO_2 use approaches and technologies.*

In addition to these investments, there are other government actions which could be taken to stimulate carbon removal and CO_2 utilization efforts.

- *Additional regulatory flexibility (see above, in response to Sen. Duckworth's questions)*
- *Expansion of the Renewable Fuel Standard to a Low-Carbon Fuel Standard, which included application of DAC or CO_2-to-Fuels*
- *Mandates for aviation fuels by 2030 requiring some fraction (e.g., 3-10%) to be made from DAC+CO_2-to fuels, waste-to-fuels, or BECCS.*
- *Directives to the Navy and Coast Guard to develop direct-ocean capture (DOC) technologies*

10. In the US, there are several direct air capture companies and research facilities. We have the Center for Negative Carbon Emissions at Arizona State University, Global Thermostat, the Center for Carbon Removal in California, and investors like Bill Gates pursuing the commercialization of these technologies. The Intergovernmental Panel on Climate Change and other reputable sources indicate that negative emission technologies along with continued climate mitigation will be necessary for us to meet our climate commitments.

    a. What role will these technologies play in mitigating the effects of climate change?

*Many recent studies and analyses conclude that it is highly unlikely the world can achieve climate stabilization targets of 2 °C or 1.5 °C without very large amounts of carbon removal through the deployment of negative emissions technologies. For example, the UN Emissions Gap Report in 2017 concluded that climate stabilization would require removal of roughly 10 billion tons CO_2/year from the air and oceans by 2050, and roughly 670 billion tons of CO_2 removal between now and 2100. This means that carbon removal technologies **must be added** to already ambitious mitigation goals to achieve these goals. Said differently, without aggressive development and deployment of NETs for carbon removal, conventional mitigation is unlikely to succeed.*

11. In 2015, Secretary Moniz published his Quadrennial Energy Review on transmission, storage, and distribution infrastructure. The report included the recommendation that, "improving CO_2 pipeline siting will improve safety and environmental protection. Several states have made substantial progress on this front and provide potential models for other states. DOE, in cooperation with Federal public land agencies, should take a convening role to promote communication, coordination, and sharing of lessons learned and best practices among states that are already involved in siting and regulating CO_2 pipelines, or that may have CO_2 pipeline projects proposed within their borders in the future."

a. Do you believe a federal task force on permitting of CO_2 pipelines is necessary? How can we ensure the task force does not work to degrade environmental regulations and safeguards?
b. Do you believe CO_2 pipeline infrastructure is needed to move captured CO_2 to permanent geologic storage to help address climate change?

A) *YES, a federal task force on CO_2 pipelines would greatly help assure their rapid and appropriate permitting. In particular, pipelines that cross state lines would benefit from a federal task force that could help identify potential barriers to deployment that would slow or impede routing, permitting, and financing.*
There are multiple ways to ensure the task force does not work to degrade environmental regulations and safeguard. One approach would be to narrow its brief to identifying barriers. Another is to charge the board to commission independent environmental risk assessments. A third is to invite interveners moderated by the Dept. of Transportation. An additional option is to explicitly exclude key environmental protections from task force recommendations (e.g., the Endangered Species Act).

B) *Building CO_2 pipelines is critically important to advancing the capture and storage of CO_2 for the purposes of climate change. This is especially true in jurisdictions that lack opportunities for enhanced oil recovery (e.g., Iowa, Nebraska, Illinois, Indiana, Ohio, West Virginia, Kentucky, Virginia, and Michigan). Said plainly, entities and companies that might consider a CO_2 capture project or a CO_2 storage operation generally would not consider financing, investing in, or operating a CO_2 pipeline. This is chiefly because it is so far outside their business model, and there are very few companies or entities who could serve them. Since many power and industrial plants suitable for CO2 capture do NOT have CO_2 storage opportunities directly underneath their operations, they could execute a CCUS project **if and only if** they had access to a pipeline. NOTE: Many of the existing CO_2 pipelines are currently at capacity and cannot accept merchant CO_2. This underscores the importance of adding pipelines and capacity.*

APPENDIX: INNOVATION AGENDA INVESTMENTS

This description is focused on S&T programs at the Dept. of Energy. A handful of specific R&D investments at the DOE would help accelerate progress in reducing cost and improving performance for CCS, DAC, and C-to-value. These R&D lines are commensurate to the level of investment the SunShot program received (at its peak, an additional $280 M/y). This work should support efforts on both coal and natural gas power systems. All work should be done in partnership with companies, National Labs, and research universities. Ideally with support from local and/or state governments

Advanced and efficient power cycles: +$70M/y. This would include work on advanced cycles (e.g., chemical looping), supercritical CO2 cycles (e.g., Brayton and Allam cycles), and advanced oxygen separation technology

Transformational technologies for fossil retrofit: +$90M/y. This would focus on solutions that dramatically increase performance and lower costs for CO2 separation, direct-air capture and direct-ocean capture systems, and systems that would harvest water from flue gas.

CO2 conversion and use: $60M/y. This would investigate and develop technologies to convert CO2 into valuable products (e.g., cement, fuels, carbon fiber)

Improved science and site assessment for CO2 storage: +$50M/y. This would include an expansion of the CarbonSAFE program, as well as pursue the last remaining key questions around rock fracture response to CO2 injection.

System Efficiency and Integration: +$70M. This would include work on systems and controls for improved plant efficiency and tools to assess & accelerate system integration (both for advanced power cycles and for retrofit CO2 control systems).

Large-scale pilots, fielding and testing: +$105/y. This would expand the pool to field and test technology that requires scale-up before commercialization. Test size would range from 20-50MW thermal equivalence.

Senator BARRASSO. Thank you very much, Dr. Friedmann. Always a pleasure to have you here.
Mr. Deich.

STATEMENT OF NOAH DEICH, EXECUTIVE DIRECTOR, CENTER FOR CARBON REMOVAL

Mr. DEICH. Good morning to the members of the Committee, and thank you for your invitation to testify.

I am the Executive Director of the Center for Carbon Removal, a nonpartisan, nonprofit organization based in the Bay Area of California. Our mission at the Center is to build what we call a new carbon economy. The essential feature of the new carbon economy is the pursuit of strong economic growth fueled by innovative strategies for cleaning up carbon from the air in a way that protects the environment. The essential strategies for achieving a new carbon economy include the carbon capture technologies advanced in the USE IT Act, as well as other forestry, agriculture, and industrial approaches for transforming carbon pollution back into a valuable resource.

In my testimony today, I will share why I believe the goals of the USE IT Act and other Federal policy efforts to advance a new carbon economy are so valuable and why bipartisan improvements to the USE IT Act could help it achieve greater positive economic and environmental impact.

To begin, the co-sponsors of the USE IT Act, Chairman Barrasso and Senators Capito, Heitkamp, and Whitehouse, deserve immense credit for designing this bill to support innovative carbon capture technologies that will be essential for future American economic competitiveness and climate leadership.

In my work, I see businesses, investors, and climate champions alike increasingly embrace both the direct air capture technologies, which use clean energy to filter carbon from ambient air, and the carbon use systems, which harness CO_2 to produce valuable products like building materials or clean fuels that are supported by this Act. We need these technologies to halt climate change.

And if we support research development and demonstration of these technologies domestically today, exactly like the USE IT Act does, we can ensure that the U.S. exports, not imports, direct air capture and carbon use systems in the decades to come, creating good jobs and wealth creation in geographies across America.

In addition, the USE IT Act is highly complementary to the 45Q tax credit, which was reformed earlier this year to include both direct air capture and carbon use systems.

Just as Julio has mentioned, I have seen 45Q improve the investment outlook for carbon capture technologies nearly overnight. But for this policy to advance, the full suite of carbon capture solutions, additional Federal investment in R&D across agencies is needed to make new solutions like direct air capture and carbon use more economically competitive.

The bipartisan nature of 45Q also provides an important model for advancing this legislation. I see bipartisanship as essential, as the investors and companies that we work with need to have confidence that any legislation will endure through routine political transitions.

The main concerns that I have heard about this legislation come from environmental groups, who primarily worry that components of this bill could lead to the erosion of foundational environmental loss. Ensuring that the amendment process for the USE IT Act is done in a bipartisan manner and that the language in the bill is bolstered to ensure that it will not be used to weaken valuable environmental laws will be essential for building support for this bill from those environmental constituencies.

I am actually very hopeful that the bipartisan process exemplified by 45Q can be a model for addressing concerns about the USE IT Act swiftly. Congressional legislation aimed at building a new carbon economy can steer us toward a future where we solve climate and economic challenges hand in hand.

I applaud this Committee for its leadership in pioneering the next generation of these carbon capture technologies, and I would also like to use this opportunity to invite the members of the Committee to join us at the Center for any future events related to building a new carbon economy, and I hope that we can be a resource to you all moving forward.

Thank you for the opportunity to testify today, and I look forward to your questions.

[The prepared statement of Mr. Deich follows:]

Noah Deich
Executive Director & Co-Founder
Center for Carbon Removal

Noah Deich is the Executive Director and co-founder of the Center for Carbon Removal, a non-profit organization dedicated to accelerating the development of carbon removal solutions. Prior to founding the Center, Noah worked in consulting, and gained experience with environmental market and carbon offset modeling, financial valuation of renewable and fossil energy power plants, energy efficiency and demand response program design and implementation, and corporate social responsibility strategy assessments. Noah received his M.B.A. from the Haas School of Business at UC Berkeley and his B.A. from the University of Virginia, and his writing has been published in GreenBiz.

Testimony of Noah Deich
Founder and Executive Director of the Center for Carbon Removal
centerforcarbonremoval.org

Before the Committee on Environment and Public Works
United States Senate
April 11, 2018

Hearing on S. 2602
The Utilizing Significant Emissions with Innovative Technologies (USE IT) Act

Executive Summary

Good morning to Members of the Committee, and thank you for your invitation to testify. I am the Executive Director of the Center for Carbon Removal, a non-profit based in the Bay Area of California.[1] Our mission is to advance innovative strategies for cleaning up carbon from the air in a way that helps halt climate change and build a growing, environmentally-sustainable economy.

I believe that the *USE IT* Act will help advance innovative carbon capture and use technologies, supporting the emergence of a new carbon economy based on cleaning up waste carbon in the air, and transforming carbon pollution back into a valuable resource. In this testimony, I will share why I believe the *USE IT* Act and other legislative efforts to advance a new carbon economy are so valuable, and why continued bipartisan support for this bill and others like it are essential to the future of a new carbon economy.

To begin, the carbon capture and use technologies supported by the *USE IT* Act offer a great opportunity for advancing domestic innovation and industrial job creation, as well as for U.S. climate leadership internationally. Carbon use is the idea of taking waste carbon -- be it from a power plant, an industrial facility like a cement or steel plant, or directly from the air -- and using it to produce valuable products. Many companies have already begun developing carbon use processes for products including: building materials such as cements and carbon fiber, and hydrocarbon fuels and chemicals that are mined from the sky, not the ground.

Direct air capture technologies are innovative carbon capture systems that use clean energy to filter carbon from ambient air -- not just smokestacks -- much like a plant does via photosynthesis. As a result, direct air capture systems can be integrated on-site at carbon

[1] Center for Carbon Removal website: www.centerforcarbonremoval.org

utilization or underground carbon storage projects, opening new possibilities for innovative manufacturing and carbon waste disposal businesses.

The *USE IT* Act is important for direct air capture and carbon use technologies for several reasons. First, these technologies are at a state of development that depend on public sector support to reach commercial maturity swiftly. Much like wind and solar energy in the 1980s, direct air capture and carbon use technologies would benefit greatly from sustained federal research, development, and commercialization support. Second, R&D support for these technologies complements and enhances the effectiveness of federal policy drivers like the 45Q tax credit, which was reformed earlier this year to include direct air capture and carbon use. Lastly, the increasing global demand for carbon use and direct air capture technologies suggests the window for leadership in this space is narrowing. For the U.S. to export -- not import -- direct air capture and carbon use systems in the decades to come, it is essential that the Federal government support domestic innovation and commercialization of these technologies today.

In conclusion, I would like to share my opinion that it is essential for the *USE IT* Act to move forward in a bipartisan manner. Bipartisanship is essential for the investors and companies that we work with to have confidence that legislation will remain durable to any future changes in Congressional leadership and Administrations. I have heard this directly in relation to the extension and expansion of the 45Q tax credits for carbon capture, use, and storage that were recently signed into law under to the bipartisan leadership of Chairman Barrasso and Senators Capito, Heitkamp, and Whitehouse. After this legislation was adopted, the startup incubator Y Combinator released a call for carbon use and direct air capture startups, citing 45Q as one reason for their interest.[2] Ensuring that the amendment process for the *USE IT* Act is done by consensus, and that language in the bill is bolstered to ensure it will not be used to weaken regulations that protect the environment, will be helpful to ensure the *USE IT* Act advances in a bipartisan manner and will form the foundation of a successful, long-term federal effort.

Thank you for the opportunity to testify before you today, and I look forward to your questions.

[2] Y combinator "Request for Startups" website: https://www.ycombinator.com/rfs/#carbon and Greentech Media article on the topic: https://www.greentechmedia.com/articles/read/y-combinator-is-looking-for-carbon-removal-startups#gs.2GLaJgU

Detailed Testimony

Direct air capture and carbon use are emerging industries

While government investment in carbon capture globally has historically focused on point-source capture (e.g. on fossil-fueled power plants and heavy industry), both carbon use and direct air capture are gaining increasing commercial traction.

On the direct air capture side, there are at least five privately-financed companies around the world that are currently commercializing direct air capture systems:

- Carbon Engineering (Canada)[3]
- Climeworks (Switzerland)[4]
- Global Thermostat (US)[5]
- Infinitree (US)[6]
- Skytree (Netherlands).[7]

In addition, there are significant direct air capture research efforts at a number of U.S. universities, including Arizona State University,[8] and at National Labs, including Lawrence Livermore.[9]

On the carbon use side, there are a number of efforts in the US and beyond focused on developing new technologies and applications. There are dozens of companies developing carbon-derived products, including cements and concretes (e.g. Solidia and Carbon Cure), fuels, plastics, and/or chemicals (e.g. Opus12 and Newlight Technologies). Other strategies for carbon use involve using CO_2 to accelerate the production of algae, which can be used in agriculture, wastewater treatment, and specialty chemicals applications economically today.

The NRG Cosia Carbon XPRIZE[10] has also fueled increased interest in commercialization of carbon use technologies, and is partnering with the Wyoming Infrastructure Authority's Integrated Test Center[11] for provide a hub of commercialization support around US carbon use solutions. In addition to the Carbon XPRIZE, there is increasing investor and startup interest in the carbon use space, as shown by efforts such as the Center for Carbon Removal's Carbon Recycling Labs incubator program[12] and by analyses from groups such as the Breakthrough Energy Ventures investment coalition.[13]

---

[3] Carbon Engineering website: http://carbonengineering.com/
[4] Climeworks website: http://www.climeworks.com/
[5] Global Thermostat website: https://globalthermostat.com/
[6] Infinitree website: http://www.infinitreellc.com/
[7] Skytree website: https://www.skytree.eu/
[8] ASU Center for Negative Carbon Emissions website: https://cnce.engineering.asu.edu/
[9] https://www.llnl.gov/news/microcapsules-capture-carbon-safely
[10] Carbon XPRIZE website: https://carbon.xprize.org/
[11] Wyoming ITC website: http://www.wyomingitc.org/
[12] Carbon Recycling Labs website: http://www.centerforcarbonremoval.org/carbon-recycling-labs/
[13] Breakthrough Energy Ventures website: http://www.b-t.energy/landscape/manufacturing/

Support today for direct air capture and carbon use are insufficient

Historically, both direct air capture and carbon use technologies have received little federal research and development support. A single direct air capture R&D effort by the U.S. Department of Energy funded about $3M in projects. DOE has supported carbon use projects at roughly $5-10M/yr recently, but this amount is still orders of magnitude less than federal funding provided for other types of carbon capture and storage and/or renewable energy systems. Since these efforts have been administered by the DOE's Office of Fossil Energy, the focus tends to be on large-scale commodity products that can use the vast quantities of CO_2 emitted by fossil-fired electricity generation. This framing detrimentally excludes higher-value, lower-volume products which offer more economically plausible first markets for the nascent carbon utilization industry.

One of the most significant policy advances for direct air capture and carbon use systems has been the recent reform of the 45Q tax credits to include both direct air capture and carbon use projects. These tax credits are essential market incentives, but additional federal R&D support is needed to drive direct air capture and carbon use system costs down to a price point that unlocks private capital to fuel their further commercialization and deployment.

Direct air capture and carbon use, along with a portfolio other carbon removal pathways, are essential for meeting climate goals and merit significant federal support on these grounds

Experts now agree that meeting climate goals will require the deployment of large-scale carbon removal strategies (also known as "negative emissions") in only a few decades -- alongside the accelerated deployment of low-carbon energy, transportation, and industrial technologies. Carbon removal pathways -- i.e. strategies for removing and reliably sequestering carbon from the atmosphere -- can include direct air capture and carbon use technologies, as well as a portfolio of other natural and technological options. Other important carbon removal solutions include reforestation, blue carbon and wetland approaches, agricultural and soil carbon sequestration (including biochar), bioenergy production (for power, fuels, and/or heat) with carbon capture and storage (BECCS), and CO2 mineralization (or enhanced weathering). The National Academies' 2015 study on "Carbon Dioxide Removal and Reliable Sequestration"[14] outlines the promising pathways for carbon removal using both natural and technological solutions, and also explains why these strategies are essential for meeting climate goals. Many solutions on the natural carbon removal solution side also offer significant carbon removal and environmental co-benefit potential, as demonstrated by the "Natural Climate Solutions" study published in the *Proceedings of the National Academy of Sciences (PNAS)* journal in October 2017.[15] It is essential to pursue a portfolio of federal R&D and policy support, to ensure that we can have the most resilient, flexible, and robust portfolio of carbon removal solutions in the

[14] National Academies Carbon Dioxide Removal and Reliable Sequestration website: http://nas-sites.org/dels/studies/cdr/

[15] Griscom, Bronson et. al (2017). "Natural Climate Solutions" in PNAS October 31, 2017. 114 (44) 11645-11650;. http://www.pnas.org/content/114/44/11645

future, as the Center for Carbon Removal outlined in our 2017 report on opportunities for federal action.[16]

To this end, there are a number of research efforts emerging to help inform the creation of a Federal portfolio of R&D around carbon removal strategies, including both direct air capture and carbon use. First, the National Academies will produce a follow up report to their 2015 study outlining R&D needs for the full portfolio of carbon removal strategies in 2018.[17] In addition, a consortium of 12 universities and National Labs across North America have contributed to produce a "Roadmap for a New Carbon Economy," also set for publication in 2018.[18] This consortium of research institutions plans to begin executing on the R&D needs identified in the roadmap in 2018, and plans to scale research in the near future with increased funding from government, corporate, and philanthropic sources.

The U.S. is well positioned to be a world leader in the field of carbon use and removal. Immediate and sustained Federal support will be essential for solidifying this leadership for the decades to come, so that the economic and environmental benefits of these technologies accrue here at home.

The *USE IT* Act is aligned with the EPA's mission to protect human health and the environment

I believe that the *USE IT* Act provisions for funding direct air capture and carbon use R&D fit well under EPA's existing authority and capabilities. In the past, EPA has supported R&D and demonstration of control technologies for other air pollutants, such as SOx and NOx in power plant exhaust. Furthermore, EPA currently has a Small Business Innovation Research (SBIR) call out for carbon capture on vehicles. Mobile source carbon capture technology will likely have many similarities to direct air capture and carbon use systems.[19]

Other federal agencies have deep expertise researching and developing similar carbon capture technologies. If EPA coordinates and collaborates with these other federal agencies, and if Congress supports expanded carbon capture RD&D and collaboration across relevant federal agencies, it can yield more robust commercial activity on carbon removal strategies. DOE and EPA bring distinct but valuable capabilities to direct air capture and carbon use research, and I believe that a sustained effort from both agencies according to their respective strengths - with regular coordination - would be complementary and not duplicative.

Constructive suggestions for the *USE IT* Act to build bipartisan support

The Center for Carbon Removal collaborates with a number of environmental NGOs around policies related to carbon capture, use, and removal. The Center for Carbon Removal is a

[16] "Carbon Removal Policy: Opportunities for Federal Action" Available at: http://www.centerforcarbonremoval.org/policy

[17] National Academies Study on Carbon Removal: http://nas-sites.org/dels/studies/cdr/

[18] New Carbon Economy Consortium website: http://www.centerforcarbonremoval.org/new-carbon-economy/

[19] EPA 2017 SBIR Solicitation topics: https://www.epa.gov/sites/production/files/2017-10/documents/epa_sbir_webinar_2017-18_solicitation_0.pdf

member of the Carbon Capture Coalition,[20] and we regularly convene and participate in meetings with other environmental NGOs outside of this coalition to discuss issues related to carbon capture. Based on conversations with stakeholders in the environmental NGO community about this bill, I believe that if certain elements were added to the bill language, it would increase support from environmental constituencies.

First, the bill could direct EPA to collaborate with other agencies that have carbon capture expertise -- and build off of the National Academies' forthcoming R&D reports on both direct air capture and carbon use technologies -- when designing and implementing the initiatives in Title I. This would help ensure that the direct air capture prize and carbon use R&D program maximize the impact of government funds.

Second, additional language to affirm that existing environmental laws -- including the Clean Air Act and the National Environmental Policy Act -- should not be weakened to advance direct air capture and carbon use objectives would help assuage concerns from environmental groups that this bill could result in undermining valuable environmental protections.

Third, additional language could be added to Section 202 to highlight the importance for the new Task Force to assess the need for additional regulations and/or guidance to ensure the robustness of carbon storage and permanence. In our work with industry participants in carbon use, we hear firsthand that additional federal guidance on how their technologies and their potential environmental virtues are counted may be needed. For example, there is no consensus framework for life cycle analysis for carbon storage in building materials or consumer products.

Lastly, language could be added to clarify that the Direct Air Capture Technology Advisory Board may be inclusive of past recipients of EPA grant funding. The field of technology experts for DAC is brilliant but small, so any policy that could exclude some of the strongest potential participants from membership on this panel would be detrimental.

Conclusion

I would like to reiterate that this bill offers an important step forward for advancing direct air capture and carbon use technologies. I commend Chairman Barrasso and his co-sponsors, Senators Heitkamp, Capito and Whitehouse, for their leadership on this topic that is critical for meeting climate and economic goals in a robust and environmentally sustainable manner. Thank you again for the opportunity to submit this testimony.

[20] Carbon Capture Coalition website: http://carboncapturecoalition.org/

Senate Committee on Environment and Public Works
Hearing entitled, *"Legislative Hearing on S. 2602, the Utilizing Significant Emissions with Innovative Technologies Act, or USE IT Act."*
April 11, 2018
Questions for the Record for Mr. Deich

Ranking Member Carper:

Please provide a response to each question, ***including each sub-part.***

1. Title II of the USE IT Act attempts to try to address some of the frustrations expressed by industry and states with the carbon dioxide pipeline permitting process.

    a. Please explain further the difficulties that industry and states are having with the process.

In my experience, I have heard that project developers and state policymakers are often challenged by the complex regulatory environment regarding CO2 infrastructure. For example, states have different property rights and liability regimes related to CO2 pipelines and storage, which can create challenges for developers working across state lines. There does not seem to be a single federal rule at fault for the difficulty that states and industry may experience. Rather, these projects are extremely complex and will trigger a number of state, local and federal regulatory requirements, which taken together require a substantial amount of work, investment, and time. Furthermore, while some states have a network of CO2 pipelines already in place, most do not. It can be challenging for developers to be first to market in a new jurisdiction.

    b. In your view, what are the top issues that the federal government should address to remedy these difficulties?

Many of the challenges faced by industry and states could be addressed by providing a forum in which stakeholders, regulators, and project developers can connect and share lessons learned. By having stakeholders collaborate proactively, project developers are able to better understand the pertinent regulations, and state policymakers are able to understand how to create regulatory environments that protect the environment and enable infrastructure to be built. The federal government can also help by providing information resources to inform stakeholders about the costs and safety for CO2 infrastructure and public safety.

In my experience, the federal government could play a larger role in advancing safe and cost-effective CO2 infrastructure by considering policy steps to make project financing more available, to offer new deployment incentives, and to support public demonstration of innovative new technologies.

The Department of Energy's recent Quadrennial Energy Review, the DOE National Energy Technology Laboratory's 2015 Review of the CO2 Pipeline Infrastructure in the U.S., *and the February 2017 whitepaper from the State CO2-EOR Deployment Work Group all contain excellent discussion on the full suite of policy options needed to advance CO2 capture, transportation, use, and storage infrastructure.*

2. As I mentioned in my opening statement during the hearing, I want to ensure this legislation does not lead to other efforts that may weaken the Clean Air Act. In your opinion, is the Clean Air Act inhibiting progress of CCUS technology development or deployment?

In my opinion, the Clean Air Act is not inhibiting progress of CCUS technology development or deployment. The main barriers that I see holding back development and deployment are:

1) lack of sufficient funding for RD&D,
2) insufficient commercial demand from the private and/or public sector, and
3) lack of clear and workable standards for measuring and monitoring lifecycle carbon emissions.

3. In your written testimony, you stated you supported bolstering the language "to ensure it will not be used to weaken regulations that protect the environment." Would you further expand on how you believe we could bolster the legislation to ensure we keep our environmental regulations in place?

To ensure robust environmental protection, the USE IT Act could expand on its direction to the task forces established in Title II. The task forces should consider both the benefits and costs of all proposed regulatory changes and what additional regulations, or clarifications to existing regulations, are needed to strengthen existing environmental laws with regards to CO2 pipelines.

4. In the hearing, I asked you how the USE IT Act could be improved. Would you please provide further details on how this bill could be improved?

I commend the Senators Barrasso, Whitehouse, Capito and Heitkamp and the Committee staff for their hard work on the bill thus far.

In Title II, additional language could be added to both Sections 202(a) and 202(b) to direct CEQ and the new Task Forces to assess the need for additional regulations and/or guidance to ensure the robustness and permanence of carbon storage. In our work with industry participants in carbon use, we hear firsthand that additional federal guidance on how the potential environmental virtues of their technologies are counted may be needed. For example, there is no consensus framework for life cycle analysis for carbon storage in building materials or consumer products. Resolving a framework will help carbon-negative materials and fuels create opportunities in state and regional programs such as the California Low Carbon Fuel Standard, or through international carbon offset programs. It would also be useful if the CEQ and the Task Forces took a look at potential data gaps that are limiting the commercial deployment of CCUS infrastructure.

Also in Title II, additional language to affirm that existing environmental laws, including the Clean Air Act and the National Environmental Policy Act, should not be weakened to advance *direct air capture and carbon use objectives. We would also recommend a direction to consult with the National Academies in the process of developing any findings or recommendations.*

Because industry is trying to move quickly now to take advantage of the carbon capture incentives made available under Section 45Q, it would be helpful for CEQ to offer a "one-stop shop" of information on the various permitting steps for carbon infrastructure as they exist under current law. Section 202(a) or Section 201 could direct CEQ to incorporate carbon utilization and related infrastructure projects into the Regulatory and Permitting Information Desktop (RAPID) Toolkit, which is a user-friendly information dashboard that roadmaps the regulatory steps that active projects have already undertaken and catalogues best practices that apply to various types of projects.

In Section 202(b), adding a Task Force participant from the Department of Transportation may be appropriate, since DOT's Pipeline and Hazardous Materials Safety Administration has jurisdiction over interstate pipeline safety matters. We would also recommend adding a representative of the environmental justice community to the Task Forces.

In Title I, a couple of targeted changes could also be useful. Section 101 could direct EPA to collaborate with other agencies that have carbon capture expertise when designing and implementing the initiatives in Title I. Recognizing that the Department of Energy already supports modest research activities in this space, this direction would help ensure that the direct air capture prize and carbon use R&D program maximize the impact of government funds. Section 101 could also direct EPA to build off of the National Academies' work on both direct air capture and carbon use technologies. The NAS has already done incredible work in this space with their 2015 report on Carbon Removal, and they have another report in the works today that could be a great foundation for EPA's research.

Senator Duckworth:

1. Direct air capture is one of many negative emissions technologies (NETs) that have the capacity to help the international community meet the climate change commitments made under the landmark Paris Climate Accord. That is why the Federal Government should invest in NET research and development initiatives, such as the work being conducted by Archer Daniels Midland in Illinois. This Illinois company is in the early stages of developing net-negative bio-energy with carbon capture and storage (BECCS) technology, which was the most common NET used in the Intergovernmental Panel on Climate Change's modeling of mitigation scenarios on how global temperature goals could be achieved.

In light of the significant potential of BECCS to reduce carbon pollution, would you agree that funding research to better understand lifecycle greenhouse gas emissions of bio-energy based net-negative emission pathways is key to achieving the carbon dioxide removal goals of this bill?

I agree that improving lifecycle assessment of greenhouse gas emissions for bioenergy-based carbon removal solutions is important to achieve the climate mitigation goals of this bill. Carbon removal solutions can present both economic and environmental opportunities. Rigorous accounting is essential to unlock the environmental potential of carbon removal. While federal *agencies have a number of well-developed tools for conducting greenhouse gas lifecycle accounting, additional funding for research and development is needed to adapt these tools to emerging carbon removal solutions like bioenergy facilities with carbon capture.*

The USE IT Act's funding for carbon utilization R&D will make the need for lifecycle assessment all the more necessary. Even the most sophisticated existing lifecycle assessment tools, such as the GREET model used by Argonne National Laboratory to evaluate transportation fuels, are limited in their ability to assess the wide range of products that could be made with waste carbon.

Lastly, it is important to have robust lifecycle accounting standards and tools across the full portfolio of carbon capture and use approaches to benefit the implementation of other federal policies such as the 45Q tax credit, as well as for emerging state-level policies such as low-carbon fuel standards that include carbon capture, use, and storage provisions.

2. The Illinois Basin has the capacity to store billions of tons of CO_2 safely and permanently, and the Federal Government should continue investing in this area. Since there are practical limits to how much carbon can be utilized, we must sequester excess carbon to achieve the benefits of carbon capture to reduce emissions.

In light of the importance of effectively sequestering excess carbon, would you agree that there would be significant benefits in amending S. 2602 to address long-term sequestration challenges? What additions to the USE IT Act would you suggest to do so?

Additional federal support to address long-term challenges related to underground carbon sequestration would complement the goals of the USE IT Act. In particular, there are three general areas where federal action would be valuable:

- *Funding for research on the subsurface, so we can understand what regions and underground formations are best suited for CO_2 injection*
- *Standards development for quantifying the permanence and lifecycle climate values of underground storage of CO_2.*
- *Regulation for permitting injection activities to ensure public safety and environmental stewardship.*

The federal government has already supported an impressive body of work to characterize the subsurface, principally through the Department of Energy's Office of Fossil Energy, so that industry can target its injection operations for the most appropriate sites. An ongoing DOE program, CarbonSAFE, aims to study multiple geologic formations for their carbon storage potential in greater detail, including through drilling exploratory wells. Further research to complement this effort at DOE would help expand our understanding of this topic, and could be designed in a way to facilitate the commercial adoption of underground carbon storage.

The EPA has also created a new class of permits for underground CO_2 storage under the Safe Drinking Water Act's Underground Injection Control (UIC) Program called Class VI. Greater certainty on EPA timelines for issuing Class VI permits could have a significant factor in supporting commercial projects. Furthermore, as part of EPA's UIC program, Class VI is a program designed to protect groundwater. Groundwater is one very essential part sequestration *safety equation, but the other is storage permanence, so that gases sequestered are realized as meaningful climate gains. Ensuring that clear guidelines for how CO_2 is permanently stored is important for complementing groundwater protection guidelines articulated in UIC regulations.*

Senator Whitehouse:

3. Both the Center for Carbon Removal and Carbon Wrangler are engaged with the various carbon utilization and direct air capture (DAC) companies around the United States and the world.

a. What is the general state of these two industries today?

Carbon utilization: The carbon utilization industry is developing rapidly, both here in the US and beyond. Carbon utilization companies are gaining the most traction when they can make a more competitive product with waste carbon -- not relying on carbon incentives to be economically viable. These opportunities are largely centered around building materials (such as cement and concrete), as well as other niche uses for waste carbon. In general, we are seeing the most new innovations for waste carbon in the production of industrial chemicals and building materials, namely concrete. Plastics represent a smaller but growing part of the industry. Federal funding for innovation and early markets would be highly valuable today to unlock additional economically-competitive segments of the carbon utilization field, which could thrive in the future with less government support.

Direct air capture: There are several direct air capture demonstration and commercial projects around the world at this time. The active demonstrations are capturing around 1,000 tons per year. In addition, there are several research efforts at U.S. universities and national laboratories focused on direct air capture. Presently, commercial applications for direct air capture are small and constrained largely to niche applications like greenhouse agriculture fertilization. With further funding for innovation and early markets, direct air capture systems could compete in much broader markets.

b. Are there examples of companies doing promising work in this space today? If yes, please describe some of this work.

Today, there are commercial companies operating in both the carbon utilization and direct air capture space. Center for Carbon Removal research has identified a number of companies working on carbon-to-value efforts (many working on converting CO_2 specifically) as of May 2018, including:

- *28 companies in agriculture/food*
- *49 companies in fuels*
- *10 companies in industrial gas/liquids*
- *17 companies in plastics*
- *18 companies in chemicals*
- *12 companies in emerging carbon-based materials (like graphene)*
- *20 companies in building materials*

For example, Solidia, based in New Jersey, mixes water, CO_2 and cement to make calcium carbonate and silica, which hardens to make concrete. Solidia is partnering with the multinational building materials company Lafarge to scale up this technology. Another company out of Iowa, EE-AGG, is *developing technology to capture CO_2 from the flue gas of industrial facilities using commercially available technology to make a syngas, which is then used to produce methanol using conventional technology. The methanol EE-AGG produces can then be blended with gasoline for enhanced emissions profiles or used a feedstock for other high value products.*

c. Do you think there is scaling feasibility for ocean direct air capture technologies to pull CO_2 from the ocean to precipitate carbonate-building materials like limestone bricks or sand? Could the act of pulling CO_2 from seawater indirectly aid in our solutions for ocean acidification?

Carbon capture from oceans could offer another pathway for carbon capture and use, but further research and development is needed to assess its commercial potential. Ocean carbon capture is technically feasible but commercially immature (even compared to the relative immature field of direct air carbon capture). I am unaware of any commercial entity in this space today. However, the Naval Research Lab is pursuing research focused on at-sea jet fuel synthesis via direct ocean carbon capture, and researchers at Lawrence Livermore National Laboratory are exploring methods for ocean capture and potential applications for the captured material. With additional funding for research and innovation, it could be possible to advance technology that converts excess carbon in the ocean into valuable building materials such as bricks or sand and use them for shoreline hardening or other priority applications.

Ocean acidification is a result of higher atmospheric CO_2 concentrations. Lowering CO_2 concentrations--via any method, including directly via ocean carbon capture--will reduce ocean acidification. Since the air and ocean rapidly equilibrate, both direct ocean and direct air capture capture technologies will have similar benefits for reducing ocean acidification.

4. The recently passed CCUS bill will provide \$35/ton for avoided carbon emissions that is utilized and \$50/ton if the CO_2 is stored permanently. The USE IT Act would direct EPA to coordinate with other agencies and stakeholders to create a DAC technology advisory board that would create a competitive prize, aimed at reducing the cost to build these technologies.

a. Do these bills put the right incentives on the table to help drive down the cost of capture for DAC projects and move this technology closer to commercialization?

The FUTURE Act, which became law as part of the February 2018 budget deal, provides important incentives for supporting direct air capture innovation that will help improve system performance and reduce system costs. While the incentives for direct air capture in the FUTURE Act are an enormous first step, additional and sustained funding for research, development, and demonstration across a range of federal agencies is critical for achieving the full potential of this technology. The USE IT Act will provide an important early injection of funding for these activities. After passing the USE IT Act, Congress should ensure these programs are extended and expanded in future years. Furthermore, collaboration across federal agencies, particularly between EPA and DOE, will help generate greater progress on developing direct air capture systems.

b. What other forms of federal investments can we make to further develop utilization and carbon removal technologies?

First, the full portfolio of research, development, and demonstration tools would help advance both utilization and carbon removal technologies. In particular, research grants, pilot cost-share, and demonstration loan guarantees offer existing mechanisms to support this work. These incentives can be provided by a number of federal offices beyond EPA, including ARPA-E, Fossil Energy, and the Office of Energy Efficiency and Renewable Energy (EERE) at DOE.

Second, demand-generating incentives and regulations would be helpful to advance these solutions. For carbon utilization, incentives could include government procurement tools similar to the USDA Biopreferred Program or tax credits like 45Q. For carbon removal where there is no monetizable product, tax incentives (including 45Q) are especially helpful. Regulations that ensure robust lifecycle assessment and clear permitting processes are also helpful for advancing projects to meaningful economic scale while protecting the environment and human health.

5. In the US, there are several direct air capture companies and research facilities. We have the Center for Negative Carbon Emissions at Arizona State University, Global Thermostat, the Center for Carbon Removal in California, and investors like Bill Gates pursuing the commercialization of these technologies. The Intergovernmental Panel on Climate Change and other reputable sources indicate that negative emission technologies along with continued climate mitigation will be necessary for us to meet our climate commitments.

a. What role will these technologies play in mitigating the effects of climate change?

Direct air capture technologies hold significant potential to mitigate climate change. For one, direct air capture could achieve large scale carbon removal because the technology has a nearly unlimited geophysical potential to capture carbon. This makes it an effective "backstop" technology that can be used to offset residual emissions and clean up large volumes of past emissions from the atmosphere. Direct air capture is also important because it could significantly limit the overall costs of fighting climate change. Currently, direct air capture is one of the most expensive carbon removal processes, but there is a strong potential for that cost to drop--in analogy to the way costs have dropped for other manufactured systems like wind turbines, solar panels, and batteries. As direct air capture matures and becomes cheaper, the "backstop" price of mitigating climate change would get reduced, and the uncertainty around any future carbon regulation would also be reduced..

The ultimate potential for these solutions is dependent on technological progress -- for direct air capture systems directly as well as complementary clean energy systems that will be needed to power DAC. The only way to improve our understanding of the ultimate potential of direct air capture as a climate solution will be to conduct research and development and demonstrate the technology in a variety of scales and settings.

6. In 2015, Secretary Moniz published his Quadrennial Energy Review on transmission, storage, and distribution infrastructure. The report included the recommendation that, "improving CO_2 pipeline siting will improve safety and environmental protection. Several states

have made substantial progress on this front and provide potential models for other states. DOE, in cooperation with Federal public land agencies, should take a convening role to promote communication, coordination, and sharing of lessons learned and best practices among states that are already involved in siting and regulating CO_2 pipelines, or that may have CO_2 pipeline projects proposed within their borders in the future."

a. Do you believe a federal task force on permitting of CO_2 pipelines is necessary? How can we ensure the task force does not work to degrade environmental regulations and safeguards?

A federal task force on permitting CO_2 pipelines could help advance a broader carbon capture, use, and storage industry by helping project developers understand the regulatory landscape, and ensuring regulatory agencies are coordinating effectively to ensure permitting reviews are conducted promptly and robustly. To ensure robust environmental protection, the task force must consider both the benefits and costs of all proposed regulatory changes and what additional regulations, or clarifications to existing regulations, are needed to strengthen existing environmental laws in regards to CO_2 pipelines.

The US already has the world's largest CO_2 pipeline network, so we have a larger base of experience to draw from than other countries in proposing strong, sound regulations.

b. Do you believe CO_2 pipeline infrastructure is needed to move captured CO_2 to permanent geologic storage to help address climate change?

Yes, the CO_2 pipeline infrastructure will improve the economics for moving CO_2 from the lowest-cost carbon capture sources to the best sites for using and/or disposing of CO_2.

However, the nature of the pipeline network changes based on the intended use of the CO_2. If the CO_2 is destined for enhanced oil recovery, where the oil fields are only in particular areas, then long-distance trunk pipelines will be required which aggregate CO_2 from many sources for delivery to the EOR site. In contrast, a CO_2 pipeline network focused on saline sequestration would be less likely to need long-distance trunk lines. The US is fortunate to have geographically diverse geology capable of sequestration, so focused on saline sequestration would be less likely to need long-distance trunk lines. The US is fortunate to have geographically diverse geology capable of sequestration, so shorter/lower volume pipelines could connect CO_2 sources with the nearest available storage location. For small emitters, the carbon captured from several sources could be delivered and combined at a single storage site to achieve economies of scale at the sequestration well. The permitting and long-term stewardship implications of a multi-party carbon repository might be an appropriate topic for the Task Forces envisioned by the USE IT Act to consider.

Regardless of the source of the emissions being injected, underground storage sites will likely be needed on private lands, state lands, federal lands, and state and federal offshore areas. If the federal government can enable carbon storage with long-term monitoring plans to develop safely on all these various types of properties and help coordinate project siting in doing so, the overall

CO_2 pipeline network could be deployed with maximum efficiency, saving money and avoiding unnecessary environmental disturbance.

Senator BARRASSO. Thank you so much for your thoughtful testimony.

Dr. Jiao.

STATEMENT OF FENG JIAO, ASSOCIATE PROFESSOR OF CHEMICAL & BIOMOLECULAR ENGINEERING AND ASSOCIATE DIRECTOR FOR THE CENTER FOR CATALYTIC SCIENCE & TECHNOLOGY, UNIVERSITY OF DELAWARE

Mr. JIAO. Thank you, Mr. Chairman, and thank you, Senator Carper, and the rest of the Committee.

My name is Feng Jiao. I am Associate Professor of Chemical and Biomolecular Engineering at the University of Delaware. I also serve as the Associate Director for the Center for Catalytic Science and Technology.

My research group currently raised support from NASA and Department of Energy, as well as the National Science Foundation to develop new CO_2 utilization technologies.

As a critical component in CCUS, carbon utilization holds the key to generate revenues which can offset the capture cost, as well as the initial investment. An example is CO_2 enhanced oil recovery technology, a most successful approach to utilize CO_2 and generate revenues. To fully utilize this kind of technology, additional capital investment in CO_2 pipelines and infrastructure are often required. In principle, the carbon capture facility could be built right next to the utilization site.

A good example is a Swiss company called Climeworks, who built the first commercial plant to capture carbon dioxide directly from air and sells locally to greenhouse for profit. The facility actually can capture up to 900 tons of CO_2 per year. The concept is very appealing, of course. There are some technical challenges for these kinds of technologies. One of them is the capture cost is still high compared to other carbon capture technologies.

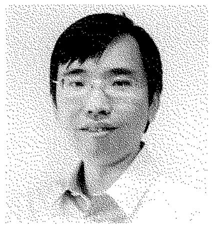
At the University of Delaware, we are actively developing alternative approaches to utilize CO_2. Thanks to the recent award from the Department of Energy National Energy Technology Laboratory, we are able to develop an electrochemical system which can convert carbon dioxide into useful chemicals. The so called CO_2 electrolyzer can produce useful chemicals, such as ethanol, ethylene, and syngas, from CO_2 and water.

The technology is intrinsically scalable and ideal for distributed systems at CO_2 point sources. If powered by low cost renewable electricity, the CO_2 electrolysis technology could provide a profitable approach to use CO_2 as the carbon source for commodity chemical production.

At Delaware, we also established a startup company called CO_2 Energy LLC to commercialize the CO_2 electrolyzer technology. Large international energy companies, such as Shell and TOTAL, are also actively involved in developing this kind of technology. Because of these efforts, the performance of CO_2 electrolyzers have been rapidly improved recently. Of course, the technology itself is still premature for commercial deployment, so more R&D efforts and more investment is urgently required in the United States to further this technology so that we can be the global leader in this clean air technology.

Again, innovations in CO_2 utilization are much needed because this is the only way to generate revenue streams for CCUS. Any CCUS operation fully relying on government subsidies is not sustainable. I fully support further investment in advanced CCUS technologies, and I will be happy to answer any questions you may have. Thank you.

[The prepared statement of Mr. Jiao follows:]



Dr. Feng Jiao
Associate Professor of Chemical & Biomolecular Engineering and Associate Director for the Center for Catalytic Science & Technology
University of Delaware

Feng Jiao obtained his BSc in chemistry at Fudan University (China, 2001) and his PhD degree in Chemistry at University of St Andrews (United Kingdom, 2008), before moving to Lawrence Berkeley National Laboratory as a postdoctoral scholar for two years. He joined the Chemical and Biomolecular Engineering Department at the University of Delaware in 2010 as an assistant professor and was promoted to associate professor in 2017. He now serves as the Associate Director of Center for Catalytic Science & Technology at the University of Delaware. Dr. Jiao has published more than 50 articles in leading scientific journals, such as Nature Communications and Journal of American Chemical Society. His work in electrochemistry and catalysis has been recognized by several awards, including the ACS Petroleum Research Foundation NDI/ND Award, the National Science Foundation CAREER Award, and the 2017 Class of Influential Researchers by the I&EC journal. His current research activities include nanoporous materials, electrocatalysis, and carbon dioxide utilization.

Written Testimony of Feng Jiao
Associate Professor of Chemical & Biomolecular Engineering
University of Delaware

I appreciate the opportunity to testify before the Committee. My name is Feng Jiao, Associate Professor of Chemical & Biomolecular Engineering at the University of Delaware. I also serve as the Associate Director of the Center for Catalytic Science & Technology at the university. I have 15 years of experience in research and development of electrochemical technologies for energy storage and conversion. My research group at University of Delaware has been previously, and is currently being funded by several federal agencies, including the National Aeronautics and Space Administration, Department of Energy (Office of Fossil Energy), and the National Science Foundation, to develop new technologies for CO_2 utilization. Today, I am going to talk about our recently funded project: the electrochemical conversion of CO_2 to high-value chemicals such as alcohols.

The massive quantities of fossil fuels used by our society have led to unprecedented atmospheric CO_2 levels with widespread climate impacts. Carbon Capture, Utilization, & Storage (CCUS) technologies are being developed to mitigate CO_2 emission issues. Large-scale centralized CO_2 capture and sequestration facilities, such as Petra Nova,[1] have been built to capture and store thousands of tons of CO_2 per day. The typical capital investment for these centralized CCUS facilities is on the scale of billion dollars, which makes it difficult for financing. Furthermore, sequestrating the captured CO_2 in geological repositories often requires additional investment for CO_2 pipelines and infrastructure, which further increases the financial challenge to rapidly deploy such highly centralized facilities. More importantly, carbon capture and sequestration process itself is not profitable without subsidies or carbon tax.

As a critical component in CCUS, <u>carbon utilization holds the key to generate revenues that can offset the capture cost and initial investments</u>. As an example, CO_2 enhanced oil recovery (accounting for ~6% of U.S. onshore oil production) is the most successful approach toward utilizing the captured CO_2 at power and chemical plants.[2] Similar to the sequestration approach, CO_2 enhanced oil recovery also requires significant capital investment for CO_2 pipelines and infrastructure if the oil field is not near the CO_2 capture facility.

<u>To circumvent large capital investments in centralized carbon capture facility and pipeline infrastructure, distributed CCUS approach may be considered as an alternative strategy.</u> In distributed CCUS, carbon capture facility using technologies that are not constrained by the carbon point sources (such as direct air capture) can be built at locations where CO_2 is utilized. By doing so, the capture facility can be built at a relatively small size to match the local CO_2 demand. Additionally, CO_2 transportation could also be reduced to minimal. A good example is a Swiss company Climeworks, who recently built the first industrial plant based on direct air capture technology.[3] The facility captures up to 900 tons per year of CO_2 directly from the air, which are directly sold to local greenhouse for revenue. It should be noted that an extremely large quantity of air must be processed by direct air capture facility in order to capture an appreciable amount of CO_2 due to the highly diluted nature of CO_2 in air (~400 ppm). Consequently, the CO_2 cost based on direct air capture technology is higher than that at large point sources where CO_2 has a much higher concentration (typically 5% or higher).[4]

Alternatively, carbon utilization technologies that can be deployed near carbon capture facilities are also attractive because the local utilization of CO_2 minimizes transportation costs and additional infrastructure investments. At the University of Delaware, we are actively developing new electrochemical reactors that can convert CO_2 into high-value chemicals, such as alcohols and ethylene. The project is funded by the Department of Energy, Office of Fossil Energy. The goal of this project is to develop an innovative approach to utilize CO_2 that is captured at coal-fired power plants for high-value chemical production. I will discuss this project in details in the following sections.

<u>Distributed chemical production using CO_2 as the carbon feedstock</u>

Current commodity chemicals are largely based on fossil fuel derived carbon sources, such as coal and crude oil. Using CO_2 as an alternative carbon feedstock is an attractive approach toward tackling CO_2 emissions in the chemical industry because it can drastically reduce, or even result in negative, carbon footprint, whereas traditional chemical processes, such as steam methane reforming and coal gasification, are carbon intensive. CO_2 conversion can be performed through biological, thermochemical, photochemical, and electrochemical means, each of which has been widely studied. At University of Delaware, we are focusing on the electrochemical conversion of CO_2 because this technology has several advantages, including fine control of production rates, wide scalability of modular electrolyzer designs, and the potential to produce a variety of high-value products.[5] More importantly, this technology can be readily powered by carbon-free energy sources, such as wind, solar, and nuclear, providing a zero-CO_2 emission (or even negative) pathway for commodity chemical production.

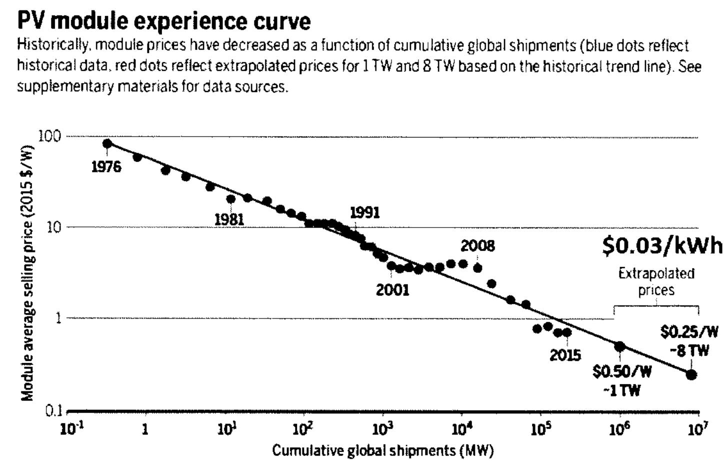


Figure 1: Prediction of electricity price based on photovoltaic module production cost. An electricity cost as low as \$0.03 per kWh is predicted for the near future.[6]

In recent years, there has been a remarkable increase in investigating electrochemical chemical production using CO_2 as the carbon source. The research efforts are largely motived by the ever-increasing CO_2 emission negatively impacting global climate and the decrease of electricity prices derived from renewable energy sources. A recent scientific study on photovoltaic (PV) clearly showed a decrease of PV electricity price over time (Figure 1) with a projected PV electricity price as low as \$0.03 per kWh in the near future.[6] Similar trend also holds for wind energy with wind electricity price already being ~\$0.02 per kWh.[7] The low electricity price makes electrochemically driven CO_2 utilization technologies potentially profitable for commercial applications.

CO_2 electrolyzer technology

CO_2 electrolyzer is an electricity-powered chemical reactor that produces valuable products using CO_2 and water as feedstocks. CO_2 electrolyzers are intrinsically scalable, making them ideal for distributed systems at CO_2 point sources. As the global energy supply shifts from fossil fuel-based resources to renewable energy sources, it becomes increasingly important to electrify chemical productions in order to take advantage of low-cost electricity obtained from renewable sources. Depending on the design of the electrolyzer (especially the choice of catalyst), a variety of valuable chemicals, such as carbon monoxide, ethanol, ethylene, and n-propanol, can be produced at appreciable rates. The products from CO_2 electrolyzers can be readily integrated into existing chemical plants for downstream fuel and fine chemical production. The overall scheme is outlined in Figure 2.

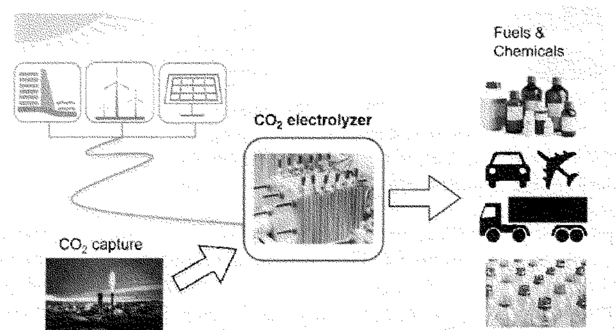
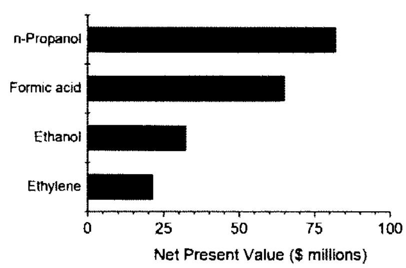


Figure 2: A renewable electricity powered CO_2 electrolyzer technology using CO_2 captured at point sources for fuel and chemical production.

In the U.S., there are a few start-up companies, including CO_2 Energy LLC, a start-up company that we recently established at Delaware, with an aim of pushing CO_2 electrolyzer technology for commercialization. However, large international energy companies, such as Shell and TOTAL, are also actively involved in developing CO_2 electrolyzer technology. Because of these efforts, the performance of CO_2 electrolyzers have been rapidly improved over the past decade, although the technology readiness level (TRL) of this technology is still relatively low (~TRL 3-4). More investment for this technology is urgently needed in the U.S. to address key technical challenges associated with the electrochemical process including cheap corrosionresistive materials, fast prototyping methods, efficient membrane separators, real time electrochemical process monitoring techniques, and standardized protocols for accelerated cell degradation tests. Otherwise, it is likely that we will lose out on the opportunity to be the leading CO_2 electrolyzer technology providers, since large international companies are rapidly becoming involved in this growing technology.

Cost analysis of electrochemical CO_2 conversion

With the financial support from DOE (through the National Energy Technology Laboratory), my research group recently developed an economic model for general CO_2 electrolyzer systems.[8] A copy of the full report is attached to the end of this testimony. The economic model calculates the material and energy balances for the process, estimates the capital investment and operating costs, and performs a cash flow analysis to determine the end-of-life net present value (NPV). The model accounts not only the cost of electrochemical CO_2 conversion, but also costs associated with CO_2 capture, purification, and product separation. By doing so, we were able to compare various CO_2 conversion products, as well as the sensitivity to the potentially changing operating and/or market conditions.



Parameter	Optimistic Case
Production Rate (ton/day)	100
Lifetime (years)	20
Operating time (days/year)	350
Electricity Price ($/kWh)	0.03
Current Density (mA/cm^2)	300
Cell Voltage (V)	2
Product Selectivity (%)	90
Conversion (%)	50
CO_2 Price ($/ton)	50
Interest Rate (%)	7.5
Electrolyzer Cost ($/m^2)	1415

Figure 3: End-of-life Net Present Values for the electrochemical production of various chemicals. All the key assumptions for the cost analysis are listed.

The net present values (NPVs) for the main products using the optimistic case assumptions are shown in Figure 3. Some of the potential products are not shown because their current market values were lower than the price of CO_2 (assuming $50 per ton) making profitability impossible regardless of process performance. Based on our analysis, a range of products from CO_2 electrolyzer technology are profitable if the operating parameters is met. Among all the potential products, propanol is the most profitable product, partially due to its high market price. To pave the way toward commercialization, further research efforts are still required to develop more efficient and selective catalysts for propanol production from CO_2.

We also analyzed the capital and operating costs of this CO_2 electrolyzer technology (Figure 4). For a CO_2 electrolyzer system with a production rate of 100 tons per day (~40 times of CO_2 process capability of Climeworks), the capital cost investment ranges from $10M to 40M USD, which could significantly reduce the capital financing barrier. Additionally, the operating costs are below $100k USD per day, with the majority of the cost being electricity. Therefore, CO_2

electrolyzer technology can greatly benefit from low-cost electricity generated from renewable sources, such as solar and wind.

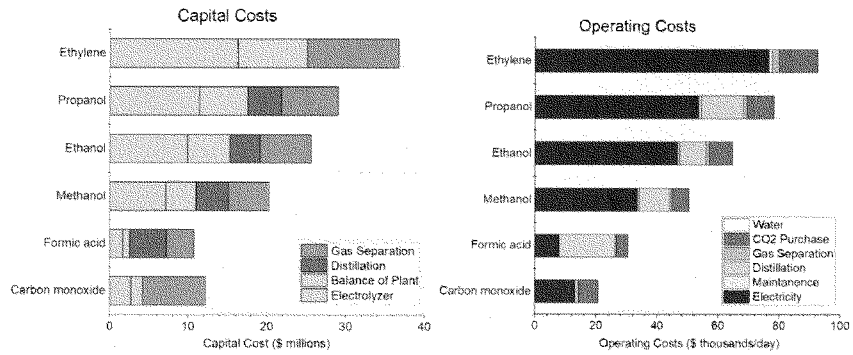


Figure 4: Capital and operating costs for various products under optimistic case assumptions.

Final thoughts

CO_2 utilization technologies that can generate high-value products from the captured CO_2 are urgently needed because the revenue stream is crucial to the long term financial sustainability of CCUS. Any CCUS operation fully relying on government subsidies is not sustainable. Innovations for distributed CCUS systems, such as direct air capture and CO_2 electrolyzer, could significantly reduce financial barriers and risks in capital and infrastructure investments, making wide deployment of CCUS possible. While many of new CO_2 utilization technologies are premature for commercialization today, their potential to be profitable should be recognized. I fully support the investment in advanced CCUS technologies. Finally, thank you for the opportunity to present my testimony today.

References:

1. www.nrg.com/case-studies/petra-nova.html
2. U. S. EOR Production. *Oil & Gas Journal* **2012**.
3. www.climeworks.com
4. Council, N. R. *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*; Washington, DC: The National Academies Press, 2015.
5. Lu, Q.; Jiao, F., Electrochemical CO_2 reduction: Electrocatalyst, reaction mechanism, and process engineering. *Nano Energy* **2016,** *29*, 439-456.
6. Haegel, N. M.; Margolis, R.; Buonassisi, T.; Feldman, D.; Froitzheim, A.; Garabedian, R.; Green, M.; Glunz, S.; Henning, H. M.; Holder, B.; Kaizuka, I.; Kroposki, B.; Matsubara, K.; Niki, S.; Sakurai, K.; Schindler, R. A.; Tumas, W.; Weber, E. R.; Wilson, G.; Woodhouse, M.; Kurtz, S., Terawatt-scale photovoltaics: Trajectories and challenges. *Science* **2017,** *356* (6334), 141-143.
7. DOE, Office of Energy Efficiency & Renewable Energy, *2016 Wind Technologies Market Report*; 2016.

8. Jouny, M.; Luc, W.; Jiao, F., General Techno-Economic Analysis of CO_2 Electrolysis Systems. *Industrial & Engineering Chemistry Research* **2018,** *57* (6), 2165-2177.

I&EC research
Industrial & Engineering Chemistry Research

Article

Cite This: Ind. Eng. Chem. Res. 2018, 57, 2165–2177

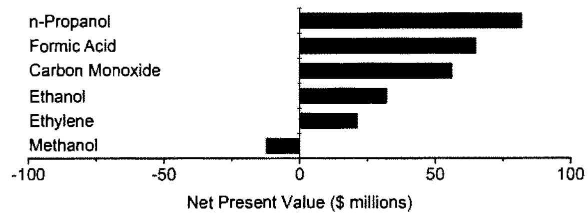
pubs.acs.org/IECR

General Techno-Economic Analysis of CO_2 Electrolysis Systems

Matthew Jouny, Wesley Luc, and Feng Jiao*

Center of Catalytic Science and Technology, Department of Chemical and Biomolecular Engineering, University of Delaware, Newark, Delaware 19716, United States

Supporting Information



ABSTRACT: The electrochemical reduction of carbon dioxide (CO_2) has received significant attention in academic research, although the techno-economic prospects of the technology for the large-scale production of chemicals are unclear. In this work, we briefly reviewed the current state-of-the-art CO_2 reduction figures of merit, and performed an economic analysis to calculate the end-of-life net present value (NPV) of a generalized CO_2 electrolyzer system for the production of 100 tons/day of various CO_2 reduction products. Under current techno-economic conditions, carbon monoxide and formic acid were the only economically viable products with NPVs of \$13.5 million and \$39.4 million, respectively. However, higher-order alcohols, such as ethanol and *n*-propanol, could be highly promising under future conditions if reasonable electrocatalytic performance benchmarks are achieved (e.g., 300 mA/cm^2 and 0.5 V overpotential at 70% Faradaic efficiency). Herein, we established performance targets such that if these targets are achieved, electrochemical CO_2 reduction for fuels and chemicals production can become a profitable option as part of the growing renewable energy infrastructure.

1. INTRODUCTION

Atmospheric carbon dioxide (CO_2) concentrations have recently reached the highest levels in human history. It is widely believed that failure to curb these rising emissions could lead to potentially devastating climate change effects.[1] Mitigating CO_2 emissions on a global scale remains a major challenge since the global population, and subsequently the global energy usage, is projected to continue to increase. Although renewable energy sources, sources such as wind and solar are beginning to gain more market share, fossil fuel resources will continue to be the dominant energy source through the midcentury. A major driver for this is the continued dependence of the transportation and chemical sectors on fossil fuels. For example, the U.S. Energy Information Administration (EIA) estimated that while renewable sources will account for over 27% of electricity generation by 2040, renewable energy in the transportation and chemical sectors will only be <1% and 9%, respectively.[2] This is because petroleum-based vehicles will continue to dominate economically, and fossil fuel sources will continue to be a critical chemical feedstock in the near future.

The conversion of CO_2 into fuels and chemicals using renewable electricity is one promising method of increasing the penetration of renewables into the fuels and chemicals industries.[3−5] CO_2 conversion can be performed through biological, thermochemical, photochemical, and electrochemical means, each of which has been widely studied.[6−8] Electrochemical conversion of CO_2 has several advantages, including fine control of reaction rates/selectivities through the applied voltage, wide scalability due to modular electrolyzer designs, and excellent coupling to intermittent renewable energy sources due to the fast response time of electrochemical systems. With this process, carbon-neutral electricity sources can be used to electrochemically reduce CO_2 to valuable fuels and chemicals, thus closing the carbon loop and reducing CO_2 emissions.

In recent years, there has been a remarkable increase in studying electrochemical CO_2 reduction (eCO_2R). Most research has been focused on the fundamental understanding of the catalysis and reaction mechanisms, while other work has involved the design of lab-scale CO_2 electrolyzer flow systems.[9−13] However, there has been limited efforts related to understanding the feasibility of this technology as a means of producing fuels and chemicals on a techno-economic basis, as

Received: August 24, 2017
Revised: December 6, 2017
Accepted: January 19, 2018
Published: January 19, 2018

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

well as what role eCO_2R could play in the future renewable energy infrastructure. Some researchers have raised questions regarding the potential of CO_2 reduction to mitigate CO_2 emissions at an appreciable level, and whether the process can be performed in an economical way competitive to traditional chemical manufacturing processes.[14] In this work, we reviewed the historical performance trends for the electrochemical reduction of CO_2 to commonly reported CO_2 reduction products. Next, we developed a techno-economic model for a generalized eCO_2R plant. Using this model, we analyzed the economic viability of various reduction products under current and future conditions and proposed performance targets to enable the profitable production of these products. Finally, we considered the role eCO_2R can play in reducing greenhouse gas emissions as part of the future renewable energy infrastructure.

2. CO_2 REDUCTION PRODUCTS

The electrochemical reduction of CO_2 can proceed through a two-, four-, six-, eight-, 12-, or even an 18-electron reduction pathway to produce various gaseous products (carbon monoxide, methane, and ethylene) and liquid products (formic acid, methanol, ethanol, and propanol). Table 1 summarizes

Table 1. Selected Standard Potentials for the Electrochemical Reduction of CO_2[15,16]

half-cell electrochemical reactions	potential (V vs SHE)
$CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow CO_{(g)} + H_2O_{(l)}$	−0.106
$CO_{2(g)} + 2H^+ + 2e^- \leftrightarrow HCOOH_{(l)}$	−0.250
$CO_{2(g)} + 6H^+ + 6e^- \leftrightarrow CH_3OH_{(l)} + H_2O_{(l)}$	0.016
$CO_{2(g)} + 8H^+ + 8e^- \leftrightarrow CH_{4(g)} + 2H_2O_{(l)}$	0.169
$2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_{4(g)} + 4H_2O_{(l)}$	0.064
$2CO_{2(g)} + 12H^+ + 12e^- \leftrightarrow C_2H_5OH_{(l)} + 3H_2O_{(l)}$	0.084
$3CO_{2(g)} + 18H^+ + 18e^- \leftrightarrow C_3H_7OH_{(l)} + 5H_2O_{(l)}$	0.095
$2H^+ + 2e^- \leftrightarrow H_{2(g)}$	0.000

seven common CO_2 electrochemical reduction products and their half-cell electrochemical reactions as well as the thermodynamic electrode potentials versus the standard hydrogen electrode (V vs SHE) under standard conditions, calculated from the standard Gibbs free energies. Others have also reported up to 16 different CO_2 reduction products, including gloyoxal, ethylene glycol, acetaldehyde, propionaldehyde, etc.[15,16] However, these products are either reported as trace amounts or uncommon; and thus, the seven major products listed in Table 1 are the main focus. In addition, if CO_2 reduction is performed in an aqueous environment, then the undesirable hydrogen evolution reaction also occurs in competition to the CO_2 reduction reaction (also listed in Table 1).

As shown in Table 1, CO_2 can be electrochemically reduced to several products at similar potentials, and thus, a critical question arises: which CO_2 reduction product should be targeted for commercialization? The answer to this question greatly depends on economics, the supply and demand of certain products, and indirectly relates to the current state-of-the-art technologies that can affect the overall costs and production rates. To help facilitate this discussion, the market price (US \$ kg^{-1}) of the seven CO_2 reduction products are listed in Table 2 and these values were taken and averaged from various sources, including the Independent Chemical Information Service (ICIS), U.S. EIA, and various published works.[17−19] The market price was also normalized to the number of required electrons to incorporate the electrical cost to produce each product since ideally, electrical energy will be used to drive the reduction of CO_2. Lastly, the annual global productions of each product were also tabulated, which reflect the market capacity and demand for each product, and were also taken from various sources including the U.S. Department of Energy (DOE), private company/organization Web sites, and various published works.[20−24]

Table 2. Market Price and Annual Global Production of Major CO_2 Reduction Products

product	number of required electrons	market price (\$/kg)	normalized price (\$/electron) × 10^3	annual global production (Mtonne)
carbon monoxide (syngas)	2	0.06	0.8	150.0
carbon monoxide	2	0.6	8.0	
formic acid	2	0.74	16.1	0.6
methanol	6	0.58	3.1	110.0
methane	8	0.18	0.4	250.0
ethylene	12	1.30	3.0	140.0
ethanol	12	1.00	3.8	77.0
n-propanol	18	1.43	4.8	0.2

In the case of carbon monoxide (CO), it was broken down into two subproducts, syngas and pure CO, since the majority of industrially produced CO is in the form of syngas and is typically produced in-line with downstream gas-to-liquid processing units. Interestingly, although formic acid had the highest normalized market price (16.1×10^{-3} \$ $electron^{-1}$), which is reflected by the number of electrons needed to produce formic acid, the annual production of formic acid was the second to lowest (0.6 million metric tons per year). This value reflects the limited industrial use of formic acid as preservative and antibacterial agent. On the contrary, being a major source for power generation and domestic heating as well as having abundant sources of natural gas, methane had the highest annual production (250 million metric tons per year) and the lowest normalized market price (0.4×10^{-3} \$ $electron^{-1}$). Turning to *n*-propanol, although this chemical is an industrially important chemical precursor, it has the lowest annual production (0.2 million metric tons per year) because it is limited by the difficulty in production. However, if *n*-propanol could be efficiently produced through CO_2 reduction, it could supplant ethanol as a transportation fuel additive due to its higher energy density, greatly increasing its market potential. From Table 2, it can be concluded that the highly desirable products include ethylene, methanol, and ethanol since these products have high market capacity as well as decent normalized market prices. These four products have major industrial uses as chemical precursors, fuel additives, and fuel for energy generation. It must be noted that these values were organized from an economic perspective to facilitate the following discussion about the economic analysis of the CO_2 electrochemical reduction process. The overall assessment of which product is the most desirable for CO_2 electrolysis technology will take into account the state-of-the-art technologies, such as catalyst, electrochemical reactor design, separation, and storage.

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

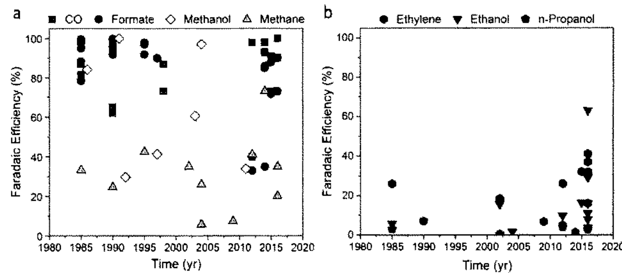


Figure 1. CO_2 reduction Faradaic efficiencies versus year (when reported) for (a) C_1 and (b) C_2–C_3 products.[15,25−28,30,31,33−37,39,43−72]

3. FIGURES OF MERIT

The CO_2 molecule is fully oxidized and thermodynamically stable and thus catalysts are needed to help facilitate the chemical transformation to minimize the energy penalty required to reduce CO_2. The study of catalysts for the electrochemical reduction of CO_2 can be dated back to the mid-1980s when Hori et al. completed a comprehensive study on various transition-based metal electrodes to determine their selectivity as well as their catalytic activity toward different CO_2 reduction products.[25,26] Metals such as Au, Ag, and Zn were discovered to be selective toward producing CO while metals such as Pb and Sn were selective toward producing formic acid. Interestingly, Cu was the only metal that could reduce CO_2 to C_2 hydrocarbons and alcohols at appreciable levels. Since then, there have been significant efforts in developing new catalysts to improve selectivity, catalytic activity, and overall stability. These efforts include developing nanostructured catalysts to increase the number of active sites,[27−31] tuning selectivity by developing bimetallic catalysts,[32,33] and even exploring catalysts beyond just simple metallics, such as transition metal chalcogenides[34,35] and even nitrogen-doped carbon-based materials that have shown interesting catalytic abilities.[36,37] In addition, the choice of electrolyte, electrochemical reactor design, electrode preparation, and delivery of reactant and products to and from the active sites have also been studied to improve the overall performance of eCO_2R.[10,11,38−41]

In general, an efficient CO_2 electrolyzer requires not only highly active, stable, and selective catalysts, but also durability with minimal ohmic resistance and high mass transport properties under reacting conditions. The characterization of each individual feature of an electrolyzer is quite complex. However, there are several figures of merit that are commonly used to characterize the performance of an electrochemical system, namely current density, Faradaic efficiency, energetic efficiency, and stability.[5,42]

The current density is defined as the current flow divided by the active electrode area at a given potential. The most commonly used is the geometric area. The current density is a measure of the electrochemical reaction rate (catalytic activity) per area of electrode and is used to determine the overall electrode size needed to obtain a desired reaction rate. Furthermore, the current density is also dependent on multiple factors, such as catalyst loading, utilization of the catalyst, and transport rate of reactants and products to and from the electrode. High current density is ideal since it minimizes the overall electrolyzer size and reduces capital investment for a desired production rate.

The Faradaic efficiency, also known as the current efficiency, for a given product is defined by the following equation:

$$\varepsilon_{\text{Faradaic}} = \frac{z \cdot n \cdot F}{Q} \tag{1}$$

where z is the number of required electrons to produce a given product, n is the number of moles of the given product, F is Faraday's constant, and Q is the total charged passed. In other words, the Faradaic efficiency of a given product is the selectivity of reducing CO_2 to that product. A high Faradaic efficiency is desired to minimize necessary separation processes that could dramatically increase the overall capital and operational costs.

The energetic efficiency is defined by the following question:

$$\varepsilon_{\text{energetic}} = \sum_i \frac{E_i^o \varepsilon_{i,\text{Faradaic}}}{E_i^o + \eta} \tag{2}$$

where E_i^o is the equilibrium cell potential for product i, $\varepsilon_{i,\text{Faradaic}}$ is the Faradaic efficiency of product i, and η is the total cell overpotentials including the anodic and cathodic kinetic activations, mass transport limitations, and ohmic resistances. The energetic efficiency describes the ratio between energy stored in the desired products versus input energy needed to produce those products. Qualitatively, a high energetic efficiency signifies a small energy penalty needed to produce the desired product.

The stability describes the gradual degradation/deactivation of the electrode catalyst and the overall electrochemical cell. Unfortunately, the durability of the electrochemical cell is probably the least studied aspect of electrochemical reduction of CO_2 and is strongly affected by the nature of the working load and operating conditions. It has also been known that slight impurities in the electrolyte can significantly deactivate or alter the catalytic performance of CO_2 reduction catalysts. In regards to other related technologies, PEM water-splitting electrolyzers have been shown to operate beyond 20 000 h under mild conditions; and therefore, CO_2 electrolyzers will probably need to operate with lifetimes of similar ranges.[5] Overall, better stability will reduce maintenance and replacement costs as well as downtime during operation.

Figure 1 shows the general trends of Faradaic efficiencies toward various CO_2 reduction products versus time dating back to the comprehensive study published by Hori et al. in 1985

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

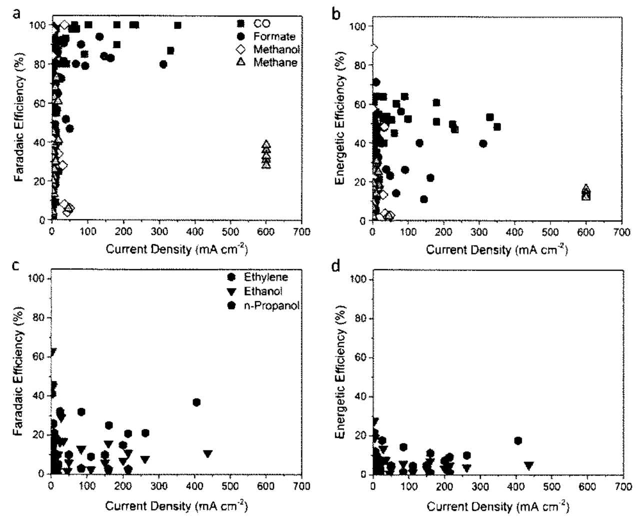


Figure 2. Faradaic efficiency versus total current density for (a) C_1 and (c) C_2-C_3 products and energetic efficiency versus total current density for (b) C_1 and (d) C_2-C_3 products.[13,15,25−28,30,31,33−37,39,43−74]

(C_1 products for Figure 1a and C_2-C_3 products for Figure 1b) to year 2016.[25,26] Although both homogeneous and heterogeneous catalysts for CO_2 reduction have been reported, heterogeneous catalysts are the main focus of this review considering the robustness of the catalysts. It must be noted that Figure 1 does not fully reflect the true performance of the state-of-the-art catalysts since some catalysts were able to achieve high selectivity (i.e., Faradaic efficiency) by sacrificing catalytic activity (i.e., current density) and vice versa, which will be discussed in detail in the following section. In the case of C_1 products, Faradaic efficiencies for CO and formic acid have been consistently high (>80%) with majority of these catalysts being Ag and Sn-based for CO and formic acid production, respectively. In the case of methanol, only a few catalysts were reported to be methanol selective and the reported methanol Faradaic efficiencies varied greatly from 30 to 98%. On the contrary, methane Faradaic efficiencies have been consistently low (<50%) with the majority of these catalysts being Cu-based. In the case of C_2 products, Faradaic efficiencies of ethylene and ethanol have, but not until recently, been consistently low and the majority of these catalysts were also Cu-based. However, in 2016, significant strides have been made on improving the Faradaic efficiency for C_2 products, achieving as high as 41 and 63% for ethylene and ethanol, respectively.[67] For the case of C_3 products, the Faradaic efficiency for *n*-propanol was still significantly low (<5%) which reflects the energy intensive (18 electrons) process and complex reaction pathway that requires multiple carbon−carbon couplings.

Figure 2a and c shows the Faradaic efficiencies versus current density while Figure 2b and d shows the energetic efficiencies for C_1 and C_2-C_3 products versus current density, respectively. Enlarged figures of the low current density region are found in the Supporting Information. In the case of energetic efficiencies, the majority of CO_2 reduction research only focused on the cathodic reaction and only reported the overpotential of the CO_2 reduction reaction. Because of this, the assessment assumed that the anodic reaction was the water oxidation reaction with a standard potential of 1.23 V vs SHE with an anode overpotential of 0.3 V, typical activation overpotential for the state-of-the-art oxygen evolution reaction catalyst.[75] It must be noted, that each data point was not consistent with each other and varied in terms of type of catalyst, electrode preparation, electrochemical cell configuration, and operating conditions. With that in consideration, Figure 2 aims to convey the general catalytic performance trends of various catalysts toward producing CO, formic acid, methanol, methane, ethylene, ethanol, and *n*-propanol. Overall, it has been difficult to simultaneously achieve high current density, Faradaic efficiency, and energetic efficiency, which illustrates that further efforts are needed to develop better CO_2 reduction catalysts. In general, high Faradaic efficiencies can be achieved at the expense of current densities, and majority of the energetic efficiencies for reduction CO_2 were less than 60%. It must be noted that the majority of reported CO_2 reduction studies were conducted under short time scales (<5 h), and thus long-term stability in the range of hundreds or even thousands of hours are unknown.

4. MODEL FOR CO_2 ELECTROLYZER SYSTEM

Despite the significant amount of research that has been performed on eCO_2R catalysts and electrolyzers, there have been few technical and economic analyses that evaluate the potential and feasibility of implementing the CO_2 electrolyzer technology on a large scale. Previously, Perez-Fortes et al.

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

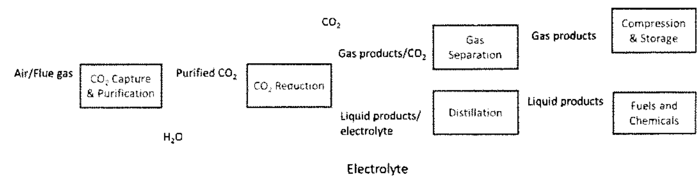


Figure 3. Schematic of a general CO_2 electrolysis process.

analyzed the economic and environmental potential of CO_2 reduction to formic acid using ChemCAD simulations.[76] Li et al. investigated the greenhouse gas emission reductions and economic viability of an electrochemical CO_2 to CO system coupled with a Fischer–Tropsch process to produce synthetic fuels.[77] Furthermore, Verma et al. developed a gross-margin model to determine and compare the maximum feasible operating voltage for the production of various CO_2 electrolysis products.[78]

Although these various investigations provide useful insights to the economic potential of CO_2 reduction, there still lacks a capital investment analysis of a general CO_2 electrolysis system from which the return on capital investment and time-valued net present value (NPV) for the production of the most commonly reported products can be determined. Due to the lack of commercially developed analogues for a CO_2 reduction process, a highly detailed analysis is difficult. However, the use of engineering approximations and assumptions based on existing technologies allows for an insightful analysis to be made.

Herein, we developed an economic model for a CO_2 electrolyzer system that calculated the material and energy balances for the process, estimated the capital investment and operating costs, and performed a cash flow analysis to determine the end-of-life net present value (NPV).[79] This allowed for the comparison of various CO_2 reduction products, as well as the sensitivity to the potentially changing operating/market conditions. A schematic of the general CO_2 reduction system is shown in Figure 3.

In a general eCO_2R process, CO_2 is first captured from either a point source or the air, and purified for use in the CO_2 electrolysis system. The concentrated CO_2 stream is fed along with water to the CO_2 electrolyzer system, where liquid and gas products are formed. The liquid products that are formed in the electrolyte stream are fed to a separation system (distillation) to extract the liquid products, while the electrolyte is recycled back to the electrolyzer. Since the single pass accumulation for liquid products is typically very small (~0.03%, see SI for calculation),[70] the electrolyte can be recycled until the liquid products accumulate to an appreciable amount before steady-state separation begins, after which the exiting electrolyte is continuously distilled. Significant accumulation of product in the electrolyte could have a negative impact on electrolyzer performance, but was not considered in this analysis. The gas products, along with unconverted CO_2 and byproduct hydrogen, are separated in a gas separation unit, from which the CO_2 is recycled back to the reactor. The gas products are then compressed for storage and transportation, or fed to another downstream chemical process.

5. MODELING OF SYSTEM COMPONENTS

5.1. CO_2 Capture. To provide an estimate for the capital costs of the CO_2 capture and purification process, various existing technologies were first examined. The CO_2 feedstock for the electrochemical process can be obtained either from a point source, such as a power plant or chemical facility, or directly from the atmosphere. The incorporation of CO_2 capture systems to coal and natural gas power plants is currently an area of intense research. The current state-of-the-art involves chemical adsorption using monoethanolamine (MEA) at a cost of $70 USD per ton of CO_2 captured.[80] This high cost is the main barrier for the incorporation of CO_2 capture to power plants. Through solvent and process design improvements, the cost of capture could be reduced to as much as $44 USD per ton CO_2.[81] Furthermore, the use of CO_2 in an electrochemical conversion to create value added products could also increase the economic viability of capture. One concern of CO_2 capture from point sources is the presence of other combustion products, such as SO_x and NO_x compounds. The impact of these compounds on electrolyzer performance is not yet understood, but the CO_2 stream likely needs to be of high purity for stable and efficient conversions.

Alternatively, the capture of CO_2 through direct air capture (DAC) has yet to be commercially developed, although a small demo facility by Climeworks in Switzerland recently opened. The cost estimates for such a system range anywhere between US$30 to US$1000 per ton of CO_2.[82,83] One advantage of DAC is the portability of the process, which allows for distributed use, which couples well with renewable energy sources. Furthermore, the capture of CO_2 from air represents a net-reduction in CO_2 as opposed to avoided emissions since the CO_2 is being taken from the atmosphere. For the purposes of this analysis, it was assumed that CO_2 was obtained at a base price of US$70 per ton.

5.2. Electrochemical Cell. Currently, CO_2 electrolyzers exist only at the bench scale. Furthermore, there is no standard design for a CO_2 electrolyzer cell with several configurations reported to date.[12,13,70] To provide an estimate for the capital costs of an electrolyzer system, an alkaline water electrolyzer stack as a representative model was used. In CO_2 electrolysis, nonprecious metal catalysts can be used to produce all products. Furthermore, the best bench-scale CO_2 electrolyzers to date utilize alkaline conditions which allow for the use of nonprecious metals at the anode, making the comparison to alkaline water electrolysis appropriate.[13,70] Furthermore, the auxiliary systems and balance of plant for a CO_2 electrolyzer are likely to be similar. The main difference would be the electrolyzer design requiring a direct feed of CO_2 to the catalyst surface, which would have a minimal cost difference. The design of the reactor between different products would also be consistent, with the exception being formate requiring

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165–2177

protonation to formic acid. This has been demonstrated at the lab scale.[13] Therefore, the capital and operating costs for the CO_2 electrolyzer were based on the DOE Current Central H2A base case for an alkaline electrolyzer.[84] In this analysis, the uninstalled capital costs attributed to the stack component were \$250/kW. To make the model sensitive to current density, a cost per surface area was also determined. This cost was calculated based on the typical operating conditions of 175 mA/cm^2 and 1.75 V for the Norsk Hydro HPE Atmospheric Type No. 5040 alkaline electrolyzer on which the base case was derived from, corresponding to an installed cost of \$920/m^2. An installation factor of 1.2 was used for the capital investment. Furthermore, it was assumed that maintenance costs were 2.5% of the capital investment per year. These costs included replenishing the catalysts and electrolytes used in the system. The balance of plant (BoP) costs were assumed to be 35% of the total cost of the electrolyzer system, and these values were derived from the H2A model.[84] The electricity usage for the electrolyzer subsystem was calculated based on the Faradaic mass balances across the electrolyzer.

5.3. Product Separation. For gas product separation, pressure swing adsorption (PSA) is an industrially used process with low operating costs, high efficiency, and a limited footprint.[85] For CO_2 electrolysis, the reactor exit gas consists of unconverted CO_2 and gas products, as well as some hydrogen. A similar separation is the upgrading of biogas, which consists of roughly equal amounts of methane and CO_2. Industrial reports have been developed regarding the costs of biogas upgrading with PSA and allowed for an estimation of the separation costs for CO_2 electrolysis gas product separation based on commercial systems.[86,87] Based on these studies, a reference cost of \$1 990 000 per 1000 m^3/h capacity was used, with a capacity scaling factor of 0.7 and operating costs consisting of only electricity at 0.25 kWh/m^3.[88] After separation, the gas products need to be compressed and stored, unless they are transported to and used immediately in a downstream process. Here, this additional cost was neglected.

Distillation was used as the separation process for the CO_2 reduction liquid products, as alcohols are separated by distillation commercially. Formic acid can also be separated by distillation, although it is highly energy intensive due to the close boiling points of water and formic acid. Furthermore, water was the distillate product leading to a high heat duty needed for the column. Alternatively, BASF utilizes a liquid–liquid extraction process to purify formic acid solutions up to 95% by weight.[89] However, to allow for consistent comparison, the separation of formic acid was also modeled through distillation. The separation processes were modeled using the RadFrac block in Aspen Plus, and capital and utility costs were estimated using the Aspen Plus Economic Analyzer. An electrolyte flow rate of 1000 L/min was assumed for the base case, with a concentration of 10% product in water. The separation was modeled as a single column with the product leaving near the azeotropic concentration. In practice, more elaborate methods, such as extractive or pressure swing distillation would allow for higher product purity. The capital costs were then scaled with a capacity factor of 0.7, while the utility costs were scaled linearly.

6. MODEL ASSUMPTIONS

6.1. Base Model Assumptions. To perform a comparison of the various CO_2 reduction products, several process assumptions were made. We considered two sets of parameters: a base case based on current feedstock prices and electrolyzer performance, and an optimistic case that considered what these values may be in the future. These assumptions are summarized in Table 3.

Table 3. Process Assumptions for CO_2 Electrolyzer Model

parameter	base case	optimistic case
production rate (ton/day)	100	100
lifetime (years)	20	20
operating time (days/year)	350	350
electricity price (\$/kWh)	0.05	0.03
current density (mA/cm^2)	200	300
cell voltage (V)	2.3	2
product selectivity (%)	90	90
conversion (%)	50	50
CO_2 price (\$/ton)	70	40
interest rate (%)	10	10
electrolyzer cost (\$/m^2)	1840	920

For both cases, a product production rate of 100 tons/day was chosen to allow for large scale chemical production, for which the capital costs were more favorable and differences between products were more discernible, while keeping the electrolyzer system power requirements within the range of the largest commercial systems (~100 MW). It was assumed that the system would require 2 weeks of downtime each year for maintenance over a 20-year lifetime. The base case electricity price of 0.05 \$/kWh was consistent with the cheapest industrial electricity rates currently available. As renewable energy sources, such as solar and wind, continue to become cheaper, the price of electricity could be as low as 0.02 \$/kWh.[90] An optimistic case value of 0.03 \$/kWh was chosen as this could be reached as soon as 2030.[91] The electrolyzer total current density of 200 mA/cm^2 has been demonstrated in numerous laboratory reactors at roughly 2.3 V.[70] For the optimistic case, a current density of 300 mA/cm^2 was assumed at cell voltage of 2 V, which fell within the range of commercial water electrolyzers. As shown in Figure 2, Faradaic efficiencies of 90% have been demonstrated for numerous CO_2 reduction products, such as CO, formic acid, and methanol, and were assumed for these cases. A baseline reactor conversion of 50% was chosen for the analysis, with the assumption that high selectivity can be reached at this conversion. It must be noted that CO_2 conversion is not often reported in the literature because most studies are performed in either a batch cell or single-pass flow cell with conversions less than 10%, although higher conversions near 35% have been shown.[13,92] A better electrolyzer design could potentially boost the CO_2 conversion to well over 50%. A low conversion results in a more challenging product separation due to the unreacted CO_2 in the reactor effluent that needs to be recycled.

6.2. Financial Model Assumptions. To estimate the return on capital investment for the development of a CO_2 electrolysis facility, a cash flow spreadsheet was developed to estimate the yearly revenue and present value of the plant over the project lifetime. It was assumed that construction of the facility was completed in the first year, with product production beginning in the second year. The working capital was assumed to be 5% of the capital investment. A modified accelerated cost recovery system (MACRS) 10-year depreciation schedule was used with a 20% salvage value at the end of plant life. A base case nominal interest rate (NIR) of 10%, compounded

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165–2177

annually, and a total effective income tax rate of 38.9% were assumed. These financial assumptions were consistent with those in the DOE's H2A analysis for water electrolysis.[84] The yearly profit was calculated as the income from selling product minus the yearly operating costs of the plant. The cost of sales, cost of labor, and inflation were not accounted for in the financial model. From this model, the net present value of the facility at the end of life was calculated.

7. ECONOMIC COST ANALYSIS

The net present value for the main products using the base case and optimistic case assumptions are shown in Figure 4.

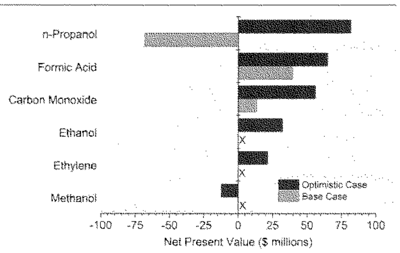


Figure 4. End-of-life NPV values for the production of various chemicals through eCO_2R under base and optimistic conditions. X's indicate that the yearly net income was negative, so NPV was not calculated.

Methane and syngas are not shown because their current market values are so low that profitability is impossible regardless of process performance. The X's indicate that the production was not even profitable on a yearly basis, so the end-of-life NPV would be highly negative.

At the base case conditions, CO and formic acid were the only profitable products for the CO_2 electrolysis system, whereas the other products, other than *n*-propanol, were not even profitable on a yearly basis. This is because CO and formic acid have the highest product value per electron (Table 2). Even at a modest electricity cost of \$0.05/kWh, the amount of electricity needed to produce hydrocarbons and alcohols outweighed the values of the chemical products. However, these products became much more favorable under the optimistic case assumptions. The production of *n*-propanol was the most favorable product, with methanol being the only product with a negative NPV. Based on CO_2 reduction studies in the literature, selectively obtaining *n*-propanol as the sole product is likely to be a major challenge, as the selectivity toward *n*-propanol is still quite low. However, a mixture of these liquid C_2-C_3 alcohols would still be economically valuable since ethanol was also favorable under the optimistic case.

To give a relative sense of the various costs of the process, the breakdown of capital and operating costs for each product under optimistic case assumptions are shown in Figure 5. Of all products, ethylene had the highest capital and operating costs due to the large amount of current (electricity) needed per kg of product. These high costs, along with a large CO_2 feedstock requirement, contributed to the low profitability of ethylene relative to other products. In contrast, formic acid and CO benefited from a small power requirement, which reduced the cost of electricity and electrolyzer size. For formic acid, much of the cost was associated with the challenging distillation process. As stated earlier, there are industrial processes that may be more cost-effective than distillation, which could further improve the profitability of formic acid. For example, a 50% reduction in the operating and capital costs for formic acid separation gave an NPV of \$84.5 million. It must be noted, that while the distillation and PSA systems had similar capital investment requirements, the PSA systems had a much lower operating cost. Although this cheaper separation was an advantage for gaseous products, they will likely require additional compression for transportation/storage, which could increase costs significantly.

To understand the sensitivity of the process profitability to different parameters, a sensitivity analysis was performed. The range of values considered for each parameter is listed in Table 4, with the results shown in Figure 6.

Table 4. Range of Values for Sensitivity Analysis

sensitivity parameters	better	base	worse
electric price (\$/kWh)	0.02	0.03	0.04
selling price (\$/kg)	+15%	base	−15%
selectivity (%)	100	90	80
voltage (V)	1.7	2	2.3
electrolyzer cost (\$/m^2)	460	920	1840
CO_2 cost (\$/ton)	0	40	70
current density (mA/cm^2)	500	300	100
conversion (%)	70	50	30

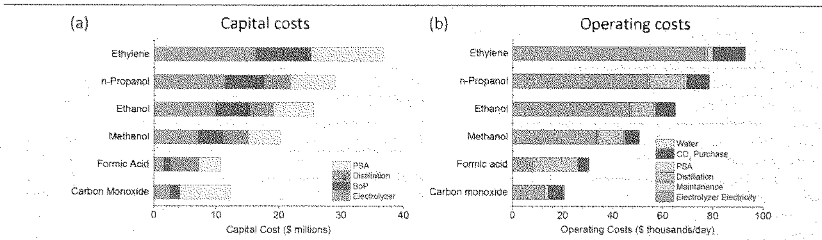


Figure 5. (a) Capital and (b) operating costs for various products under optimistic case assumptions.

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

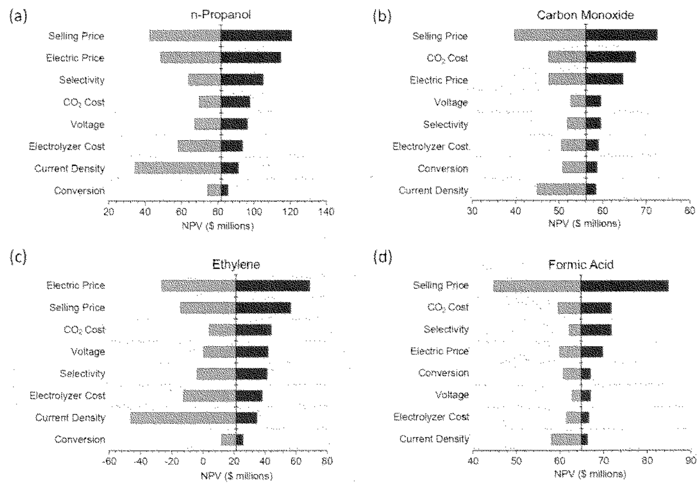


Figure 6. Sensitivity analysis of end-of-life NPV for CO_2 reduction products: (a) *n*-propanol, (b) carbon monoxide, (c) ethylene, and (d) formic acid.

For all products, a deviation in selling price of 15% had a significant impact on the end-of-life NPV of the process. Over a 20-year period, the product price could fluctuate significantly due to changes in market demand and development of new technologies. Therefore, the production of products, such as CO, *n*-propanol, and formic acid, are advantageous since they remained profitable even if the product selling price dropped significantly. For all products, other than CO and formic acid, electricity was the major operating cost, resulting in a strong economic dependence on the price of electricity. Even a change of just \$0.01/kWh resulted in a NPV difference of nearly \$40 million for *n*-propanol production. Therefore, it is critical for the CO_2 electrolyzer to have a steady supply of cheap electricity if hydrocarbons and alcohols are produced, which could be obtained through renewable sources in the near future.[90]

In terms of electrolyzer performance, selectivity and voltage were the most important parameters for higher electron products such as alcohols and ethylene. A higher selectivity reduced the total current needed because less electricity was wasted on hydrogen generation. This led to a lower power requirement and subsequently a lower electricity operating cost. Less hydrogen also reduced the separation requirement for recycling the CO_2, which was a significant cost even for liquid products. Also, a decrease in total current reduced the total electrolyzer area, resulting in a lower electrolyzer capital cost. Reducing the cell voltage (overpotentials) lowered the overall power requirement, which significantly impacted products with high electricity operating cost fraction. Furthermore, the reactor conversion also impacted the economics. A lower reactor conversion resulted in a higher separation cost due to an increased amount of unconverted CO_2 in the separation/recycle loop, and this consequentially increased the size/capital cost of the PSA system. However, in the case of low conversion and high selectivity toward liquid products, the gas stream exiting the reactor would consist almost entirely of CO_2 with some residual hydrogen. Thus, multiple passes could be made before separation, as a small dilution of the CO_2 feedstock would not significantly influence reactor performance.

Interestingly, the current density was the least important parameter of electrolyzer performance once above a certain threshold. This was due to the inverse square relationship between the electrolyzer capital cost and current density. Thus, for products that required large amounts of electricity, increasing the current density to at least 250−300 mA/cm^2 was critical. In the case of ethanol, a decrease in current density to 100 mA/cm^2 resulted in a NPV decrease of \$42 million, while an increase to 500 mA/cm^2 only gave an extra \$8 million (Figure S2). After a certain threshold, the capital costs of the electrolyzer, which were directly influenced by current density, became insignificant to the other costs. Stemming from these calculations, since the cell voltage was a significant cost due to the extra power requirement, the CO_2 electrolyzer should operate at as low of a voltage possible while still maintaining an appreciable current density.

8. CATALYST ACTIVITY TARGETS

The CO_2 electrolyzer model was used to define activity targets for electrolyzer performance needed to be profitable for a given CO_2 reduction product. As shown in the sensitivity analysis, cell potential and selectivity were the major parameters. Since the anode of the CO_2 electrolyzer is typically water oxidation, and anion exchange membrane development is vastly improving, the cell potential was simplified to the overpotential associated with the electrochemical reduction of CO_2. We assumed the optimistic base case conditions with a current density of 300 mA/cm^2. The anodic overpotential was estimated as 0.3 V with a cell resistance overpotential of 0.1 V. Figure 7 shows

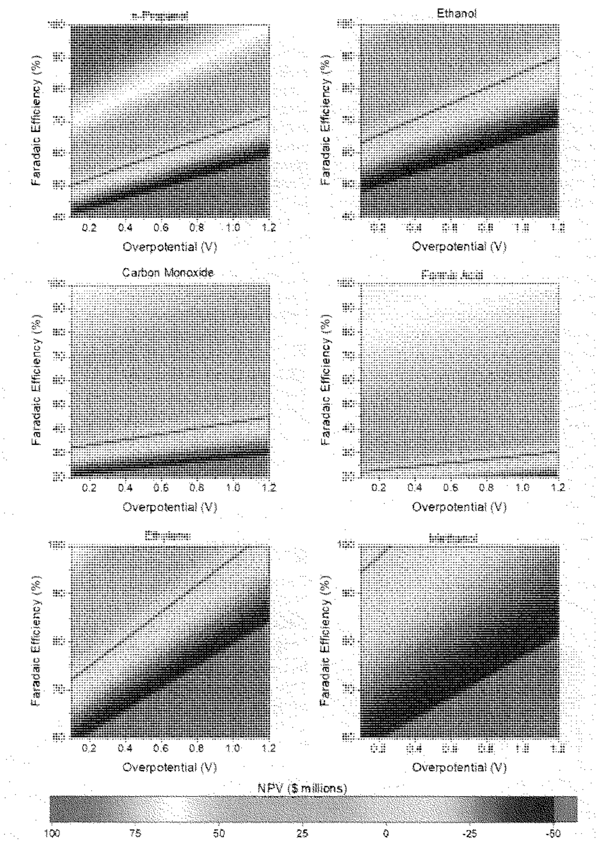


Figure 7. Electrolyzer performance contour plots showing the dependence of end-of-life NPV on overpotential and selectivity under optimistic conditions with a current density of 300 mA/cm^2. The solid line depicts an NPV of \$0 (IRR = 10%).

overpotential/selectivity contour plots for various products with the calculated end-of-life NPV. The solid line depicts the performance needed for an NPV of \$0 (i.e., an investor's rate of return (IRR) of 10%). For the process to be profitable, the electrolyzer performance must lie above the curve. As shown, the production of CO and formic acid can be done profitably under the optimistic base conditions with relatively poor electrolyzer performance, requiring Faradaic efficiencies much lower than currently obtained. Since these products require only 2 electrons/mol, they are much less sensitive to inefficiency when electricity prices are low. Thus, they are highly promising products under future conditions, although there are concerns associated with the limited market potential (Table 2). *n*-Propanol requires a modest selectivity of 62% at 0.7 V overpotential, with the potential for significant profitability at high selectivities (>80%). Ethanol and ethylene require relatively high Faradaic efficiencies of 77% and 89% at 0.7 V overpotential, respectively. Altogether, it is promising that the activity targets for the profitable production of these hydrocarbon and alcohol products are technologically feasible, as they have a much larger market potential compared to CO and formic acid. However, as shown by the current state-of-art in Figure 2, drastic improvements in electrolyzer performance are needed for ethylene, ethanol, and *n*-propanol.

9. CO_2 EMISSIONS REDUCTION

Although eCO_2R has the potential to profitably produce valuable chemical feedstocks, it is unlikely that the technology alone can significantly reduce the atmospheric CO_2 concentration for a couple of reasons. First, as discussed earlier, the

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165–2177

direct air capture of CO_2 is still expensive. Second, the total amount of CO_2 emission is too large to be handled by electrochemical processes alone. Per the EIA, the US emitted roughly 5.2 million metric tons of CO_2 from the energy-sector alone in 2015.[18] Reducing this CO_2 to only a two-electron product, like formic acid, would require ~1.5 TW, which is equivalent to roughly 8% of the world's energy output.

However, if low-carbon electricity sources such as wind and solar are used, additional CO_2 emissions can be mitigated if the CO_2 is sourced from industrial sources, such as fossil fuel power plants and chemical facilities, since converting this CO_2 through eCO_2R would then be a reduction of emissions as opposed to the commonly used case where the CO_2 is simply emitted. This is true even if the CO_2 reduction product is a fuel that is later burned, provided it replaces those derived from fossil fuels. For example, consider the electrochemical reduction of CO_2 to ethanol for use as a fuel additive. We estimated the greenhouse gas emissions (reported as grams of CO_2 equivalent) for the process associated with the electricity used, as this is the major operating cost. Additional emissions would result from construction of the facility materials and other process costs (steam, heating, etc.), which were not considered as they are assumed to be minor compared to the electrical system. Despite being "renewable" sources, wind and solar have some associated emissions due to construction and maintenance. These values were derived from the IPCC.[93] As illustrated in Figure 8, the associated emissions with the electrochemical

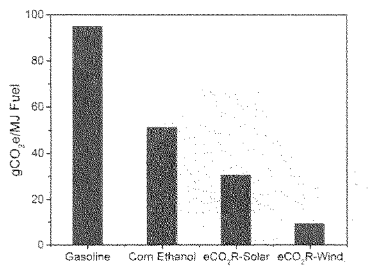


Figure 8. Greenhouse gas emissions for the production of gasoline and corn ethanol (ref 89) compared to electrochemical CO_2 reduction.

production of ethanol from CO_2 are much less than those of gasoline, and comparable to ethanol derived from corn feedstocks, which is the current dominant production method.[94] This shows that CO_2-derived chemicals and fuels can indirectly lead to a reduction of CO_2 emissions.

10. CONCLUSIONS

The generalized techno-economic model for eCO_2R presented in this work provides insight into the feasibility of various common CO_2 reduction products for large-scale chemical production. We found that current density is the least important electrolyzer parameter after a certain threshold (200–400 mA/cm^2) is reached, while selectivity and over-potential are critical, especially for high-electron products. Simple products, such as CO and formic acid, were more profitable under current economic conditions and performance based on the current state-of-the-art electrocatalysts, although only lab-scale electrolyzer systems have been demonstrated. However, the small market potential for formic acid and the difficulty associated with storing/transporting gaseous products motivates the production of liquids, such as ethanol and *n*-propanol, which could be profitable under more favorable economic conditions in the future and may have a much higher market potential. For higher-order alcohols to become profitable, cheaper electricity costs and improved catalytic performance are needed. However, with continual efforts, the electrocatalytic performance benchmarks for these alcohols can be achievable, and the use of C_2–C_3 alcohols produced from eCO_2R would allow for renewable energy sources to penetrate into the transportation and chemical sectors while potentially reducing GHG emissions. Overall, the electrochemical reduction of CO_2 is a promising technology that could play a significant role in the future renewable energy infrastructure if further strides are made.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.iecr.7b03514.

Enlarged figures, calculation of single-pass liquid product accumulation, a detailed derivation of NPV for ethanol case, and NPV and capital cost vs current density for ethanol case (PDF)

Economic analysis of CO_2 electrolyzer system (XLSX)

■ AUTHOR INFORMATION

Corresponding Author

*jiao@udel.edu.

ORCID

Feng Jiao: 0000-0002-3335-3203

Notes

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency DE-FE0029868, Base Award Page 9 of 19 thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material is based upon work supported by the Department of Energy under Award Number DE-FE0029868. The authors also thank the National Science Foundation Faculty Early Career Development program (Award No. CBET-1350911).

■ REFERENCES

(1) IPCC *IPCC Fifth Assessment Synthesis Report*; Cambridge University Press: Cambridge, UK New York, NY, USA, 2014.

(2) U.S. Energy Information Administration *Annual Energy Outlook*; 2017.
(3) Seh, Z. W.; Kibsgaard, J.; Dickens, C. F.; Chorkendorff, I.; Norskov, J. K.; Jaramillo, T. F. Combining theory and experiment in electrocatalysis: Insights into materials design. *Science* **2017**, *355* (6321), eaad4998.
(4) Whipple, D. T.; Kenis, P. J. Prospects of CO2 utilization via direct heterogeneous electrochemical reduction. *J. Phys. Chem. Lett.* **2010**, *1* (24), 3451−3458.
(5) Martin, A. J.; Larrazabal, G. O.; Perez-Ramirez, J. Towards sustainable fuels and chemicals through the electrochemical reduction of CO2: lessons from water electrolysis. *Green Chem.* **2015**, *17* (12), 5114−5130.
(6) Goeppert, A.; Czaun, M.; Jones, J. P.; Surya Prakash, G. K.; Olah, G. A. Recycling of carbon dioxide to methanol and derived products - closing the loop. *Chem. Soc. Rev.* **2014**, *43* (23), 7995−8048.
(7) Mikkelsen, M.; Jørgensen, M.; Krebs, F. C. The teraton challenge. A review of fixation and transformation of carbon dioxide. *Energy Environ. Sci.* **2010**, *3* (1), 43−81.
(8) Li, H.; Liao, J. C. Biological conversion of carbon dioxide to photosynthetic fuels and electrofuels. *Energy Environ. Sci.* **2013**, *6* (10), 2892.
(9) Li, Y.; Sun, Q. Recent Advances in Breaking Scaling Relations for Effective Electrochemical Conversion of CO2. *Adv. Energy Mater.* **2016**, *6* (17), 1600463.
(10) Luc, W.; Rosen, J.; Jiao, F. An Ir-based anode for a practical CO 2 electrolyzer. *Catal. Today* **2017**, *288*, 79−84.
(11) Delacourt, C.; Ridgway, P. L.; Kerr, J. B.; Newman, J. Design of an Electrochemical Cell Making Syngas (CO+H2) from CO2 and H2O Reduction at Room Temperature. *J. Electrochem. Soc.* **2008**, *155* (1), B42−B49.
(12) Dufek, E. J.; Lister, T. E.; McIlwain, M. E. Bench-scale electrochemical system for generation of CO and syn-gas. *J. Appl. Electrochem.* **2011**, *41* (6), 623−631.
(13) Yang, H.; Kaczur, J. J.; Sajjad, S. D.; Masel, R. I. Electrochemical conversion of CO 2 to formic acid utilizing Sustainion membranes. *Journal of CO2 Utilization* **2017**, *20*, 208−217.
(14) Pletcher, D. The cathodic reduction of carbon dioxide—What can it realistically achieve? A mini review. *Electrochem. Commun.* **2015**, *61*, 97−101.
(15) Kuhl, K. P.; Cave, E. R.; Abram, D. N.; Jaramillo, T. F. New insights into the electrochemical reduction of carbon dioxide on metallic copper surfaces. *Energy Environ. Sci.* **2012**, *5* (5), 7050−7059.
(16) Kuhl, K. P.; Hatsukade, T.; Cave, E. R.; Abram, D. N.; Kibsgaard, J.; Jaramillo, T. F. Electrocatalytic conversion of carbon dioxide to methane and methanol on transition metal surfaces. *J. Am. Chem. Soc.* **2014**, *136* (40), 14107−13.
(17) Independent Chemical Information Services https://www.icis.com/.
(18) U.S. Energy Information Administration https://www.eia.gov/.
(19) Lu, Q.; Jiao, F. Electrochemical CO2 reduction: Electrocatalyst, reaction mechanism, and process engineering. *Nano Energy* **2016**, *29*, 439.
(20) Gasification & Syngas Technologies Council http://www.gasification-syngas.org.
(21) TechnipFMC http://www.technip.com/en.
(22) Mondal, P.; Dang, G. S.; Garg, M. O. Syngas production through gasification and cleanup for downstream applications — Recent developments. *Fuel Process. Technol.* **2011**, *92* (8), 1395−1410.
(23) International Gas Union http://www.igu.org/.
(24) U.S. Depertment of Energy Alternative Fuels Data Center https://www.afdc.energy.gov/.
(25) Hori, Y. Electrochemical CO_2 Reduction on Metal Electrodes. In *Modern Aspects of Electrochemistry*; Vayenas, C. G., White, R. E., Gamboa-Aldeco, M. E., Eds.; Springer New York: New York, NY, 2008; pp 89−189.
(26) Hori, Y.; Wakebe, H.; Tsukamoto, T.; Koga, O. Electrocatalytic process of CO selectivity in electrochemical reduction of CO2 at metal electrodes in aqueous media. *Electrochim. Acta* **1994**, *39* (11), 1833−1839.
(27) Lu, Q.; Rosen, J.; Zhou, Y.; Hutchings, G. S.; Kimmel, Y. C.; Chen, J. G.; Jiao, F. A selective and efficient electrocatalyst for carbon dioxide reduction. *Nat. Commun.* **2014**, *5*, 3242.
(28) Zhang, S.; Kang, P.; Meyer, T. J. Nanostructured Tin Catalysts for Selective Electrochemical Reduction of Carbon Dioxide to Formate. *J. Am. Chem. Soc.* **2014**, *136* (5), 1734−1737.
(29) Zhu, W.; Michalsky, R.; Metin, Ö.; Lv, H.; Guo, S.; Wright, C. J.; Sun, X.; Peterson, A. A.; Sun, S. Monodisperse Au Nanoparticles for Selective Electrocatalytic Reduction of CO2 to CO. *J. Am. Chem. Soc.* **2013**, *135* (45), 16833−16836.
(30) Chen, Y.; Li, C. W.; Kanan, M. W. Aqueous CO2 Reduction at Very Low Overpotential on Oxide-Derived Au Nanoparticles. *J. Am. Chem. Soc.* **2012**, *134* (49), 19969−19972.
(31) Li, C. W.; Kanan, M. W. CO2 reduction at low overpotential on Cu electrodes resulting from the reduction of thick Cu2O films. *J. Am. Chem. Soc.* **2012**, *134* (17), 7231−4.
(32) Ren, D.; Ang, B. S.-H.; Yeo, B. S. Tuning the Selectivity of Carbon Dioxide Electroreduction toward Ethanol on Oxide-Derived CuxZn Catalysts. *ACS Catal.* **2016**, *6*, 8239−8247.
(33) Luc, W.; Collins, C.; Wang, S.; Xin, H.; He, K.; Kang, Y.; Jiao, F. Ag−Sn Bimetallic Catalyst with a Core−Shell Structure for CO2 Reduction. *J. Am. Chem. Soc.* **2017**, *139* (5), 1885−1893.
(34) Asadi, M.; Kim, K.; Liu, C.; Addepalli, A. V.; Abbasi, P.; Yasaei, P.; Phillips, P.; Behranginia, A.; Cerrato, J. M.; Haasch, R.; Zapol, P.; Kumar, B.; Klie, R. F.; Abiade, J.; Curtiss, L. A.; Salehi-Khojin, A. Nanostructured transition metal dichalcogenide electrocatalysts for CO_2 reduction in ionic liquid. *Science* **2016**, *353* (6298), 467−470.
(35) Asadi, M.; Kumar, B.; Behranginia, A.; Rosen, B. A.; Baskin, A.; Repnin, N.; Pisasale, D.; Phillips, P.; Zhu, W.; Haasch, R.; Klie, R. F.; Král, P.; Abiade, J.; Salehi-Khojin, A. *Nat. Commun.* **2014**, *5*, 4470.
(36) Wu, J.; Ma, S.; Sun, J.; Gold, J. I.; Tiwary, C.; Kim, B.; Zhu, L.; Chopra, N.; Odeh, I. N.; Vajtai, R.; Yu, A. Z.; Luo, R.; Lou, J.; Ding, G.; Kenis, P. J. A.; Ajayan, P. M. *Nat. Commun.* **2016**, *7*, 13869.
(37) Zhang, S.; Kang, P.; Ubnoske, S.; Brennaman, M. K.; Song, N.; House, R. L.; Glass, J. T.; Meyer, T. J. Polyethylenimine-Enhanced Electrocatalytic Reduction of CO2 to Formate at Nitrogen-Doped Carbon Nanomaterials. *J. Am. Chem. Soc.* **2014**, *136* (22), 7845−7848.
(38) Ma, S.; Luo, R.; Moniri, S.; Lan, Y.; Kenis, P. J. A. Efficient Electrochemical Flow System with Improved Anode for the Conversion of CO2 to CO. *J. Electrochem. Soc.* **2014**, *161* (10), F1124−F1131.
(39) Verma, S.; Lu, X.; Ma, S.; Masel, R. I.; Kenis, P. J. A. The effect of electrolyte composition on the electroreduction of CO2 to CO on Ag based gas diffusion electrodes. *Phys. Chem. Chem. Phys.* **2016**, *18* (10), 7075−7084.
(40) Wu, K.; Birgersson, E.; Kim, B.; Kenis, P. J. A.; Karimi, I. A. Modeling and Experimental Validation of Electrochemical Reduction of CO2 to CO in a Microfluidic Cell. *J. Electrochem. Soc.* **2015**, *162* (1), F23−F32.
(41) Jhong, H.-R. M.; Brushett, F. R.; Kenis, P. J. A. The Effects of Catalyst Layer Deposition Methodology on Electrode Performance. *Adv. Energy Mater.* **2013**, *3* (5), 589−599.
(42) Jhong, H.-R. M.; Ma, S.; Kenis, P. J. A. Electrochemical conversion of CO2 to useful chemicals: current status, remaining challenges, and future opportunities. *Curr. Opin. Chem. Eng.* **2013**, *2* (2), 191−199.
(43) Furuya, N.; Koide, S. Electroreduction of carbon dioxide by metal phthalocyanines. *Electrochim. Acta* **1991**, *36* (8), 1309−1313.
(44) Kaneco, S.; Iiba, K.; Ohta, K.; Mizuno, T.; Saji, A. Electrochemical reduction of CO2 at an Ag electrode in KOH-methanol at low temperature. *Electrochim. Acta* **1998**, *44* (4), 573−578.
(45) Kaneco, S.; Iiba, K.; Ohta, K.; Mizuno, T.; Saji, A. Electrochemical reduction of CO2 on Au in KOH + methanol at low temperature. *J. Electroanal. Chem.* **1998**, *441* (1), 215−220.

(46) Gao, D.; Zhou, H.; Wang, J.; Miao, S.; Yang, F.; Wang, G.; Wang, J.; Bao, X. Size-Dependent Electrocatalytic Reduction of CO2 over Pd Nanoparticles. *J. Am. Chem. Soc.* **2015**, *137* (13), 4288−4291.

(47) Rasul, S.; Anjum, D. H.; Jedidi, A.; Minenkov, Y.; Cavallo, L.; Takanabe, K. A Highly Selective Copper−Indium Bimetallic Electrocatalyst for the Electrochemical Reduction of Aqueous CO2 to CO. *Angew. Chem., Int. Ed.* 2015, *54* (7), 2146−2150.

(48) Kornienko, N.; Zhao, Y.; Kley, C. S.; Zhu, C.; Kim, D.; Lin, S.; Chang, C. J.; Yaghi, O. M.; Yang, P. Metal−Organic Frameworks for Electrocatalytic Reduction of Carbon Dioxide. *J. Am. Chem. Soc.* **2015**, *137* (44), 14129−14135.

(49) Zhou, L. Q.; Ling, C.; Jones, M.; Jia, H. Selective CO2 reduction on a polycrystalline Ag electrode enhanced by anodization treatment. *Chem. Commun.* **2015**, *51* (100), 17704−17707.

(50) Ma, S.; Luo, R.; Gold, J. I.; Yu, A. Z.; Kim, B.; Kenis, P. J. A. Carbon nanotube containing Ag catalyst layers for efficient and selective reduction of carbon dioxide. *J. Mater. Chem. A* **2016**, *4* (22), 8573−8578.

(51) Wang, H.; Chen, Y.; Hou, X.; Ma, C.; Tan, T. Nitrogen-doped graphenes as efficient electrocatalysts for the selective reduction of carbon dioxide to formate in aqueous solution. *Green Chem.* **2016**, *18* (11), 3250−3256.

(52) Sen, S.; Liu, D.; Palmore, G. T. R. Electrochemical Reduction of CO2 at Copper Nanofoams. *ACS Catal.* **2014**, *4* (9), 3091−3095.

(53) Furuya, N.; Yamazaki, T.; Shibata, M. High performance Ru Pd catalysts for CO2 reduction at gas-diffusion electrodes. *J. Electroanal. Chem.* 1997, *431* (1), 39−41.

(54) Gao, S.; Lin, Y.; Jiao, X.; Sun, Y.; Luo, Q.; Zhang, W.; Li, D.; Yang, J.; Xie, Y. Partially oxidized atomic cobalt layers for carbon dioxide electroreduction to liquid fuel. *Nature* **2016**, *529* (7584), 68−71.

(55) Won, D. H.; Choi, C. H.; Chung, J.; Chung, M. W.; Kim, E.-H.; Woo, S. I. Rational Design of a Hierarchical Tin Dendrite Electrode for Efficient Electrochemical Reduction of CO2. *ChemSusChem* **2015**, *8* (18), 3092−3098.

(56) Kortlever, R.; Peters, I.; Koper, S.; Koper, M. T. M. Electrochemical CO2 Reduction to Formic Acid at Low Overpotential and with High Faradaic Efficiency on Carbon-Supported Bimetallic Pd−Pt Nanoparticles. *ACS Catal.* **2015**, *5* (7), 3916−3923.

(57) Summers, D. P.; Leach, S.; Frese, K. W. The electrochemical reduction of aqueous carbon dioxide to methanol at molybdenum electrodes with low overpotentials. *J. Electroanal. Chem. Interfacial Electrochem.* **1986**, *205* (1), 219−232.

(58) Frese, K. W. Electrochemical Reduction of CO2 at Intentionally Oxidized Copper Electrodes. *J. Electrochem. Soc.* **1991**, *138* (11), 3338−3344.

(59) Bandi, A.; Kühne, H. M. Electrochemical Reduction of Carbon Dioxide in Water: Analysis of Reaction Mechanism on Ruthenium-Titanium-Oxide. *J. Electrochem. Soc.* **1992**, *139* (6), 1605−1610.

(60) Popić, J. P.; Avramov-Ivić, M. L.; Vuković, N. B. Reduction of carbon dioxide on ruthenium oxide and modified ruthenium oxide electrodes in 0.5 M NaHCO3. *J. Electroanal. Chem.* **1997**, *421* (1), 105−110.

(61) Kobayashi, T.; Takahashi, H. Novel CO2 Electrochemical Reduction to Methanol for H2 Storage. *Energy Fuels* **2004**, *18* (1), 285−286.

(62) Le, M.; Ren, M.; Zhang, Z.; Sprunger, P. T.; Kurtz, R. L.; Flake, J. C. Electrochemical Reduction of CO2 to CH3OH at Copper Oxide Surfaces. *J. Electrochem. Soc.* **2011**, *158* (5), E45−E49.

(63) Hara, K.; Sakata, T. Electrocatalytic Formation of CH4 from CO2 on a Pt Gas Diffusion Electrode. *J. Electrochem. Soc.* **1997**, *144* (2), 539−545.

(64) Takahashi, I.; Koga, O.; Hoshi, N.; Hori, Y. Electrochemical reduction of CO2 at copper single crystal Cu(S)-[n(111)×(111)] and Cu(S)-[n(110)×(100)] electrodes. *J. Electroanal. Chem.* **2002**, *533* (1), 135−143.

(65) Yano, H.; Tanaka, T.; Nakayama, M.; Ogura, K. Selective electrochemical reduction of CO2 to ethylene at a three-phase interface on copper(I) halide-confined Cu-mesh electrodes in acidic solutions of potassium halides. *J. Electroanal. Chem.* **2004**, *565* (2), 287−293.

(66) Loiudice, A.; Lobaccaro, P.; Kamali, E. A.; Thao, T.; Huang, B. H.; Ager, J. W.; Buonsanti, R. Tailoring Copper Nanocrystals towards C2 Products in Electrochemical CO2 Reduction. *Angew. Chem., Int. Ed.* **2016**, *55* (19), 5789−5792.

(67) Song, Y.; Peng, R.; Hensley, D. K.; Bonnesen, P. V.; Liang, L.; Wu, Z.; Meyer, H. M.; Chi, M.; Ma, C.; Sumpter, B. G.; Rondinone, A. J. High-Selectivity Electrochemical Conversion of CO2 to Ethanol using a Copper Nanoparticle/N-Doped Graphene Electrode. *ChemistrySelect* **2016**, *1* (19), 6055−6061.

(68) Manthiram, K.; Beberwyck, B. J.; Alivisatos, A. P. Enhanced Electrochemical Methanation of Carbon Dioxide with a Dispersible Nanoscale Copper Catalyst. *J. Am. Chem. Soc.* **2014**, *136* (38), 13319−13325.

(69) Kwon, Y.; Lum, Y.; Clark, E. L.; Ager, J. W.; Bell, A. T. CO2 Electroreduction with Enhanced Ethylene and Ethanol Selectivity by Nanostructuring Polycrystalline Copper. *ChemElectroChem* **2016**, *3* (6), 1012−1019.

(70) Ma, S.; Sadakiyo, M.; Luo, R.; Heima, M.; Yamauchi, M.; Kenis, P. J. A. One-step electrosynthesis of ethylene and ethanol from CO2 in an alkaline electrolyzer. *J. Power Sources* **2016**, *301*, 219−228.

(71) Chen, C. S.; Wan, J. H.; Yeo, B. S. Electrochemical Reduction of Carbon Dioxide to Ethane Using Nanostructured Cu2O-Derived Copper Catalyst and Palladium(II) Chloride. *J. Phys. Chem. C* **2015**, *119* (48), 26875−26882.

(72) Ohya, S.; Kaneco, S.; Katsumata, H.; Suzuki, T.; Ohta, K. Electrochemical reduction of CO2 in methanol with aid of CuO and Cu2O. *Catal. Today* **2009**, *148* (3), 329−334.

(73) Kopljar, D.; Wagner, N.; Klemm, E. Transferring Electrochemical CO2 Reduction from Semi-Batch into Continuous Operation Mode Using Gas Diffusion Electrodes. *Chem. Eng. Technol.* 2016, 39 (11), 2042−2050.

(74) Sen, S.; Skinn, B.; Hall, T.; Inman, M.; Taylor, E. J.; Brushett, F. R. Pulsed Electrodeposition of Tin Electrocatalysts onto Gas Diffusion Layers for Carbon Dioxide Reduction to Formate. *MRS Advances* 2017, 2 (8), 451−458.

(75) McCrory, C. C. L.; Jung, S.; Ferrer, I. M.; Chatman, S. M.; Peters, J. C.; Jaramillo, T. F. Benchmarking Hydrogen Evolving Reaction and Oxygen Evolving Reaction Electrocatalysts for Solar Water Splitting Devices. *J. Am. Chem. Soc.* **2015**, *137* (13), 4347−4357.

(76) Pérez-Fortes, M.; Schöneberger, J. C.; Boulamanti, A.; Harrison, G.; Tzimas, E. Formic acid synthesis using CO2 as raw material: Techno-economic and environmental evaluation and market potential. *Int. J. Hydrogen Energy* **2016**, *41* (37), 16444−16462.

(77) Li, X.; Anderson, P.; Jhong, H.-R. M.; Paster, M.; Stubbins, J. F.; Kenis, P. J. A. Greenhouse Gas Emissions, Energy Efficiency, and Cost of Synthetic Fuel Production Using Electrochemical CO2Conversion and the Fischer−Tropsch Process. *Energy Fuels* **2016**, *30* (7), 5980−5989.

(78) Verma, S.; Kim, B.; Jhong, H. R.; Ma, S.; Kenis, P. J. A Gross-Margin Model for Defining Technoeconomic Benchmarks in the Electroreduction of CO2. *ChemSusChem* **2016**, *9* (15), 1972−9.

(79) Seider, W. D.; Seader, J. D.; Lewin, D. R. *PRODUCT & PROCESS DESIGN PRINCIPLES: SYNTHESIS, ANALYSIS AND EVALUATION*; John Wiley & Sons, 2009.

(80) Ho, M. T.; Allinson, G. W.; Wiley, D. E. Factors affecting the cost of capture for Australian lignite coal fired power plants. *Energy Procedia* **2009**, *1* (1), 763−770.

(81) Raksajati, A.; Ho, M. T.; Wiley, D. E. Reducing the Cost of CO2 Capture from Flue Gases Using Aqueous Chemical Absorption. *Ind. Eng. Chem. Res.* **2013**, *52* (47), 16887−16901.

(82) Sanz-Perez, E. S.; Murdock, C. R.; Didas, S. A.; Jones, C. W. Direct Capture of CO2 from Ambient Air. *Chem. Rev.* **2016**, *116* (19), 11840−11876.

(83) Zeman, F. Reducing the cost of Ca-based direct air capture of CO2. *Environ. Sci. Technol.* **2014**, *48* (19), 11730−5.

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

(84) Steward, D.; Ramsden, T.; Zuboy, J., H2A Central Hydrogen Production Model, Version 3 User Guide. *National Renewable Energy Laboratory*; 2012.

(85) Wiheeb, A.; Helwani, Z.; Kim, J.; Othman, M. Pressure swing adsorption technologies for carbon dioxide capture. *Sep. Purif. Rev.* **2016**, *45* (2), 108−121.

(86) Tamm, D.; Persson, T.; Hulteberg, C.; Bauer, F. Biogas upgrading-Review of commercial technologies. *SGC Rapport* **2013**, *270*, 1.

(87) Persson, M.; Jönsson, O.; Wellinger, A. In *Biogas upgrading to vehicle fuel standards and grid injection*; 2006.

(88) Paturska, A.; Repele, M.; Bazbauers, G. Economic Assessment of Biomethane Supply System based on Natural Gas Infrastructure. *Energy Procedia* **2015**, *72*, 71−78.

(89) Wolf, D.; Schmidt, R.; Block, U.; Schoenmakers, H.; Bott, K.; Kaibel, G., Production of anhydrous or substantially anhydrous formic acid. U.S. Patent US4326073 A, 1982.

(90) Wiser, R.; Bolinger, M. *2014 Wind Technologies Market Report*; Lawrence Berkeley National Laboratory, 2015.

(91) Haegel, N. M.; Margolis, R.; Buonassisi, T.; Feldman, D.; Froitzheim, A.; Garabedian, R.; Green, M.; Glunz, S.; Henning, H.-M.; Holder, B.; et al. Terawatt-scale photovoltaics: Trajectories and challenges. *Science* **2017**, *356* (6334), 141−143.

(92) Kim, B.; Ma, S.; Jhong, H.-R. M.; Kenis, P. J. Influence of dilute feed and pH on electrochemical reduction of CO2 to CO on Ag in a continuous flow electrolyzer. *Electrochim. Acta* **2015**, *166*, 271−276.

(93) Schlömer, S.; Bruckner, T.; Fulton, L.; Hertwich, E.; McKinnon, A.; Perczyk, D.; Roy, J.; Schaeffer, R.; Sims, R.; Smith, P. Annex III: Technology-specific cost and performance parameters. *Climate change* **2014**, 1329−1356.

(94) Wang, M.; Han, J.; Dunn, J. B.; Cai, H.; Elgowainy, A. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ. Res. Lett.* **2012**, *7* (4), 045905.

DOI: 10.1021/acs.iecr.7b03514
Ind. Eng. Chem. Res. 2018, 57, 2165−2177

U.S. Senate Committee on Environment and Public Works
Full Committee Hearing on "Legislative Hearing on S. 2602, the Utilizing Significant Emissions with Significant Technologies Act, or USE IT Act"
April 11, 2018
Questions for the Record for Dr. Feng Jiao

Ranking Member Carper:

Please provide a response to each question, ***including each sub-part.***

1. Would you provide further details on how your work at the University of Delaware is so important for a carbon-free future?

Response: One of my current research projects related to CCUS is funded by the Office of Fossil Energy in DOE (Award #: DE-FE0029868). The goal of this project is to develop an electrochemical reactor that could convert greenhouse gas CO_2 into valuable chemicals, such as ethanol and propanol, in a cost-competitive way. Because renewable electricity price is declining and projected to reach $0.03 per kWh in the near future, electrochemical approaches for CO_2 utilization become more economically favorable than traditional thermal driven carbon utilization processes. If successful, this technology could potentially disrupt current chemical industries for commodity chemical production. Additionally, switching from petroleum based processes to CO_2 based processes could generate significant impacts on CO_2 emission by providing the society carbon-neutral fuels and chemicals.

2. What more, beyond this legislation, should the federal government be doing to ensure carbon capture and utilization becomes mainstream?

Response: The key to get people, particular industry, onboard is to develop profitable CCUS technologies that have less financial dependency on government subsidy. Currently, the investments in CCUS technologies are primarily on the capture and storage side. Although such technologies are important, they have difficulties to generate revenues, and therefore, they are not sustainable businesses. More attention should be paid to carbon utilization technologies, which include not only enhanced oil recovery, but also other advanced carbon utilization technologies to generate revenues. Federal investments and policies on these frontiers are crucial to help them mature and ready for market deployment. Once the carbon capture and utilization become profitable, they will be quickly adapted by industries.

3. Is the United States a global leader in CCUS or falling behind other countries? If the United States is falling behind, why do you think that is the case?

Response: While the United States is currently a global leader in CCUS, other countries, such as EU and China, are investing heavily on CCUS technologies, which poses a serious threat to the leading position of the U.S. technologies.

4. In the hearing, I asked you how the USE IT Act could be improved. Please provide further details on how this bill could be improved.

Response: There are a few changes that I would like to suggest for consideration. Department of Energy, especially the Office of Fossil Energy, has a long history to invest on carbon capture technologies, including direct air capture, which is explicitly mentioned in the USE IT Act. Because the direct air capture technology deals with highly dilute CO_2, the capture cost is inevitably higher than other carbon capture methods that deal with point sources (such as power and chemical plants). The capture cost goal ($200 per ton CO_2) in the USE IT Act could be more aggressive to ensure that this technology could eventually be cost-competitive. Additionally, the R&D efforts proposed in the USE IT Act will be administrated by EPA. A close coordination between EPA and DOE may be beneficial because DOE is certainly more experienced in managing R&D efforts in CCUS technologies.

Senator BARRASSO. We are very grateful for your testimony. Thank you for joining us today from Delaware.

We will start with rounds of questions for 5 minutes, and I will start with Dr. Northam, if I could.

The State of Wyoming's leadership in carbon capture and utilization is very impressive. Through the university's work and initiatives like the Integrated Test Center in Gillette, Wyoming has already established itself as an innovative hub. The recent passage of the FUTURE Act has spurred interest in investment in carbon capture projects.

Do you think the USE IT Act's focus on permitting capture projects and pipelines is going to increase the interest that you are seeing, and can you explain why?

Mr. NORTHAM. Thank you, Mr. Chairman. There is a large demand for carbon dioxide for enhanced oil recovery in the State of Wyoming, a demand that cannot be met by traditional supply. For example, in the Big Horn Basin, where there is no supply of CO_2 today, there is easily a billion barrels of incrementally recoverable oil if we had access to CO_2.

Infrastructure is certainly a large obstacle. The FUTURE Act has great potential for incentivizing anthropogenic CO_2 availability. The USE IT Act's impact on easing the development of infrastructure——

Senator CARPER. What is anthropogenic?

Mr. NORTHAM. I am sorry. Anthropogenic CO_2 is carbon dioxide that has been captured from some source that is created by man, combustion of coal, fossil fuels, or some industrial process, as opposed to natural CO_2 which we use today, which is carbon dioxide that is stripped from natural gas where the two are comingled in the reservoir.

Senator CARPER. The Chairman and I knew this. We just wanted to make sure our colleagues did, so thank you very much for your clarification.

Mr. NORTHAM. Yes, I assumed that you knew that.

[Laughter.]

Mr. NORTHAM. But I apologize. I will be more careful.

Senator BARRASSO. That was for the record only. Everybody here knew it. Everyone here on the panel knew it.

Mr. NORTHAM. It comes from the Latin. No, never mind.

[Laughter.]

Mr. NORTHAM. The USE IT Act's impact on easing the development of infrastructure is the next step in the process of developing infrastructure, so I would say that, absolutely, yes, the USE IT Act has a great potential for not only spurring the carbon capture and utilization side of the process, but will have an economic impact on the State of Wyoming.

Senator BARRASSO. Dr. Friedmann, if I could go to you. What I want to point out is you mention in your written testimony the current scale of CO_2 pipelines is inadequate, inadequate to support widespread carbon capture projects.

Don't we need a coordinated and rapid buildout of CO_2 infrastructure in the country to meet the projected needs, and would the USE IT Act address that need?

Mr. FRIEDMANN. Thank you. Yes, this is not the first time this question has been asked or studied. Back in 2008 Pacific Northwest National Lab did a fairly comprehensive study to figure out how much CO_2 pipeline network we needed in this country, and their estimate was, to hit our goals by 2030, we needed something on the order of 20,000 to 30,000 miles of CO_2 pipelines, and we also needed them in areas that are not traditional EOR provinces.

We needed them in places where they could provide access to sale and formation storage, and a lot of those are actually in the Midwest, in particular, Illinois, Indiana, Ohio, West Virginia, Pennsylvania, Michigan. These are States that currently lack CO_2 infrastructure, but would benefit from the ability to store CO_2.

As I said earlier, and I want to underscore this point, that infrastructure, like any other substantial shared infrastructure, becomes a magnet for industry; becomes a magnet for development; becomes an opportunity for economic growth, so I see these things as highly complementary and positive.

Senator BARRASSO. Dr. Northam, you talked about carbon dioxide being used in enhanced oil recovery. Part of the purpose of the bill is also to promote research in additional uses of carbon. It is going to allow carbon dioxide to have commercial purposes even in areas across the country that aren't blessed, like we are in Wyoming, with oil resources.

Can you talk a little bit about how this bill could encourage research in those other areas as well?

Mr. NORTHAM. Thank you, Mr. Chairman, yes. Wyoming's Integrated Test Center is an example of how this bill will encourage research into other uses. It provides a facility with adequate space for research and access to significant emission stream; it provides space for scale up of successful projects, which I would say is our most critical need at this time; and it provides for competitive funding to be put to work.

All of these elements, especially the stated support for scale up, are critical to the success of CO_2 utilization schemes. The ITC went from concept to reality rapidly, but there is still a need for additional programs like the ITC to expand and sustain this effort, and I believe that that is a critical deliverable from the USE IT Act.

Senator BARRASSO. Dr. Friedmann, section 202 of the bill I think is critical. This section brings stakeholders together to promote the development of capture projects in CO_2 pipelines across the country. How would this part of the USE IT Act address the need for better State and Federal coordination, a point that you raised in your written testimony?

Mr. FRIEDMANN. Thank you for asking, and happy to discuss. One of the things that is the case is that we haven't actually deployed a lot of CO_2 storage wells. We haven't deployed a lot of carbon capture facilities in this country. As a consequence, we haven't actually tested or coordinated the existing regulatory base that is out there, and in many cases what we have there we recognize can be an impediment.

Just as one example, there has only been one class VI well permitted in this country. There haven't been a whole bunch of people asking to permit them, but there has been one request and one permitted. It took 54 months. It took a very, very long time, and that is a hurdle to investors.

If people are looking at this and say it is going to take 6 years to get the pipeline built, while it is going to take 5 years to get the well permitted, then it makes it much harder for them to make the investment decision to build whatever needs to be built, including this kind of infrastructure.

And I mention this specifically because the wise individuals who put together the FUTURE Act also put together a fuse on it. You have to have projects begin construction by January 1st, 2024, and that timeline is actually a very good one; it creates an incentive for people to get busy and get moving.

However, if people can overcome the financial hurdle and then see a regulatory hurdle behind it that they think will limit the chance for them to take advantage of those tax credits or take advantage of the opportunities that CCUS projects and technologies provide, then it will just limit the pool of applicants, it will limit the projects, and it will limit deployment.

Senator BARRASSO. Thank you.

Senator Carper.

Senator CARPER. Thanks, Mr. Chairman.

Again, our thanks to all of you. Every now and then we ask unanimous consent to enter for the record a question or series of questions, and I would ask unanimous consent, Mr. Chairman, a letter from 14 environmental groups that have some concerns about Title II of the legislation.

Senator BARRASSO. Without objection.

Senator CARPER. Thanks very much.

[The referenced information was not received at time of print.]

Senator CARPER. Let me start off, if I could, with Dr. Jiao.

Thank you so much for your work at the University of Delaware. You make us proud every day. Is anybody here with you from the University of Delaware, like anybody from Angie's List over your left shoulder? Angie, welcome. And for others who might be here who are also part of Blue Hen Nation. Thank you.

Dr. Jiao, in your opinion, what is the smartest way we could be investing Federal dollars to ensure that carbon capture and utilization become mainstream? And why is your work at the University of Delaware so important for a carbon-free future?

Mr. JIAO. Thank you, Senator. So, I think the key to get people onboard, particularly the people from industry, is to make CCUS profitable. So, I think I concur with some of the earlier points by made by Senator Whitehouse, as well. In the past, the investment in CCUS was mostly on the capture side and storage. Although such technology is fantastic, and we definitely need it, I don't think it can generate any revenue, which becomes the problem because this is not a sustainable business by itself.

So, I believe we should pay more attention to the utilization side, particularly I think the USE IT Act actually creates a lot of efforts in moving toward that direction, which I am really glad to see.

We work on universal data which is actually kind of motivated by this motion. We are trying to make the utilization more favorable or economically more favorable compared to other technologies on the market, and if we can find a way to make CO_2 into some valuable chemicals, that will potentially disrupt the current chemical production process. Mostly, we use derived carbon source, but now we can move away from that using CO_2 instead, and I think that will actually help us to reduce the CO_2 emissions.

Senator CARPER. All right, thank you.

I want each of you to answer this question very briefly, and if you say no way, that would be OK too.

Almost every piece of legislation I have introduced, and sometimes with colleagues that are here today on this Committee, it is rare that I introduce legislation that is perfect. Maybe never. I would just say, Dr. Jiao, if you had to pick maybe one area that we could improve this legislation, very briefly, what might that be? Then I am going to ask our other witnesses to do the same. Just one area where you think we can actually make an improvement, please. Just briefly.

Mr. JIAO. I think my work quite recently is mostly funded by DOE, so I think DOE has a lot of experience investing in these carbon capture utilization technologies, so the bill actually is going to ask EPA to administer these efforts, so I think probably they should coordinate across the agency somehow so they then will make the investment more efficient.

Senator CARPER. Thank you.

Mr. Deich.

Mr. DEICH. Thank you, yes. I think section 202, with the Task Force, can be strengthened, both to build on what Dr. Friedmann said, around the environmental integrity for storing carbon long term, as well as for understanding really what the frontier of the regulations need to look like, especially around carbon use and the carbon accounting there. I think the National Academies are a great resource, so coordinating with them for implementing this task force would be very valuable.

Senator CARPER. Good. Thank you.

Dr. Friedmann. Do you pronounce your name Julio?

Mr. FRIEDMANN. Yes, sir, Julio.

Senator CARPER. Good, the right way.

Mr. FRIEDMANN. Super quickly, a different variant on what Dr. Jiao said, it would be great to have DOE engagement in this process because they understand how to do this, and it has been a while since the EPA has executed research of this type. They would be strengthened by having that joint partnership.

I would also agree with Mr. Deich about the opportunity to try to strengthen and clarify the purpose of section 202, that you want to ensure that you do in fact find ways to amend and improve the permitting and the regulatory aspects of this without actually endangering key environmental provisions. And if there is some way to add language that would strengthen and clarify those goals, I think that would probably be valuable.

The last point I would just make is there is in fact a need to have improved lifecycle analyses and understanding of the true carbon emissions associated with all of this work. Having that maybe under NIST, maybe some other organization, maybe the EPA, but trying to find a way to formalize the standards around these kinds of technologies would be helpful.

Senator CARPER. OK, good. Thanks.

Same question, Dr. Northam.

Mr. NORTHAM. Thank you very much. So, I would cite two simple ways that I think this could be improved. Title 101 that focuses on air capture, I would love to see it expanded to focus on any type of capture of CO_2. Capture from point sources is critically important. The technologies are farther along in terms of their development, so supporting the deployment of that I think would be an important improvement.

The second would be to not only focus on research, but one of the most critical needs for technology developers is funding for the development and scale up process, and that is the valley of death that tends to be very difficult for inventors and innovators to overcome, so some addressing that part of the process would also, I think, improve this Act.

Senator CARPER. Great. Thank you all for those responses.

Thanks, Mr. Chairman.

Senator BARRASSO. Thank you, Senator Carper.

Senator Inhofe.

Senator INHOFE. Thank you, Mr. Chairman.

Let me just make an observation here that I don't think anyone has made yet, and it has to do with fossil fuels. I can remember 9 years ago, when President Obama first came in, he had this commitment to do away with fossil fuels, and I can remember going back to Oklahoma. I remember it so well because it was Shattuck, Oklahoma. I doubt any of you have ever been to Shattuck, Oklahoma.

Someone said, Senator Inhofe, I don't quite understand. We have a President who is against fossil fuels, coal, oil, and gas, and yet that is accountable for 80 percent of the energy it takes to run this machine called America. He said, now, if he is successful in doing away with it, how do we run the machine called America?

That was a logical question, and we dealt with that for a long period of time. Now, today, we have an answer, and I think this is really exciting. This is something that is a recognition that we will have to continue to use fossil fuels as a major part of our energy supply in a way that satisfies everyone. So, it is one of these rare cases where you have a lot of agreement from people who have disagreed in the past.

Dr. Friedmann, I was here for the opening statements. We go back and forth because we have nine members in common between this Committee and the Commerce Committee, so you are seeing people come and go. But I remember you made reference in your opening statement to the FAST Act permitting reform, and I think more people need to talk about that, because we can get things done. The FAST Act is a good example. We did the FAST Act primarily because of that permitting reform. We are able to do things on a timeline that can be enjoyed by all Americans, so I appreciate your bringing that up.

Dr. Friedmann, your testimony illustrates a problem that exists regarding the need for CO_2 pipeline infrastructure and its effect in deploying the CCUS in the United States. Now, specifically, I will read the quote that is the basis of my question: "Ambiguities in the process or delays in permitting directly affect the financial viability of projects and their ability to attract investors."

What are the roadblocks that you see out there that are in the development of the CO_2 pipeline?

Mr. FRIEDMANN. Thank you for asking.

Senator INHOFE. You know, I think about it, it might have been——

Mr. FRIEDMANN. Dr. Northam.

Senator INHOFE [continuing]. Northam who brought up the question on permitting, so I am sorry. Either one of you guys.

Mr. FRIEDMANN. You want to talk about section 201?

Mr. NORTHAM. You go ahead.

Mr. FRIEDMANN. All right, I will go.

It is sad, but true, pipelines are orphaned in this whole discussion. A lot of people are happy to run storage projects, EOR projects, even capture projects on industrial plants, power plants. Not a lot of people want to build or operate the pipelines, so it is hard to gather the financing to build them. So, it is born problematic; it is just one of those parts of the system that is hard to get done.

So, if people look at the setup and say, wait a second, I am not sure if the permit will go through, or I think it will take a very long time, and I am going to be paying interest on capital before anything gets built, it just chills the investment environment. It is just that simple. It is hard to pull together an investment of that scale and size. Many of these pipelines will cost hundreds of millions of dollars to build, and that is not easy to pull together.

Senator INHOFE. Yes, good.

Dr. Northam, the Integrated Test Center in Wyoming will be used to test different ways to repurpose carbon dioxide from a coal fired power plant. I am really interested in the repurposing element of this, and I would like to have you elaborate on your feelings how successful this could be and what we need to do to give you the resources you need to make this happen.

Mr. NORTHAM. Thank you for the question. So, the chemistry of converting carbon dioxide into anything else is very difficult. It is a very energetically stable molecule, so we need research to understand how to go from an energetically stable molecule into other products. A lot of what we use today is carbon based products, plastics, petrochemicals, fuels, so it is entirely doable. The question is can we do it efficiently and at a cost that competes with other sources of carbon.

Integrated Test Center has overcome some of the big hurdles for people who are working in this arena by providing not only an emission stream, but space for them to work. And then enterprises like the XPRIZE and some of the competitions that are promised in the USE IT Act are going to spur people to take on these difficult problems because the prize at the end of the pipeline, if you will, is significant.

Senator INHOFE. My time has expired, but I would be interested, for the record, in any of the rest of you who have ideas and thoughts on the repurposing element of this, and I would like very much to have the benefit of that, if you don't mind doing it. Any comments right now, but my time has expired.

Mr. DEICH. I will volunteer quickly that I think there is an important role of sequestering carbon in building materials, whether that is cements, roads, et cetera; and that the Federal Government can play a large role in being a first customer and a driver of those markets. So, the extent to which we can build on the first title of this bill to support those utilization technologies in our built environment will be very valuable.

Senator INHOFE. Good.

Any other comments for the record.

Thank you, Mr. Chairman.

Mr. FRIEDMANN. I would agree that building materials, in particular concrete and cement, is very important. We move 55 billion tons of concrete every year around the world. That is a big sink; and actually adding CO_2 to it improves the performance and makes it heavier and makes it more durable. There are a lot of good things that come from it.

Eventually, we will also reach a day when we will directly convert carbon dioxide into fuels. Right now that costs about twice or three times what a conventional liquid fuel would cost, but if in fact you can pull carbon dioxide out of the air, and you can upgrade it to a fuel, then you have a circular economy.

What I do believe is every major oil and gas company is looking at that. They are not going to deploy it anytime in the next 5 or 10 years, but they all see that that is something that they need to track and would like to figure out a way to offer something like that to their customers. CCUS technology is helpful.

Senator INHOFE. That is fascinating.

Thank you, Mr. Chairman.

Senator BARRASSO. Thank you very much, Senator Inhofe.

Senator Whitehouse.

Senator WHITEHOUSE. Thank you, Chairman. I appreciate being here today on a matter where, to quote Senator Inhofe, we have agreement from people who have disagreed in the past; and indeed disagree in the present; and indeed will continue to disagree in the future about many things.

Senator INHOFE. But every time we have agreed it has been very successful. You look at the chemical act, the FAST Act.

Senator WHITEHOUSE. I have learned that when we agree, Senator Inhofe is perhaps the most effective legislator in the Senate. Certainly, I have seen nobody produce more. So, we just need to find out how to agree on more. But I really appreciate this and look forward to working with my colleagues.

I guess what I would ask in my time is the record be clear what the sort of baseline proposition is here, why it matters to reduce our emissions of carbon dioxide, our anthropogenic emissions of carbon dioxide, starting with Dr. Northam.

Why are we doing this? Why does it matter? What does this help?

Mr. NORTHAM. Senator Whitehouse, thank you very much. On Saturday I was on a panel with the Ambassador from the EU to the United States, and one of the statements he made was Europe got over the hurdle of recognizing that carbon dioxide was contributing to global warming 20 years ago and has a very effective set of policies and procedures for reducing the CO_2.

I think it is important because time is ticking. Most of the scientific community recognizes that CO_2 is contributing to global warming; we are starting to see the impacts of it. These solutions are extremely technically difficult and expensive, and if we don't start actually making some progress, the progress we do make could be too late for staving off these major impacts.

Senator WHITEHOUSE. Plus, other countries might steal a march on us technologically.

Mr. NORTHAM. Absolutely.

Senator WHITEHOUSE. Same question, Dr. Friedmann.

Mr. FRIEDMANN. Thank you, Senator. All of this actually flows back in a real politic context; not in a scientific context, but in a real practical politics concept back to the Paris Agreement, and this is completely independent of whether or not the United States remains in it, although I personally think that would be a lovely thing.

First of all, the punchline is that greenhouse gases emissions represent a threat to national security of the United States; they represent a threat to our——

Senator WHITEHOUSE. And carbon dioxide.

Mr. FRIEDMANN. Sorry?

Senator WHITEHOUSE. Carbon dioxide is one of those greenhouse gases?

Mr. FRIEDMANN. Carbon dioxide is the most important of those.

Senator WHITEHOUSE. Got it.

Mr. FRIEDMANN. We emit 38 billion tons over the year, and that is an issue; "we" meaning the globe, not the United States.

It represents an environmental threat. We have extinctions, we are losing species, we have sea level rise, coral bleaching, all those other sorts of things, which are directly attributable to greenhouse gas emissions.

In addition to that, we are starting to have economic impacts that are associated with that that are rather grim and problematic.

That, however, as important as that is and as much as I spend my time on it, it is not the most important thing. The most important thing is actually 197 countries have all said that they care about it, which means the entire global market is organized now. The entire global market is organized now to figure out ways to reduce emissions and to turn carbon dioxide into value.

Senator WHITEHOUSE. And putting aside everything else, participating in that global market has economic value for the United States.

Mr. FRIEDMANN. Indeed. As export technologies to the United States, both in terms of product and in terms of heavy equipment.

Senator WHITEHOUSE. Mr. Deich. Did I pronounce your name right? If I didn't, I apologize.

Mr. DEICH. You did. Thank you, Senator.

Senator WHITEHOUSE. Great. Thank you.

Mr. DEICH. So, I think the bottom line here is this is going to be the economy of the future, figuring out how to take the carbon that is already in the air and pulling it back in a way that improves the economy and the environment.

Senator WHITEHOUSE. And we need to get the carbon dioxide out of the atmosphere because of what?

Mr. DEICH. Because of both the environmental harm that could come from climate change, as well as all of the other changes to our society. But I really see this as an opportunity. There are 2 trillion tons of CO_2—trillion with a T—that have been put into the atmosphere. All of that can come back out as a valuable resource, and that is the biggest business opportunity that we have ever seen. So, if we can figure out how to do that across the economy, that is a huge opportunity that simultaneously solves these massive global challenges on hand.

Senator WHITEHOUSE. Hard to do any of that if there is no price on carbon, though, because then there is no revenue stream, correct?

Mr. DEICH. I would actually argue that there is now a price on carbon in not a clean way, as an economist like myself would want, but we do have, both with 45Q, a price on sequestering carbon——

Senator WHITEHOUSE. Precisely.

Mr. DEICH [continuing]. And through a series of other——

Senator WHITEHOUSE. Precisely. That is what we did in that bill, was to create a very narrow specific version of it, correct?

Mr. DEICH. The extent to which we can expand on that and make sure that there is a robust market, and that that market happens here first is essential.

Senator WHITEHOUSE. Dr. Jiao, the reason we want to or benefit from reducing carbon dioxide anthropogenic emissions into the atmosphere is?

Mr. JIAO. So, I think much has been said about the potential climate impact when we emit tremendous amount of CO_2 into the atmosphere. I also concur with some of the points made before. I see this as an opportunity to generate profitable pathways to utilize CO_2. We definitely have an abundant source of CO_2. If we can figure out a way how we can make CO_2 into valuable chemicals or fuels, probably, and in an efficient way, then this will solve our issue, I think.

Senator WHITEHOUSE. Thank you.

Thank you, Chairman.

Senator BARRASSO. Thank you, Senator Whitehouse.

Senator Capito, again, thank you so much for your co-sponsorship and your hard work on this piece of legislation.

Senator CAPITO. Thank you. I want to thank everybody on the panel, too, and I want to start out talking again on the pipeline issue because I think this is a concern if we are going to move forward. In the answers you gave to the previous question, obviously, this is a stumbling block.

I have a figure here that says 4,500 miles of CO_2 pipelines are in this country now, but are any of those interstate; do any of them cross State lines, as far as you know?

Mr. NORTHAM. Yes. The quick answer is yes. There are pipelines that deliver CO_2 that is produced in Colorado to west Texas for enhanced oil recovery. There are others as well, but yes, there are interstate.

Senator CAPITO. OK. My point being there, obviously, is the permitting interstate obviously is a part of this bill, it is critically important.

The next question I have is on what we were talking about just a few minutes ago. I think you all have done a really nice job talking about why CCUS is important for the environment, for our economy, and for job creation and others. I come from, obviously, a heavy coal State. This is very important to us in terms of being able to have the longevity in the coal industry, but also the environmental benefits are important to us, as well.

So, in our experts' opinion, would you say that the United States is a leader now in CCUS technologies? I think you have already mentioned—I am just going to throw this up to anybody—what other countries are really forward thinking here? I know you mentioned the European Union. Are there other countries that we should be looking at who are developing this technology at a more rapid and more advanced state?

Dr. Friedmann.

Mr. FRIEDMANN. So, I am pleased to say that the United States is now the unambiguous leader in carbon capture and storage technology, and in no small part, again, because of the passage of the FUTURE Act.

I would say that there are many countries that are working to catch up. Canada is most notable in this regard. Also, Norway has been an international class leader. In the context of both carbon capture, but even more importantly for CO_2 conversion and use, China is coming on strong, for real.

I would point, among other things, to the Strategic Applied Research Institute, SARI, in Shanghai Technical University. They have built a building there that has 100 scientists; they are gearing up to 1,000 scientists. It is underwritten by the Chinese Academy of Sciences. All of that is focused on carbon capture and utilization.

The same thing can be said about Japan. Again, the same thing can be said about Canada. Out of the 10 finalists for the NRG COSIA XPRIZE, four of them are Canadian. Not a knock on Canada, we love Canada, but it would be lovely to see America's unambiguous leadership in this arena.

Senator CAPITO. Well, obviously, there would be tremendous economic benefits to us, and I would like to see that as well.

Do the two of you have anything to add on that?

Mr. DEICH. Thank you, Senator. I think one of the things where we have not seen a leader emerge yet is in the direct air capture field. I think there are many places that are positioned to do that, and the United States is one of them, but unless there is action from policymakers, that leadership could easily go somewhere else right now. So, I think that figuring out how to be that leader is essential today.

Senator CAPITO. Dr. Jiao.

Mr. JIAO. Regarding the technology I am working on, actually, Canada, Europe, and even China, they are actually very aggressive in this area, so if we don't act now, I think we will lose the leadership.

Senator CAPITO. We just had a discussion in your answers about global warming and the threat that you all perceive there. Is there any realistic way for the world to stay below the commonly identified 2 degree Celsius global mean temperature in increase target this century without broad CCUS? Can we do it as a Nation without this development of this technology and utilization of the technology?

Mr. NORTHAM. My opinion, but the simple answer is no, we cannot.

Senator CAPITO. Dr. Friedmann.

Mr. FRIEDMANN. Doubling down on that, actually, we are, instead, poised to massive overshoot, and every credible scenario not only has large scale CCUS deployment in the next 20 years, but also large scale carbon removal after 2050, which requires carbon capture and storage and things like direct air capture.

Senator CAPITO. Did you have a comment?

Mr. DEICH. I would agree.

Senator CAPITO. Right.

Mr. JIAO. Yes, I agree.

Senator CAPITO. All right. Thank you all very much.

Senator BARRASSO. Thank you, Senator Capito.

Senator Van Hollen.

Senator VAN HOLLEN. Thank you, Mr. Chairman.

Thank all of you. Sorry I missed the testimony; I was in another committee, but I have had a chance to look it over, and I strongly support this legislation. I should mention that in Maryland we have a company called AES. It is the Warrior Run power plant in Cumberland, Maryland, where they capture 4 percent of the carbon dioxide generated and sell 150 tons per day to beverage grade carbon dioxide in the food and beverage industry. So, I support this legislation.

But I do want to pick up on some of the comments Senator Whitehouse made and responses that you all made, which is that the reason we are doing this, the reason we are actually spending taxpayer dollars to do this is that there is a public good to be had from reducing carbon, and therefore, trying to address the problem of climate change.

Just a yes or no from each of you.

Mr. NORTHAM. Yes.

Mr. FRIEDMANN. Oh, yes.

Mr. DEICH. Yes.

Mr. JIAO. Yes.

Senator VAN HOLLEN. So, I am looking at a lot of the projects that have been funded by DOE, and all of these projects for carbon capture, at least at this point in time, have required some public financing in order to be economically viable, right?

Mr. NORTHAM. Yes.

Mr. FRIEDMANN. Yes. Happy to talk more about that, too.

Mr. DEICH. Yes.

Mr. JIAO. Yes.

Senator VAN HOLLEN. And the FUTURE Act that was just passed is another tax incentive, right? So, I just want to be clear with my colleagues; we are spending taxpayer money to reduce carbon dioxide, and the only reason I can see for spending taxpayer money on doing that is if we have a benefit from reducing carbon dioxide. That benefit, as the witnesses have said, is trying to address climate change and making sure we are well positioned in a global economy where the rest of the world recognizes we need to head in that direction.

As of today, as of today, we are trying to change that; what is the cost per ton in terms of the public subsidy to make carbon removal economically viable?

Mr. FRIEDMANN. To ask a clarifying question, are you asking what is required or what is it today?

Senator VAN HOLLEN. What is required today, in terms of a public subsidy, to make a carbon capture enterprise economically feasible? I mean, the FUTURE Act was part of that, right?

Mr. FRIEDMANN. Yes. So, when I was working in the Department of Energy, I worked with the White House and the Treasury, and we put forward a specific proposal for something about the order of $60 per ton as essentially like a production tax credit, along the lines of the FUTURE Act, and we also suggested a 30 percent investment tax credit. You need some capital treatment as well as some operating treatment.

Senator VAN HOLLEN. So, you need a public subsidy on both pieces there.

Mr. FRIEDMANN. It is worth noting that that incentive on the order of $60 a ton is about the same as the wind production tax credit. It is along the lines of other incentives we have made for other kinds of clean energy.

Senator VAN HOLLEN. And you made the important point, Dr. Friedmann, all of you said that carbon capture needs to be part of the solution to climate change, but Dr. Friedmann, you mentioned all the scenarios there. Those scenarios, to make sure we are under the 2 percent Celsius, they also require reduction in carbon emissions, do they not?

Mr. FRIEDMANN. That is in fact their primary constraint. The scenarios all say we have to stay to a 2 degree world, so we have to deeply reduce our carbon dioxide and other greenhouse gas emissions.

Senator VAN HOLLEN. Right. So, I am glad that we are spending some public dollars for this public good, to sequester carbon and to reduce carbon that is generated, but when you look at those models, how much of the reduction has to come, Dr. Friedmann, from actually reducing the overall emissions?

Mr. FRIEDMANN. So, in order to hit a 2 degree target by 2020, you have to have something on the order of 85 percent reduction in greenhouse gas emissions. There are many pathways to do that; it requires efficiency improvements, deep deployment of renewable power, as well as carbon capture and storage.

Senator VAN HOLLEN. Appreciate it.

I would just say, Mr. Chairman, to all my colleagues, and this is an appeal, what we are doing here is using taxpayer dollars for the purpose of helping the market toward carbon sequestration, and that is putting a price implicitly on this project, and as of today, for quite a smaller price, you can actually generate some reductions today. So, I would just hope, if we are going to be taking this public policy direction as a Committee, that we not look at just this very important piece, and it is an important piece, but that we look at everything else at the same time.

I appreciate all of you for being here today, and thank you for your efforts in this particular area.

Senator BARRASSO. Thank you, Senator Van Hollen.

Senator Markey.

Senator MARKEY. Thank you, Mr. Chairman, very much.

I would just note this at the top. I see that this is a bill ultimately that is $25 million that would be going to the EPA administrator for Direct Air Capture Technology Advisory Board and then another $50 million for the USE IT Act, and I just want to stipulate this once again, that back in 2009, in the House of Representatives, we passed the Waxman-Markey bill, and Henry Waxman and I put in $200 billion for carbon capture and sequestration, $200 billion. And the coal industry turned it down cold, $200 billion they turned down.

So here we are now, and they are asking for this money, and I step back, and I keep saying to myself you missed your shot; it was there. The $200 billion would have done the research, would have had the advisory boards, could have given the money to each one of the utilities or to oil companies or coal companies to be able to do the job, and they said they didn't want it. And that is fine, OK, that is a decision they made.

And again, I am looking at this now, and I am saying, OK, I believe in research and I believe in advisory committees, but I just think it is important to understand that, again, a vision without funding is a hallucination. So, I just don't want anyone to get false hope from this, that the magnitude of this funding in any way affects the trajectory of this technology; it is just not real. We put in a real number based upon what all the experts told us in the utility industry to deal with it, it was $200 billion, and it was turned down, just absolutely, we don't want that money, 2009–2010, by the way, in this Committee. No, don't want it.

So, that is where we are, and again I definitely want to make sure that we do the research, but I also want everyone here to understand that there is another vision which is taking place. There are 109,000 new clean energy jobs in Massachusetts that have been created, most of them over the last decade, 109,000.

The United States installed 10,000 new megawatts of solar last year and 7,000 new megawatts of wind. That is 17,000 new megawatts. We now have 89,000 megawatts of wind capacity and 53,000 megawatts of solar installed in the United States, so that is about 140,000 wind and solar megawatts now installed in our country and globally, in 2016—in 1 year—globally, 74,000 new megawatts of solar and 52,000 new megawatts of wind capacity were installed. Overall, renewables now represent 55 percent of all new electrical generating capacity over the past 10 years, 55 percent, just so we get it all out here on the table.

And again, the $200 billion in the Waxman-Markey bill that passed the House of Representatives was turned down over here in the Senate. Didn't want the money.

So, again, I believe in research and am happy to work in a bipartisan fashion to support new technologies for our future low carbon economy, but I also want to have everyone understand where this whole thing is headed. It is all heading in the direction that now they realize they need the money.

Now they say, oh, is there any way you can help us? We turned that down, and now what is left over that you can help us with that is kind of a penny on the dollar of what was being offered just

6 or 7 years ago. And as long as we understand that, then I feel better about it.

So, I guess my concern is, and I would ask you this question, Mr. Deich, is they need financing, but we are opening up the Clean Air Act here. What is the fear that you might have if we open up the Clean Air Act in terms of other changes that might take place? On this, I would support it. I just want to make that clear, I do support the bill. I just want to put it in its total context. But I do have some apprehension about whether or not the Clean Air Act then becomes vulnerable for other purposes in the course of deliberation.

Can you give me that answer?

Mr. DEICH. Thank you, Senator. That is something that we are very sensitive to. We work closely with environmental groups, as well as startups and other investors in this space, and recognize that the Clean Air Act has not been amended in nearly 30 years at this point.

And what I think the environmental groups are looking for from this Committee is insurance that the bill will move forward in a bipartisan way to achieve the spirit that we have heard here at this hearing, and not to use it as a way to weaken or otherwise erode the foundational environmental law.

Senator MARKEY. That is good.

Do we have that commitment, Mr. Chairman?

Senator BARRASSO. That was in my opening statement.

Senator MARKEY. Oh, I am sorry.

Senator BARRASSO. I referred to that, that we are going to move forward, Senator Whitehouse and I, in a bipartisan way on not allowing——

Senator MARKEY. As Senator Inhofe mentioned over in the Commerce Committee, there are nine of us on two committees, the Commerce Committee and this simultaneously, so he and I have been running back and forth.

Senator BARRASSO. Thank you.

Senator MARKEY. So, thank you for that statement, Mr. Chairman.

Senator BARRASSO. Thank you. Appreciate your questions.

Senator MARKEY. Thank you.

Senator BARRASSO. Before turning to Senator Inhofe, I would point out that the Clean Air Task Force is writing in support of this piece of legislation. I am going to introduce that as part of the permanent record. Without objection.

[The referenced information follows:]

CLEAN AIR
TASK FORCE

April 11, 2018

The Honorable John Barrasso
Chairman
U.S. Senate Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, D.C. 20510-6175

The Honorable Tom Carper
Ranking Member
U.S. Senate Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, D.C. 20510-6175

Dear Chairman Barrasso and Ranking Member Carper:

The Clean Air Task Force is writing you in support of the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act - introduced by Chairman Barrasso and cosponsored by Senators Whitehouse, Capito and Heitkamp. This legislation is an important step that builds on the recent adoption of the FUTURE Act, which made significant important revisions to and extended the 45Q CCUS tax credit. The USE IT Act addresses several important issues that will help us reach the potential of carbon capture utilization and storage (CCUS) including:

- Providing a boost to early stage technology efforts of direct capture of CO_2 from the air by establishing a $25 million x-prize
- Providing $50 million in support for R&D on innovative carbon utilization efforts
- Helping facilitate CO_2 pipeline infrastructure development by clarifying CO_2 pipeline eligibility under the FAST Act
- Requiring the Council on Environmental Quality to develop guidance and regional task forces that address project and pipeline permitting efficiency improvements and identify activities that can transform carbon into a valuable commercial product

Helping bring new technologies into the commercialization process is an important complement to the market "pull" offered by the 45Q tax incentive. Moreover, building pipeline infrastructure will be crucial for all aspects of technology development and deployment.

While there are many economic and technological benefits for CCUS, it is a critical-path technology for reducing carbon emissions. The most recent assessment by the Intergovernmental Panel on Climate Change (IPCC) in 2014 underscored the critical-path role CCUS will need to play in meeting the temperature targets agreed to under the Paris accords. In the vast majority of emissions reduction scenarios developed by the IPCC, CCUS was necessary to meet temperature goals – and atmospheric carbon removal was an important component of CCUS in those scenarios. Only those few scenarios that included global land use change on a massive scale were able to meet the goal without significant use of CCUS.

CATF greatly appreciates the continued support for CCUS and Chairman Barrasso's commitment to ensure this legislation moves forward on a bi-partisan consensus basis. We look forward to working with you to ensure the USE IT Act is enacted by Congress.

Sincerely,

Kurt Waltzer
Managing Director
Clean Air Task Force

18 Tremont St., Suite 530 | Boston, MA 02108 | www.catf.us | 617.624.0234

Senator BARRASSO. Senator Inhofe.

Senator INHOFE. I just want, now that this hearing is about to be over, to repeat something that I said in my questioning, that it is a relief to know that we have come to the point not where we were 9 years ago, when the solution was you have to do away with fossil fuels, but now we recognize fossil fuels is going to be a part of our energy mix, a very important part, most likely, at least for the next few years, the same percentage as it has been in the past.

Now, I know that you folks, the response that you gave on the science. I know it is still mixed. You guys know it too. I always enjoy using the quote from Richard Lindzen, when he said, "Controlling carbon is a bureaucrat's dream. If you control carbon, you control life." So I would just like to hope that we can get beyond this discussion, because it is no longer necessary; we now are going to have this as a part of our energy mix. For the record, OK?

Senator BARRASSO. For the record, absolutely.

And to follow up on your statement about the percentage being the same, what I have been reading is that 20 years from now, with the overall need of increased energy—and we need it all—that 20 years from now we will be using a significant more amount of coal than we are right now, planet-wise, so that we need to come to the solutions involved here.

I have a number of letters in support of the legislation I am going to ask to be made part of the record, but I do want to thank all the witnesses for being here. I appreciate your time and your testimony. The record is going to be open for a couple weeks so that you may get some written questions from some other members who weren't able to be here, because there are a number of members on multiple committees, and everybody can't be at all committees at all times. But I appreciate all of you being here.

With that, the hearing is ended. Thank you.

[Whereupon, at 11:55 a.m. the Committee was adjourned.]

[An additional statement submitted for the record follows:]

STATEMENT OF HON. TAMMY DUCKWORTH,
U.S. SENATOR FROM THE STATE OF ILLINOIS

Climate change is a grave threat to our national security, economic security, and environmental health. Across Illinois, across our country, and across the globe, we are already experiencing the harmful effects of climate change. Growing seasons are lengthening, heat waves are increasing, and extreme floods are becoming more frequent and severe.

The United States must act to prioritize cutting carbon pollution. Fortunately, reducing carbon emissions will not only combat climate change, it holds the potential to strengthen our economy, advance new industries, and create new American jobs. For example, emerging technological capabilities, such as carbon capture, utilization, and storage (CCUS), will play a critical role in helping our Nation limit carbon emissions in a cost effective manner.

The Intergovernmental Panel on Climate Change, the world's foremost authority on climate change research, noted the cost of reducing carbon emissions will be approximately 140 percent higher without CCUS. The bottom line is that failing to embrace emerging technologies that facilitate net negative emissions will endanger the world's ability to limit temperature increases to below 2 degrees Celsius per year.

The bipartisan USE IT Act will help to make sure this does not happen. This important legislation will bolster States such as Illinois, which are leading in CCUS research and development. In addition, the bill promotes investment in low carbon technology infrastructure, which is necessary to facilitate full adoption of CCUS. I look forward to working with my colleagues on this Committee to advance and further improve this promising legislation.

[Additional material submitted for the record follows:]

PRESS RELEASES (/PUBLIC/INDEX.CFM/PRESS-RELEASES-REPUBLICAN)

Bipartisan Group of Senators Introduce Bill to Promote Carbon Capture Research and Development (/public/index.cfm/press-releases-republican?ID=B368E757-F8F6-4072-A0AA-56D63AD38D5B)

March 22, 2018

Barrasso, Whitehouse, Capito, and Heitkamp Introduce USE IT Act to Incentivize Carbon Capture Development and Deployment.

WASHINGTON, D.C. — Today, U.S. Senator John Barrasso (R-WY), chairman of the Senate Committee on Environment and Public Works (EPW), joined with Sen. Sheldon Whitehouse (D-RI) to introduce the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act. The legislation is cosponsored by Sens. Shelley Moore Capito (R-WV) and Heidi Heitkamp (D-ND).

The USE IT Act would support carbon utilization and direct air capture research. The bill would also support federal, state, and non-governmental collaboration in the construction and development of carbon capture, utilization, and sequestration (CCUS) facilities and carbon dioxide (CO2) pipelines.

"Wyoming is blessed with an abundance of coal, natural gas, and oil resources that fuel the state's economy and provide Americans with affordable and reliable power," **said Barrasso**. "The bipartisan USE IT Act will promote the long term use of these critical natural resources and keep America on the path to energy dominance. My legislation will make Washington a helpful partner to efforts taking place in Wyoming to develop carbon capture technologies, convert carbon into a useful product, and reduce emissions."

"After passing bipartisan legislation to encourage investing in carbon capture and utilization, we have a chance to advance these technologies even further. This bipartisan bill will help innovators around the country, including a growing number of businesses in Rhode Island, to come up with new ways to take carbon pollution out of the air and either stow it permanently underground or turn it into usable products. That's a win for our climate, a win for innovative bioalgae and other utilization companies in Rhode Island, and a win for the economy overall," **said Whitehouse.**

"For America to reach its full energy potential, we need to continue pursuing a true all-of-the-above energy strategy—utilizing the many natural resources available to us while also working to develop new and innovative ways to use our energy resources," **Capito said.** "This bipartisan legislation will build on the success of our bipartisan FUTURE Act and provide additional incentives for the deployment of carbon capture technologies. It will also help us ensure there are no unnecessary obstacles for those trying to reduce their emissions and find innovative ways to use—rather than waste—carbon."

"Carbon capture technology is essential in a carbon-constrained world, especially for states like North Dakota which will rely on a diverse energy mix that includes coal well into the future," **said Heitkamp**. "After passage of the FUTURE Act to expand tax credits that will spur innovation and implementation of carbon capture systems and encourage further utilization, our bipartisan USE IT Act will take the next logical step in furthering CCUS in this country. This bipartisan bill – led by the same four senators who drove the drafting and passage of the FUTURE Act – will promote efficient and effective regulations for expediting CO2 pipeline permitting, require ongoing work on overall guidance for the development and use of CCUS technologies and pipelines, and direct EPA to support CCUS research. This is just good policy and will further enhance our efforts to provide a path forward for coal-fired power in North Dakota while reducing emissions, and for increased CCUS development across the board."

The USE IT Act would:

- Narrowly amend the Clean Air Act to direct the Environmental Protection Agency (EPA) to use its existing authority to support carbon utilization and direct air capture research;
- Clarify that CCUS projects and CO2 pipelines are eligible for the permitting review process established by the FAST Act;
- Direct the Council on Environmental Quality (CEQ) to establish guidance to assist project developers and operators of CCUS facilities and CO2 pipelines;
- Establish task forces to hear input from affected stakeholders for updating and improving guidance over time; and

- Build on the FUTURE Act, bipartisan legislation – now signed into law – introduced by Heitkamp, Capito, Whitehouse, and Barasso to extend and expand the 45Q tax credit to provide certainty to utilities and other industrial sources and incentivize the build-out of CCUS projects.

Read the text of the USE IT Act here (https://www.epw.senate.gov/public/_cache/files/0/f/0fd32eef-de44-4737-8453-5ff966ece095/4325D95E20EDABD6DA299ADEA7FA6745.use-it-act.pdf).

Background Information:

On November 15, 2017, Kipp Coddington, director of the Carbon Management Institute at the School of Energy Resources at the University of Wyoming (UW), testified (https://www.epw.senate.gov/public/index.cfm/press-releases-republican?ID=512FA6C5-5AD1-4ADC-9D05-9263F1D6AE7A) before the EPW committee at a hearing (https://www.epw.senate.gov/public/index.cfm/hearings?ID=9A307B2D-B63E-4E9E-BA65-C7FBEBE3A368) on "Promoting American Leadership in Reducing Air Emissions Through Innovation." Coddington outlined the numerous ways UW is examining to reduce carbon emissions through innovative technologies.

On September 13, 2017, Matt Fry, policy advisor to Wyoming Governor Matt Mead, testified (https://www.epw.senate.gov/public/index.cfm/press-releases-republican?ID=1D1F2850-761A-4D9E-9E6B-62844601A8FB) at an EPW Committee hearing (https://www.epw.senate.gov/public/index.cfm/hearings?ID=46419E63-564B-465A-8B6A-96D9F990FDF8) on "Expanding and Accelerating the Deployment and Use of Carbon Capture, Utilization, and Sequestration (CCUS)." Fry told the committee about Wyoming's efforts to facilitate development of a CO2 pipeline network.

On July 25, 2017, Jason Begger, executive director of the Wyoming Infrastructure Authority testified (https://www.epw.senate.gov/public/index.cfm/press-releases-republican?ID=8B0417BE-66C6-49B8-A0B4-521C8E863BCF) at an EPW Clean Air and Nuclear Safety Subcommittee hearing (https://www.epw.senate.gov/public/index.cfm/hearings?ID=B65EC8DE-D144-4109-A469-5B5F77A16540) on "Developing and Deploying Advanced Clean Energy Technologies." Begger detailed how Wyoming is an emerging leader in CCUS development and how public-private partnerships help incentivize the development of carbon capture technologies.

###

Permalink: https://www.epw.senate.gov/public/index.cfm/2018/3/bipartisan-group-of-senators-introduce-bill-to-promote-carbon-capture-research-and-development (https://www.epw.senate.gov/public/index.cfm/2018/3/bipartisan-group-of-senators-introduce-bill-to-promote-carbon-capture-research-and-development)

ALGAE BIOMASS ORGANIZATION

Matt Carr
Executive Director
125 St. Paul Street
P.O. Box 369
Preston, MN 55965-0369
(202)579-0557
mcarr@algaebiomass.org

The Honorable John Barrasso
Chairman
Committee on Environment and Public Works
United States Senate
410 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Tom Carper
Ranking Member
Committee on Environment and Public Works
United States Senate
456 Dirksen Senate Office Building
Washington, DC 20510

10 April 2018

Dear Chairman Barrasso and Ranking Member Carper,

On behalf of the men and women of the U.S. algae industry, I write to express our strong support for S. 2602, the *Utilizing Significant Emissions with Innovative Technologies* (USE IT) Act.

The Algae Biomass Organization (ABO) is the non-profit trade association for the algae industry. Its membership is comprised of individuals, businesses and other research institutions across the algae value chain, including leading developers of algae-based carbon capture and use (CCU) technologies.

The USE IT Act supports the research and regulatory actions necessary to speed the development and deployment of emerging CCU technologies. In combination with the reauthorization and enhancement of the section 45Q CCU tax credit enacted in the *Bipartisan Budget Act*, the USE IT Act will help drive investment in algae and other technologies that will transform carbon emissions from environmental challenge into economic opportunity.

This bill is a great example of how all sides can come together in support of smart policy that makes protecting our planet good for business.

We urge the Committee to move without delay to approve S. 2602 and to work for its enactment into law.

Sincerely,

Matt Carr
Executive Director

ALLETE

Alan R. Hodnik
Chairman, President and
Chief Executive Officer

April 9, 2018

The Honorable John Barrasso
United States Senate
Washington, DC 20510

The Honorable Sheldon Whitehouse
United States Senate
Washington, DC, 20510

Dear Senators Barrasso and Whitehouse:

ALLETE wishes to express its support for S. 2602, the USE IT (Utilizing Significant Emissions with Innovative Technologies) Act.

ALLETE is an energy company headquartered in Duluth, Minnesota. In addition to its electric utilities, Minnesota Power and Superior Water, Light and Power of Wisconsin, ALLETE owns ALLETE Clean Energy, based in Duluth; BNI Energy in Bismarck, North Dakota; U.S. Water Services in St. Michael, Minnesota; and has an 8 percent equity interest in the American Transmission Company.

The USE IT Act creates an innovative framework to encourage research in carbon capture, utilization and sequestration, including the use of "technology prizes" to spur development of cutting-edge technologies.

In addition, the bill addresses some of the challenges to siting and building the infrastructure for systems that capture, utilize or sequester carbon dioxide. S.2602 directs the Chair of the Council on Environmental Quality to prepare guidance (in cooperation with the Environmental Protection Agency and the Departments of Energy and Interior) to help provide clarity over the myriad federal and state reviews necessary to develop and deploy carbon capture, utilization and sequestration projects. Importantly, the bill creates two task forces that include state, local and tribal representation to help identify common approaches to facilitate reviews, find common models that can be

30 West Superior Street | Duluth, Minnesota 55802-2093 | 218.355.3642 | Fax 218.723.3960 | ahodnik@allete.com

used for state level reviews, provide input to federal agencies on their research priorities, and suggest improvements to the federal permitting process.

As our electric energy system changes, it is important to acknowledge the role that large, dependable and dispatchable sources of electric generation play in assuring electric reliability and grid resiliency. These large electric generators, along with "fast-ramp" types of generation resources, are important and needed in order to seamlessly integrate intermittent energy resources such as wind and solar power into our electric grid. S.2602 can help play a role in assuring that fossil-fired electric generation can both keep providing these essential reliability services to the electric grid while deploying the latest carbon capture, utilization and sequestration technologies.

ALLETE thanks you for your efforts in moving this important piece of legislation forward.

Sincerely,
ALLETE, Inc.

Alan R. Hodnik
Chairman, President & CEO

/cll

ASU IRA A. FULTON SCHOOLS OF engineering
ARIZONA STATE UNIVERSITY

Center for Negative Carbon Emissions
School of Sustainable Engineering
and the Built Environment

Klaus S. Lackner
PO Box 873005
Tempe, AZ 85287-3005

Klaus.Lackner@asu.edu
(480) 727-2499
http://engineering.asu/cnce

April 8, 2018

The Honorable John Barrasso
Chairman, Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Tom Carper
Ranking Member, Committee on Environment and Public Works
456 Dirksen Senate Office Building
Washington, DC 20510

Ref.: Committee deliberations on the *USE IT* Act

Dear Chairman Barrasso and Ranking Member Carper,

I support S. 2602, the *USE IT* Act, and urge your committee to give it due consideration and move it swiftly to the Senate floor. It is an excellent approach to give Environmental Protection Agency an important stake in developing direct air capture technology. Direct air capture bridges the gap between energy and environmental technologies. Carbon dioxide is the waste from the combustion of fossil fuels. It pollutes the air. A mandate to develop technology options for cleaning up carbon dioxide streams that escape (and will continue to escape) to the atmosphere will empower EPA to better manage this pollutant. EPA needs to assure the availability of affordable tools for recovering carbon dioxide from the environment. Direct capture of carbon dioxide from ambient air is the most straightforward approach. It can recover all the carbon for which emission avoidance is impossible, too expensive, or simply ignored. Direct air capture in combination with carbon dioxide storage or reuse can assure that the carbon budget is fully balanced. Because direct air capture can be applied to any emission, it will cap the price of carbon. The more direct air capture is researched, developed and practiced, the cheaper it will be.

Direct air capture technology is innovative and still new, but it has been demonstrated to work. It works in the laboratory. Outdoor prototypes have been made to work by several groups, including by us at ASU. It also works in small-scale commercial designs, as demonstrated in Europe by Climeworks. However, just like the first airplanes were not yet ready for global passenger travel, air captured must be readied for large-scale deployment.

We have plenty of ideas how to reduce energy consumption and costs but need the resources to follow through. Aviation enabled by the invention of the Wright Brothers, became an industry only when Guggenheim invested into commercialization and research that blossomed into the engineering discipline of aeronautics. Similarly, EPA could advance air capture to realize cost reductions like those enjoyed by renewable energy. Wind energy costs have come down fifty-fold over the last sixty years and photovoltaic energy costs dropped hundred-fold. If direct air capture could reduce its cost only ten-fold, its implementation could be fully paid for by the 45q tax credit.

I very much support the *USE IT* Act in creating an EPA program that helps develop direct air capture technology. An EPA advisory board on this technology would give it the visibility it deserves. I envision Direct Air Capture Institutes that provide the scientific underpinning and systems engineering for this new technology as well as industry – and venture – based R&D that in cooperation with EPA would create economically viable air capture technology.

I appreciate the opportunity to comment on the *USE IT* Act and welcome any questions you may have.

Sincerely,

Klaus S. Lackner

Klaus S Lackner
Professor and Director of the Center for Negative Carbon Emissions

Cc: Senator Shelley Moore Capito

Senator Sheldon Whitehouse

Senator Heidi Heitkamp

BASIN ELECTRIC POWER COOPERATIVE
A Touchstone Energy® Cooperative

March 22, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington, DC 20510

Dear Senators Barrasso and Whitehouse:

On behalf of Basin Electric Power Cooperative, I write in support of the "Utilizing Significant Emissions with Innovative Technologies" (USEIT) Act. Thank you for your leadership in authoring this legislation.

Basin Electric is a generation and transmission cooperative based in Bismarck, North Dakota, serving approximately three million consumers through 141 rural electric cooperatives across nine states. Basin Electric has long sought solutions to the carbon question, and continues to explore options to allow utilization of affordable and abundant fossil fuels for electric power generation in a carbon constrained future. The Great Plains Synfuels Plant, operated by Basin Electric subsidiary Dakota Gasification Company, is currently the largest carbon sequestration project in the world. The facility has captured and transported nearly 35 million tons of carbon dioxide for sequestration since 2000.

More recently, Basin Electric has expanded its interest in developing carbon capture solutions through its partnership with the Integrated Test Center, located at Basin Electric's Dry Fork Station outside of Gillette, Wyoming. Using flue gas provided by the Dry Fork Station, this test facility will provide space for researchers to explore new and innovative solutions to turn carbon dioxide into a marketable commodity. The State of Wyoming invested in design and construction of this facility, and will oversee its operation. Basin Electric supports this legislation because it will help leverage the resources of states, industry, universities, and the Federal Government, and build on these efforts to develop cost-effective carbon capture utilization and storage (CCUS).

In addition to technical and financial assistance to support research, your legislation would establish interagency guidance and a task force to facilitate CCUS infrastructure. Basin Electric supports these provisions as well given the new infrastructure that will need to be developed on a considerable scale to deploy CCUS technology.

The USEIT Act is important legislation to advance the development of CCUS technology. Basin Electric again thanks you for your efforts to support commonsense solutions for electric power generation. We hope that this legislation can receive prompt consideration by the Senate.

Sincerely,

Paul M. Sukut
CEO & General Manager

1717 East Interstate Avenue | Bismarck, ND 58503 | 701.223.0441 | Fax 701.557.5336 | basinelectric.com

Dr. Gary C. Young, Ph.D., P.E.
President

Bio-Thermal-Energy, Inc.

Bio-Thermal-Energy, Inc.
7707 Marquette Drive, N.E.
Cedar Rapids, IA 52402-6967
319-373-5191, FAX 319-373-5744
Cell ph. 319-310-6866
gycoinc@aol.com
www.b-t-einc.com

April 9, 2018

The Honorable John Barrasso
Chairman, Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Tom Carper
Ranking Member, Committee on Environment and Public Works
456 Dirksen Senate Office Building
Washington, DC 20510

Ref.: Committee deliberations on the USE IT Act

Dear Chairman Barrasso and Ranking Member Carper,

I support this legislation and give it due consideration. Carbon dioxide (CO_2) is the waste from the combustion of fossil fuels and is a valuable feedstock for the conversion to fuels such as Ethanol, Methanol, Gasoline, Diesel, and/or Jet Fuel.

CASE-I. APPLICATION OF CO_2 TO THE PRODUCTION OF ETHANOL:

Subject: Application of B-T-E's Patented SMR+® CO_2 Conversion Technology to Corn-Ethanol Plant; Increasing Ethanol Production from Corn-Ethanol Plant by converting byproduct CO_2 Emissions from the Corn-Ethanol plant to Ethanol; **[Grant for Feasibility Study]**

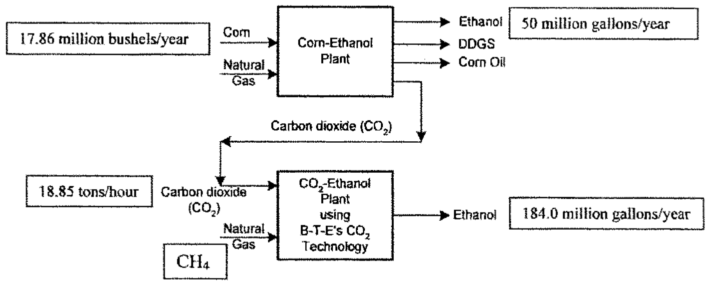
Executive Summary: B-T-E's patented SMR+® technology increases Ethanol production from a Corn-Ethanol plant by converting byproduct CO_2 emissions into additional Ethanol. This patented technology applies to site specific location by building or utilizing an existing Corn-Ethanol plant in an area and by constructing a CO_2-Ethanol plant adjacent the Corn-Ethanol plant. **This new technology will financially benefit the site specific location and create over 100+ jobs.** A facility with a combination of a Corn-Ethanol plant and a CO_2-Ethanol plant should be considered by conducting a feasibility study to determine site specific economics for a site specific location. **[Grant for Feasibility Study for a Site Specific Location.]**

B-T-E's patented CO_2 conversion technology has seven (7) U.S. patents, one (1) Canadian patent, one (1) Japanese patent, one (1) Indian patent, one (1) Brazilian patent, twelve (12) European patents, and other patents pending. **B-T-E owns and holds the rights to the Patented B-T-E CO_2 Conversion Technology.**

A patented SMR+® technology increases Ethanol production from a Corn-Ethanol plant by converting byproduct CO_2 emissions into additional Ethanol. As illustrated below, CO_2 emissions from a Corn-Ethanol Plant are converted into additional Ethanol in the CO_2-Ethnaol Plant using B-T-E's patented CO_2 conversion technology. The combined plant operations would make it the most efficient Ethanol facility in the United States.

Description and Preliminary Economics of Corn-Ethanol Plant & CO_2-Ethanol Plant Facility:

1. **An illustration of a Corn-Ethanol & CO_2-Ethanol Facility is shown below:**



CO_2 + CH_4 + H_2O → Reformer (SMR+®) → Syngas (CO & H_2) → Ethanol (Fermentation Process - Commercially existing)

2. **Preliminary Economics are shown by considering the additional cash revenue to the bottom line of an Ethanol Facility using B-T-E's SMR+® patented technology. Case below will be presented for the Ethanol Facility and will use the CO_2 emissions from a 50 MM GPY Corn-Ethanol Plant. Carbon dioxide (CO_2) emissions from the 50 MM GPY Corn-Ethanol plant are 18.85 tons CO_2/hour.**

   Case: Economics of a CO_2-Ethanol Plant, B-T-E's SMR+® Catalytic CO_2-Ethanol Process: Production cost includes CAPEX (ISBL & OSBL) and OPEX (includes Labor & Maintenance), **Natural gas at $2.733/MM** Btu, and **Electricity at $0.0693/kWh**. Capital considered at 6% for 20 years. A Greenfield plant was considered with the OSBL/ISBL at 0.50 ratio.

CO_2-Ethanol Plant: 184.0 MM GPY **(B-T-E's SMR+® Catalytic CO_2-Ethanol Process);**
Production Cost = $0.490/gallon Ethanol produced
(30.7 MW of Utility Power, Net Export to the GRID.)

SMR+® CO_2-Ethanol Process: CO_2 + CH_4 + H_2O to Reformer (Syngas) to Fermentation (Ethanol)

Note: CO_2 + CH_4 + H_2O to Syngas uses B-T-E's patented SMR+® Catalytic CO_2 Conversion Technology

Revenue: (Selling Price = $1.4600/gallon Ethanol)
184.0 MM GPY x $1.4600/gallon Ethanol selling price = $268.6 MM/yr
Revenue = $268.6 MM/year

Cost of Production: (Production Cost = $0.490/gallon Ethanol)
184.0 MM GPY x $0.490/gallon = $90.16 MM/yr
Cost of Production: $90.16 MM/year

Net Revenue = ($268.6 - $90.2 MM/yr) = $178.4 MM/year

TIC = $541 MM; Total Installed Cost (TIC), (Greenfield Plant)
Payout = 3.0 years

From the analysis, the CO_2-Ethanol plant generates 30.7 MW of Utility Power, Net Export to the GRID.

NOTE: "NO SUBSIDIES" WERE USED IN THE ABOVE ECONOMIC EVALUATIONS.

RIN's were "NOT" considered in the economic evaluation in this correspondence but "for the record only": 2018 year RINs D6 (Corn Ethanol) \$0.450/gallon and 2018 year RINs D5 ("Other" Adv. Bio.) \$0.640/gallon; Chicago Board of Trade, 3/29/2018.

3. Economics of a Corn-Ethanol Plant & CO_2-Ethanol Plant Facility and Considering RINs

Using RINs, a Corn-Ethanol Plant and CO_2-Ethanol-Ethanol Plant Facility becomes more profitable and capital investment can be repaid in fewer years. NOTE, the Corn-Ethanol plant & CO_2-Ethanol plant Facility is profitable even if RINs are "no longer" available. Thus, the combined two plants can be profitable without RINs but a stand-alone Corn-Ethanol plant may not be profitable in the future.

In addition, RIN's D6(Corn Ethanol) would likely be obtained for the Corn-Ethanol Plant and RIN's D5("Other" Adv. Bo.) would likely be obtained for the CO_2-Ethanol Plant.
Under these conditions for just a couple of years, the Ethanol Facility becomes a "CASH COW."

4. At this time a likely approach would consist of:

a. First, have a study (feasibility study) done by a large independent engineering firm to assess the technical and economic feasibility for a Corn-Ethanol Plant & CO_2-Ethanol Plant Facility using B-T-E's New Patented CO_2 Conversion Technology. Such a feasibility study would be done by B-T-E, Inc. and an independent engineering firm. Likely, such as feasibility study could be done with a grant from the Federal Government.

   Currently, estimated cost for the feasibility study would be less than \$350,000.

b. Second and based upon the feasibility study results from above, a project would be initiated to construct a Pilot Plant to verify and optimize the new technology from CO_2-Ethanol production.

   Then, investors would participate in the construction, completion, and operation of the Corn-Ethanol Plant & CO_2-Ethanol Plant Facility.

   Likely, the B-T-E's CO_2-Ethanol Process could be pilot plant tested using a slip stream of Carbon dioxide (CO_2) from one of an existing Corn-Ethanol plants at that location. This approach and any other considerations would be determined in the feasibility study. This pilot plant would prove out the process from CO_2 feedstock to Ethanol production.

   Note, B-T-E's CO_2 Conversion Technology to SYNGAS has already been pilot plant tested (experimentally verified). A pilot plant operation from CO_2 feedstock to SYNGAS to Ethanol production is logical to test out the entire process from beginning to end. The feasibility study will provide valuable information for making that decision.

CASE-II. APPLICATION OF CO_2 TO THE PRODUCTION OF GASOLINE:

The CO_2 Opportunity & Patented SMR+® Catalytic Technology: Coal-Fired Power Plant Emission Source to Gasoline, Diesel, Jet Fuel, and/or Hydrogen

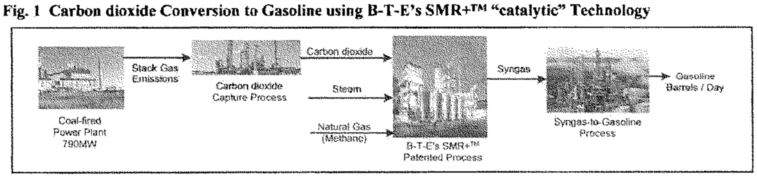
An economical commercial process is needed to provide an incentive for the utility industries to engender win-win support for Governmental regulations on Carbon dioxide (CO_2) emissions.
Current approach to mitigating CO_2 emissions is carbon capture and sequestration (CCS) which involves CO_2 capture followed by CO_2 sequestration involving costly CO_2 compression, transportation, underground storage and/or used for Crude Oil recovery from reservoirs.

Recently, an alternative proprietary catalytic process has been developed for mitigating CO_2 emissions which solidifies the aims of both parties, i.e., industry and government. The recent alternative "catalytic" process by B-T-E, Inc. was developed for mitigating CO_2 emissions from industrial plants by conversion to fuels and is in addition to the previously published "non-catalytic" B-T-E process, [Ref. 11]. The catalytic process converts CO_2 into Syngas (CO & H_2) with B-T-E's patented catalytic process technology and further conversion to fuels such as Gasoline, Diesel, Jet Fuel, Hydrogen, Methanol, and/or Ethanol with established mature technologies, [Refs. 1,2,3,4,8]. The patented technology for the conversion of CO_2 to Syngas was developed by Bio-Thermal-Energy, Inc. (B-T-E, Inc.) and has seven (7) U.S. patents, one (1) Japanese patent, European Patent (EP), and other patents pending, [Ref. 5].
B-T-E's proprietary catalytic technology is referred to as the patented SMR+® process.

The Process

Figure 1 provides a pictorial representation of the new catalytic technology as used for the conversion of CO_2 emissions from a representative coal-fired power plant (790 MW) to gasoline, with an estimated production of 137,200 barrels/day.

Fig. 1 Carbon dioxide Conversion to Gasoline using B-T-E's SMR+™ "catalytic" Technology



The over-all process, from CO_2 to fuels (using B-T-E's technology and a comparable coal-fired power plant) is comprised of these three steps:

Step 1 – Capturing Emissions

Coal-fired stack gas emissions are sent to a carbon dioxide capture plant to remove CO_2 from the stack gas. The stack gas is comprised mainly of Nitrogen (about 70% vol.), water, CO_2 (about 20%), and impurities of SO_2, NOx, and mercury. CO_2 capture system can recover up to about 90% of the CO_2 from the stack gas such as by Shell Oil Company CO_2 capture system.

Step 2 – Conversion to Syngas

CO_2 is then converted to Syngas (mostly CO & H_2) with B-T-E's proprietary technology in a CO_2-to-Syngas process plant. Note, B-T-E's novel technology has been proven experimentally on a gasification pilot plant with a capacity of 12.5 TPD (tons per day). Pilot plant tests have experimentally verified a reduction of CO_2 of about 70 percent, with significant improvements anticipated with further optimization.

This second step involves B-T-E's patented SMR+® catalytic technology. Carbon dioxide (CO_2), natural gas (methane, CH_4), and steam are fed to a Reformer to produce Syngas as illustrated below:

CO_2 + Methane (CH_4) + Steam (H_2O) → Syngas (CO & H_2)

Note, this step uses the typical Steam-Methane Reformer process but B-T-E's SMR+® Catalytic process utilizes an independent external supply of Carbon dioxide (CO_2), U.S. 9,212,059.

Step 3 – Conversion to Gasoline

Syngas is then fed to a syngas-to-gasoline plant for the conversion of syngas to gasoline, such as by using ExxonMobil's GTL (gas to liquids) process, as illustrated:

Syngas (CO & H_2) → Gasoline

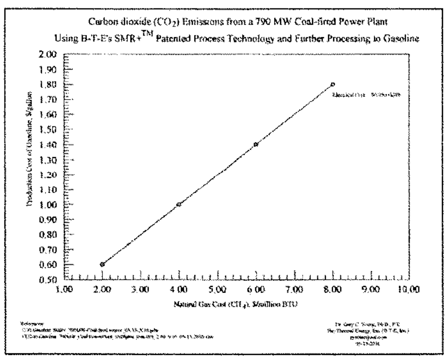
The Economics

With B-T-E's recently patented SMR+® catalytic process coupled with CO_2 Capture process and GTL process to Gasoline, the over-all process to convert CO_2 emissions from a coal-fired power plant into Gasoline becomes:

CO_2 + Methane (CH_4) + Steam (H_2O) → Syngas (CO & H_2) → Gasoline

Figure 2 illustrates the overall economics of using carbon dioxide emissions from a representative 790-MW coal-fired power plant to produce gasoline, using B-T-E's SMR+® proprietary technology, in terms of gasoline production costs as a function of the wholesale natural gas price and retail industrial rate for electricity.

Fig. 2 Gasoline Production Cost using B-T-E's SMR+® Technology



In our case, the 790 MW Coal-fired plant produces stack gas emissions of 775.1 tons/hour carbon dioxide, which in turn can produce about 137,200 barrels/day of gasoline. Production cost includes Total CAPEX (ISBL & 50% of ISBL as OSBL), OPEX including labor & maintenance, with capital financing cost at six percent for 20-years. Cost includes CO_2 capture and environmental requirements. (Ed. – CAPEX denotes capital expenditures; OPEX denotes operating expenses; ISBL and OSBL denote "inside battery limits" and "outside battery limits.")

Using today's economic parameters for wholesale cost of natural gas, the cost of electricity, and the current low prices for gasoline at the pump, we can show that the proposed CO_2-to-Gasoline process is more economical than the conventional method of producing gasoline by refining crude oil.

For example, if crude oil is selling at about $30+/barrel, and if regular-grade gasoline is selling at the pump at a price of about $1.90 per gallon, we can break down the per-gallon (gasoline) costs for the conventional crude oil refining process as shown in Figure 3.

Fig. 3 Gasoline Production Costs – Conventional Refining

	As Cost of Regular Gasoline at the Pump
Taxes	$0.453 / gallon gasoline
Distribution & Marketing	$0.256 / gallon gasoline
Refining	$0.473 / gallon gasoline
Crude Oil	$0.788 / gallon gasoline
Total	$1.970 / gallon gasoline

Refer again to Figure 2, illustrating the economics of the proposed process, using SMR+® technology, for producing gasoline from CO_2. The graph shows that with natural gas prices at wholesale at $2.00/MMBtu and electricity prices at $0.050/kWh, the production cost of gasoline will come in at about $0.60/gallon. The non-catalytic process (Ref. 11) would have a production cost of over $1.00/gallon. As another example, with natural gas at $4.00/MMbtu and electricity at $0.050/kWh, the production cost of gasoline will come in at about $1.00/gallon.
In the economic analysis, cost of CO_2 capture was equivalent to $45/ton CO_2 captured.

By contrast, Figure 3 indicates that the production cost of gasoline using the conventional process of refining crude oil will run $1.261/gallon. That cost represents $0.473 per gallon for refining plus $0.788 for the crude oil commodity. Thus, our analysis indicates that the proposed CO_2-to-gasoline process using SMR+® catalytic technology is competitive with crude-oil refining.

The Other Advantages

Consider the positive attributes of B-T-E's proposed patented SMR+™ CO_2-to-gasoline process:

- B-T-E's patented SMR+® process for CO_2 conversion to Syngas is a catalytic process using the conventional Steam-Methane-Reforming (SMR) process but unique by using an additional independent external feed of low cost Carbon dioxide (CO_2);
- A 60-percent reduction of CO_2 from coal-plant stack gas emissions;
- One gallon of gasoline from about 5.81 lbs CO_2 emissions;
- An environmentally sound process;
- Saves jobs and capital by avoiding closure of coal-fired power plants;
- Produces liquid fuel (gasoline, diesel, and/or Jet Fuel) from Coal-Fired Power Plant Emission;
- Utilizes low cost raw materials, such as CO_2, and natural gas from directional drilling and "fracking" of shale deposits;
- B-T-E's unique and patented catalytic SMR+® process can be used to produce other fuels or chemicals, such as Methanol, Ethanol, etc.

In summation for B-T-E's SMR+® CO_2-to-Syngas-to-Gasoline application to a Coal-fired Power Plant, B-T-E's technology would benefit both the Coal-Fired Power industry and Governmental EPA environmental regulatory agencies. It is a win-win proposition created by "novel" technology for all to benefit: jobs, business assets, environmental, and United States' energy independence.

One could envision a Company's 790 MW Coal-fired Power Plant as supplying the current stack gas emissions, (including any environmental issues), steam, and electricity to a "new" customer's CO_2-Gasoline facility which consists of a CO_2 Capture Plant, SMR+® Catalytic CO_2 Conversion Plant, and the CO_2-to-Gasoline, Diesel, and/or Jet Fuel plant. In other words, the Coal-fired Power Plant supplies energy to a new customer, i.e., the customer's CO_2-to-Gasoline/Diesel/and/or Jet Fuel facility. A new customer is created for the Coal-fired Power Plant.

B-T-E's unique SMR+® patented CO_2 conversion technology is a game changer for the economic potential of producing fuels and chemicals from Carbon dioxide (CO_2) and placing the United States on the pathway to energy independence.

Grants are needed for the feasibility study(s) of the Corn-Ethanol Plant & CO_2-Ethanol Plant Facility and the CO_2-Gasoline Facility based upon B-T-E's Patented CO_2 Conversion Technology.

These feasibility study(s) and future project(s) will need the cooperation and participation of the City, State, Federal, and other parties if a site specific location is selected for the pilot plant and/or commercial facility.

I appreciate the opportunity to express my opinions on this legislation. If you have questions, please call me at ph. 319-373-5191 or cell ph. 319-310-6866.

Sincerely, Gary C. Young 04/09/2018

Dr. Gary C. Young, Ph.D., P.E., Chemical Engineer
President/Owner, Bio-Thermal-Energy, Inc. / (B-T-E, Inc.)

Bio-Thermal-Energy, Inc.
7707 Marquette Drive, N.E.
Cedar Rapids, IA 52402-6967
319-373-5191, FAX 319-373-5744
Cell ph. 319-310-6866
gycoinc@aol.com
www.b-t-einc.com

***Dr. Gary C. Young**, Ph.D., P.E.*
President

Bio-Thermal-Energy, Inc.

Bio-Thermal-Energy, Inc.
7707 Marquette Drive, N.E.
Cedar Rapids, IA 52402-6967
319-373-5191, FAX 319-373-5744
gycoinc@aol.com
www.b-t-einc.com

Published Article:

HP Special Focus
| Clean Fuels
| G. C. Young, Bio-Thermal-Energy, Inc., Cedar Rapids, Iowa

Mitigate CO_2 emissions from industrial plants by conversion to fuels

Hydrocarbon Processing | FEBRUARY 2017, p. 47

G. C. YOUNG, Bio-Thermal-Energy Inc., Cedar Rapids, Iowa

Mitigate CO_2 emissions from industrial plants by conversion to fuels

An economical commercial process is necessary to provide an incentive for the utility industries to engender win-win support for government regulations on carbon dioxide (CO_2) emissions.

A standard approach for mitigating CO_2 emissions is carbon capture and sequestration (CCS), which involves CO_2 capture, sequestration and costly CO_2 compression, transportation and/or underground storage used for crude oil recovery from reservoirs.[1]

An alternative proprietary catalytic process[a] for mitigating CO_2 emissions from industrial plants by conversion to fuels has been developed to solidify the aims of both industry and government.[2,3] This is in addition to a previously published "non-catalytic" process.[4] The catalytic process technology converts CO_2 into syngas [carbon monoxide (CO) and hydrogen (H_2)], with further conversion to fuels, such as gasoline, diesel, jet fuel, H_2, methanol (CH_3OH) and/or ethanol (C_2H_6O), with established, mature technologies.[1,2,5,6,7] The technology consists of seven US patents, one Japanese patent, one European patent and other patents pending.[3]

THE PROCESS

FIG. 1 provides a pictorial representation of the technology as used for the conversion of CO_2 emissions to gasoline from a representative 790-MW, coal-fired power plant. The overall process, from CO_2 to fuels, comprises three steps.

Step 1—Capturing emissions. Coal-fired stack gas emissions are sent to a CO_2-capture plant to remove CO_2 from the stack gas. The stack gas is comprised of approximately 70 vol% nitrogen (N_2), water (H_2O), CO_2 (20%) and impurities of SO_2, nitrogen oxides (NO_x) and mercury (Hg). A CO_2-capture system, like that of Shell Oil Co.,[8] can recover up to 90% of the CO_2 from stack gas.

Step 2—Conversion to syngas. CO_2 is then converted to syngas. The proprietary technology has been proven experimentally on a gasification pilot plant with a capacity of 12.5 tpd.[9] Pilot-plant tests have verified a 70% reduction of CO_2, with significant improvements anticipated with further optimization. This second step involves the catalytic technology that feeds CO_2, natural gas and steam to a reformer to produce syngas, as illustrated in Eq. 1:

$$CO_2 + \text{methane } (CH_4) + \text{steam } (H_2O) \rightarrow \text{syngas } (CO \text{ and } H_2) \quad (1)$$

Note: This step uses a typical steam methane reformer process, but the proprietary catalytic technology utilizes an independent external supply of CO_2.[3]

Step 3—Conversion to gasoline. Syngas is then fed to a syngas-to-gasoline plant for conversion, such as the use of a gas-to-liquids (GTL) process.[5]

The economics. By combining the catalytic process, CO_2-capture process and GTL process, Eq. 2 illustrates the overall process to convert CO_2 emissions from a coal-fired power plant into gasoline:

$$CO_2 + \text{methane } (CH_4) + \text{steam } (H_2O) \rightarrow \text{syngas } (CO \text{ and } H_2) \rightarrow \text{gasoline} \quad (2)$$

FIG. 2 illustrates the overall economics of using CO_2 emissions from a representative 790-MW, coal-fired power plant to produce gasoline, in terms of gasoline production costs as a function of the wholesale natural gas price and retail industrial rate for electricity.

In this case, the plant produces stack gas emissions of 775.1 tph of CO_2, which, in turn, can produce 137.2 Mbpd of gasoline. Production costs include:

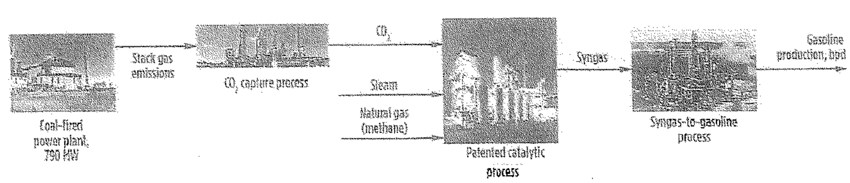


FIG. 1. CO_2 conversion to gasoline using proprietary catalytic technology.

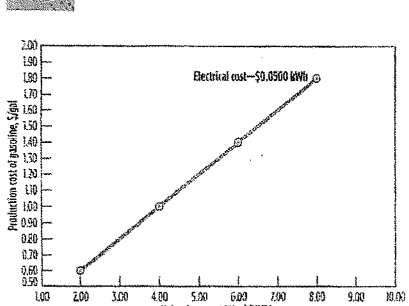


FIG. 2. Gasoline production cost using the proprietary catalytic technology.

TABLE 1. Gasoline production costs, conventional refining

	As cost of regular gasoline at the pump
Taxes	$0.453/gal gasoline
Distribution and marketing	$0.256/gal gasoline
Refining	$0.473/gal gasoline
Crude oil	$0.788/gal gasoline
Total	$1.970/gal gasoline

- Total capital expenditures (CAPEX) and inside battery limits (ISBL), with 50% of ISBL as outside battery limits (OSBL)
- Operating expenditures (OPEX), including labor and maintenance
- Capital financing cost at 6% for 20 yr
- CO_2 capture and environmental requirements.

Using recent economic parameters for the wholesale cost of natural gas, the cost of electricity and recent gasoline pump prices, it was shown that the proposed CO_2-to-gasoline process is more economical than the conventional method of producing gasoline by refining crude oil.

For example, if crude oil is selling for more than $30/bbl, and if regular-grade gasoline is selling at a pump price of approximately $1.90/gal, then the per-gal costs for the conventional crude oil refining process can be calculated as shown in TABLE 1.[10]

FIG. 2 shows that with wholesale natural gas prices at $2/MMBtu and electricity prices at $0.05/kWh, the production cost of gasoline is estimated to be $0.6/gal. The noncatalytic process would have a production cost of more than $1/gal.[4] With natural gas at $4/MMBtu and electricity prices at $0.05/kWh, the production cost of gasoline is estimated to be $1/gal. In the economic analysis, the cost of CO_2 capture is equivalent to $45/t.

By contrast, TABLE 1 indicates that the projected production cost of gasoline using the conventional process of refining crude oil will be $1.261/gal. That cost represents $0.473/gal for refining, and $0.788/gal for the crude oil commodity. Therefore, the analysis indicates that the proposed CO_2-to-gasoline process using the catalytic technology is competitive with crude oil refining.

Additional advantages. Positive attributes of the CO_2-to-gasoline process include:

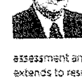
- Reduces CO_2 from coal-plant stack gas emissions by 60%, lowering environmental impact
- Yields 1 gal of gasoline from approximately 5.81 lb of CO_2 emissions
- Protects jobs and capital by further utilizing coal-fired power plants
- Utilizes low-cost raw materials, such as CO_2 and natural gas from directional drilling and fracking of shale deposits
- Produces other fuels or chemicals, such as CH_3OH, C_2H_6O, etc.
- Creates a new market for coal-fired energy producers—i.e., the customer's CO_2-to-gasoline/diesel/jet fuel facility. HP

NOTE

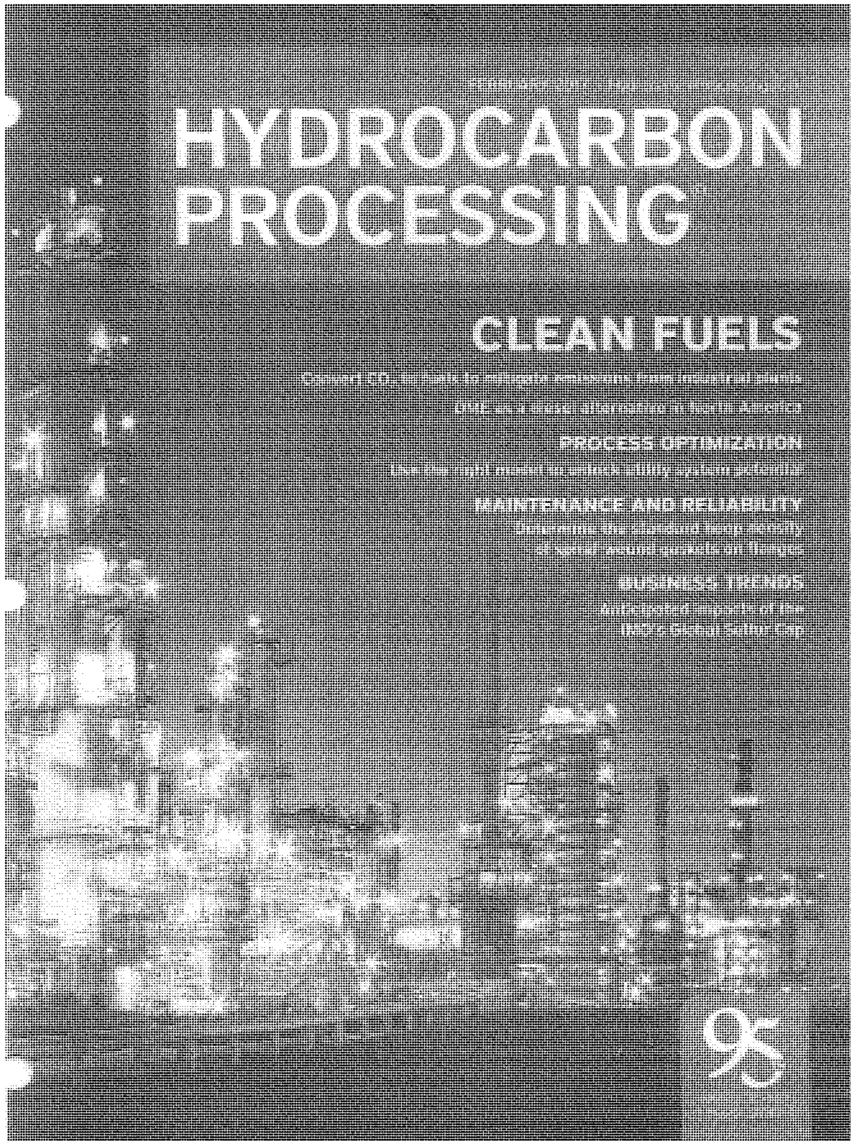
[a] B-T-E's SMR+ CO_2 conversion to syngas technology is a catalytic process using a conventional steam methane reforming process with an additional independent external feed of low-cost CO_2.

LITERATURE CITED

[1] Horn, J. and R. Zbacnik, "Post-combustion carbon-capture technologies," *Chemical Engineering*, March 2015.
[2] Young, G. C., "B-T-E's proprietary process for conversion of CO_2 to green fuels and chemicals," National Advanced Biofuels Conference and Expo, Minneapolis, Minnesota, October 13, 2014.
[3] B-T-E Inc. patents: US 9,212,059; US 7,923,476; US 7,932,298; US 8,178,588; US 8,507,567; US 8,916,617; US 8,937,103; JP 5,406,208; EP 2,217,554; and other patents pending.
[4] Young, G. C., "The CO_2 opportunity, converting emissions from coal-fired plants to gasoline, diesel or jet fuel," *Public Utilities Fortnightly*, August 2015.
[5] ExxonMobil Research & Engineering, "An alternative for liquid fuel production," Gasification Technologies Conference, Colorado Springs, Colorado, October 2009.
[6] Technip Stone & Webster Process Technology Inc., "Waste CO_2 to energy feasibility study for EE-AGG LLC / B-T-E Inc.," February 2014.
[7] Young, G. C., *Municipal Solid Waste To Energy Conversion Processes: Economic, Technical, and Renewable Comparisons*, John Wiley & Sons Inc., Hoboken, New Jersey, 2010.
[8] "Technip and Shell Cansolv to strengthen CO_2 capture technology," Press release, September 2013, http://www.technip.com/en/press/technip-and-shell-cansolv-strengthen-co2-capture-technology
[9] Westinghouse Plasma Corp., "Test report for gasification of metallurgical coke, CO_2 and steam in the pilot scale," Plasma Gasification Vitrification Reactor, for Bio-Thermal-Energy Inc. (B-T-E), December 2011.
[10] "Gasoline and diesel fuel update," US Energy Information Administration (EIA), Washington, D.C., March 2016.



GARY C. YOUNG is the Owner/President of GYCO Inc. (d.b.a. Bio-Thermal-Energy Inc./B-T-E Inc.). He has spent the last 15 years operating his own consulting engineering company, performing process and project economic analyses on industrial and commercial plants and processes, and developing B-T-E's patented CO_2 conversion to syngas. Dr. Young has more than 50 years of experience in the research, development, economic assessment and commercialization of industrial processes. His industry knowledge extends to research and development, design, construction and operations in coal gasification, biomass gasification, waste gasification, CO_2 conversion to fuels/energy, gas processing, food processing, pharmaceutical processing, agricultural and industrial processing, and enhanced energy recovery. Dr. Young holds BS and MS degrees and a PhD, all in chemical engineering, from the University of Nebraska, and is a licensed professional engineer in California, Texas, Illinois, Iowa and Wisconsin. He holds several patents and has produced numerous articles, publications and presentations around the world.


HYDROCARBON PROCESSING
CLEAN FUELS
PROCESS OPTIMIZATION
MAINTENANCE AND RELIABILITY
BUSINESS TRENDS
95

CARBON CAPTURE COALITION

April 11, 2018

The Honorable John Barrasso
Chairman
U.S. Senate Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, D.C. 20510-6175

The Honorable Tom Carper
Ranking Member
U.S. Senate Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, D.C. 20510-6175

Dear Chairman Barrasso and Ranking Member Carper:

On behalf of diverse companies, unions and environmental, energy and agricultural organizations participating in the Carbon Capture Coalition (www.carboncapturecoalition.org/about-us/), we write in support of the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act introduced by Chairman Barrasso and cosponsored by Senators Whitehouse, Capito and Heitkamp.

Building on recent landmark reform of the federal 45Q tax credit to incentivize deployment of carbon capture technology, the USE IT Act will support research and development of direct air capture technology and of beneficial uses of carbon captured from industrial facilities and power plants to reduce emissions, as well as foster cooperative planning and permitting of pipeline infrastructure to transport carbon dioxide (CO_2) from where it is captured to where it can be safely and permanently stored.

Even as we accelerate deployment of today's carbon capture technologies through the revamped 45Q tax credit, we believe Congress should continue to encourage research, innovation and investment in future capture technologies. The establishment of a $25 million prize program for early stage direct air capture research and demonstration in the USE IT Act will stimulate needed attention, investment, and innovation in a technology that, by removing CO_2 directly from the atmosphere, could play a crucial role in achieving future emissions reductions.

The U.S. also has the opportunity be a leader in the productive and beneficial utilization of captured CO_2 and carbon monoxide as building blocks for producing fuels, chemicals and useful products. We support the provision in the USE IT Act to provide $50 million in federal funding for research and development of new uses of captured carbon. This funding will help lay the groundwork for development of new technologies, industries, jobs and markets that expand on the current use and storage of CO_2 through enhanced oil recovery.

CARBON CAPTURE
COALITION

Finally, we call for the inclusion of CO_2 pipelines in a comprehensive national infrastructure policy and for the federal government to help foster the buildout of robust pipeline infrastructure to enable the deployment of carbon capture, utilization and geologic storage projects in multiple industries and in states and regions throughout the country. The USE IT Act takes important steps toward this goal by clarifying that CO_2 pipelines are eligible for the Fix America's Surface Transportation Act and by directing the Council on Environmental Quality to coordinate the development of CO_2 pipeline permitting guidance and establish regional task forces to address permitting challenges.

In addition, we believe that the federal government should also play a targeted role in supplementing private capital to finance the buildout of critical CO_2 pipeline infrastructure to industries and regions not currently served. We call on Congress to provide for such financial incentives to complement the CO_2 pipeline provisions in the USE IT Act.

We look forward to working with you to secure the enactment of the USE IT Act.

Sincerely,

Brad Crabtree
Vice President for Fossil Energy
Great Plains Institute

Bob Perciasepe
President
Center for Climate and Energy Solutions

CLEARPATH ACTION

March 22, 2018

Senator John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

Senator Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington, DC 20510

Dear Senator Barrasso and Senator Whitehouse,

On behalf of ClearPath Action, a 501(c)4 organization working to accelerate conservative clean energy policy, I am writing to support the *Utilizing Significant Emissions with Innovative Technologies Act* (USE IT Act). The bipartisan bill contains common-sense policy solutions that support innovative carbon emission reducing technologies, such as enhanced public private partnerships, carbon infrastructure permitting improvements and innovative research and development (R&D).

Renewable and conventional energy facilities, in addition to electricity transmission, are currently eligible for a more coordinated and expedited permitting process. The USE IT Act takes the commonsense approach of clarifying the eligibility to carbon capture and carbon dioxide transportation projects. It also establishes task forces made up of federal agencies, industry, and nonprofit organizations to recommend ways to facilitate reviews on carbon capture, utilization, and storage projects.

Prolonged and unclear permitting periods discourage private sector investment due to the capital-intensive nature of carbon capture infrastructure. A recent capture project can be in the range of $1 billion and a single carbon dioxide pipeline can easily cost $1 million per mile.

The USE IT Act is a strong step in enabling market-driven carbon capture and realizing its benefits for American consumers.

Sincerely,

Rich Powell
Executive Director, ClearPath Action

CLOUD PEAK
ENERGY®

Colin Marshall
President and Chief Executive Officer

April 10, 2018

The Honorable John Barrasso
Chairman
U.S. Senate Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, DC 20510-6175

Dear Chairman Barrasso,

Earlier this year, your leadership in the Senate delivered the fossil fuel industry and environmental groups across the country a remarkable bipartisan win in the form of passage of the FUTURE Act, amending and improving the 45Q tax credit for carbon capture, utilization, and sequestration. The vocal support from many very different organizations following passage of the FUTURE Act demonstrated that there is significant common ground between those in the utility, coal, and oil and gas industries that see CO_2 as a valuable commodity and those for whom CO_2 emissions represent a serious concern that needs to be addressed.

Your recent introduction of the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act, cosponsored by Senators Capito, Whitehouse, and Heitkamp, represents a further opportunity for bipartisan progress in this area. In promoting the development of the CO_2 pipeline infrastructure needed to move large-scale carbon capture forward, as well as research into beneficial uses for CO_2, we see the USE IT Act as the logical next step in the development and deployment of carbon capture, utilization, and storage technology supported by the 45Q tax credit.

U.S. energy dominance, a strong and robust future for the coal industry and addressing concerns about CO_2 emissions will all be served by legislation like the USE IT Act. To ensure that the U.S. retains a competitive advantage in reliable, affordable, and resilient power generation, plentiful coal must be a part of the nation's energy future, and we believe the USE IT Act will contribute to that future. Thank you for your continued leadership and support.

Yours sincerely,

Colin Marshall

CLOUD PEAK ENERGY INC. | 385 Interlocken Crescent, Suite 400 | Broomfield, CO 80021
T +1 720 566 2900 | F +1 720 566 3095 | www.cloudpeakenergy.com

CO_2 SCIENCES, INC.

We've reached a pivotal moment in the United States to galvanize American researchers and businesses into action on climate innovation.

We applaud the bipartisan work from U.S. Senators John Barrasso and Sheldon Whitehouse in introducing the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act on March 26, 2018. The USE IT Act provides the necessary government infrastructure that can lead to breakthroughs in carbon capture utilization and sequestration (CCUS) research.

Global authorities on climate change, including the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), agree that CCUS is essential to meet the Paris Agreement.

Carbon capture technologies take advantage of a virtually limitless, free resource while mitigating the rising levels of a greenhouse gas. Converting CO_2 into products can lead to a $1 trillion business opportunity by 2030 with the potential to consume 10% of annual, global CO_2 emissions (source: http://bit.ly/2usMzRx).

Government intervention is essential for limiting the global temperature increase to two degrees Celsius, and that is why the USE IT Act is a huge win for all international and local players in the CO_2-based ecosystem.

As business leaders, researchers, scientists and members of the CO_2 Sciences Board of Directors, we write in strong support of plans to increase the spending and building for carbon capture research in the United States. We see it as a necessary step to ensure a prosperous planet for future generations. We will leverage our network of collaborations in the scientific and business communities to raise awareness and generate support for your efforts.

We greatly appreciate your support and attention.

CO_2 Sciences Board of Directors

Bernard J. David, Chairman, CO_2 Sciences
David Douglas, Applied Invention
Thomas E. Lovejoy, United Nations Foundation
Louisa G. Ritter, Pisces, Inc.
Thomas Sheldon, Chief Financial Officer, CO_2 Sciences
Dr. Ellen Williams, Professor, University of Maryland

CO_2 Sciences, Inc.
www.globalco2initiative.org • Twitter: @reuseCO2

COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT

April 17th, 2018

The Honorable John Barrasso
Chairman, Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Tom Carper
Ranking Member, Committee on Environment and Public Works
456 Dirksen Senate Office Building
Washington, DC 20510

Dear Chairman Barrasso and Ranking Member Carper,

I am currently an Associate Professor and Interim Department Head in the Chemical and Biological Engineering Department at the Colorado School of Mines. My research is primarily in the area of carbon capture, utilization, and reliable storage. I am the author of the first textbook on Carbon Capture (Springer, 2012) in addition to co-author on a number of studies associated with carbon dioxide removal, published by the American Physical Society (2011) and the National Academy of Sciences (2014, 2018).

Although many of the CO2 utilization opportunities are not on a large enough scale to impact climate, these strategies will play a key role in the cost reduction of carbon capture strategies. In order to have an impact on climate, it is crucial that the separated CO2 be removed from the atmosphere permanently, which means storing it back underground. Unfortunately, the economic incentive to do this today is not sufficient, but the conversion of CO2 to useful products such as fuel, plastics, and even synthetic gravel, will aid in providing the incentive to build new carbon capture plants. Building new plants will lead to opportunities to learn, ultimately resulting in reduced costs such that this path is critical to making geologic storage of CO2 cost-effective.

I appreciate the opportunity to comment on this legislation and welcome any questions you may have.

Sincerely,

Jennifer Wilcox, Ph.D.

Cc:
Senator Shelley Moore Capito
Senator Sheldon Whitehouse
Senator Heidi Heitkamp

Chemical and Biological Engineering Department
Jennifer Wilcox
Associate Professor and Interim Department Head

MINES.EDU

EERC
Energy & Environmental Research Center

April 10, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington, DC 20510

Dear Senators Barrasso and Whitehouse:

On behalf of the Energy & Environmental Research Center (EERC) at the University of North Dakota, I write in support of the "Utilizing Significant Emissions with Innovative Technologies" (USEIT) Act. Thank you for your leadership in authoring this legislation.

The EERC is a unique organization dedicated to providing practical, pioneering solutions to the world's energy and environmental challenges. The EERC has a rich history of dynamic working relationships with industry, government, and research entities throughout the world. Since 2003, the EERC has worked with those partners to develop solutions to carbon management issues, with an emphasis on developing value-added carbon dioxide (CO_2) utilization options that will enable continued use of affordable and abundant fossil fuels.

The EERC currently manages the Plains CO_2 Reduction (PCOR) Partnership, a multiyear, multimillion-dollar collaboration of over 100 stakeholders that has laid the groundwork for practical and environmentally sound CO_2 utilization and associated storage projects in the heartland of North America. The PCOR Partnership membership includes stakeholders representing a diverse cross section of CO_2 producers, end users, environmental groups, and regulators. The EERC strongly supports this legislation because it will help leverage the resources of states, industry, universities, and the federal government and build on these efforts to develop cost-effective carbon capture, utilization, and storage (CCUS).

In addition to technical and financial assistance to support research, your legislation would establish interagency guidance and a task force to facilitate CCUS infrastructure. The EERC supports these provisions as well, given the new infrastructure that will need to be developed on a considerable scale to commercially deploy CCUS technology at a meaningful scale.

The USEIT Act is important legislation to advance the development of CCUS technology. The EERC again thanks you for your efforts to support cost-effective solutions for electric power generation. We hope that this legislation can receive prompt consideration by the Senate.

Sincerely,

Thomas A. Erickson
CEO

TAE/rss

Global
Thermostat

April 5, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington, DC 20510

Dear Senators Barrasso and Whitehouse:

On behalf of Global Thermostat, I write in support of the "Utilizing Significant Emissions with Innovative Technologies" (USEIT) Act. We understand there will be a hearing on April 11, 2018 at 10:15am in the Dirksen Senate Office Building Room 406. Thank you for your leadership in authoring this legislation.

Global Thermostat has pioneered a breakthrough low-cost technology that removes CO2 directly from air and is now entering its commercial stage. Our cost is sufficiently low that we can sell the CO_2 we remove from the atmosphere for commercial use, for example to carbonated beverage companies, such as Coca Cola, and for the production of plastics from CO2 that is used by firms such as Ikea. Global Thermostat has built a commercial demonstration carbon capture plant at SRI, 333 Ravenswood Avenue in Menlo Park, CA (Silicon Valley) and is currently building commercial plants to remove CO2 directly from air (direct air capture or "DAC") at our factory in Huntsville, AL.

The UN Intergovernmental Panel on Climate Change that is composed of thousands of scientists around the world and has received the Nobel Prize for its work on carbon capture has determined that removal of CO2 directly from air as Global Thermostat does is now needed on a massive scale in order to avert catastrophic risks from climate change. The groundbreaking legislation of the FUTURE Act (45Q) and the important current bill together with technologies like Global Thermostat place the United States at the leadership of world efforts to reverse climate change and does so while favoring economic growth, creating jobs and expanding US exports to the entire world economy.

About 30,000 Global Thermostat plants suffice to remove all the CO2 that humans emit every year. We will be able to build these plants in every state of the US leveraging the resources of every state, industry, university and the Federal Government and build on these efforts to develop cost-effective carbon capture utilization and storage ("CCUS") and DAC. Your bill can help prioritize resources to build projects and clean the atmosphere while enhancing economic growth.

335 Riverside Drive New York, NY 10025 (212) 678-1148 http://globalthermostat.com

I understand that in addition to technical and financial assistance to support research, your legislation would establish interagency guidance and a task force to facilitate cost-effective CCUS infrastructure and DAC. Global Thermostat supports these provisions given the new infrastructure that will need to be developed on a considerable scale to deploy DAC technology.

The USEIT Act is important legislation to advance the development of CCUS and in particular DAC technology which is necessary for resolving the climate change problem. Global Thermostat again thanks you for your efforts to support commonsense solutions for electric power generation. We hope that this legislation can receive prompt consideration by the Senate.

Sincerely,

Dr. Graciela Chichilnisky
CEO & Co-Founder
Professor of Economics and Statistics
Columbia University
New York, NY 10025
(c) 646.623.3333

GREAT RIVER ENERGY™

12300 Elm Creek Boulevard
Maple Grove, Minnesota 55369-4718
763-445-5000
greatriverenergy.com

April 9, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington DC 20510

Dear Senators Barrasso and Whithouse:

On behalf of Great River Energy, I write to support S. 2602, the "Utilizing Significant Emissions with Innovative Technologies" (USEIT) Act. Thank you for sponsoring this bill that would provide a possible pathway for electric utilities and others to research and implement carbon capture, utilization and sequestration (CCUS) technology.

Great River Energy is a generation and transmission cooperative based in Minnesota that provides electricity to 695,000 members by serving 28 distribution cooperatives in Minnesota and Wisconsin. We own power plants and (through a subsidiary) ethanol plants in North Dakota that could be sources of carbon dioxide under the act.

CCUS has the potential to be a beneficial method of reducing the emission of carbon dioxide, a greenhouse gas, into the atmosphere. If the carbon dioxide could be used for a commercially valuable purpose, such as enhanced oil recovery, then the economic feasibility of CCUS would be advanced. The bill would direct the EPA to provide technical and financial assistance to carbon dioxide utilization projects. This could be very beneficial to industry as it seeks to reduce or control carbon dioxide emissions.

S. 2602, Title II, Section 201, would clarify that CCUS projects are covered projects for purposes of Title XLI of the FAST Act, which is intended to improve the timeliness of the Federal environmental review and permitting process. We support this section of the bill, as well, because delays in permitting can adversely affect the feasibility of innovative projects.

Thank you for the opportunity to comment on such an innovative and constructive bill that could be beneficial both to industry and to the environment.

Sincerely,

GREAT RIVER ENERGY

Rick Lancaster

Rick Lancaster
Vice President and Chief Generation Officer

4/9/2018 S:\Generation\Executive Assistant Files\Rick Lancaster\040918 Barrasso-Whithouse Letter.Docx

Lignite Energy Council
LEADING THROUGH ADVOCACY AND INNOVATION

April 10, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washinton, DC 20510

Dear Senators Barrasso and Whitehouse:

On behalf of the Lignite Energy Council, I write in full support of the "Utilizing Significant Emissions with Innovative Technologies" (USEIT) Act. I greatly appreciate your leadership in authoring this legislation.

The Lignite Energy Council is a regional trade association for coal mines, electric utilities and about 300 business providing good and services to the mines and plants that supply power to over two million people in the upper Midwest region of the United States. The primary objective of the Lignite Energy Council is to maintain a viable lignite coal industry and enhance development of the region's lignite coal resources for use in generating electricity, synthetic natural gas and valuable byproducts. This legislation will be of great importance for our industry to meet our members' goals and objectives.

Our region has been a leader in carbon capture utilization and storage (CCUS) as one of our electric generation members, Basin Electric Power Cooperative, has been operating the largest carbon sequestration project in the world known as The Great Plains Synfuels Plant for the past twenty years. In addition, we are currently supporting the advancement of many breakthrough CCUS research and development programs to ensure the long-term viability of North Dakota's lignite coal and energy generation industries for future generations.

The USEIT Act will greatly advance CCUS technology development by giving our industry access to solutions that will be necessary to build new test facilities and infrastructure that are important and commonsense solutions for lignite electric power generation. The Lignite Energy Council and our members support this legislation because it will help provide much needed financial and technical assistance to further our efforts towards CCUS. Thank you for your leadership on this legislation and for your consideration in the Senate.

Sincerely,

Jason Bohrer
CEO & President

1016 E. Owens Ave. | PO Box 2277 | Bismarck, ND 58502

701.258.7117 www.lignite.com LEC@lignite.com

HAL QUINN
President & CEO

May 7, 2018

The Honorable John Barrasso
Chairman
Committee on Environment and Public Works
United States Senate
Washington, DC 20510

Dear Chairman Barrasso:

The National Mining Association commends you for your leadership in authoring and introducing S. 2602, the "Utilizing Significant Emissions with Innovative Technologies Act."

Specifically, we support provisions that promote further research and development of technologies that will convert carbon into products of commercial value. We also support the goal of reviewing and developing policy guidance to facilitate the permitting of the necessary supporting infrastructure including carbon dioxide pipelines.

Thank you for putting forward this legislation.

Sincerely,

Hal Quinn

You Tube ND Living

NDARECs
North Dakota Association of Rural Electric Cooperatives
3201 Nygren Drive NW • P.O. Box 727 • Mandan, ND 58554-0727

Phone: 701.663.6501 or 800.234.0518
Fax: 701.663.3745 www.ndarec.com

April 5, 2018

The Honorable John Barrasso
U.S. Senate
307 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Sheldon Whitehouse
U.S. Senate
530 Hart Senate Office Building
Washington, DC 20510

Re: Support for Utilizing Significant Emissions with Innovative Technologies (USEIT) Act

Dear Senators Barrasso and Whitehouse:

On behalf of North Dakota's electric cooperatives, I write to express our organization's support for the Utilizing Significant Emissions with Innovative Technologies (USEIT) Act. Our organization is comprised of 21 electric generation, transmission and distribution cooperatives that have invested billions in electrical infrastructure and proudly provide electrical service to hundreds of thousands of people.

Our cooperatives have long been on the forefront of innovation and technology, which is essential in providing affordable and reliable power to the member-owners they serve, maintaining a diverse energy portfolio made up of both renewable and baseload energy resources. Within our membership, our generation cooperatives are pursuing important carbon capture and storage projects that will enhance existing assets and more efficiently utilize fuel resources.

The support, research, technical and financial assistance that this legislation intends to channel will help to encourage further development and investment into carbon capture, utilization facilities and carbon dioxide pipelines, which will allow electric cooperatives to continue to invest in a diverse energy portfolio and benefit from utilization of North Dakota's 800-year supply of coal.

On behalf of North Dakota's electric cooperatives, thank you for putting forward innovative viable solutions. The USEIT Act is key legislation that, if passed, will contribute to a more reliable, resilient and secure energy future for many years to come.

Sincerely,

Josh Kramer
Executive Vice President & General Manager
North Dakota Association of Rural Electric Cooperatives

April 10, 2018

Chairman John Barrasso
Committee on Environment and Public Works
410 Dirksen Senate Office Building
Washington, DC 20510

Ranking Member Tom Carper
Committee on Environment and Public Works
456 Dirksen Senate Office Building
Washington, DC 20510

Chairman Barrasso and Ranking Member Carper:

I am writing in support of S.2602, the USE IT Act, your bill to incentivize carbon use and direct air capture, and to better understand carbon capture infrastructure needs. Carbon capture is a key climate technology that many models show will likely be necessary to meeting emissions targets. The United States should continue to support the development and deployment of the full range of carbon capture technologies - from direct air capture to industrial emissions to carbon use.

Reducing emissions as quickly as possible domestically and abroad should be a top priority. However, many climate scientists expect that we will need negative emissions technologies to avoid the worst impacts of climate change. Direct air capture is a cutting edge technology that could prove vital in protecting our planet and we appreciate that this bill would support further development.

We also appreciate that this bill would provide necessary federal support for the growing carbon use industry. While there are dozens of carbon use projects globally, the United States is home to more than any other single country. We should support and cultivate this industry, which has the potential to establish new opportunities to beneficially use and store carbon dioxide.

Finally, particularly after the recent passage of the FUTURE Act, which we expect to lead to increased deployment of carbon capture projects, there is a need to consider what infrastructure will be required to widely deploy this technology. The provisions in the USE IT Act track closely with the recommendations of the 2015 Quadrennial Energy Review and other expert recommendations, and we applaud the committee's interest in this issue.

We appreciate your leadership on this issue and look forward to continuing to work with your Committee.

Sincerely,

Josh Freed
Vice President for Clean Energy
Third Way

February 6, 2018

The Honorable Paul D. Ryan
Speaker of the House
1233 Longworth House Office Building
Washington, DC 20515

The Honorable Nancy Pelosi
House Minority Leader
223 Cannon House Office Building
Washington, DC 20515

The Honorable Mitch McConnell
Senate Majority Leader
317 Russell Senate Office Building
Washington, DC 20510

The Honorable Chuck Schumer
Senate Minority Leader
322 Hart Senate Office Building
Washington, DC 20510

The Honorable Kevin Brady
Chairman
Committee on Ways and Means
1102 Longworth House Office Building
Washington, DC 20515

The Honorable Richard Neal
Ranking Member
Committee on Ways and Means
1139E Longworth House Office Building
Washington, DC 20515

The Honorable Orrin Hatch
Chairman
Committee on Finance and Taxation
104 Hart Senate Office Building
Washington, DC 20510

The Honorable Ron Wyden
Ranking Member
Committee on Finance and Taxation
221 Dirksen Senate Office Building
Washington, DC 20510

Dear Speaker Ryan, Democratic Leader Pelosi, Majority Leader McConnell, Democratic Leader Schumer, Chairman Brady, Ranking Member Neal, Chairman Hatch and Ranking Member Wyden:

As governors committed to technology innovation and investments that increase American energy production, create good-paying, highly-skilled jobs, and reduce emissions, we urge you to enact federal financial incentives to capture carbon dioxide (CO_2) from power plants and industrial facilities. These incentives are necessary to ensure that CO_2 is put to productive use and subsequently stored safely and permanently underground.

We specifically urge Congress to support the following:

- Bipartisan legislation to extend and reform the federal Section 45Q Tax Credit for Carbon Dioxide Sequestration (the FUTURE Act, S. 1535, was introduced in the Senate in July with 25 sponsors, and the companion Carbon Capture Act, H.R. 3761, was introduced in the House in September and currently has 48 sponsors);
- Bipartisan legislation to make carbon capture projects eligible for tax-exempt private activity bonds (the Carbon Capture Improvement Act has been introduced this year in both the U.S. House, H.R. 2011, and the U.S. Senate, S. 843); and
- Policies and incentives to foster the development and financing of additional long-distance, large-volume CO_2 pipelines as part of a broader national infrastructure agenda.

Our immediate priority is extension and reform of the existing federal 45Q tax credit. Senate Finance Committee Chairman Orrin Hatch introduced the Tax Extender Act, S. 2256, on December 20th, which includes the provisions of the FUTURE Act in their entirety. Extending and reforming 45Q will provide financial certainty for investors in carbon capture projects, increase the value of the tax credit, expand eligibility to benefit additional industries and regions of the country, and provide flexibility to accommodate different business models, project developers and investors. While the 45Q tax credit is essential to accelerating deployment, tax-exempt private activity bonds can provide a valuable complementary incentive, further enhancing the financial feasibility of carbon capture projects.

With respect to CO_2 pipelines, Congress should implement policies that enable the federal government to play a targeted role to finance additional capacity for priority trunk pipelines, built to transport CO_2, by supplementing private investment. This will facilitate the buildout of pipeline infrastructure over time, reduce project development costs and encourage investors to make capital available on better financial terms.

Carbon capture provides a long-term, low-carbon path for production and use of America's abundant coal, oil and natural gas resources. Continued growth of traditional energy and industrial sectors will lead to the creation of many good-paying, highly-skilled jobs.

As governors from both political parties representing diverse states and regions, we believe carbon capture represents a key element of a broader, cost-effective portfolio of energy production and carbon management options. This technology merits federal policy support to accelerate its commercial deployment. We look forward to working with you to implement a robust package of federal financial incentives and other policies, as Congress has accomplished for other energy technologies, to help grow this critically important industry.

Sincerely,

Matt Mead
Governor of Wyoming

Jeff Colyer
Governor of Kansas

Mary Fallin
Governor of Oklahoma

Doug Burgum
Governor of North Dakota

Steve Bullock
Governor of Montana

Tom Wolf
Governor of Pennsylvania

MATTHEW H. MEAD
GOVERNOR

THE STATE OF WYOMING

2323 Carey Avenue
CHEYENNE, WY 82002

Office of the Governor

February 16, 2018

The Honorable Steve Bullock
Governor of Montana
PO Box 200801
Helena, MT 59620-0801

The Honorable Doug Burgum
Governor of North Dakota
600 East Boulevard Ave
Bismarck, ND 58505-0001

The Honorable Pete Ricketts
Governor of Nebraska
PO Box 94848
Lincoln, NE 68509-4848

The Honorable John Hickenlooper
Governor of Colorado
136 State Capitol Bldg
Denver, CO 80203

The Honorable Jeff Coyler
Governor of Kansas
300 SW 10th Ave, Ste 241S
Topeka, KS 66612-1590

The Honorable Kim Reynolds
Governor of Iowa
1007 East Grand Ave
Des Moines, IA 50319

The Honorable Bruce Rauner
Governor of Illinois
207 State House
Springfield, IL 62706

The Honorable Rick Snyder
Governor of Michigan
PO Box 30013
Lansing, Michigan 48909

The Honorable Eric Holcomb
Governor of Indiana
200 W Washington St, Room 206
Indianapolis, IN 46204

The Honorable John Kasich
Governor of Ohio
77 S High St, Riffe Center 30th Floor
Columbus, OH 43215-6117

The Honorable Tom Wolf
Governor of Pennsylvania
508 Main Capitol Bldg
Harrisburg, PA 17120

The Honorable Matt Bevin
Governor of Kentucky
700 Capital Ave, Ste 100
Frankfort, KY 40601

The Honorable Asa Hutchinson
Governor of Arkansas
500 Woodlane Ave, Room 250
Little Rock, AR 72201

The Honorable Mary Fallin
Governor of Oklahoma
2300 N Lincoln Blvd, Room 212
Oklahoma City, OK 73105

The Honorable Greg Abbott
Governor of Texas
PO Box 12428
Austin, TX 78711-2428

The Honorable John Bel Edwards
Governor of Louisiana
PO Box 94004
Baton Rouge, LA 94004

The Honorable Phil Bryant
Governor of Mississippi
PO Box 139
Jackson, MS 39205

Dear Governors,

Our states each have potential to benefit from carbon capture, utilization, and storage (CCUS) technologies. Now, with Congressional passage of the extension and reform of the Section 45Q tax credit as part of the budget agreement this month, we have a powerful federal incentive to encourage carbon capture and carbon dioxide (CO_2) pipeline infrastructure. This is key to our coal, ethanol, natural gas, oil and other CO_2-producing industries transforming their carbon emissions into a valuable commodity.

In 2015, the Western Governors' Association enacted a policy resolution on Enhanced Oil Recovery (EOR). Subsequently, Governor Bullock and I convened a multi-state CO_2-EOR Deployment Work Group. This Work Group was tasked with developing policy recommendations on deployment of carbon capture technologies. The Work Group has produced several reports and recommended incentives that would encourage private investment in commercial projects that benefit industries. The extension and reform of 45Q enacted by Congress was one of the initiatives and the Work Group played an important role in building congressional support for its passage.

In Wyoming, we have been working for a number of years on an intrastate pipeline corridor system. Development of pipeline infrastructure is critical to further deployment of CCUS technology. It is expensive and time consuming. We are completing an Environmental Impact Statement to reduce that burden on project developers. These corridors are intended to avoid multiple pipeline routes and minimize widespread environmental impact. They have the support of many industry and environmental groups.

I write to ask for your support in a logical next step – promoting broad scale development of regional infrastructure for carbon capture, CO_2 pipelines, EOR and other forms of geologic storage. This would include identifying, analyzing and evaluating opportunities for regional pipeline corridors that would transport industrial and power plant CO_2 for beneficial use and storage. For example, states with ethanol and other industrial sources of CO_2 that have lower capture costs could transport that CO_2 to regions with opportunities for large-scale storage. As CO_2 capture technology becomes more available on electrical generation facilities, pipeline infrastructure will be available to handle additional supply.

Such an initiative is timely. The 45Q tax credit has passed and Congress is considering major infrastructure legislation. Tangible regional plans and partnerships would allow our states to work together on carbon management infrastructure. This will facilitate the ability to maximize use of our abundant energy, industrial and geologic assets.

The Work Group has begun early work on regional carbon capture networks and pipeline infrastructure. Many of you are involved in the Work Group and have been since its inception. I ask for your active support and participation to move this innovative idea, which will provide myriad benefits to our states and the nation, forward.

Please have your staff contact Matt Fry in my office at 307-777-4510 to discuss details, or you may contact me directly.

Sincerely,

Matthew H. Mead
Governor

MATTHEW H. MEAD
GOVERNOR

THE STATE OF WYOMING

2323 Carey Avenue
CHEYENNE, WY 82002

Office of the Governor

April 10, 2018

The Honorable John Barrasso	The Honorable Sheldon Whitehouse
U.S. Senate	U.S. Senate
307 Dirksen Senate Office Building	Hart Senate Office Building, Rm 530
Washington, DC 20510	Washington, DC 20510

Dear Senator Barrasso and Senator Whitehouse,

I support the Utilizing Significant Emissions with Innovative Technologies (USE IT) Act. This legislation will facilitate the deployment of carbon capture, utilization and storage (CCUS) technologies.

Wyoming's fossil fuel resources benefit our economy and provide the nation with reliable energy. The ability to manage carbon and put it to productive use gives Wyoming and the nation a long-term low-carbon path to continued production and use of these resources.

The Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions (FUTURE) Act brought needed financial incentives and assurances to developers of CCUS projects. I appreciate your efforts that led to its passage. The USE IT Act provides support for carbon capture research and CO_2 pipeline infrastructure, which are limiting factors in project deployment. This bill is a logical next step and will lead to projects being developed and allow continued use of abundant resources while lowering the nation's carbon footprint. Thank you for your work on this important legislation.

Sincerely,

Matthew H. Mead
Governor

MHM:dp

cc: The Honorable Mike B. Enzi, U.S. Senate
The Honorable Liz Cheney, U.S. House of Representatives

PHONE: (307) 777-7434

FAX: (307) 632-3909

WESTERN GOVERNORS' ASSOCIATION

DENNIS DAUGAARD

DAVID IGE

JAMES D. OGSBURY

August 3, 2017

Honorable Orrin Hatch	Honorable Ron Wyden
Chairman	Ranking Member
Committee on Finance	Committee on Finance
United States Senate	United States Senate
219 Dirksen Senate Office Building	219 Dirksen Senate Office Building
Washington, D.C. 20510	Washington, D.C. 20510

Dear Chairman Hatch and Ranking Member Wyden:

Western Governors support the responsible use of enhanced oil recovery (EOR) using carbon dioxide (CO2) and appreciate efforts to develop federal policy designed to promote deployment of this technology. Language contained in the bipartisan Furthering Carbon Capture, Utilization, Technology, Underground storage, and Reduced Emissions (FUTURE) Act, S. 1535, would help increase the use of EOR technology by providing greater regulatory certainty for the Carbon Dioxide Sequestration Credit, created by Section 45Q of the Internal Revenue Code of 1986.

Given the importance of EOR to western states, the Governors enacted Western Governors' Association (WGA) Policy Resolution 2015-06, *Enhanced Oil Recovery*. This resolution (attached for your reference) reads in part:

> In recognition of the environmental and economic benefits of EOR, Western Governors support policies and incentives that advance investment in EOR projects, infrastructure, technology, and research.
>
> Further, in order to expand deployment of CO2 capture at power plants and other industrial sources, the President and Congress should enact federal incentives to increase CO2 supply available for the oil industry to purchase and use in EOR. Federal incentives have the potential to leverage private and state investment, harness the ingenuity of entrepreneurs and capitalize on billions of dollars' worth of [Department of Energy] sponsored research and development to enable new commercial carbon capture and pipeline projects.

The use of CO2 for EOR was pioneered in the United States during the 1970s. Since that time, this technology has proven to be a safe, effective way to increase domestic oil production while

CALL (303) 623-9378
VISIT 1600 Broadway
Suite 1700
Denver, CO 80202

WESTGOV.ORG

Honorable Orrin Hatch
Honorable Ron Wyden
August 3, 2017
Page 2

sequestering millions of tons of CO_2. Many western states have demonstrated their commitment to CO_2-EOR by proactively addressing then-existing regulatory barriers, establishing tax incentives, and providing financial assistance.

The FUTURE Act would clarify the regulatory requirements for secure geological storage of carbon dioxide for the purposes of the Carbon Dioxide Sequestration Credit.

Western states look forward to helping provide for the energy needs of the United States through the continued efficient and responsible development of our natural resources. Western Governors stand behind federal policies – like the FUTURE Act – that enable cost-effective development of new commercial carbon capture and pipeline projects.

Sincerely,

Jim Ogsbury

James D. Ogsbury
Executive Director

WESTERN GOVERNORS' ASSOCIATION

Western Governors' Association
Policy Resolution 2015-05

Enhanced Oil Recovery

A. BACKGROUND

1. Enhanced oil recovery (EOR), using carbon dioxide (CO_2), when performed appropriately and responsibly offers a safe and commercially proven method of domestic oil production. The U.S. oil and gas industry, which pioneered the CO_2 EOR process in West Texas in 1972, is the world leader. Over four decades, the EOR industry has captured, transported, and injected large volumes of CO_2 for oil recovery with no major accidents, serious injuries or fatalities reported.

2. The CO_2 EOR process works by injecting CO_2 obtained from natural and anthropogenic sources into existing oil fields – often referred to as "brownfields" – to free up additional crude trapped in rock formations. This CO_2 "flooding" can result in recovery of about twenty percent of the original oil in place.[1] CO_2 flooding utilizes existing assets to recover significant additional resources stimulating the economy and minimizing surface disturbance that new exploration and development projects necessarily entail. In addition, many areas favorable for CO_2 application exist where new or continued significant drilling activity is unlikely to occur at a meaningful scale for years, if ever.

3. As of 2013, EOR using CO_2 produced approximately 280,000 barrels of domestic oil per day, or four percent of U.S. crude oil production.[2]

4. America has an estimated 21.4 billion barrels of oil, requiring 8.9 billion metric tons of CO_2, that could be economically recovered with today's EOR technologies. With advances in technology, 63.3 billion barrels of oil, requiring 16.2 billion metric tons of CO2, could be economically recovered, which is roughly double current U.S. proven reserves[3].

5. EOR enhances our nation's energy and fiscal security by reducing dependence on foreign oil, often imported from unstable and hostile regimes. It allows reduction of our trade deficit by keeping dollars now spent on oil imports here at home and at work in the U.S. economy.

---

[1] National Energy Technology Laboratory – *Untapped Domestic Energy Supply and Long Term Carbon Storage Solution*
[2] Energy Information Administration – Annual Energy Outlook 2015
[3] U.S. Department of Energy, National Energy Technology Laboratory

6. Coal and oil production and utilization and other industrial processes are a vital component of many western states' economies. EOR provides a long-term path for continued low-carbon production and use of our nation's coal and oil resources and presents an opportunity for state and local governments to stimulate economic activity and realize additional revenue at a time when most governments face significant fiscal challenges.

7. CO_2 is currently limited in availability from high-volume sources needed for EOR – natural sources will not close a supply gap projected to grow. Further, CO_2 capture and pipeline transport capacity to oil fields is not sufficient.

8. CO_2 capture equipment, installed on a broad range of industrial processes, has the potential to supply significant volumes of CO_2 to the EOR industry enabling the U.S. to achieve significant net carbon reductions through the sequestration of CO_2.[4]

9. The U.S. has the opportunity to provide global leadership in carbon capture research and technology development, hydrocarbon recovery and geologic storage research and technologies, manufacturing, engineering and other services.

B. GOVERNORS' POLICY STATEMENT

1. In recognition of the environmental and economic benefits of EOR, Western Governors support policies and incentives that advance investment in EOR projects, infrastructure, technology and research.

2. Western Governors support efforts to increase the awareness of the many benefits CO_2 EOR.

3. In order to expand deployment of CO_2 capture at power plants and other industrial sources, the President and Congress should enact federal incentives to increase CO_2 supply available for the oil industry to purchase and use in EOR. Federal incentives have the potential to leverage private and state investment, harness the ingenuity of entrepreneurs and capitalize on billions of dollars' worth of DOE-sponsored research and development to enable new commercial carbon capture and pipeline projects.

---

[4] As of 2014, approximately 13.6 million metric tons of CO2 was captured that would otherwise be released into the atmosphere has been sequestered as a result of EOR (U.S. Department of Energy – Quadrennial Energy Review). Over the life of a project, for every 2.5 barrels of oil produced, it is estimated that a typical commercial EOR project can safely prevent one metric ton of CO_2 from entering the atmosphere (Kuuskraa, Godec, Dipietro – Energy Procedia). Further, the volume that could be captured and sequestered from industrial facilities and power plants to support economically recoverable EOR reserves could be 8.9 to 16.2 billion metric tons of CO_2. This is equal to the total U.S. CO_2 production from fossil fuel electricity generation for approximately 4 to 8 years (EPA 2015 Green House Gas Inventory).

4. Federal policies aimed to limit CO_2 emissions should promote, and not impede, development and deployment of CO_2 capture and commoditization. Federal regulations should allow states to create programs tailored to individual state needs, industries and economies and recognize CO_2 sequestration that results from EOR in meeting federal regulatory objectives. As such, EPA should abide by principles already established by the Agency in its regulations promulgated to ensure the long-term storage of CO_2 in different geologic formations.

C. GOVERNORS' MANAGEMENT DIRECTIVE

1. The Governors direct the WGA staff, where appropriate, to work with EPA and other federal agencies, Congressional committees of jurisdiction, and the Executive Branch to achieve the objectives of this resolution including funding, subject to the appropriation process, based on a prioritization of needs.

2. Additionally the Governors direct the WGA staff to develop, as appropriate and timely, detailed annual work plans to advance the policy positions and goals contained in this resolution. Those work plans shall be presented to, and approved by, Western Governors prior to implementation. WGA staff shall keep the Governors informed, on a regular basis, of their progress in implementing approved annual work plans.

Western Governors enact new policy resolutions and amend existing resolutions on a bi-annual basis. Please consult westgov.org/policies for the most current copy of a resolution and a list of all current WGA policy resolutions.

WESTERN GOVERNORS' ASSOCIATION

DENNIS DAUGAARD
GOVERNOR OF SOUTH DAKOTA
CHAIR

DAVID IGE
GOVERNOR OF HAWAII
VICE CHAIR

JAMES D. OGSBURY
EXECUTIVE DIRECTOR

April 24, 2018

Honorable John Barrasso
Chairman
Committee on Environment and Public Works
United States Senate
410 Dirksen Senate Office Building
Washington, D.C. 20510

Honorable Thomas R. Carper
Ranking Member
Committee on Environment and Public Works
United States Senate
456 Dirksen Senate Office Building
Washington, D.C. 20510

Dear Chairman Barrasso and Ranking Member Carper:

The U.S. is the global leader in carbon dioxide (CO_2) capture, utilization and sequestration (CCUS) research, development and deployment. Given the appropriate resources and regulatory environment, we will advance our technologies so that we can continue to use our abundant resources while minimizing our carbon footprint. Western Governors support the bipartisan Utilizing Significant Emissions with Innovative Technologies (USE IT) Act (S. 2602), which will facilitate development and deployment of CCUS infrastructure.

Western Governors have long supported advancement of carbon capture technology due to its environmental and economic benefits. S. 2602 directs the Environmental Protection Agency to support research on direct air capture and CO_2 utilization, with a focus on technologies that transform CO_2 into a product or product input with commercial value. The bill also clarifies that carbon capture and utilization projects and pipelines are eligible for the streamlined permitting process under the Fixing America's Surface Transportation (FAST) Act and directs the Council on Environmental Quality to develop guidance on reviews of CCUS projects and CO_2 pipelines.

Furthermore, WGA Policy Resolution 2017-01, *Building a Stronger State-Federal Relationship*, advocates for greater state representation on committees and panels advising federal agencies on scientific, technological, social, and economic issues. We are pleased that this bill requires the task force to include states (at their request) and to provide models for, and technical assistance to, states for CCUS projects and CO_2 pipeline regulation.

Thank you for your leadership in this area of crucial importance to our nation's economy, energy, and environment, as well as for your recognition that states have a critical role in promoting the development and utilization of carbon capture technologies. Please do not hesitate to contact us if we can be of further assistance.

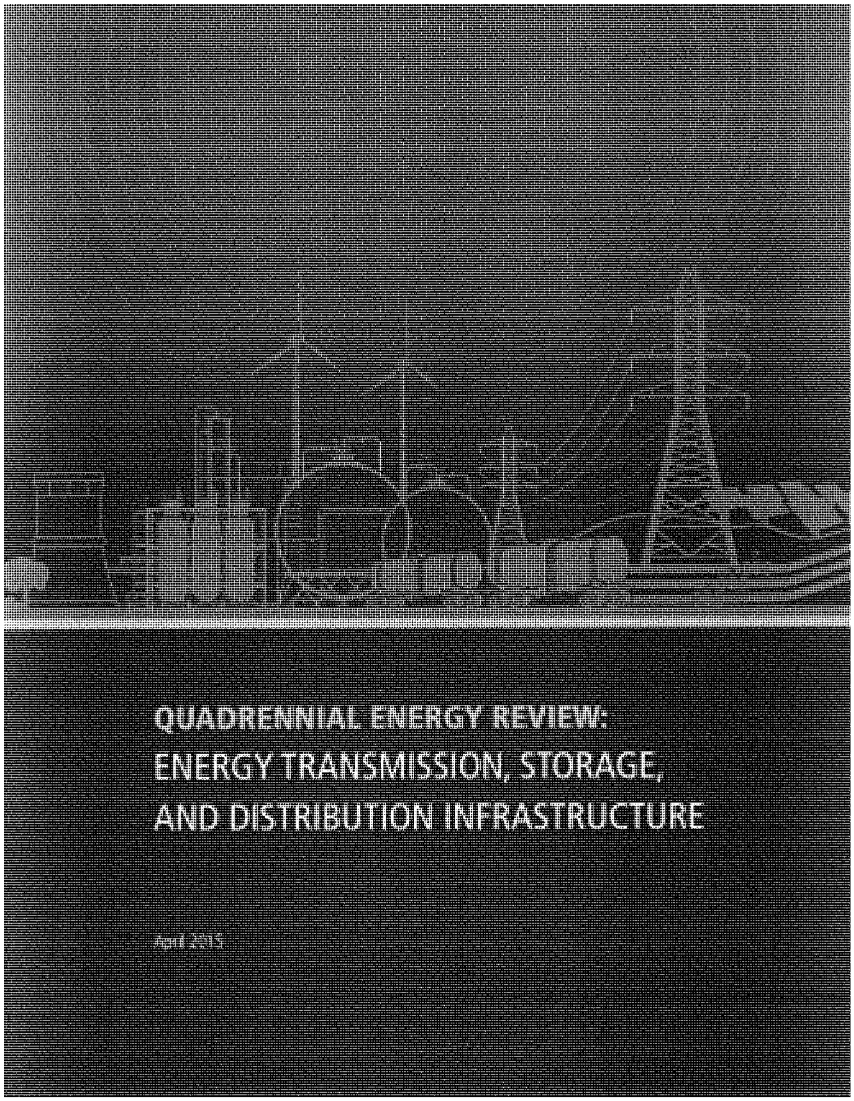
Sincerely,

Dennis Daugaard
Governor of South Dakota
Chair, WGA

David Ige
Governor of Hawaii
Vice Chair, WGA

CALL (303) 623-9378
VISIT 1600 Broadway
Suite 1700
Denver, CO 80202

WESTGOV.ORG


QUADRENNIAL ENERGY REVIEW:
ENERGY TRANSMISSION, STORAGE,
AND DISTRIBUTION INFRASTRUCTURE
April 2015

QUADRENNIAL ENERGY REVIEW

ENERGY TRANSMISSION, STORAGE, AND DISTRIBUTION INFRASTRUCTURE

April 2015

QER Recommendations

OTHER ENVIRONMENTAL ISSUES

As noted above, the Administration has a broad range of activities and proposed rules underway in the area of addressing oil spills, so further recommendations in that area are not needed at this time. Similarly, environmental controls on wastewater discharges from TS&D infrastructure are adequate. To continue to make progress on the handling and disposal of dredging materials and to address issues involving environmental data, we recommend the following:

Conduct research needed on dredging materials. The Army Corps of Engineers, in collaboration with other appropriate Federal agencies, should continue to undertake research and development on treating dredged material and then either beneficially using or disposing of it. As efforts continue—by the Federal Government and other stakeholders—to enhance shared infrastructures for energy commodity transport, focusing on waterway and port improvements, the amount of such material may grow substantially and pose a barrier to enhancing waterborne TS&D infrastructure.

Improve environmental data collection, analysis, and coordination. DOE should work with other Federal agencies to improve data and analysis on the environmental characteristics and impacts of TS&D infrastructures. This work should be designed to fill the host of data gaps on environment, safety, and public health issues with respect to TS&D infrastructure. DOE's activities should take into account the recent recommendations by the National Transportation Safety Board on data gaps related to natural gas pipelines.

CO_2 Pipelines: Enabling Infrastructure for GHG Emissions Reductions

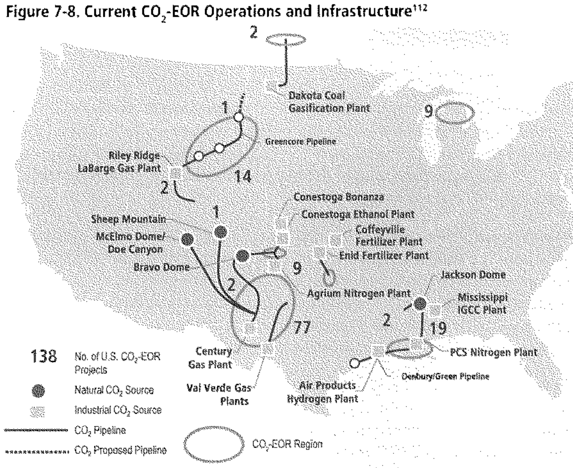
CO_2 pipelines are an important enabling infrastructure for reducing GHG emissions in the future. Carbon dioxide sequestration, particularly in connection with enhanced oil recovery (EOR),[ah] may involve moving CO_2 significant distances from power plants (or other sources) to the sequestration site or EOR field.

Spanning across more than 12 U.S. states and into Saskatchewan, Canada, a safe and regionally extensive network of CO_2 pipelines has been constructed over the past four decades. Consisting of 50 individual CO_2 pipelines, with a combined length of more than 4,500 miles (see Figure 7-8), these CO_2 transportation pipelines represent an essential building block for linking the capture of CO_2 from electric power plants and other industrial sources with its productive use in oil fields and its safe storage in saline formations. The Pipeline and Hazardous Materials Administration (PHMSA)[ai] is responsible for overseeing the safe construction and operation of CO_2 pipelines, which includes technical design specifications and integrity management requirements.

[ah] The injection of CO_2 gas into oil reservoirs at high pressure forces the CO_2 to mix with oil, which reduces the viscosity of the oil and ultimately increases the total cumulative volume of oil produced, thus the percentage of oil-in-place that is recovered.

[ai] While CO_2 is not considered a hazardous material by the Department of Transportation, CO_2 transportation pipelines are regulated under 49 C.F.R. § 195, Transportation of Hazardous Liquids by Pipeline.

Figure 7-8. Current CO_2-EOR Operations and Infrastructure[112]



U.S. regions with large-scale CO_2 pipeline systems currently in operation	Miles of Pipeline
Permian Basin (W. TX, NM, and S. CO)	2,320
Rocky Mountains (N. CO, WY and MT)	810
Gulf Coast (MS, LA and E. TX)	740
Mid-Continent (OK and KS)	480
Other (ND, MI, Canada)	215

The current CO_2 pipeline system has been built to deliver CO_2 for CO_2-EOR to oil fields in the Permian Basin of west Texas and eastern New Mexico. This system spans across more than a dozen U.S. states and into Saskatchewan, Canada.

The vast majority of the CO_2 pipeline system is dedicated to CO_2-EOR[aj] and connects natural and industrial sources of CO_2 with EOR projects in oil fields. In 2014, roughly 1,250 billion cubic feet of CO_2 (or 68 million metric tons) flowed through U.S. pipelines—roughly 80 percent of which is from natural (geologic) sources. In the next few years, several new industrial CO_2-capture facilities[ak] are expected to bring online another 1,100 billion cubic feet of CO_2, with nearly 600 miles of new pipeline by 2020. At that point, the portion of CO_2 from industrial sources would nearly exceed that from natural sources.

Currently, just more than 4 percent of total U.S. crude oil production is produced through EOR, and this is projected to increase to 7 percent by 2030.[113] Additionally, as recent trends[114] in CO_2 pipeline planning and construction have shown, there is considerable potential for low-cost CO_2 capture from ethanol refineries, other industrial facilities, and EOR in nearby oil production basins in regions of the country that do not yet have CO_2 pipeline networks in place. However, given the upfront capital costs associated with pipeline construction and the absence of policy incentives for reducing industrial carbon pollution, financial support would likely be needed to spur private investments in some regions.

A national carbon policy would create investment certainty and spur significant new investment in CO_2 pipeline infrastructure, creating incentives for electric power plants and other industrial facilities to reduce CO_2 emissions through carbon capture technologies and improving the economics for oil production through EOR.

[aj] A small fraction is used for other industrial uses, such as delivering CO_2 to the beverage industry.

[ak] For example, Air Products' PCS Nitrogen plant in Louisiana and Southern Company's integrated gasification combined cycle plant in Kemper County, Mississippi.

In a low-carbon scenario analysis case analyzed for the QER,[115] construction through 2030 would more than triple the size of current U.S. CO_2 pipeline infrastructure through an average annual build rate of nearly 1,000 miles per year.[al]

The regulation of CO_2 pipelines is currently a joint responsibility of Federal and state governments.[116] CO_2 transportation pipelines are subject to Federal safety regulations that are administered by PHMSA.[am] PHMSA directly oversees pipeline safety for all interstate lines, while intrastate pipelines are subject to state agency oversight (as long as the standards are at least as stringent as the Federal rules).[an] The Federal Energy Regulatory Commission and the Surface Transportation Board have determined that CO_2 pipelines are not within their jurisdiction.[117,118] Otherwise, requirements for siting (including the use of eminent domain), construction, and operations of CO_2 pipelines are largely handled at the state level. If a pipeline crosses Federal land, permits from the relevant Federal agencies (e.g., rights of way) and the accompanying environmental review under NEPA are required prior to siting and construction.[ao]

State laws that are specific to CO_2 pipelines, EOR, and underground storage are varied and generally limited to those regions with CO_2-EOR projects. Texas, for example, has several laws that pertain specifically to CO_2 for EOR and geologic sequestration. A CO_2 pipeline operator in Texas may exercise its right of eminent domain if it has declared itself a common carrier, which deems the CO_2 pipeline open to transport for hire by the public.[ap] Texas also has policy incentives, including a reduction in its severance tax rate by 50 percent for oil produced from EOR using anthropogenic CO_2.[119] The Wyoming Pipeline Authority has begun to plan for and establish corridors for future CO_2 pipelines.[aq] Rather than leave future pipeline planning up to individual operators, the Wyoming Pipeline Authority is seeking to assist pipeline developers through the pipeline construction process by serving as a facilitator and information provider to industry, state government, and the public.[120,121]

[al] The model projects 11,000 miles of new pipeline construction, which is more than half the scale that would potentially be needed by 2050, to accommodate climate stabilization scenarios modeled by Dooley et al. "Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks." Energy Procedia. 1(1). p. 1,595–1,602. February 2009.

[am] While CO_2 is not considered a hazardous material by the Department of Transportation, CO_2 transportation pipelines are regulated under 49 C.F.R. § 195, *Transportation of Hazardous Liquids by Pipeline*. This distinction is made due to the nature of the transportation pipelines, which carries the highly pressurized CO_2 in a liquid phase similar to other hazardous material transportation pipelines. Smaller CO_2 distribution lines, which transport the CO_2 from the trunk line to individual wells, generally are not subject to Federal safety standards.

[an] Other Federal agency requirements, depending upon the area involved, can include threatened and endangered species consultations and permits for wetlands fill. Currently, the Bureau of Land Management regulates CO_2 pipelines under the Mineral Leasing Act as a commodity shipped by a common carrier. See: 30 U.S.C. § 185(r); Buys and Associates, Inc. "Environmental Assessment for Anadarko E&P Company L.P. Monell CO_2 Pipeline Project." Prepared for the Department of the Interior, Bureau of Land Management. February 2003. See also: U.S. Court of Appeals. "970 F. 2d 757 – Exxon Corporation v. Lujan." July 23, 1992.

[ao] Currently, the Bureau of Land Management regulates CO_2 pipelines under the Mineral Leasing Act as a commodity shipped by a common carrier. See: 30 U.S.C. § 185(r); Buys and Associates, Inc. "Environmental Assessment for Anadarko E&P Company L.P. Monell CO_2 Pipeline Project." Prepared for the Department of the Interior, Bureau of Land Management. February 2003. See also: U.S. Court of Appeals. "970 F. 2d 757 – Exxon Corporation v. Lujan." July 23, 1992.

[ap] Texas Natural Resources Code Annotated § 111.019(a) (West); Texas Natural Resources Code Annotated § 111.002(6) (West).

[aq] The Wyoming Pipeline Authority recently announced its application to the Bureau of Land Management for a Wyoming Pipeline Corridor Initiative. See: Wyoming Pipeline Authority. "Wyoming Pipeline Corridor Initiative." www.wyopipeline.com/projects/wpci/. Accessed January 26, 2015. As described by the Wyoming Pipeline Authority, the initiative is a proposed pipeline right-of-way network designed to connect sources of CO_2 to oil fields that are suitable for EOR. The initiative, as proposed to the Bureau of Land Management, would establish 1,150 miles of corridors on Federal lands in Wyoming. The Wyoming Pipeline Authority would be the project proponent receiving the right of way, which would then be assigned to individual project proponents, which would construct and operate pipelines. See: Wyoming Pipeline Authority. "Wyoming Pipeline Corridor Initiative Plan of Development." May 2014. www.wyopipeline.com/wp-content/uploads/2014/06/WPCI_POD_may_2014.pdf. Accessed January 27, 2015.).

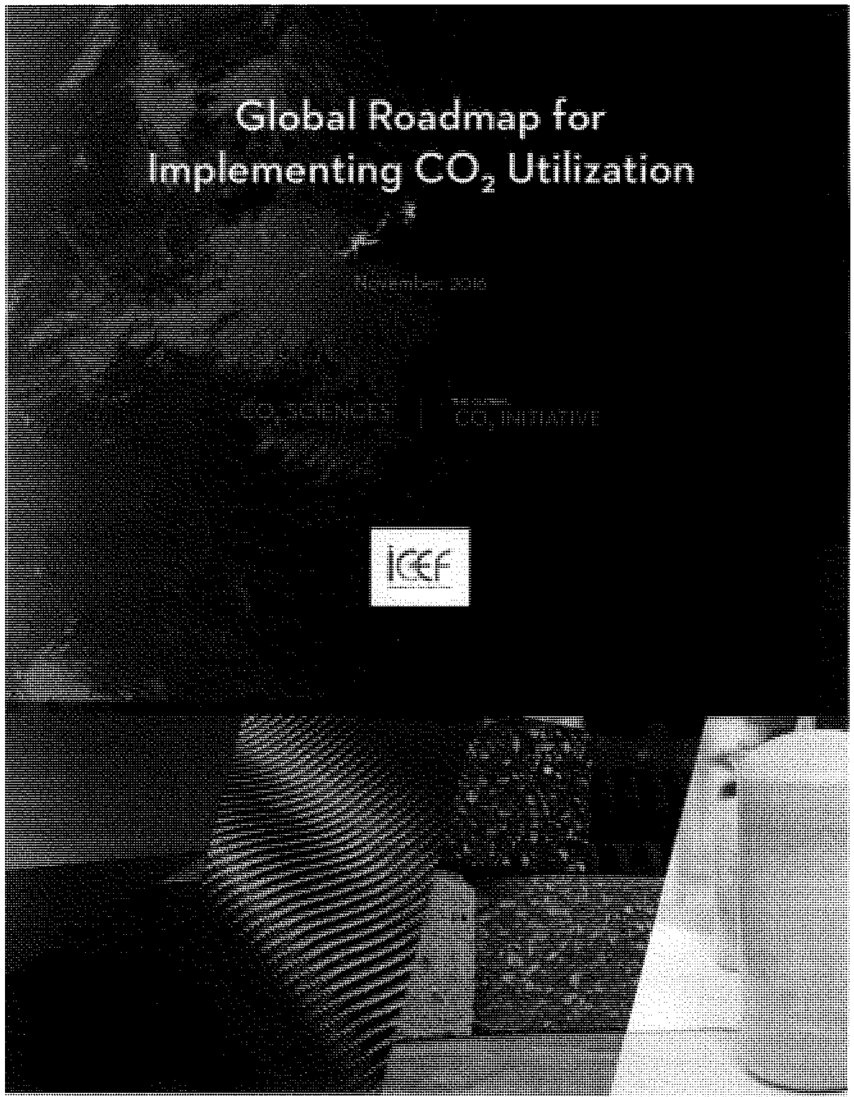
QER Recommendations

CO_2 PIPELINES

Meeting U.S. GHG emission goals will require a more concerted Federal policy, involving closer cooperation among Federal, state, and local governments. The development of a national CO_2 pipeline network capable of meeting Federal policy initiatives should build on state experiences, including lessons learned from the effectiveness of different regulatory structures, incentives, and processes that foster interagency coordination and regular stakeholder engagement. To expand current Federal efforts to meet these challenges, we recommend the following:

Work with states to promote best practices for siting and regulating CO_2 pipelines. Improving CO_2 pipeline siting will improve safety and environmental protection. Several states have made substantial progress on this front and provide potential models for other states. DOE, in cooperation with Federal public land agencies, should take a convening role to promote communication, coordination, and sharing of lessons learned and best practices among states that are already involved in siting and regulating CO_2 pipelines, or that may have CO_2 pipeline projects proposed within their borders in the future.

Enact financial incentives for the construction of CO_2 pipeline networks. Expanding and improving CO_2 pipeline infrastructure could enable GHG reductions through carbon capture, utilization, and storage, while promoting domestic oil production through EOR. Providing incentives such as grants or tax incentives will spur activity to link low-cost CO_2 from industrial sources to nearby oil fields and saline storage formations. The President's Fiscal Year 2016 Budget Request proposes the creation of a Carbon Dioxide Investment and Sequestration Tax Credit in order to accelerate commercial deployment of carbon capture, utilization, and storage, as well as to catalyze the development of new carbon capture, utilization, and storage technologies. Specifically, the proposal, part of the President's POWER+ Plan to invest in coal communities, would authorize $2 billion in refundable investment tax credits for carbon capture technology and associated infrastructure (including pipelines) installed at new or retrofitted electric generating units that capture and permanently "sequester" CO_2.[122] Congress should enact this proposed tax credit.


Global Roadmap for
Implementing CO_2 Utilization
November 2016
CO_2 SCIENCES
CO_2 INITIATIVE
ICEF

Acknowledgements

We are deeply grateful to the Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO), Japan, for launching and supporting the ICEF Roadmap Project of which this is a part. NEDO commissioned CO_2 Sciences to conduct this roadmap on CO_2 Utilization.

We acknowledge, with great appreciation, the support from The Lemelson Foundation and the RK Mellon Family Foundation for this work.

TABLE OF CONTENTS

Executive Summary

Background: Confronting an urgent challenge

This study presents a roadmap for commercialization potential of carbon dioxide utilization (CO_2U) technologies through 2030.

A significant reduction of carbon emissions is crucial to avoiding enormous economic and environmental damages. Renewable power generation and other low- and zero-carbon technologies are an important part of the solution. Carbon negative technologies (those that reduce atmospheric CO_2 concentrations) are also needed to achieve the agreed global goal of keeping temperature increases well below a 2°C increase over pre-industrial levels. CO_2U technologies can play an important role, but have not yet received much attention nor have their potential been explored in a comprehensive fashion.

A detailed market assessment study that was completed earlier in 2016 by GCI found that CO_2U has the potential to reduce carbon emissions over 10% by 2030 (GCI's website provides more details). One goal of this work is to create greater awareness concerning the potential for developing and deploying profitable, emissions-negative CO_2U technologies on a mass scale.

The study: Identifying and forecasting market opportunity

This study analyzes the current state of CO_2U technology, assessing almost 180 global technology developers on the basis of their technology feasibility, readiness, markets and momentum.

Research revealed that significant progress in CO_2U has been made in the past five years (2011-16), with many technologies shown to be scalable. Momentum is favorable for four major markets – **building materials, chemical intermediates, fuels** and **polymers.**

Within those markets, the study further identifies eight product categories to pursue, based on the maturity of their technology, market promise, and potential impact on the mitigation of carbon emissions. Those categories are:

- **Building materials**
  - Concrete
  - Carbonate aggregates
- **Chemical Intermediates**
  - Methanol
  - Formic acid
  - Syngas
- **Fuels**
  - Liquid fuels
  - Methane and
- **Polymers** (polyols and polycarbonates)

Funding and incentives are necessary for most of these products to accelerate development and achieve full-scale commercial roll out capability. This study presents a commercialization roadmap for each of the eight categories.

The roadmap was developed with three dimensions in mind: policy, technology and market. Those three dimensions greatly impact the path and speed to commercialization. The results are presented by considering the business as usual case (status quo), which is also the worst case scenario. The best case represents likely outcomes if swift strategic actions are taken to remove barriers and mitigate risks.

Strategic actions to accelerate CO_2U commercialization

Best-case scenarios in the forecast would support and hasten commercialization of CO_2U-derived products across the eight identified product categories. These optimal scenarios will be driven by the implementation of strategic actions recommended in this study. They are:

Technology

- Research to improve catalysis for CO_2 reduction must be funded. The needed substantial increase in funding should come from government, corporations and private institutions.
- Research in improving electrolysis to produce hydrogen must be funded.
- Government funding is critical for exploring early stage technologies and creating future options for CO_2U technologies.

Market

- Collaborations among research institutes, start-ups, governments and corporations for process integration of CO_2 conversion, hydrogen generation, and carbon capture must be funded.
- A CO_2 pipeline infrastructure is critical for the deployment of CO_2U technologies at scale. This opportunity creates new business options/models and creates a new value chain critically needed to scale CO_2U technologies.

Policy

- Substantial increase in government funding for R&D
- Carbon pricing, either through emissions trading or tax mechanisms.
- Tax and other incentives
- Mandates
- Government procurement
- Government support for certification and life cycle assessments.

Life cycle analysis (LCA)

The climate benefit of a CO_2U product depends not only on how much CO_2 the product contains. The amount of CO_2 emitted in making the product also matters. So does the amount of CO_2 emitted in making any competitive products that may be displaced. To the extent that climate benefits are a goal of those promoting CO_2U products, LCA is essential. Considerable work is needed to standardize LCA methodologies for CO_2U. The Global CO_2 Initiative is planning a major project in 2017 to bring together stakeholders to address this issue.

CO_2U's potential: Profitable markets and mitigated CO_2 emissions

At full scale, 5 CO_2U products (see below) could create a market over US $800 billion by 2030. CO_2U has the potential of utilizing 7 billion metric tons of CO_2 per year by 2030 – the equivalent of approximately 15 percent of current annual global CO_2 emissions. CO_2U can create new business opportunity and simultaneously contribute to CO_2 reduction. Both conclusions are consistent with an earlier market study that the GCI commissioned concluding that CO_2U can remove over 10% of the emitted CO_2 and represents an annual market opportunity of $0.8-1.1 Trillion.

Roadmap to 2030: Market size and mitigation impact

Market size and CO_2 reduction potential can be significantly impacted by taking action now. Below are examples from five markets. For example, the market for CO_2-based fuels can be quadrupled by 2025 (from $50b to $200b), increasing the CO_2 reduction by 15 fold (from 0.03b tons to 0.5b tons). Similarly, decisive and timely action can have a major impact on both the market size and potential to mitigate CO_2 emissions for other CO_2-based products.

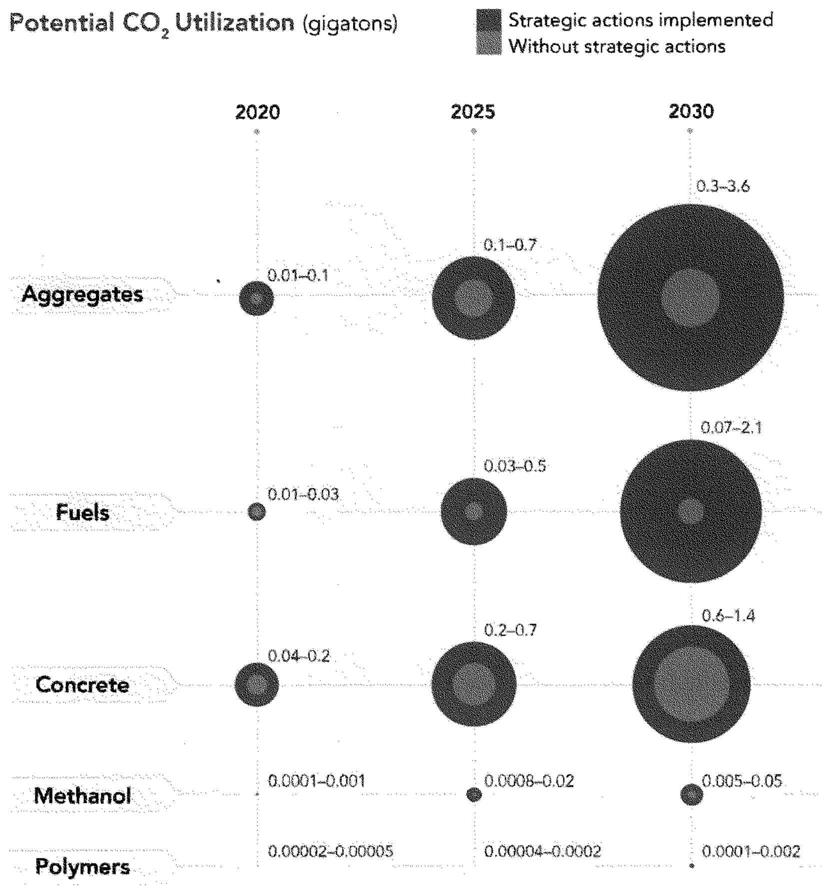


Figure 0.1: Potential CO_2 reduction due to implementing strategic actions

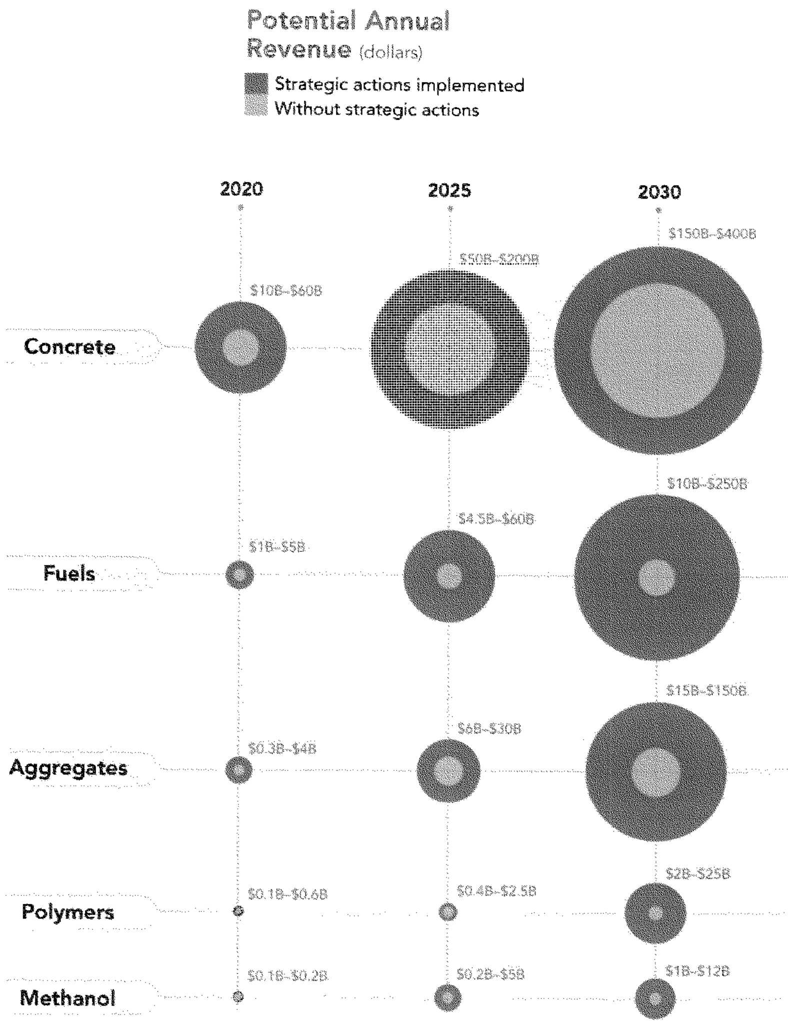


Figure 0.2: Potential increase in market size due to implementation of strategic actions

I. Background and goals of the study

The Grand Challenge of the Planet: Reducing carbon emissions

Over 35 GT of CO_2 are emitted into the atmosphere every year, altering the Earth's climate system and threatening catastrophic damages in the years ahead. The implications of climate change are massive:

- Economic and political instability
- Food and clean water scarcity
- Health or survival risks for all animal species
- More volatile and extreme weather
- Loss of landmass

The United Nations' December 2015 Paris COP21 conference – in which 195 sovereign nations, in both the developed and developing world, agreed on a framework that committed each to taking action against climate change – was judged historic on several levels.

After Paris: A new impetus for zero-carbon research

Among other covenants, the signers of the Paris accord agreed to:

- Limit global temperatures to "well below" 2° C (3.6 F) above pre-industrial levels and "endeavor to limit" them even more, to 1.5° C, between 2015 and 2030.
- Restrict the amount of greenhouse gases emitted by human activity to the levels that trees, soil and oceans can naturally absorb, beginning at some point between 2050 and 2100.
- Review each country's contribution to cutting emissions every five years, enabling them to address the urgency of the challenge.

Similar conclusions have been voiced by the IEA and IPCC experts about the critical need for carbon-negative technologies. Figure 1.1 shows that continuing to deploy energy efficiency and renewable power generation will limit the increase in temperature rise but we may end up with a 4°C increase. We need to have CO_2 absorbing solutions. Of course, plants are nature's great weapon, however, they are slow and we need solutions that can absorb CO_2 at a much faster rate. Figure 1.2 presents the two other options: Carbon Capture and Sequestration (CCS) and Carbon Capture and Utilization (CCU).

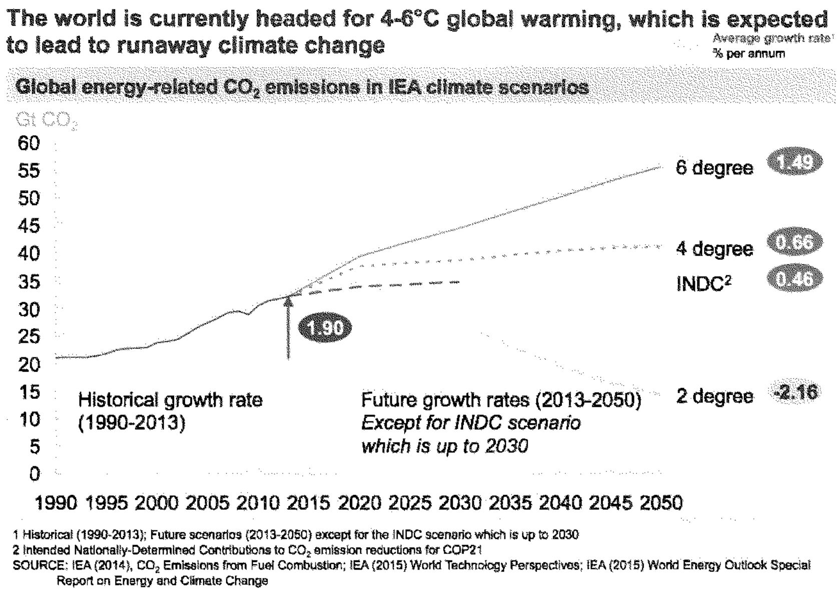


Figure 1.1: The need for carbon-negative technologies to limit temperature increase

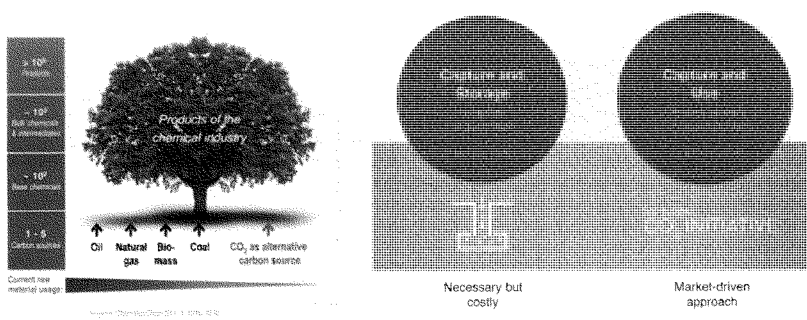


Figure 1.2: Examples of carbon-negative technologies

Carbon dioxide utilization (CO_2U)

CO_2U differs from prevalent carbon capture and storage (CCS) solutions in one basic way. CCS captures CO_2 emissions exclusively for storage, usually reinjecting them into geological formations; the goal of CO_2U is to convert CO_2 into end products that in turn are emissions-neutral or negative.

The development of CO_2U technologies is being promoted for three key reasons:

- It can be used for mitigation to meet internal or external standards for CO_2 emissions for carbon dioxide producers.
- It would allow for carbon dioxide to be used as an alternative to fossil-fuel-derived feedstocks.
- It can contribute to achieving national or global aims for decreasing carbon emissions.

As this report and other studies show, CO_2U has been the focus of a myriad of research tracks investigating multiple conversion processes and potential markets and end products in recent years. However, the Paris agreement and recent private and public initiatives have added new urgency and momentum to fundamental R&D efforts that will lead to more rapid commercialization of products that use CO_2 conversion to reduce carbon emissions.

These initiatives include the Carbon XPRIZE, a US $20 million global competition designed to "incentivize and accelerate" CO_2U solutions development, and the SCOT (Smart CO_2 Technology) project, a public-private-academic collaboration community based in the European Union and the Global CO_2 Initiative.

This study: Presenting a global CO_2U commercialization roadmap through 2030

This is a roadmap of the global commercialization potential of carbon dioxide utilization technologies through 2030. CO_2U technologies use CO_2 (pure or as emitted) either unchanged (e.g., enhanced oil recovery/EOR, carbonated drinks, supercritical CO_2 solvents) or by converting it into a value-added end product like a fuel or a chemical.

This study focuses on products **derived by conversion of CO_2**. Identifying the most mature, economically promising and impact-mitigating applications for CO_2 conversion is critical to driving further investment and innovation in catalytic fashion. That investment will accelerate time-to-market for solutions that capture and reduce global CO_2 emissions, and offer sustainable climatological benefits.

Conversion challenges have historically created a bottleneck in the rapid development, production scaling, and commercialization of CO_2U-based products. Fundamental challenges have included:

- CO_2 has been more difficult and expensive to obtain than the petroleum, coal and natural gas sources of raw material for most chemical manufacturing. This concern has been amplified in 2015-16 by the fall in global petroleum prices.
- Converting a stable CO_2 molecule to a useful chemical has generally required lots of energy, typically generated from fossil-fuel sources – thus potentially causing a net *increase* in CO_2 emissions.

- It has been costly to provide the hydrogen feedstock necessary to create the desired end products.
- It's therefore been difficult to assess the true potential (and by when) of CO_2 mitigation, and tie that to policy and funding decisions.

However, greatly increased attention to CO_2 conversion by both developers and policy-makers has produced new research, initiatives and collaborations that have the potential to address these challenges. These advances include, but aren't limited to:

- **The development of catalysts** that enable new technology pathways and make conversion processes more efficient.
- Consideration of renewable energy sources (solar or wind energy) to power CO_2 conversion. The reduction in the cost of renewable power generation technologies is a major parameter that is making CO_2U more feasible than it was 5 years ago.
- **Advances in mineralization** technologies to produce building materials.
- **Advances in photocatalytic reduction** of CO_2, which uses light directly in conversion.

This study identifies:

- **Product categories and sub-categories** with the most realistic deployment prospects based on policy considerations, analysis of technology and forecasts of market potential.
- **Current barriers** to development and potential means of overcoming them. Criteria include an assessment of conversion technology pathways and their relative impact on CO_2 reduction, potential market demand and geographical/geopolitical impacts on development and commercialization.
- **Centers of activity** in CO_2U research and development.
- Projected timelines for deployment.

This ten-to-fifteen-year roadmap will enable decision makers and key stakeholders to make appropriate and informed funding/investment decisions regarding technology development and commercialization of CO_2U technologies. Its ultimate focus is on clearly prioritized market entry. The study will also show how policy/market/technology levers can be used to accelerate market penetration.

II. Overview of findings

Six major markets identified

We have identified and analyzed 180 global developers who are actively engaged in CO_2U and, ultimately, the development of end products.

A database of CO_2U developers was compiled from multiple sources: conference proceedings, the SCOT Project and PitchBook databases, patent searches, consortium websites, and in-house knowledge. These entities include start-ups, mid-sized companies, corporations, consortia and research institutes.

The study defined six markets or product clusters by number of active developers, conversion technology pathways, and targeted end products:

- **Algae** (processed separately to create biofuels or food additives)
- **Building materials** (for conversion to carbonates or infusion of CO_2 into materials)
- **Chemical intermediates** (such as methanol, syngas, formic acid and malic acid)
- **Fuels** (mainly for methane and alcohol)
- **Novel materials** (such as carbon fiber)
- **Polymers** (e.g., polycarbonates, polyurethane and PHA)

Concentration of active developers

We found that the number of developers was especially concentrated in three of these segments:

- Chemical intermediates
- Fuels
- Building materials

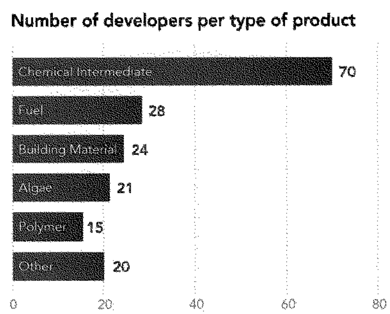


Figure 2.1: Number of active developers by end-product market cluster.

The study also identified and analyzed a wide range of technology pathways. Catalytic conversion, mineralization and electrochemical conversion are the most widely studied pathways based on number of developers (see Figure 2.2). Time-to-commercialization depends heavily on this concentration of research efforts.

Catalyst development is critical in the drive to make conversion processes more efficient; research in this field builds upon decades of work in catalysis in general. Other processes – photocatalytic, photosynthesis and algae production – focus directly on using sunlight as a low-cost energy source for conversion.

The study concurrently identified and analyzed the strengths and weaknesses of six technology pathways that are being used, or are being considered for use, in the conversion of CO_2 to commercial products: **catalytic, electrochemical, fermentation, mineralization, photocatalytic** and **photosynthetic.**

Mineralization, catalytic conversion, and electrochemical processes have the highest number of developers and researchers, which will help propel these technologies forward.

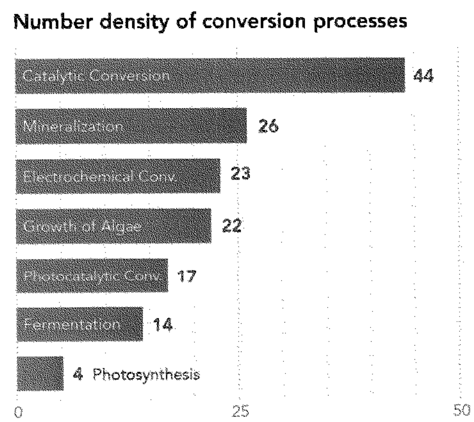


Figure 2.2: Number of developers by CO_2U technology pathway. (Some developers serve more than one market.)

Catalytic conversion and mineralization are the most well developed pathways. Mineralization of CO_2 is the only conversion technology pathway currently being used for building materials. Catalytic conversion is widely used for production of chemical intermediates, fuels, and polymers.

Fermentation is less established as a process for CO_2 conversion. Two companies at scale, LanzaTech and Newlight Technologies, respectively, use carbon monoxide and methane as the main carbon sources for their processes, respectively. At this time, photocatalytic and electrochemical conversion technologies require more development and evidence of scalability.

Consortia and collaborations have been founded, notably in Europe, to fully utilize the impact of CO_2U technology on CO_2 mitigation. In addition, the study found a significant increase in the number of new publications on conversion of CO_2 via catalytic reduction. More than 600 papers on this topic were published by academic and government entities on this topic in 2015, compared to about 350 two years earlier.

Maturity and momentum of each market

Armed with direct interviews with over a dozen developers as well as secondary research, the study applied a technology readiness level (TRL) scale of 1 (least) to 9 (most) to determine the relative stage of development and create a framework for expected time-to-market.

The TRL applied in this study ranges from basic and applied research, proof of concept and laboratory testing (stages 1-5), to prototyping, piloting and final development (stages 6-8), to full-scale deployment/market introduction (9).

We also applied standardized rubrics to better quantify the mitigation potential and technology fit of each market.

Four markets recommended for funding and investment

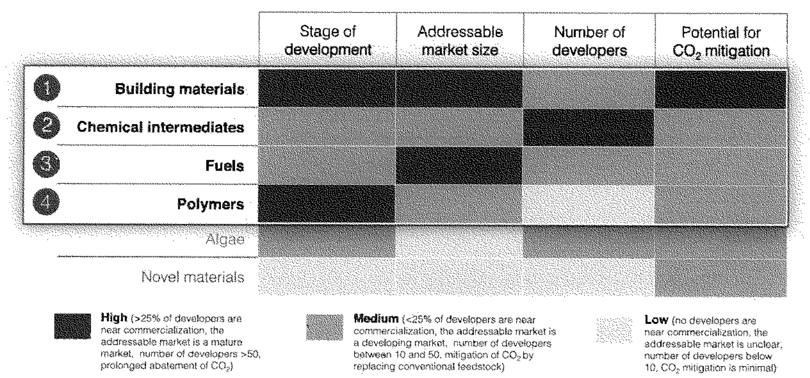


Figure 2.3. The study has identified four markets that offer the best opportunities for support and investment. The assessment is based on an analysis of active developers, first-person interviews, in-house expertise and scientific momentum.

Another important consideration that was factored in our analysis is "permanence". Permanence refers to the period during which CO_2 is stored in a product. Products such as cement can fix CO_2 in solid form for centuries if not longer. Products such as polymers may decompose in years or decades, returning CO_2 to the atmosphere and minimizing the benefits of using the CO_2 in those products.

A related concept is displacement. If CO_2 is used as a feedstock for liquid fuels, that can displace the extraction of petroleum that would otherwise be used to produce those liquid fuels. (This will depend on market conditions, but in many circumstances today that is the most likely result of using CO_2 as a liquid fuel feedstock.) To the extent CO_2 in product creation displaces the extraction of petroleum, there is a very high CO_2 benefit because that petroleum remains underground and is not combusted.

This study recommends further investment in four clusters or markets – **building materials, chemical intermediates, fuels** and **polymers** – based on the following summary of findings:

- **Building materials**
    - It's thermodynamically favorable to make carbonates and requires less energy input to achieve. This makes this market attractive for developers because the technology is more readily scalable today.
    - The two main CO_2U technologies used in building materials are mineralization for carbonate aggregates and the use of CO_2 to cure concrete. Key innovators include Carbon8, Solidia Technologies and CarbonCure. Aggregates are coarse particles used in construction and can be gravel or crushed stones or other similar materials.
- **Chemical intermediates**
    - There are many research projects underway to make conversions more efficient; for example, by developing more effective catalysts which could offer breakthroughs in conversion efficiencies.
    - Niche markets have been commercialized; one example is the production in Iceland of methanol using geothermal energy. Methanol, syngas and formic acid are the most widely developed. (Please note that some developers categorize these chemicals under *fuels*.)
- **Fuels**
    - Production of fuels from CO_2 fits within the macro trend toward low carbon fuels. CO_2 competes with petroleum-derived feedstock, as well as bio-based feedstocks such as sugar cane.
    - Fuels represent one of the largest potential markets for CO_2U technology given the many global mandates for greener alternatives.
- **Polymers**
    - Several production routes, such as polyhydroxyalkanoates and polycarbonates, have already been commercialized for high-value products in niche markets.
    - Key developers include Covestro, Novomer and Asahi Kasei.

Two markets eliminated from further consideration

The study also eliminated two markets, **algae** and **novel materials**, from further consideration.

- **Algae** is not yet cost-effective due to high downstream processing costs. Although algae biofuel projects received over US $1 billion in funding in 2009-2010, largely for development and pilot-scale testing, investment began to dry up in 2011. The category has been hampered by intrinsic limitations in algae production and a weak (to date) business case for production at scale. Some projects remain active and some new entrants have been identified. However, a majority of players from 2011 have exited the market through bankruptcies (such as Abengoa, Independence Bio Products and A2BE Carbon Capture) or strategic pivots, while others are idle.

- **Novel materials** have to this point received very limited developer focus. While we strongly believe that such products can have significant impact on CO_2 reduction, there is a great uncertainty in time to market and scale. The case for CO_2 to carbon fiber is a prime example. The study identified one research effort (George Washington University) for CO_2 conversion to **carbon fiber**, and it is at a very early-stage of development. If the new process can make fibers at lower cost, then emissions reductions can occur in three ways:

    - Use of a low-carbon-footprint carbon fiber product (assumes no change in market penetration).
    - Greater use of carbon fibers in additional markets (assumes increase in market penetration rates).
    - Replacement of steel by carbon fiber. This will have a significant impact on overall emissions since steel contributes 6.7% to global emissions; there would be associated benefits from reducing fuel use in transportation and freight sectors due to light-weighting.

However, we recognize that there are a number of technological barriers that need to be overcome to attain such potential and for the purpose of this study market estimates are not included. We strongly believe that funding of this area is critically important given the game-changing nature of this technology option.

III. Momentum within recommended markets

Eight sub-categories identified

We further segmented each recommended market to identify sub-sectors: end-product categories with the earliest and highest likelihood of commercialization and success. Differentiation was based on three major considerations:

- **Concentration of developers:** The study considered both the number of developers in a segment and how far along they were on the path to commercialization those developers were. Success of commercialization was linked to:
    - Relatively low energy requirements for conversion technology pathway.
    - Simplicity of reaction mechanisms or processes.
    - Size of potential markets.
- **Market Dynamics:** The study also assessed the progress of individual developers towards commercialization in the 2011 to 2016 timeframe.
    - It considered how many development efforts were at an early stage in 2011 and then progressed, stalled or were disbanded.
    - It also considered the growth or decrease in the number of developers over this time frame.
- **Outlook:** It forecast how long it would take to bring technologies in each segment to scaled production, while being cost competitive with incumbent solutions.

Based on these criteria, the study identified eight promising product categories within the four markets:

- **Building materials**
  1) Concrete
  2) Carbonate aggregates
- **Chemical intermediates**
  3) Methanol
  4) Formic acid
  5) Syngas
- **Fuels**
  6) Liquid fuels
  7) Methane
- **Polymers**
  8) Polyols and polycarbonates

Visualizing CO_2U innovation momentum, 2011-16

To gain a greater understanding of the dynamic progress among CO_2U development organizations during the past five years, we plotted their progress in technology and commercial innovation and CO_2 mitigation potential using a standard weighting system.

- The **technology score** (vertical or Y-axis) is weighted based on (in descending order) technology value, competitive landscape, IP strength and regulatory factors.
- The **commercial development score** (horizontal or X-axis) is weighted based on (in descending order) TRL (technology readiness level), developer base and commercial maturity.
- The **mitigation potential** (bubbles) is weighted based on (in descending order) market size, ease of set-up and extent to which CO_2 is used as feedstock.

We then compared the status of developer organizations in 2011 vis-à-vis 2016. Those followed from 2011 were color-coded based on their 2016 status.

- **Green** = Active
- = Strategic pivot
- **Red** = Discontinued
- **Gray** = Idle or unknown

Building materials: Significant progress, immediate opportunity

The study found that the use of CO_2U in concrete curing represents an immediate opportunity. Moreover, with additional allocated resources, building materials can have a significant mitigation impact on CO_2 emissions. The study found:

- **Concentration of developers:** A relative high density of developers, with many near commercialization and a relatively low number in early stage. Two significant factors drive the success of commercialization:
  - Relatively little energy is required for carbonation.
  - Concrete made by curing with CO_2 has better performance characteristics than traditional curing methods.

- **Market Dynamics:** Developers were able to move from pilot to commercialization in both the concrete and carbonate aggregates segments. Overall:
  - Several early-stage entities disappeared because they were not able to develop a product beyond pilot stage.
  - Several new developers focusing on carbonation to produce aggregates have entered the market in the last five years

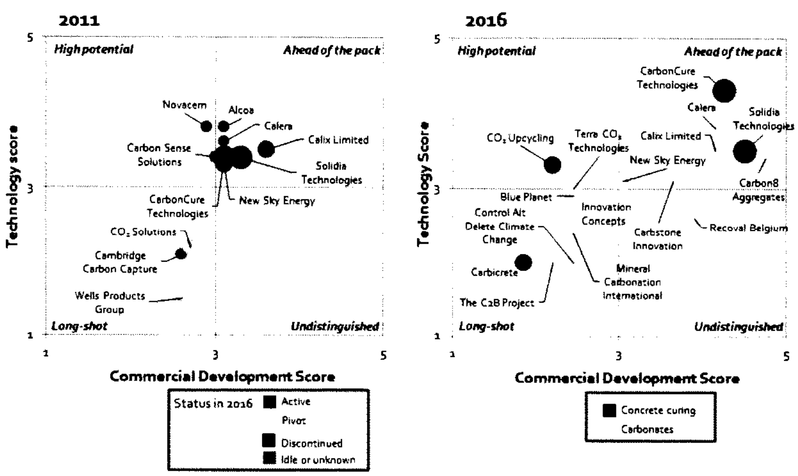


Figure 3.1: A visualization of the CO_2U building materials market, 2011 and 2016.

Chemical intermediates: Long-term opportunities; those with fuel applications are closest to commercialization

In general, the study found limited progress in the chemical intermediates market over the past five years due to lack of incentives and concerns about economic feasibility. Those products that can also be used as fuels or in fuel production – methanol, formic acid and syngas – offer the best opportunity. The study found:

- **Concentration of developers:** A low number are near commercialization, with many in early stages. The most widely developed products are CO (syngas), methanol and formic acid, for three major reasons:
  - Their reduction reactions are less complicated than those for other potential end products within the chemical intermediates market.
  - They can be used as chemical intermediates and as fuels or precursors to fuels.
  - Governments have incentivized fuel production from CO_2 to lower carbon emissions, but this policy has not been the case for the production of chemicals.

- **Market Dynamics:** Very few developers moved from pilot to commercialization stage for all market segments. The number of start-ups investigating solutions for energy-efficient conversion of CO_2 has increased dramatically, with most start-ups tending to focus on catalysis and conversions by reduction.

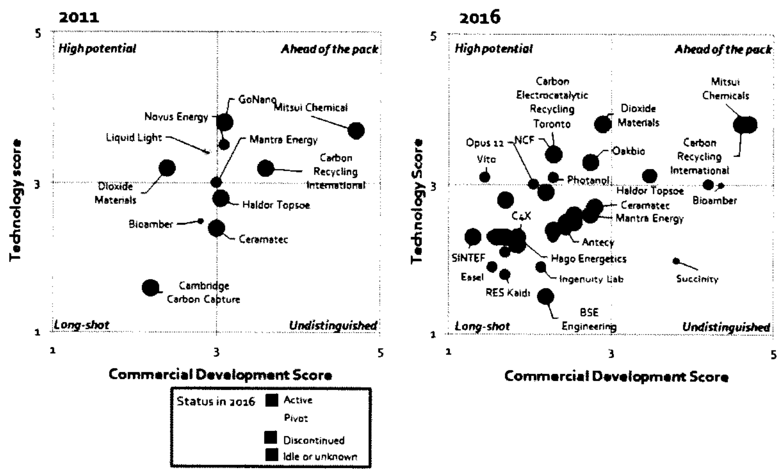


Figure 3.2: A visualization of the CO_2U chemical intermediates market, 2011 and 2016.

Drilling deeper, a further analysis of the methanol, formic acid and syngas product categories reveals:

- **Concentration of developers:** There are currently very few methanol developers, but two companies (Mitsui Chemical and Carbon Recycling International) have been identified with commercialized technology; in syngas and formic acid, the study identified multiple early-stage efforts focusing on conversion by catalysis.

- **Market Dynamics:** Across all market segments, very few developers moved from pilot to commercialization stage.
    - Several startups have been formed for the three markets, indicating potential growth. Many are developing technologies for chemical production.
    - The focus of most developers of syngas from CO_2 is on using excess energy (e.g., from chemical or steel plants) to produce syngas that can be converted to a different product by another process.

Fuels: Two sub-categories are at – or near – commercialization

Liquid fuels: Ready to produce at scale

Significant progress within the liquid fuels sub-category during the last five years shows that the technology is primed for production at scale. The study found:

- **Concentration of developers:** Four developers are near commercialization or have already commercialized CO_2U; LanzaTech is able to produce in scale.
  - LanzaTech converts carbon monoxide into ethanol, hence the low impact shown on the CO_2 mitigation score.
  - Methanol from CO_2 is closest to production in scale.

- **Market Dynamics:** Development has progressed relatively quickly for liquid fuels due to available government funding for projects and mandates for renewable fuels.
  - Stage of development went from pilot testing in the lab in 2011 to pilot testing at commercial scale in 2016.
  - The focus of developments has been on integrating CO_2 capture, renewable energy supply, hydrogen generation and CO_2 conversion in the case of methanol and on efficient (multi-step) conversion of CO_2 into fuels in the case of other liquid fuels.
  - Europe is leading because it has set targets to create a low-carbon-emission mobility economy.

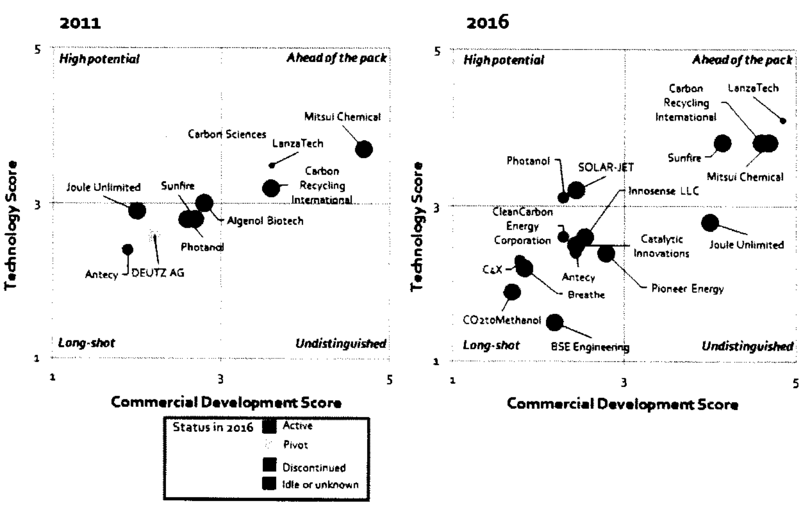


Figure 3.3: A visualization of the CO_2U liquid fuels market, 2011 and 2016.

Methane: Significant technological progress

Progress has been especially pronounced in Europe because of funding support. However, the low price of natural gas poses a significant competitive challenge. Additionally needing to add 4 Hydrogen molecules while eliminating 2 Oxygen molecules makes such development extremely energy intensive.

- **Concentration of developers:** Three CO_2U methane developers were found to be near commercialization.
  - Although the processes have been shown to be at scale, it remains to be seen if they will be cost-effective without subsidized funds.

- **Market Dynamics:** Development has been relatively fast for the methane sub-category compared to the others due to funding and collaborations in Europe.
  - Stage of development went from pilot testing in the lab in 2011 to pilot testing at commercial scale in 2016.
  - Focus of collaborations is on integrating CO_2 capture, renewable energy supply, hydrogen generation and CO_2 conversion into gaseous or liquid fuels.
  - Europe is leading because it has set targets to create a low carbon-emission mobility economy.
  - Projects often focus on the use of overcapacity of electricity or excess heat from industrial plants.

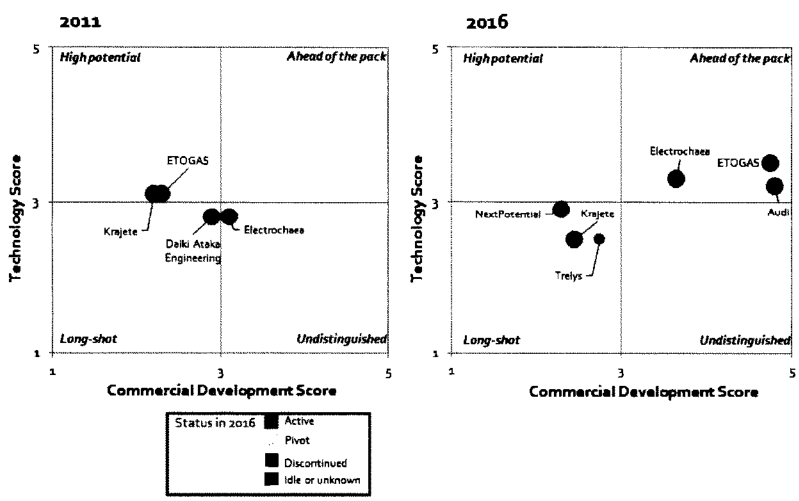


Figure 3.4: A visualization of the CO_2U methane market, 2011 and 2016

Polymers: A dearth of incentives, and startups

The creation of polymers through CO_2U is possible, but not yet economical. A limited number of developers are investing in it, but lack of incentives is inhibiting the entry of startups. The study found:

- **Concentration of developers:** Several are near commercialization, but there are very few early-stage developers.
  - Several companies have shown that polymers from CO_2 can be produced at scale.
  - Most companies have focused on polycarbonates and polyols (used to produce polyurethane). These companies were able to build on years of expertise in catalysis to commercialize their CO_2U technology. This allows developers to replace technology that uses dangerous phosgene gas.
  - Some developers are corporations (e.g., Covestro and Asahi Kasei) that have used their know-how in catalysis to develop commercial pilot plants for producing polymers from CO_2.
  - Production capacity remains a fraction (less than one percent) of the current capacity available to develop polymers from conventional feedstocks.

- **Market Dynamics:** Developers have successfully moved from lab and pilot to commercialization stage. However, the lack of new initiatives indicates that follow-up projects from those developers and competing companies will be rare – most likely due to the current relatively high cost of polymers made from CO_2.

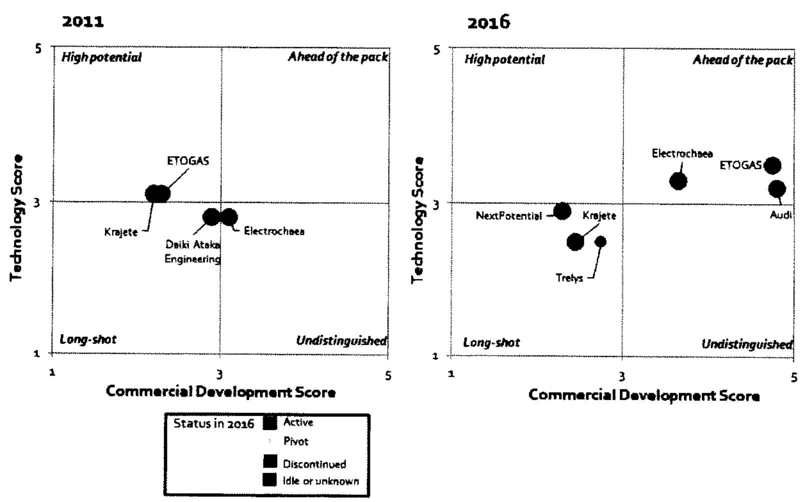
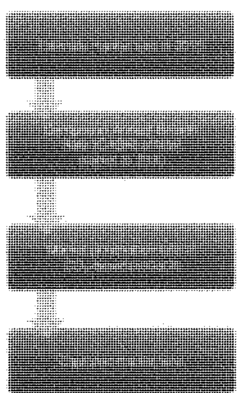


Figure 3.5: A visualization of the CO_2U polymers market, 2011 and 2016.

IV. CO_2U market sub-category projections through 2030

Market sizing

The study estimated the 2015 market size and estimated compounded annual growth rates (CAGR) of each of the eight categories within the four markets. The findings were based on existing proprietary research and secondary information from annual reports, published market studies and industry publications. The below diagram shows the methodology used in assessing addressable markets.



- Analysis of in-house knowledge and secondary information from annual reports, market reports, and publications.
  - Triangulation and vetting of numbers from different sources
- Analysis of in-house knowledge and secondary information from annual reports, market reports, and publications.
  - Analysis of drivers and constraints
- Estimation of market penetration based on 3 scenarios. Every scenario has different timelines for mitigating barriers and driving market penetration.
- Estimation of the captured market size based on the overall market size in 2015, CAGR of the total incumbent market and market penetration for the three scenarios.

We have used **several references** (see table below) to estimate: market size, market growth, use of CO_2, penetration rate, etc.

Market	Market size 2015	Sources	Comments
Concrete	20-30 B metric tons	1, 2, 3	Based off market size for cement assuming 12.5% of concrete is cement.
Aggregates	25-35 B metric tons	1, 2, 4	Triangulated with concrete (70-80 wt% aggregates) and asphalt/construction fill (~90 wt% aggregates) market size. We assumed ~50% of incumbent aggregates to be suitable to be replaced.
Methanol	60-70 M metric tons	5, 6 , 7, 8	None
Formic acid	0.5-1.0 M metric tons	9, 10	None
Syngas	130-150 GW thermal	11, 12, 13	Difficult to estimate as syngas is used as an intermediate at the same plant as production, as such producers of syngas do not report output
Polymers	8-10 M metric tons	14, 15	Market size is for polyols and polycarbonates only. Percentage polyols for PU is assumed to be 35%, based on Covestro split.
Methane	3,000-4,000 B m³	16	None
Liquid fuels	800-1,000 B gallons	17, 18	Conversion factor of 31.5 from barrels to gallons

The study then projected each cluster's market penetration rate based on three scenarios:

- **Best case**: Strategic actions are taken that remove barriers at earliest possible opportunity.
- **Optimistic**: Strategic actions are taken to mitigate barriers.
- **Pessimistic**: Status quo is maintained.

Each category and scenario has different timelines for mitigating technology, policy and business barriers and driving market penetration. The study then estimated addressable market size by five-year milestones (2020, 2025 and 2030).

In order to go from market projections to corresponding levels of CO_2 consumed by different products, we used the following table:

Product	Mt of CO_2 used / Mt of product	Assumptions	Source
Aggregates	0.34	Based on CO_2 mineralized to calcium carbonate from wollastonite	19
Concrete	0.085	We assumed the conversion factor is the average of the 3 values found from the sources given	20
Fuels	3	We assumed that gasoline consists of C_8H_{18} on average. We assumed the conversion factor to be 3 on average based on the stoichiometry of the reaction of CO_2 to C_8H_{18}	21
Methanol	1.37	We assumed the conversion factor to be 1.37 on average based on the stoichiometry of the reaction of CO_2 to CH_3OH	22
Polymers	0.3	We assume the conversion factor to be 0.3 on average based on the sources given	23, 24

We now can estimate the amount of CO_2 used for the different scenarios cited above.

Building materials: concrete and carbonate aggregates

Concrete

Concrete curing using CO_2 offers immediate investment opportunities, with a potential for high ROI, while also delivering on CO_2 abatement. We expect the market to grow under existing conditions, but additional incentives could accelerate that growth by as much as five years.

- **Estimated total market size in 2015**: 20-30 billion metric tons. The study estimates that the total concrete market is expected to grow to approximately 40 billion metric tons by 2030, with a CAGR between 3 and 4 percent.
- **Technology pathway**: Curing of concrete by CO_2 injection is an add-on to current processes (heat and steam), driven by performance and cost.
- **CO_2U forecast and considerations:** By 2030, the CO_2U concrete curing market is forecast to grow to between 6.5 billion (pessimistic), 10.5 billion (optimistic) and 16.5 billion (best case) metric tons.
  - Concrete curing using CO_2 is partially driven by the need to increase performance and reduce cost.
  - No changes in codes and standards are necessary.
  - Concrete production is a source of high CO_2 emissions. Incentives to reduce carbon emissions are few.
  - Funding was available for developers in the past, especially in the US and Canada. Several companies are in the commercialization stage.
  - Concrete offers a solution for permanent CO_2 storage.
  - CO_2 curing would reduce water usage.

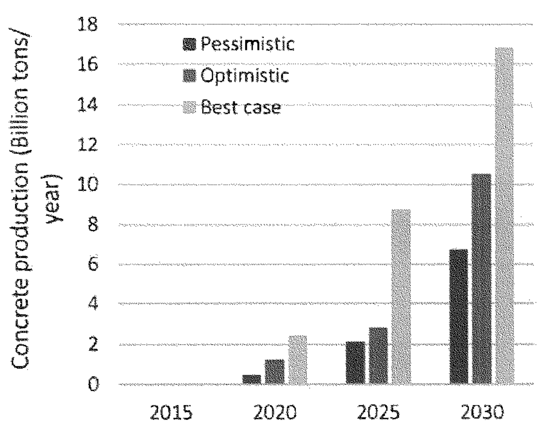


Figure 4.1: Estimated growth of CO_2U concrete curing market through 2030.

Concrete: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of successful mitigation by 2030
Availability of CO_2 for curing	Capture of CO_2 during production of cement; development of a supply infrastructure.	High. If demand is proven, a comprehensive supply chain will follow.
Lack of incentive for concrete manufacturers to adopt process	Concrete manufacturers could be incentivized to reduce carbon emissions by governments.	High. Concerns about global warming will drive governments to seek solutions with an immediate impact.
Lack of developers	Increase funding for "green" concrete.	High. Technology has proven to be viable.

Carbonate aggregates

Carbonate aggregates from CO_2U have high potential to abate CO_2 emissions, but they need to become cost-competitive. The category offers an attractive long-term opportunity, if investments are made in CO_2 infrastructure and the scaling up of technology.

Carbonate aggregates produced from CO_2U can be used in concrete, asphalt, and construction fill.

Conversion of CO_2 into carbonates offers the potential to convert low-value materials (such as solid wastes containing calcium oxide) into useful products. However, materials from municipal waste sites or steel plants must be transported from their point of generation to the carbonate production site, increasing the price of CO_2-derived products.

- **Estimated total market size 2015**: 25-35 billion metric tons. The total aggregate market is expected to grow to approximately 50 billion metric tons by 2030 with a CAGR between 3 and 4 percent.
- **Technology pathways**: Direct carbonation; indirect carbonation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U carbonate aggregates market is forecast to grow to between 1 billion (pessimistic), 3.5 billion (optimistic) and 10.5 billion (best case) metric tons. Drivers:
  - Concrete production is a source of high CO_2 emissions. Currently, concrete production via CO_2U is not incentivized. If enacted, incentives would accelerate growth.
  - As noted above, concrete production is a source of high CO_2 emissions. Incentives to reduce carbon emissions are low.
  - Funding was available for developers in the past, especially in the US and Canada. Several companies are in the commercialization stage.
  - Concrete offers a solution for permanent CO_2 storage.

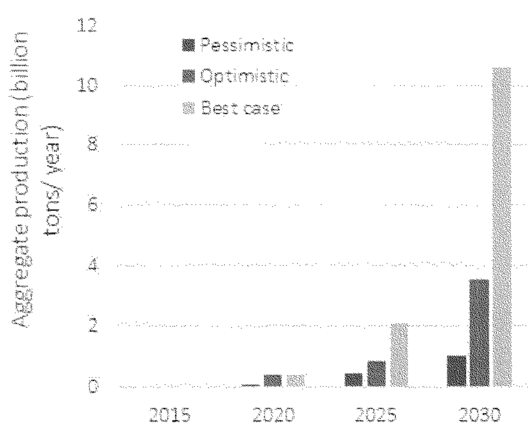


Figure 4.2: Estimated growth of CO_2U carbonate aggregates market through 2030.

Carbonate aggregates: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Demonstration at large scale at low-cost	Process integration of conversion to carbonates and local supply of solid waste and CO_2	High, infrastructures can be set up to be cost competitive with traditional aggregates.
Lack of incentives for aggregate producers; Payback periods could be too long	Subsidize early developers of CO_2 conversion to carbonates or tax carbon emissions at cement factories	High, programs and regulations connected to COP21 will take time to be implemented. Europe is most likely the early adopter.
Product will have to be qualified by existing regulations	Expedite standardization and regulations to lower time to less than 5 years	High, regulations and standards will have been resolved by 2030.

Other barriers include access to CO_2, lack of funding to move the technology past low capacity production, and lack of cost competitiveness due to transportation costs involved with waste material to be used as feedstock.

Carbon8 is currently producing 180,000 metric tons of carbonate aggregates per year, but scalability of the technology remains to be determined.

Chemical intermediates: methanol, formic acid and syngas

Methanol

Today, methanol is largely used in chemical production as an intermediate in the production of formaldehyde, methyl tert-butyl ether, acetic acid and dimethyl ether; olefins is an emerging sector.

However, its emerging application – as a fuel blend – is potentially highly significant. The market for conversion of CO_2 to methanol is driven by the demand for fuels from renewable sources. CO_2U-derived methanol offers great promise as this demand continues to grow, but investments are necessary to drive this market to its full potential.

- **Estimated total market size in 2015**: 60-70 million metric tons. The total methanol market is expected to grow to approximately 190 million metric tons by 2030, with a CAGR between 7 and 9 percent. The estimate assumes that the bio feed stock market share for methanol used as a fuel is 50 percent by 2030, and the overall market share of methanol used a fuel increases from 12 percent in 2015 to 30 percent in 2030.
- **Technology pathways**: Catalytic hydrogenation; photocatalytic; electrochemical.
- **CO_2U forecast and considerations:**
  - By 2030, the **CO_2U methanol market for fuels** is forecast to grow to between 4 million (pessimistic), 23 million (optimistic) and 34 million (best case) metric tons.
  - CO_2U methanol for use as a chemical intermediate lacks clear incentives for CO_2 mitigation; no projects targeting the chemical production market currently exist. By 2030, the **CO_2U methanol market for chemical intermediates** is forecast to grow to between 1.3 million (optimistic) and 9.3 million (best case) metric tons.
  - Methanol from CO_2 is currently only cost competitive in special scenarios.
    - Funding for "renewable" methanol is tied to production of energy from renewable sources.
    - Major hurdles for methanol via CO_2U are current high production costs and low production volumes.
    - Methanol from CO_2 conversion, usually produced by the electrolysis of water, requires cheap hydrogen and demands inexpensive/renewable sources of electricity (e.g., hydrothermal in Iceland or wind in Germany).
    - Policies and regulations for CO_2 mitigation driven by the Paris COP21 agreement could help reduce costs.

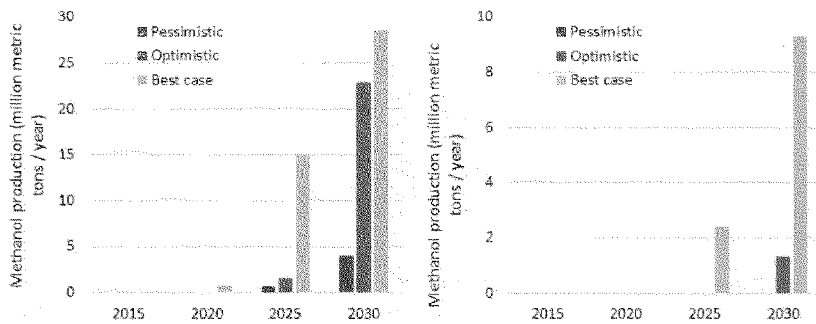


Figure 4.3: Estimated growth of CO_2U methanol (fuel) and CO_2U methanol (chemical intermediate) markets through 2030.

Methanol from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Access to low-cost H_2	Development of electrolysis and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion to syngas	High, pilot programs are in place
Reduction of compounds besides CO_2, especially H_2O and catalyst efficiency	Catalysts promoting CO_2 production and inhibitors of side reactions; Further catalyst R&D	High, catalyst improvements are expected
Current mandates for fuels from renewable sources can be met by biofuels from bio-based feedstocks	Increase mandates, implement carbon tax or replace bio-based feedstocks	High: Mandates are likely to become more strict by 2030

Other barriers include access to a clean energy supply, relatively low energy density of methanol as compared to gasoline, creation of a CO_2 capture and/or methanol infrastructure, and uncertainty about funding. Some of these concerns are also valid for other markets for fuels, polymers or chemicals.

Formic acid

Currently, formic acid is used as a chemical intermediate in adhesives, preservatives, dimethylformamide (DMF), and other products. Because it's more reactive than methanol, formic acid is more suitable as a chemical intermediate. Research in the reduction of CO_2 to formic acid (CH_2OH) is still early-stage. Formic acid also has been proposed as a fuel source for fuel cells. This application is still in a proof-of-concept phase.

Funding and incentives drive formic acid; potential is small as compared to other market segments. CO_2 conversion to produce formic acid has high potential in theory because formic acid is suitable as a chemical intermediate. However, demand will remain low unless specific applications are more developed.

- **Estimated total market size in 2015**: 500,000 to 700,000 metric tons. The total formic acid market is expected to grow to approximately 1.0 million metric tons by 2030 with a CAGR between 3 and 4 percent.
- **Technology pathways**: Catalytic hydrogenation; electrochemical.
- **CO_2U forecast and considerations**: By 2030, the CO_2U formic acid market is forecast to grow to between 10k (pessimistic), 50k (optimistic) and 475k (best case) metric tons annually.
  - Applications need to be developed; current demand is relatively low.
  - The driver for using CO_2 conversion to produce formic acid is weak, because governments are not incentivizing creation of chemical intermediates from renewable sources.
  - Use as a fuel for fuel cells would allow for carbon-neutral transportation, if formic acid were made from renewable sources.

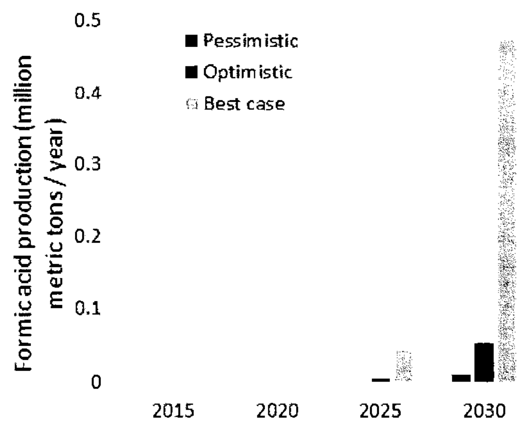


Figure 4.4: Estimated growth of CO_2U formic acid market through 2030.

Formic acid from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
More efficient conversion	Research into improving catalyst selectivity and increasing catalyst life. This includes catalysts that would allow for contaminated CO_2.	High, development will take 10-15 years
Lack of funding for programs to focus on formic acid from CO_2	Set up government or private programs, especially in APAC and the US. Incentivize collaboration between renewable energy suppliers and converters.	High, funding is available in Europe. US and APAC will follow suit if programs are successful
Lack of current demand for formic acid	Formic acid could be developed as an alternative 'green' chemical intermediate or a fuel to fuel cells	Low, demand in these fields is unlikely to be high unless there is a breakthrough in fuel cells

Formic acid from CO_2 cannot compete for another 10 years, perhaps 15. CO_2U formic acid is more early stage than methanol and syngas.

Other barriers include access to a clean energy supply, creation of a CO_2 capture infrastructure, insufficient incentive for formic acid producers to reduce carbon emissions, and lack of access to plants for scale-up projects. These concerns may also be valid for other markets for fuels, polymers or chemicals.

Syngas

Syngas (synthesis gas) is a versatile chemical intermediate; it is more reactive. Its uses include making liquid fuels (by Fischer-Tropsch reaction) as well as methanol itself. Syngas is also used in power generation, but this application is not considered a CO_2U end product because other methods are more efficient and lower in cost. Although it's currently relatively small, the syngas market derived from carbon monoxide and hydrogen is growing at a healthy CAGR (8 percent).

Syngas from CO_2 has significant potential as it can be used as an intermediate in the production of many chemicals and materials. Many developers are investigating CO_2 conversion to syngas. However, efforts must be incentivized to be able to compete with more conventional production methods by 2030.

- **Estimated total market size in 2015**: The development of syngas for power generation makes the total market size difficult to quantify because syngas is normally converted to other chemicals or used for power generation; this study estimates the current market to be 130-150 gigawatts annually. The total syngas total market is forecast to grow to approximately 500 gigawatts annually by 2030 with a CAGR of between 8 and 10 percent.
- **Technology pathways**: Electrochemical; catalytic hydrocarbon reformation.
- **CO_2U forecast and considerations**: The CO_2U syngas market is forecast to grow to between 15 (pessimistic), 110 (optimistic) and 265 (best case) gigawatts by 2030.
  - Syngas from CO_2 conversion can be used to produce a range of chemicals and fuels.
  - Because it enables developers to produce fuels or chemical intermediates downstream, CO_2U syngas production can be added on to an existing manufacturing plant. For example, the technology can be added on by steel plants to decrease carbon emissions and generate an additional revenue stream.
  - There are currently no direct incentives for companies to use renewable sources to produce syngas; renewable alternatives include generation of syngas from biomass.

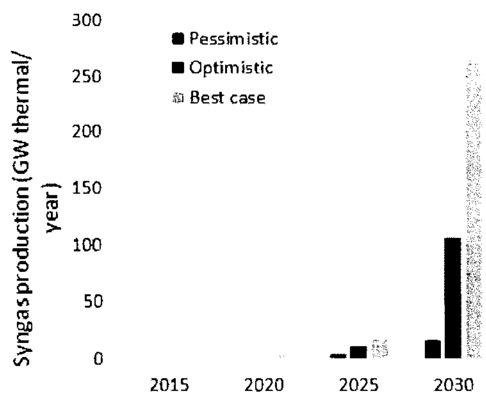


Figure 4.5: Estimated growth of CO_2U syngas market through 2030.

Syngas from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Access to low-cost hydrogen and access to a clean energy supply	Development of electrolysis and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion to syngas	High if excess energy of plants or renewable sources can be utilized
Lack of demonstration facilities	Increase funding for pilot programs and for scaling up production of syngas	High, Funding in Europe has focused on pilot programs
Lack of incentives to reduce carbon emissions	Tax on carbon emissions or mandate reduction of carbon emissions	Low, although Europe could be an early adopter

Other barriers include competition with syngas generated from biomass, creation of a CO_2 capture and/or syngas infrastructure, and competition with alternatives to reduce carbon emissions at plants. Some of these are also valid for other markets for fuels, polymers or chemicals.

Fuels: liquid fuels and methane

Liquid fuels

Liquid fuels include gasoline, diesel and kerosene, and additives such as methanol and formic acid. Biofuels from renewable sources such as sugar cane have been growing through funding and incentives, but fuels from CO_2 conversion have a negligible market share at present.

Yet liquid fuels from CO_2U have the potential to replace polluting alternatives. CO_2 conversion to liquid fuel production demands an integrated approach to developing the technology, incentivizing renewable fuels by policy, and creating an infrastructure for low-cost CO_2.

- **Estimated total market size in 2015**: 800 billion to one trillion US gallons annually. The overall liquid fuels market is expected to exceed one trillion US gallons annually by 2030 with a CAGR of 1-2 percent.
- **Technology pathways**: Photocatalytic; biocatalysis; catalytic hydrogenation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U liquid fuels market is expected to grow to between 7 billion (pessimistic), 45 billion (optimistic) and 165 billion (best case) US gallons annually.
  - Europe leads in funding to lower carbon emissions.
  - Europe has a mandate to derive 10 percent of liquid fuels from renewable sources by 2021. Sources of energy for conversion must also be to be renewable.
  - European consortia have been established comprising members of the value chain (universities, energy suppliers, CO_2 suppliers, converters and users).
  - Fuels from CO_2 conversion target the same market as fuels from bio-based feedstocks.

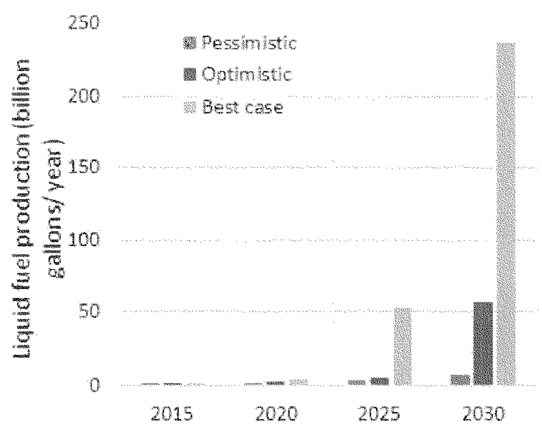


Figure 4.8: Estimated growth of CO_2U liquid fuels market by 2030.

Liquid fuels from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Current mandates for fuels from renewable sources can be met by biofuels from bio-based feedstocks	Increase mandates or replace bio-based feedstocks	High: Mandates are likely to become more strict by 2030
Access to renewable energy at a low price	Increase availability from energy from solar, wind and other renewable sources	High: in areas of oversupply of solar and wind energy
Efficient conversion of CO_2	Technological advances in conversion of CO_2 are necessary to allow for different quality feedstocks to be used and to increase the yield of the conversion	High: Advances in catalysis and photocatalysis should allow for more efficient conversion

Other barriers include lack of access to a low-cost hydrogen and clean energy supply and creation of a CO_2 capture infrastructure. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Methane

Methane is produced from resources such as shale gas, tight gas and coal beds. According to the Energy Information Administration, shale accounts today for one-half of US natural gas production, with its share expected to approach 70 percent by 2040.

Producing methane from CO_2 is possible, but it remains to be seen if it can be profitable. It can only be cost-competitive if alternatives are made more expensive through carbon taxes or by mandating methane production from renewable sources. Developers are investigating bio-methane from renewable sources to reduce CO_2 emissions, and methane from CO_2 conversion will compete with these renewable sources. European consortia have been established comprising members of the value chain (universities, energy suppliers, CO_2 suppliers, converters and users).

- **Estimated total market size in 2015**: 3-4 trillion cubic meters annually. The overall methane market is expected to grow to 4-5 trillion cubic meters by 2030 with a CAGR between 1 and 2 percent.
- **Conversion technologies**: Fermentation; catalytic hydrogenation; photocatalytic.
- **CO_2U forecast and considerations:** By 2030, the CO_2U methane market is expected to grow to between 4 billion (pessimistic), 13 billion (optimistic) and 65 billion (best case) cubic meters annually.
- Funding in Europe for the co-electrolysis of CO_2 and water is ongoing, with several countries possessing significant alternative energy sources, such as hydroelectric and wind power.
- Shale-gas-fired technology is replacing coal-burning plants in the US, thereby reducing carbon emissions and reducing the drive in the US to reduce CO_2 emissions.

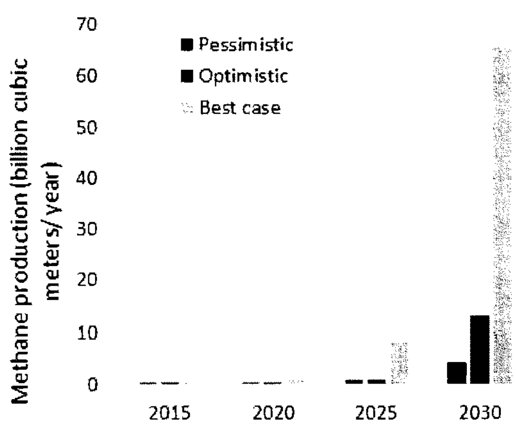


Figure 4.7: Estimated growth of the CO_2U methane market through 2030.

Methane from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
Requirement of process integration	Development of conversion technology and access to low-cost renewable energy, i.e. process integration of renewable energy or excess energy, carbon capture and conversion	High, pilot programs are in place
No incentive to change; gas is seen as an improvement over oil and coal in countries such as the US	Change in policy to mandate more strict requirements for CO_2 emissions or implement carbon taxes	Low; the US is meeting its current standards
Low-cost and effective catalysts	Funding into development of more durable and selective catalysts; Development of fermentation technology	High: catalyst improvements are expected

Other barriers include low gas price of fossil derived methane, lack of access to a low-cost hydrogen and clean energy supply and creation of a CO_2 capture infrastructure. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Polymers

Polyols and polycarbonates

While there are a smaller number of developers compared to the building materials, chemical intermediates and fuels categories identified in this study, several large companies with access to technical knowledge and production facilities are focusing on the production of polycarbonates and polyols from CO_2. Research into other types of polymers is more fragmented.

Polyols and polycarbonates from CO_2 have been commercialized, but it remains to be seen if the technology can compete. Reduction of the cost of CO_2 and/or greater incentives to reduce carbon emissions must be implemented to be able for CO_2U polymers compete with those from conventional feedstock.

- **Estimated total market size in 2015**: 8-10 million metric tons for polyols and polycarbonates. The total market for these two polymers is forecast to grow to 17 million metric tons by 2030, with an estimated CAGR of 3-5 percent. Other polymers, such as polyhydroxyalkanoates (PHA), are far from commercialization.
- **Technology pathways**: Epoxide copolymerization; fermentation.
- **CO_2U forecast and considerations**: By 2030, the CO_2U polymers (polyols and polycarbonates) market is forecast to grow to between 0.4 million (pessimistic), 1.7 million (optimistic) and 6.8 million (best case) metric tons annually.
  - The major contemporary driver for the development of CO_2U polymers is to reduce CO_2 emissions from chemicals and materials manufacturing processes and facilities.
  - Funding is available in Europe to companies exploring using CO_2 as a feedstock.
  - The thermo-catalytic conversion process is not currently cost competitive.

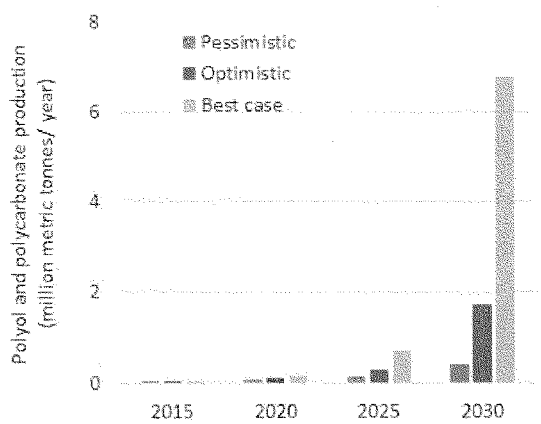


Figure 4.6: Estimated growth of the CO_2U polymers (polyols and polycarbonates) market through 2030.

Polymers from CO_2: Barriers and risks

Key barrier/risk	Means to mitigate	Likelihood of success mitigation by 2030
No incentive for reduction of CO_2 emissions for polymers and chemicals at plants	Set up mandates and regulations. Incentivize collaboration between renewable energy suppliers and converters.	Low, although Europe could be an early adopter
Not cost competitive	Improve conversion efficiency, reduce cost of feedstock and/or energy, implement carbon tax	Low, a global carbon tax is unlikely
Access to low priced CO_2	Development of capture of CO_2 and creation of a supply chain infrastructure	High, supply chain will be developed based on progress in other markets

Other barriers include time for qualification of polymers by customers, access to a low-cost clean energy supply, and uncertainty about funding. Note that some of these are also valid for other markets for fuels, polymers or chemicals.

Overall drivers, barriers and constraints

While there are different market forces that influence near term and long term potential of the different market segments, we summarize the overall drivers, barriers and constraints in terms of three dimensions: policy, technology and market.

Policy

- **The Paris agreement sets global goals for reducing CO_2 emissions and establishes a system to support national governments in doing so.** The agreement entered into force in early November 2016.
- **The drive toward a carbon-neutral economy and less dependence on oil,**
- **In general CO_2U is not a priority in government R&D strategies.**
- In recent years CCS has received more attention than CO_2U. That has helped drive down costs of carbon capture, which are essential for both approaches, but the funding for utilization technologies has been limited. However CO_2U is now receiving greater attention around the world. CO_2U is often called "CO_2 transformation," "CO_2 usage" or "CO_2 re-use" by European policy makers and developers.

Technology

- Lack of coherent funding strategies from governments to support CO_2U technologies.
- Another barrier is **the lack of access to facilities** to scale up CO_2U technologies.
- **Lack of access to feedstocks** – for hydrogen, CO_2, and renewable energy – is an additional barrier.

Recently, we began to see activities clustering in research centers. We believe this will critical mass to accelerate the development of early stage technologies. Appendix 1 shows examples of such activity centers.

Market

- A barrier is **the lack of access to facilities** to scale up CO_2U technologies.
- **Cost: CO_2U must compete** with conventional feedstock and bio-based feedstocks, which are often lower in cost.
- Access to a national CO_2 infrastructure.
- Lack of process integration of renewable energy and conversion processes (no robust value chain)

The above barriers and constraints affect the different market segments in different ways. In some cases, technology may be the biggest barrier while in others it may be the policy. Fig.4.7 attempts to show how the relative influence of the three dimensions: policy, technology and market on the development of different products. We have scored (1 through 5) the four market segments as shown below.

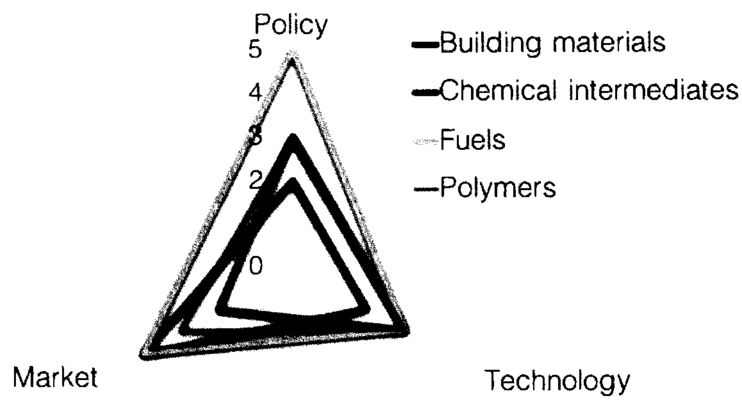


Fig. 4.7 Relative influence of the dimensions on different CO_2- based products

For example, Policy has a greater impact on the development and market penetration of fuels versus polymers. Another example is the smaller influence that technology will play on the market deployment of building materials versus polymers.

V. Life cycle assessment

The climate benefit of a CO_2U product depends not just on how much CO_2 the product contains. The amount of CO_2 emitted in making the product also matters. So does the amount of CO_2 emitted in making any competitive products displaced. To the extent that climate benefits are a goal of those promoting CO_2U products, life cycle analysis is essential.

Understanding the full life cycle emissions impacts of CO_2U technologies is especially important for validating policy support and for guiding research. At first glance, technologies that divert one ton of CO_2 into an economically valuable product would seem to reduce emissions by one ton of CO_2, but this is not the case, for several reasons.[i] As shown in Figure 5.1, a true understanding of the emissions impacts of CO_2U technologies must be based on rigorous life-cycle assessment (LCA), which takes several other factors into account:

- The CO_2 capture process, including any energy penalty that must be offset through additional power generation;
- Compressing and transporting CO_2 to the location of the CO_2U process;
- The energy consumed in the CO_2U process itself;
- The production of additional feedstocks, catalysts and other materials used in the CO_2U process; and
- The emissions resulting from end-of-life treatment for the CO_2-based product.

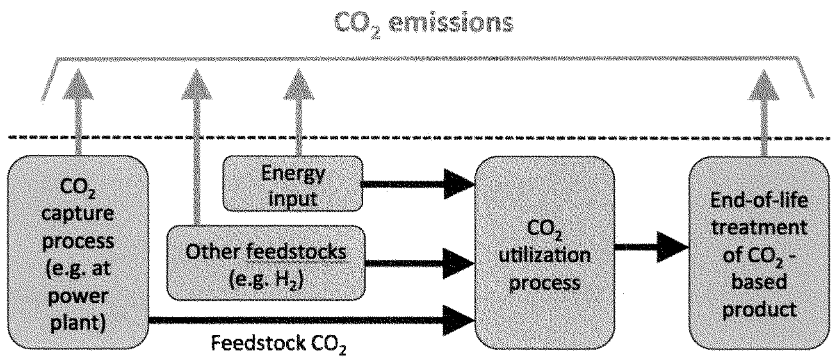


Figure 5.1: Emissions sources for CO_2U technologies. Adapted from von der Assen, 2015.

The ISO 14000 series establishes a standard framework and general procedure for performing LCA calculations, and is widely accepted.[ii] However, even when using this framework, there are many other complications that occur in practice.

The first complication comes from the impact of using different CO_2 sources as feedstock for a CO_2U process. Electric power generation is the largest source of emissions, but many others exist, such as natural gas processing and fertilizer production.[iii] These sources have different energy requirements for capture (largely based on their purity) so a LCA must take this into account. It is possible to define an "environmental merit order" that ranks CO_2 sources by the environmental impacts of using them as feedstock[iv]. This is fine in principle, but CO_2U processes in the market will probably decide which sources to use based on capture costs[v] or pipeline infrastructure[vi] instead of environmental benefits.

A second complication is to correctly specify what comparison the LCA will be used to make. For example, comparing the emissions impacts of different possible end-uses for a specific amount of captured CO_2 (such as storage, EOR, mineralization or chemical intermediate production) is different from comparing the emissions impacts of switching from a conventional process for producing a specific product (such as aggregates or methanol) to one based on captured CO_2.

Third, in all cases other than air capture[vii], the production of CO_2 for use as feedstock in CO_2U technologies is accompanied by co-products such as electricity, steel, cement, ammonia, etc., and the overall emissions of these processes cannot be entirely assigned to the CO_2-based product(s). The preferred method for handling this is known as "system expansion", in which the scope of the analysis is increased to include all other relevant products.[viii] Unfortunately, this can get extremely unwieldy for processes that involve lots of products, and it also means that the LCA does not result in a clear emissions impact from a single CO_2-based product.

The alternative method, known as "proportional allocation", parcels out the total emissions among the various co-products, usually based on mass. However, this method sometimes leaves room for ambiguity, and different approaches to allocation have been shown to lead to significantly different LCA conclusions.[ix]

A fourth complication is the lack of data on some of the non-CO_2 reactants, catalysts and other parts of the full CO_2U system. Tracking the emissions footprints of these items is a significant supply-chain information challenge, and it is often impossible in practice to use complete information for a LCA study. Therefore there is a need for standard approximations or estimates to compare LCAs for multiple products on an equal basis.

Finally, it's important to note that while the primary focus of climate policy is on CO_2 emissions, there are other environmental impacts from CO_2U technologies that should be considered, such as the acidification potential, ozone layer depletion potential, etc.

Because of these complications, LCA experts can come to very different conclusions about the overall emissions impact of the same or similar CO_2U technologies. For example, a review of 16 individual studies of CO_2U technologies including mineral carbonation (mineralization), chemical production, biofuels production, and EOR found a wide range of results, whose variation is so big that it is difficult to draw conclusions about their relative emissions impact, or give guidance to policymakers.[x]

Unfortunately, because of limited research funding, the CO_2U LCA research community is small, and there are very few additional studies. Some additional studies have looked at the production of plasticizers[xi], synthetic hydrocarbon fuels[xii], polyols for polyurethane production[xiii], dimethyl carbonate[xiv], and dry reforming of methane for dimethyl ether production[xv], but there are large gaps in the literature. These LCA studies are relatively low-cost, and should receive more funding.

As governments and industry consider increasing policy support for CO_2U, ideally, they will need to compare and harmonize their approach to LCA as it applies to policy decisions. Governments and industry should increase their focus on this topic and ensure that LCA is included in all CO_2U research coordination efforts. However, given the increasing interest in CO_2U, other stakeholders may need to act sooner. The Global CO_2 Initiative is planning to convene a global expert panel in an attempt to 'standardize' LCA analysis for CO_2U technologies. Additionally, the X Prize Foundation is pursuing rigorous LCA for all entries in its Carbon X Prize, and will gather detailed process data, putting it in a position to contribute to standardizing LCA approaches for CO_2U.

Policy and industry support for CO_2U may also need to consider other key factors beyond the environmental impacts as analyzed by LCA, such as whether the revenue from CO_2U technologies can cover the costs of feedstock CO_2, and the scalability of the technology.[xvi] A related challenge is the perceived trade-off between CO_2U business models that maximize profit through producing small volumes of high-value products, and those that maximize emissions reductions by producing large volumes of lower-value products.[xvii]

Of course, the challenges faced in applying LCA to CO_2U technologies are not entirely new, as LCA has been a key part of environmental analysis and policymaking for many years, most notably relating to biofuels and bioenergy.[xviii] Increasing funding for CO_2U LCA could draw the attention of experts currently focused only on biofuels/bioenergy issues and bring their expertise to bear on CO_2U issues.

VI. Recommendations for strategic actions

CO_2U will only help meet climate goals if CO2 products are widely deployed. The prospects for that are good in some market segments, although in others high costs, well-established alternatives and entrenched incumbents create barriers to market entry. Sound market strategies, targeted technological development and supportive policies all have a role in accelerating deployment and supporting CO_2U technologies in the market.

Technology

Decrease the cost of CO_2 utilization

Fund research to improve catalysis for CO_2 reduction and to improve electrolysis to produce hydrogen.

Conversion of CO_2 into CO_2U products requires more energy than conversion from conventional feedstocks because of the thermodynamic stability of carbon dioxide. Research and development is focusing on catalysis and other conversion processes to reduce the amount of required energy.

Thermo-catalytic conversion of CO_2 has been commercialized for several applications. In general, yields, half-life, and selectivity of catalysts need to be further increased. In addition, operating temperatures should be reduced to lower operating costs. Funding should go into applied research in catalysis.

A hydrogen feed is needed in many processes. Generation of H_2 by electrolysis using renewable energy at a low cost is necessary to make CO_2U cost-competitive. Funding also should go into applied research in electrolysis.

Funding also should be applied to research on alternative processes to thermo-catalytic conversion: fermentation, electrochemical, and photocatalytic means. These processes typically demand less energy usage. And additionally, funding support is needed for research that enables CO_2 feeds with contaminants to be used in CO_2U technology, which currently requires relatively high-purity CO_2 to optimize catalyst life.

Maximize high-potential long shots

Fund applied research on long-shot technologies and applications that have the highest CO_2 abatement potential.

In addition to the four markets analyzed in this work, there are early-stage CO_2U technologies and applications that could offer solutions beyond 2030. It's essential to fund fundamental and applied research into these technologies to further maximize the potential of CO_2U for CO_2 mitigation. We propose that the focus for these long shots be CO_2U technology that allows for sustained capture of CO_2, rather than making CO_2-neutral products. One of the highest-potential technical areas in this regard is the production of carbon fiber.

Figure 6.1 depicts a potential timeline for implementing the technology levers.

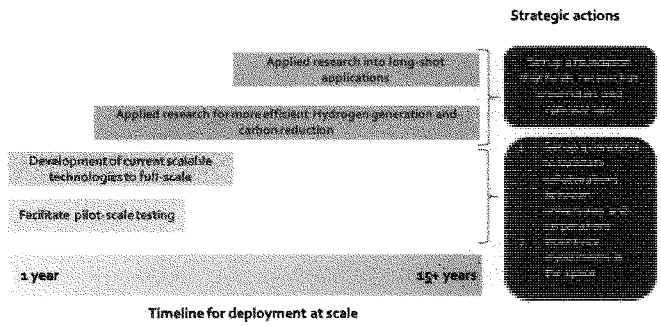


Figure 6.1: Potential timeline for implementing Technology levers

Market

Scale up production

Make funding available to establish collaborations among research institutes, start-ups, governments and corporations for process integration of CO_2 conversion, hydrogen generation and carbon capture.

Consortia should be established to enable the CO_2U value chain, integrating carbon capture; the supply of affordable hydrogen from sources such as a chemical plant or a technology like electrolysis; access to low-cost renewable energy (such as over-capacity electricity); and physical plants for CO_2 conversion and CO_2U product manufacturing.

One example that currently exists in the US is the DOE-supported Joint Center for Artificial Photosynthesis (JCAP). China has also created a research cluster around CO_2U technologies at SARI (Shanghai Advanced Research Institute).

Access to Capital

Various institutions are not aware of the value proposition of CO_2U technologies.

Articulating the value proposition of CO_2U solutions will drive more capital, especially impact capital, that has social and financial returns in mind.

Such capital enables a faster adoption and faster market deployment of CO_2-based products.

Figure 6.2 Depicts a potential timeline for implementing the market levers.

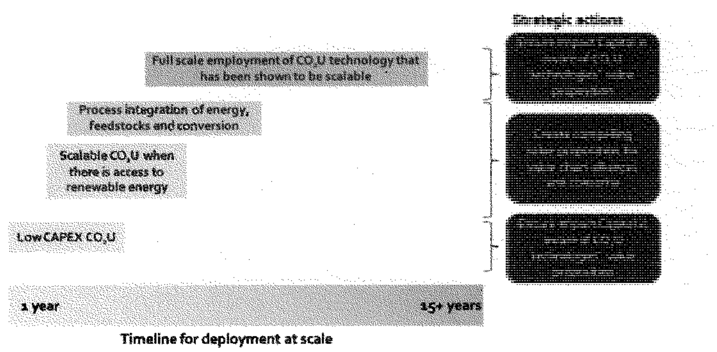


Figure 6.2: Potential timeline for implementing market levers

Policy

Supportive policies can help start and build markets for CO_2U products. Different policies may be appropriate in different jurisdictions, depending on local circumstances. In this section we catalogue policies that can play an important role in promoting CO_2U products.

Government support for R&D

Governments spend billions of dollars every year on research and development for clean energy technologies. Yet support for R&D on carbon dioxide utilization is modest. A significant increase in funding in this area could speed deployment of CO_2U technologies and yield important dividends.

In December 2015, heads of state from more than 20 countries announced Mission Innovation, a pledge to double R&D on clean energy within five years. Governments participating in Mission Innovation include the United States, China, Japan, the European Union and Saudi Arabia. The increase in R&D budgets from these countries in the next few years offers an important opportunity to scale up government R&D funding for CO_2 utilization. This could be part of the R&D portfolio of all Mission Innovation governments (as well as many industries).

Carbon Price

A price on carbon dioxide emissions, whether through an emissions trading program or tax mechanism, provides emitters with an important incentive to cut emissions. There are many strategies for doing so. In the power sector, for example, emitters could respond to a carbon price by (i) improving efficiencies, (ii) switching to lower carbon fuels, (iii) capturing carbon dioxide and sequestering it underground, (iv) capturing carbon dioxide and using it in products, or (v) some combination of the foregoing. In cases in which capturing carbon dioxide and using it in products is cheaper than the alternatives, a carbon price will provide an important incentive for CO_2 utilization. Even when capturing and using CO_2 in products is not the cheapest alternative in the short-term, a carbon price may help incentivize investments into CO_2 utilization technologies if market participants expect the price to endure for the medium or long-term.

Tax Incentives

Governments could offer tax credits for the use of CO_2 in products to help spur development of the industry. This type of focused, direct incentive can have a significant impact. However to the extent the objective of the tax credit is to cut CO_2 emissions, it would be important to establish eligibility criteria that took into account (i) the permanence of the removal of CO_2 from the atmosphere due to the product, and (ii) the life cycle emissions associated with the product. These create significant methodological challenges and are an important area for future research.

Mandates

Governments could mandate the use of CO_2 in certain products as a tool for spurring the market. Broader mandates, such as those requiring the use of renewable fuels in liquid fuel supplies, could also provide incentives for CO_2 use, if costs of CO_2 use are competitive with other compliance strategies.

Pipeline and other infrastructure development

CO_2 must either be used at the point of capture or transported by pipeline. Considerable investment in CO_2 pipeline networks will be needed for CO_2 utilization to flourish. Governments have an important role in helping establish these pipeline networks, both by facilitating regulatory approvals for pipeline construction and potentially by assisting with financing.

Government procurement

Government (including military) procurement can provide early market demand for emerging technologies, such as the US Navy's procurement of biofuels.[xix] This form of market stimulation also helps establish standard technical specifications for new products, which can help catalyze efficient supply chains. Several CO_2U technologies may be good targets for government procurements, such as CO_2-cured cement and CO_2-based aggregates, which could be included in government procurement guidelines for construction projects.[xx]

Product labeling

Providing consumers with easy-to-understand labels on products indicating their environmental qualities can increase demand for those products. Some of the most prominent examples of this strategy are the US Energy Star and Energy Guide programs, the Japanese Energy Efficiency Label program, and the EU Energy Labeling Directive. Consumer products based on captured CO_2 could be incorporated into these or similar labeling programs. The most appropriate CO_2U technologies for this may be CASE (coatings/adhesives/sealants/elastomers) and related plastics products.

Credits under regulatory and voluntary programs

Governments could offer additional credits under existing regulatory programs tied to the use of CO_2U products. For example, vehicle emissions regulations and appliance energy efficiency regulations could include additional credit for vehicles or appliances that are manufactured using CO_2U products such as foam insulation. Governments could also work with voluntary labeling programs such as LEED to include credit for buildings that use CO_2U -based construction materials.

Support for certification and testing

Governments could fund the certification and testing of CO_2U -based products by organizations such as UL, ASHRAE, ASME and others. These accreditation processes can accelerate the adoption of new technologies into existing supply chains, but do require funding in order to conduct the necessary testing and certification steps.

Support for expanded Lifecycle Assessment studies

Governments could increase funding support for LCA research, with a focus on specific CO_2U technologies that are industrially relevant. If so, this should be pursued in coordination with private-sector efforts to improve and standardize CO_2U LCA, such as the efforts by GCI and X Prize. Governments could also work to improve data availability throughout the supply chains relevant to CO_2U technologies.

Market-focused recommendations

Market-focused recommendations may also be useful as we believe there are current market opportunities that can proceed without policy initiatives. Combining major technology and market recommendations for specific product categories leads to the following recommendations:

Building materials

CO_2 curing of cements offers a superior product and superior price and should be able to move quickly if the following strategic actions are taken:

- Ensure financing for conversions of precast concrete facilities.
- Focus on converting the practices of incumbents rather than creating competitive companies.
- Identify the most cost effective places to capture CO_2 for this purpose.
- Build an infrastructure to deliver CO_2 – pipelines ultimately, but probably rail, ship or truck initially.
- Conduct detailed market surveys to determine optimum places to begin deployment on a country-by-country basis.

Carbonate based aggregates offer a very large volume sink for carbon dioxide but face more entrenched competitors and a price sensitive market. The following strategic actions are recommended:

- Conduct detailed market surveys to determine optimum places to begin deployment on a country-by-country basis starting with core material sources.
- Research needs to ensure that core material that may be hazardous is properly contained by the carbonate and the intended use
- Ensure that appropriate certifications are obtained for the material produced to be used in concrete.
- CO_2 sources and delivery systems need to be identified to support the locations identified
- Obtain financing for facilities based on the above, taking advantage of green bank and development bank options in less developed countries.

Fuels, chemical feedstock and plastics

Practically all of these applications are in direct competition with fossil fuel enabled value chains for the same product. To date these uses of CO_2 have been strongly affected in the market by the price of petroleum. Four classes of strategic action need to be taken:

- R&D to lower the cost of the CO_2 based product such as:
  - Improved catalysts for the generation of hydrogen and to drive the conversion process.
  - Emphasis on products that can use existing parts of the production and distribution infrastructure.
- Ensure low cost capture of carbon dioxide and to the extent possible sources that are not fossil fuel derived.
  - Infrastructure for delivery as noted above will be critical.

- Work with incumbents to ensure faster access to market and smooth transition to non-fossil based products.

High potential early stage technologies

There are a number of technologies that have high potential impact but are in an early stage of development. The acceleration of the products to market and application is essential. The following strategic actions are recommended:

- Provide "end in mind" funding for research and development that does the following:
  - ARPA-e like supervision of development
  - Early engagement with market partners
  - Rapid identification and handling of regulatory issues.

The implantation of the above cited levers will lead to significant increase in CO_2 reduction (Figure 6.3) and will create significant business opportunities (Figure 6.4)

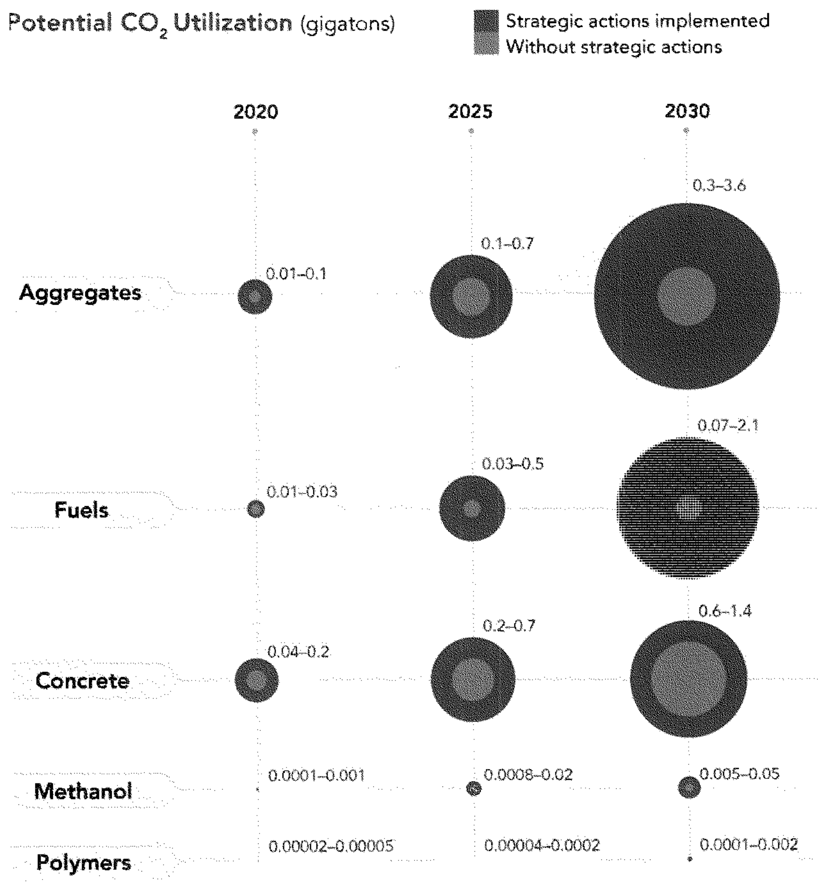


Figure 6.3: Potential in CO_2 reduction due to implementing strategic actions

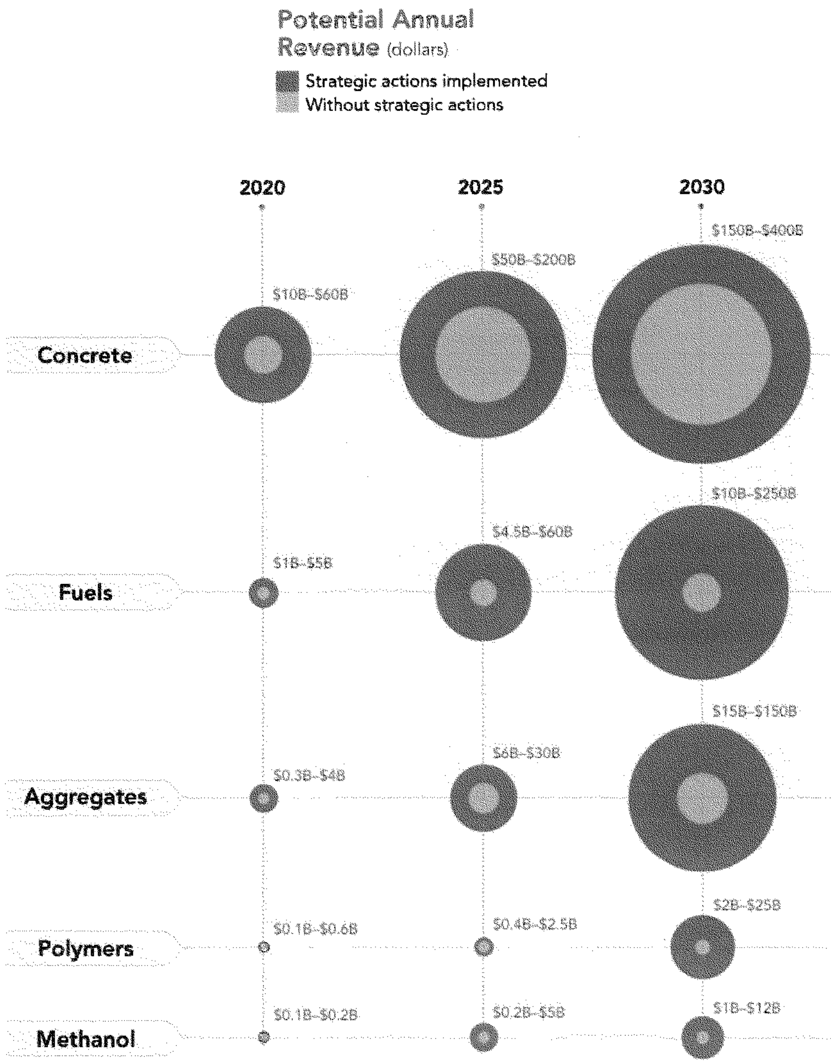


Figure 6.4: potential increase in financial returns due to implantation of strategic actions

VII. Conclusions

- **The commercialization of products derived from carbon dioxide utilization (CO_2U) offers opportunities to mitigate CO_2 emissions at a profit.**

- CO_2 mitigation and CO_2U are critical to decreasing the risks associated with climate change. CO_2U utilizes CO_2 to produce materials, fuels, or chemicals, whereas mitigation strategies like carbon capture and storage remain an added cost.

- Significant progress has been made CO_2U during the last five years, with many technologies proving to be scalable and visible momentum in four major markets:

    - Building materials
    - Chemical intermediates
    - Fuels
    - Polymers

- Funding, incentives and prompt strategic actions are necessary to move CO_2U toward full-scale capabilities. At full scale, CO_2U could open markets reaching or exceeding US $800 billion by 2030.

- CO_2U has the potential to utilize 7 billion metric tons of CO_2 per year by 2030 – the equivalent of approximately 15 percent of global CO_2 emissions today.

Resources – Market Estimates

1. http://www.lafarge.com/sites/default/files/atoms/files/04152015-customers_activities-cement_market_2014-uk.pdf
2. http://www.worldcement.com/europe-cis/27082015/Global-demand-cement-billion-tons-449/
3. http://www.betonabq.org/images/imguser/WorldReport_Aug_2013final__01__cement.pdf
4. http://www.rockproducts.com/features/13045-world-aggregates-market.html#.WCSIUWsrLb0
5. http://press.ihs.com/press-release/chemicals/driven-china-global-methanol-demand-rise-nearly-80-percent-2023-north-americ
6. http://ac.els-cdn.com/S0306261915009071/1-s2.0-S0306261915009071-main.pdf?_tid=f380e50a-802e-11e6-b29f-00000aacb360&acdnat=1474485162_73a26316639140889fe672c6681af8f3
7. http://www.methanol.org/about-methanol/
8. https://www.methanex.com/sites/default/files/investor/MEOH Presentation - June 2016_0.pdf
9. http://www.sciencedirect.com/science/article/pii/S0360319915313835
10. http://chemplan.biz/chemplan_demo/sample_reports/Formic_Acid_Profile.pdf
11. http://www.marketsandmarkets.com/PressReleases/syngas.asp
12. http://www.businesswire.com/news/home/20160405005127/en/Global-Syngas-Market-Reach-290-MW-2020
13. http://www.prnewswire.com/news-releases/concise-analysis-of-the-international-syngas-market--derivatives-market---forecast-to-2018-246304851.html
14. https://members.luxresearchinc.com/research/report/16519
15. http://investor.covestro.com/securedl/13817
16. https://www.iea.org/Textbase/npsum/MTGMR2016SUM.pdf
17. http://www.lukoil.com/materials/doc/documents/global_trends_to_2025.pdf
18. https://www.eia.gov/forecasts/steo/report/global_oil.cfm
19. http://www.sciencedirect.com/science/article/pii/S0920586106000800
20. https://hub.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/appendix-g-co2-concrete
21. http://www.sciencedirect.com/science/article/pii/S0959652616001876
22. http://www.sciencedirect.com/science/article/pii/S0306261915009071
23. http://press.covestro.com/news.nsf/id/aazc7n-address-by-patrick-thomas
24. http://www.econic-technologies.com/catalyst-technology/polymerisation-process/

References - Life Cycle Analysis

[i] N. von der Assen, "From Life-Cycle Assessment toward Life-Cycle Design of Carbon Dioxide Capture and Utilization", Ph.D dissertation, RWTH Aachen University (2015).
[ii] ISO 14040:2006, "Environmental Management – Lifecycle Assessment – Principles and framework"; ISO 14044:2006, "Environmental Management – Lifecycle Assessment – Requirements and guidelines".
[iii] "Cradle-to-Gate Life Cycle Analysis Model for Alternative Sources of Carbon Dioxide", DOE/NETL-2013/1601 (2013.)
[iv] N. von der Assen et al., "Selecting CO_2 Sources for CO_2 Utilization by Environmental Merit-Order Curves", Env. Sci. & Tech. 50 (2016).
[v] H. Naims, "Economics of carbon dioxide capture and utilization – a supply and demand perspective", Env. Sci. & Pol. Res. (2016).
[vi] "A Review of the CO_2 Pipeline Infrastructure in the U.S.", DOE/NETL-2014/1618 (2015).
[vii] R. Socolow et al, "Direct Air Capture of CO_2 with Chemicals", American Physical Society, 2011; "Ten Reasons to Take Direct Air Capture Seriously", Lenfest Center, Earth Institute, Columbia University, July 18, 2014.
[viii] R. Heijungs, "Ten easy lessons for good communication of LCA", The International Journal of Life Cycle Assessment 19 (2014).
[ix] P. Jaramillo et al., "Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System", Env. Sci. & Tech. 43 (2009).
[x] R. M. Cuéllar-Franca and Adisa Azapagic, "Carbon capture, storage and utilization technologies: A critical analysis and comparison of their life cycle environmental impacts", Journal of CO_2 Utilization 9 (2015).
[xi] B. Schäffner et al., "Synthesis and Application of Carbonated Fatty Acid Esters from Carbon Dioxide Including a Life Cycle Analysis", ChemSusChem 7 (2014).
[xii] C. van der Giesen et al., "Energy and Climate Impacts of Producing Synthetic Hydrocarbon Fuels from CO_2", Env. Sci. & Tech. 48 (2014).
[xiii] N. von der Assen and A. Bardow, "Life cycle assessment of poyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study", Green Chem. 16 (2014).
[xiv] I. Garcia-Herrero et al., "Environmental Assessment of Dimethyl Carbonate Production: Comparison of a Novel Electrosynthesis Route Utilizing CO_2 with a Commercial Oxidative Carbonylation Process", ACS Sus. Chem. & Eng. 4 (2016).
[xv] W. Schakel et al., "Assessing the techno-environmental performance of CO_2 utilization via dry reforming of methane for the production of dimethyl ether", Journal of CO_2 Utilization 16 (2016).
[xvi] S. Bennett et al., "Towards a framework for discussing and assessing CO_2 utilisation in a climate context", Energy Procedia 63 (2014).
[xvii] M. Extavour and P. Bunje, "CCUS: Utilizing CO_2 to Reduce Emissions", CEP Magazine, June 2016.
[xviii] M. McManus and C. Taylor, "The changing nature of life cycle assessment", Biomass and Bioenergy 82 (2015).

[xix] "Biofuels are included in latest U.S. Navy fuel procurement", US Energy Information Administration, July 25, 2014.
[xx] See, e.g. "Comprehensive Procurement Guidelines for Construction Products", US EPA website.

About The Global CO_2 Initiative and ICEF

The Global CO_2 Initiative (GCI) and CO_2 Sciences, Inc.

The Global CO_2 Initiative (GCI) was announced at the January 2016 World Economic Forum in Davos. The Initiative is focused on funding the R&D and commercialization of CO_2-based products that will reduce carbon dioxide emissions by up to ten percent annually.

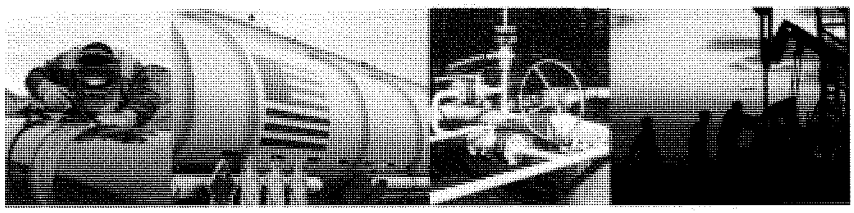
The GCI established CO_2 Sciences, Inc., a non-profit organization that funds innovative R&D in CO_2U to create CO_2-based products. CO_2 Sciences is structured to aggressively catalyze innovative research funding in carbon capture and use by granting up to $400 million in the next ten years to qualified research applicants throughout the world.

By harnessing market demand for products that capture and reuse CO_2 – and through "impact investing" – GCI aims to catalyze substantial economically driven change in the form of markets and products that reuse increased amounts of CO_2.

Innovation for Cool Earth Forum

The Innovation for Cool Earth Forum (ICEF) is aimed at addressing climate change through innovation. ICEF investigates via discussion what innovative measures should be developed, how innovation should be promoted and how cooperation should be enhanced among stakeholders in fighting climate change.

ICEF is held every year in Tokyo. The ICEF Steering Committee helps make decisions regarding the agenda and program to reflect the wide range of views of the international community. Policymakers, businesspeople and researchers from around the globe participate. The ICEF Roadmap Project helps to promote the development and deployment of clean energy technologies with roadmaps released each year.



21st Century Energy Infrastructure:

Policy Recommendations for Development of American CO_2 Pipeline Networks

White paper prepared by the
State CO_2-EOR Deployment Work Group

February 2017

Acknowledgements

While the final recommendations of this white paper represent the joint conclusions of state officials in the State CO_2-EOR Deployment Work Group, participating state officials want to recognize the contributions of leading private sector stakeholders and CO_2-enhanced oil recovery experts who lent their expertise and guidance to the effort. The state representatives extend their thanks to all who contributed to this white paper, and to the Hewlett Foundation for the funding that made this work possible.

State CO_2-EOR Deployment Work Group Participant List

Representatives of Co-convening Governors

- Matthew Fry, Policy Advisor, Office of Wyoming Governor Matt Mead
- Dan Lloyd, Business Development Specialist, Office of Montana Governor Steve Bullock

Participating State Officials

- Stuart Ellsworth, Engineering Manager, Colorado Oil & Gas Conservation Commission
- Michael Kennedy, Assistant Director, Kentucky Energy & Environment Cabinet
- Shawn Shurden, Commission Counsel, Mississippi Public Service Commission
- Patrick McDonnell, Secretary, Pennsylvania Department of Environmental Protection
- Leslie Savage, Chief Geologist, Railroad Commission of Texas
- Rob Simmons, Energy Policy & Law Manager, Utah Governor's Office of Energy Development
- Michael Teague, Oklahoma Secretary of Energy & Environment
- Ted Thomas, Chairman, Arkansas Public Service Commission
- Robert Worstall, Deputy Chief, Division of Oil & Gas Resources, Ohio Department of Natural Resources
- Tristan Vance, Director, Indiana Office of Energy Development

Participating Stakeholders & Experts

- Fatima Ahmad, Solutions Fellow, Center for Climate & Energy Solutions
- Shannon Angielski, Executive Director, Carbon Utilization Research Council
- Jeff Brown, Lecturer in Management, Stanford University Graduate School of Business
- Steven Carpenter, Director, Enhanced Oil Recovery Institute, University of Wyoming
- Al Collins, Senior Director for Regulatory Affairs, Occidental Petroleum Corporation
- Ben Cook, Assistant Professor, Enhanced Oil Recovery Institute, University of Wyoming
- Phil DiPietro, Technology Manager, GE Oil & Gas Technology Center
- Sarah Forbes, Scientist, Office of Fossil Energy, U.S. Department of Energy
- Julio Friedmann, Senior Adviser for Energy Innovation, Lawrence Livermore National Laboratory
- Judith Greenwald, Principal, Greenwald Consulting
- Scott Hornafius, President, Elk Petroleum
- Rob Hurless, Deputy Director, Enhanced Oil Recovery Institute, University of Wyoming

- Dina Kruger, Principal, Kruger Environmental Strategies
- Sasha Mackler, former Vice President, Summit Power Group (now at Enviva LP)
- Steve Melzer, Geological Engineer and Principal, Melzer Consulting
- Julie Moore, Senior Director, State Government Affairs, Occidental Petroleum Corporation
- Deepika Nagabhushan, Policy Associate, Clean Air Task Force
- John Thompson, Director, Fossil Transition Project, Clean Air Task Force
- Keith Tracy, former Director of CO_2 Midstream Operations, Chaparral Energy

Great Plains Institute Staff

- Brad Crabtree, Vice President for Fossil Energy
- Brendan Jordan, Vice President
- Patrice Lahlum, Program Consultant
- Dane McFarlane, Senior Research Analyst
- Doug Scott, Vice President for Strategic Initiatives

About the State CO_2-EOR Deployment Work Group

Wyoming Governor Matt Mead (R) and Montana Governor Steve Bullock (D) jointly convened the State CO_2-EOR Deployment Work Group in September 2015 as a key follow-on to the Western Governors Association resolution calling for federal incentives to accelerate the deployment of carbon capture from power plants and industrial facilities and increase the use of CO_2 in enhanced oil recovery, while safely and permanently storing the CO_2 underground in the process.

Twelve states currently participate in the Work Group: Arkansas, Colorado, Indiana, Kentucky, Mississippi, Montana, Pennsylvania, Ohio, Oklahoma, Texas, Utah and Wyoming. State participation varies by state and includes governors' staff, cabinet secretaries, utility commissioners, and agency and commission staff. Some state representatives participate at the direction of the governor; others do not. State representatives were joined by leading enhanced oil recovery, electric power, coal industry, regulatory and NGO experts.

The Work Group identified three principal roles for its work, including modeling analysis and policy identification, developing recommendations for state and federal policy makers, and supporting the implementation of those policy recommendations. The Work Group aims to foster:

- Expansion of CO_2 capture from power plants and industrial facilities;
- Buildout of pipeline infrastructure to transport that CO_2; and
- Use of CO_2 in oil production, along with its safe and permanent storage.

The Work Group released a comprehensive set of federal and state policy recommendations in December 2016 – Putting the Puzzle Together: State & Federal Policy Drivers for Growing America's Carbon Capture & CO2-EOR Industry.

Table of Contents

Introduction

Development of regional and national carbon dioxide (CO_2) pipeline networks, together with proposed tax credits and other financial incentives for industrial and power plant carbon capture, can support long-term production and use of America's abundant and affordable coal, oil and natural gas resources, put our nation further down the path of replacing imported oil and create high-paying jobs in energy-producing and industrial states and regions of the country, all while significantly reducing net carbon emissions.

American oil fields are poised to rapidly expand production through utilization of man-made CO_2 for enhanced oil recovery (EOR). This promise can be realized, if the oil industry can gain access to large, secure volumes of CO_2, transported via pipeline networks and purchased from industrial facilities and power plants where that CO_2 would otherwise be emitted to the atmosphere and wasted.

Nearly a half-century ago, the EOR industry got its start by capturing CO_2 at commercial scale from man-made sources, and it later began drilling for and utilizing naturally occurring geologic CO_2. The oil industry first purchased CO_2 captured through natural gas processing, then expanded to fertilizer production, coal gasification, chemical and ethanol production and, most recently, added refinery hydrogen production, coal-fired electric power generation and steel manufacturing (see Figure 1 on the next page).

However, in most cases, the costs of CO_2 capture, compression and pipeline transport remain higher than revenue received from sales of the CO_2 to the oil industry. Expanding carbon capture at industrial and power generation facilities would transform CO_2 from a liability into a resource, by driving an increase in American oil production and by storing that CO_2 safely and permanently underground in the process. In addition to federal incentives needed to deploy carbon capture equipment across industries, **a primary obstacle to scaling up this national opportunity is the lack of infrastructure: trunk pipelines are needed to link industrial and power plant CO_2 sources to oilfield customers, and they must be built at very large scale across regions to make economic sense.**

Report Outlines Federal Financial Incentives for CO_2-EOR

Putting the Puzzle Together: State & Federal Policy Drivers for Growing America's Carbon Capture & CO_2-EOR Industry, a report released by the State CO_2-EOR Deployment Work Group in December 2016, provides analyses and federal and state incentive recommendations, including:

- Improving and expanding the existing section 45Q tax credit for storage of captured CO_2;
- Deploying a revenue neutral mechanism to stabilize the price paid for CO_2—and carbon capture project revenue—by removing volatility and investment risk associated with CO_2 prices linked to oil prices; and
- Offering tax-exempt private activity bonds and master limited partnership tax status to provide project financing on better terms.

Today's lack of necessary long-distance, large-volume CO_2 pipelines creates a serious transport problem for potential CO_2 suppliers and customers that stifles both energy and industrial development. This dilemma is not unlike the situation for Midwestern farmers and Western ranchers prior to the coming of the railroads, Texas natural gas producers before the development of long-distance interstate gas pipelines, the unrealized hydropower potential in the Northwest before construction of huge electric transmission lines, or the slow crawl of truck traffic before President Eisenhower spurred the buildout of an efficient interstate highway system. The federal government initially had a hand in fixing all four of these national infrastructure problems before ultimately passing the torch to industry and the states.

Importantly, no safety or technical barriers exist to large-scale CO_2 pipeline deployment. CO_2 pipelines have an excellent safety record of over 40 years of operation with no serious injuries or fatalities ever reported. Today, over 4,500 miles of pipeline transport CO_2 for EOR at wells producing 400,000 barrels of oil per day. These pipelines have operated for decades under existing policy and regulatory oversight at the local, state and federal level.

Figure 1: Past Commercial Carbon Capture Deployment Milestones

Successful commercial-scale carbon capture deployment has a long history through the capture, compression and pipeline transport of CO_2 for EOR with geologic storage, especially in the U.S. Industrial processes where large-scale carbon capture is demonstrated and in commercial operation include natural gas processing, fertilizer production, coal gasification, ethanol production, refinery hydrogen production and, most recently, coal-fired electric power generation and steel production.

1972: Val Verde gas processing plants in Texas. Several natural gas processing facilities began supplying CO_2 in West Texas through the first large-scale, long-distance CO_2 pipeline to an oilfield.

1982: Koch Nitrogen Company Enid Fertilizer plant in Oklahoma. This fertilizer production plant supplies CO_2 to oil fields in southern Oklahoma.

1986: Exxon Shute Creek Gas Processing Facility in Wyoming. This natural gas processing plant serves ExxonMobil, Chevron and Anadarko Petroleum CO_2 pipeline systems to oil fields in Wyoming and Colorado and is the largest commercial carbon capture facility in the world at 7 million MT of capacity annually.

2000: Dakota Gasification's Great Plains Synfuels Plant in North Dakota. This coal gasification plant produces synthetic natural gas, fertilizer and other byproducts and has supplied over 30 million MT of CO_2 to Cenovus and Apache-operated EOR fields in southern Saskatchewan as of 2015.

2003: Core Energy/South Chester Gas Processing Plant in Michigan. CO_2 is captured by Core Energy from natural gas processing for EOR in northern Michigan, with over 2 million MT captured to date.

2009: Chaparral/Conestoga Energy Partners' Arkalon Bioethanol plant in Kansas. The first ethanol plant to deploy carbon capture, it supplies 170,000 MT of CO_2 per year to Chaparral Energy, which uses it for EOR in Texas oil fields.

2010: Occidental Petroleum's Century Plant in Texas. The CO_2 stream from this natural gas processing facility is compressed and transported for use in the Permian Basin.

2012: Air Products Port Arthur Steam Methane Reformer Project in Texas. Two hydrogen production units at this refinery produce a million tons of CO_2 annually for use in Texas oilfields.

2012: Conestoga Energy Partners/PetroSantander Bonanza Bioethanol plant in Kansas. This ethanol plant captures and supplies approximately 100,000 MT per year of CO_2 to an EOR field in Kansas.

2013: ConocoPhillips Lost Cabin plant in Wyoming. The CO_2 stream from this natural gas processing facility is compressed and transported to the Bell Creek oil field in Montana via Denbury Resources' Greencore pipeline.

2013: Chaparral/CVR Energy Coffeyville Gasification Plant in Kansas. The CO_2 stream (approximately 850,000 MT per year) from a nitrogen fertilizer production process based on gasification of petroleum coke is captured, compressed and transported to a Chaparral-operated oil field in northeastern Oklahoma.

2014: SaskPower Boundary Dam project in Saskatchewan, Canada. SaskPower commenced operation of the first commercial-scale retrofit of an existing coal-fired power plant with carbon capture technology, selling CO_2 locally for EOR in Saskatchewan.

2016: Abu Dhabi Carbon Capture Project, United Arab Emirates. This project involves the capture of CO_2 from the Emirates Steel Factory in Abu Dhabi and its transportation to the Abu Dhabi National Oil Company (ADNOC) reservoirs for EOR.

2017: Petra Nova in Texas. Commencing commercial operation in January 2017, this project is designed to capture 1.6 million tons of CO_2 per year from an existing coal-fired power plant. At 240 MW, Petra Nova is the world's largest post-combustion carbon capture facility installed on an existing coal-fueld power plant.

Key Recommendations and Benefits

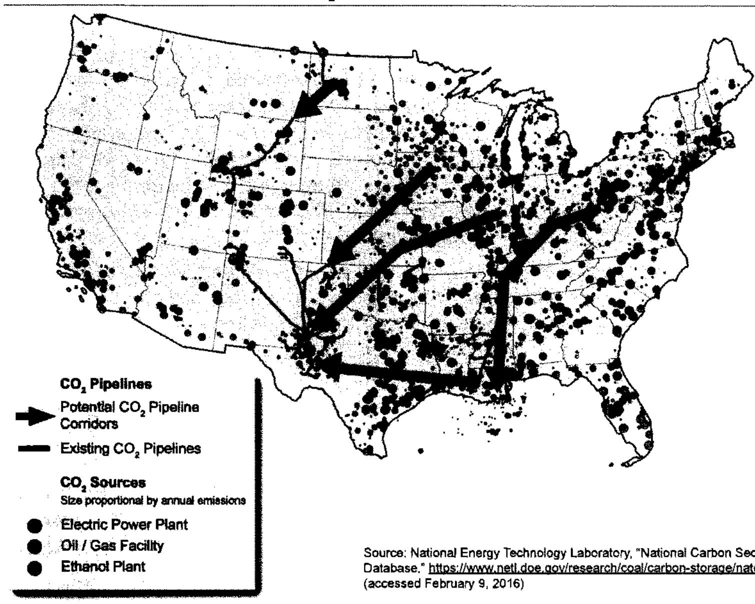
The State CO_2-EOR Deployment Work Group recommends that President Trump and Congress incorporate the development of long-distance, large-volume CO_2 pipelines as a priority component of a broader national infrastructure agenda. The state officials, industry leaders and other experts in the Work Group launched their work in 2015 with the development and deployment of carbon capture and CO_2 pipeline infrastructure as a top priority. Thus, Work Group members and participating states support the Administration and Congress' new focus on our nation's infrastructure, and they would welcome the opportunity to be partners in this effort.

Work Group participants also urge implementation of policies that direct the federal government to play a targeted role, supplementing private capital, in financing increased capacity for priority trunk pipelines to transport CO_2 from industrial facilities and power plants not currently served by pipeline infrastructure to oilfields for EOR.

Finally, Congress and the President should, in consultation with states, tribal governments and key stakeholders, identify and foster the development of five such priority CO_2 trunk pipelines, including support for planning, streamlined permitting, and financing. These trunk pipelines should link key industrial, fossil power-generating, and agricultural regions of the country with the potential to supply significant CO_2 to major hubs of domestic oil and gas production. A vital element in the design of the larger pipeline network is the enormous potential of the Permian Basin region and its proven CO_2 potential and vast resources of residual oil zones.[1] Each trunk pipeline for man-made CO_2 would be comparable in scale and volume to the 30-inch diameter Cortez pipeline, the world's largest CO_2 pipeline. Cortez can transport approximately 30 million tons of CO_2 annually along a 500-mile route from southern Colorado and through New Mexico to the Permian Basin of Texas.

The map below (see Figure 2) does not reflect any decisions to site, permit or build particular CO_2 pipelines by states and stakeholders participating in the Work Group, nor the federal government. Instead, **this map was prepared by the Work Group for illustrative purposes to show how just five pipeline corridors, strategically placed, could expand on existing commercial CO_2 pipeline networks to build out a national system of infrastructure with the capacity to help scale up American oil production and geologic storage of power plant and industrial carbon emissions.** With the addition over time of several connecting pipelines of modest length, this roughly horseshoe-shaped system would link the Upper and Lower Midwest in the east to the Gulf Coast and the Permian Basin of Texas and New Mexico in the south to the Rockies and Northern Plains of the U.S. and Canada in the west.

Figure 2: Potential Regional CO_2 Pipeline Corridors (Illustrative Purposes Only)



Source: National Energy Technology Laboratory, "National Carbon Sequestration Database," https://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas (accessed February 9, 2016)

The five potential priority CO_2 trunk pipeline corridors suggested by this map are:

- **North Dakota to Montana, Wyoming and Colorado.** Moving CO_2 from coal gasification, coal and natural gas-fired power generation and ethanol production southwest into southeastern Montana, connecting the existing North Dakota-Saskatchewan and Wyoming-Colorado-Montana pipeline systems;
- **Upper Midwest to the Permian Basin.** Moving CO_2 from ethanol, fossil power generation, fertilizer production and other industries in the corn-producing heartland of the Upper Midwest into the vast potential and proven reservoirs of the Permian Basin of Texas and New Mexico;
- **Illinois Basin-Midwest to the Permian Basin.** Moving CO_2 from Midwestern ethanol production, fossil power plants and other industries to midcontinent oilfields in Oklahoma, Kansas and Arkansas and the Permian Basin;
- **Louisiana Gulf Coast to the Permian Basin.** Moving CO_2 from the cluster of refining, petrochemical and other industrial facilities in Louisiana to oilfields along the Louisiana and Texas Gulf Coast and on into the Permian Basin; and
- **Ohio River Valley-Lower Midwest to Gulf Coast.** Moving CO_2 from fossil power generation, steel production, and other industries in the industrial and manufacturing heartland of the Lower Midwest to Midwestern oilfields and down to onshore and offshore fields of the Gulf Coast of Alabama, Mississippi and Louisiana.

Benefits of Building Out a National CO_2 Pipeline Infrastructure Network

Establishing a CO_2 pipeline infrastructure of this magnitude, in conjunction with targeted federal incentives for deployment of carbon capture technology, could expand the annual supply of man-made (anthropogenic) CO_2 available for EOR by 150 million tons by 2030, resulting in:

- A tripling of the U.S. EOR industry, with new domestic oil production of approximately 375 million barrels per year;
- An estimated reduction of 22 percent in current U.S. oil imports or $30 billion in reduced annual expenditures on foreign oil; and
- A reduction of roughly four percent in U.S. stationary source CO_2 emissions from current levels.

This level of CO_2 pipeline infrastructure development has the potential to:

- Drive an estimated $75 billion of capital investment;
- Stimulate more than $30 billion per year in economic activity;
- Support thousands of high-paying construction, energy, mining, manufacturing, engineering and technically-skilled operations and services jobs;
- Generate additional state and federal revenues through new energy production and other economic activity; and
- Secure and expand a major competitive advantage the U.S. oil and gas industry holds in utilizing CO_2 for hydrocarbon recovery with safe and permanent geologic storage.

By providing needed common infrastructure, new CO_2 pipelines will improve the competitiveness of existing domestic manufacturing, attract new manufacturing, and help onshore and return industrial production of petrochemicals, cement, steel, and other heavy industries.

There are a number of ways the federal government could provide assistance, including:

1. Federal financial support could leverage substantially greater pipeline infrastructure capacity at a small proportion of total pipeline cost by financing the modest incremental expense of constructing increased capacity up front through, for example, the U.S. Department of Energy's (DOE) Loan Programs Office;[2]

2. DOE Office of Fossil Energy's Regional Industrial Carbon Capture Initiative could work with states and private sector partners to identify corridors for these pipelines that would connect industrial CO_2 sources with EOR opportunities, provide technical and financial analyses to support early private investment and commercial deployment and help address financial and other barriers to investment and deployment;

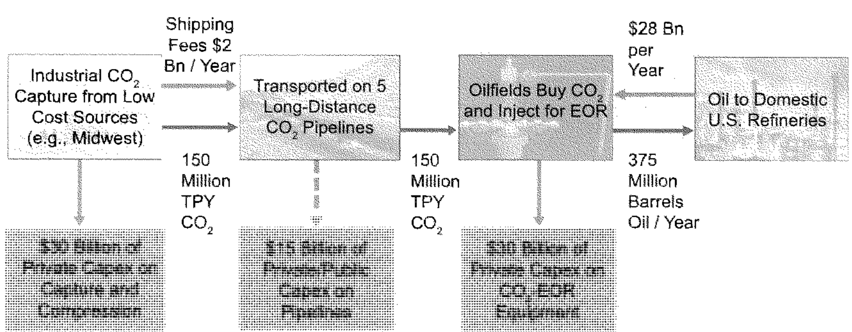
3. Governors or federal agencies could nominate these pipelines as high priority infrastructure projects for streamlined environmental review and approval, and these pipelines can use American-made equipment and materials, in accordance with President Trump's January 24th executive orders;[3,4]

4. These projects could be included as high priority projects in federal infrastructure legislation being developed by Congress, for example by expanding the scope of the Transportation Infrastructure Finance and Innovation Act (TIFIA) to include pipelines; and

5. Congress could enact tax incentives for carbon capture, pipeline transport and storage, such as extension and reform of the Section 45Q Tax Credit for Carbon Dioxide Sequestration and eligibility of carbon capture projects for tax-exempt Private Activity Bonds, both of which enjoy broad bipartisan support.

While the total pipeline investment for five such large projects would be approximately $15 billion, the amount of federal support needed would be considerably smaller. The federal investment might be only the debt, or a portion of the debt. For instance, if the federal government made all the loans, and loans were 50 percent of total pipeline financing, the federal share would be $7.5 billion. If, as described later in this document, the federal government acted as a short-term "bridge lender" to support super-sized, scale-efficient pipelines, the federal share would likely be on the order of only $2-4 billion.

Figure 3: Economic Power of Proposed CO_2 Pipeline Investment:
$75 Billion of Investment & $30+ Billion/Year Activity



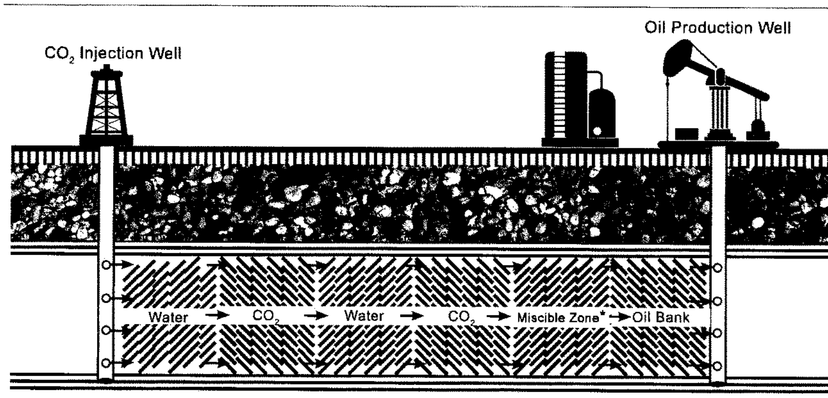
Today's CO_2 Industry – Opportunities for the Future

CO_2-EOR represents a well-understood and commercially successful technique for oil production that enables cost-effective recovery of remaining crude from mature oil fields. In the early or primary phase of traditional oil production, the extraction of oil and gas decreases the fluid pressures in a reservoir. Often, a secondary phase involving injection of water to restore reservoir pressure has followed the primary phase, enabling production of still more of the original oil in place. Eventually, waterflooding reaches a point of diminishing economic returns.[5] Then, most of those fields are suitable for a tertiary phase of production that commonly involves CO_2 injection—referred to as "CO_2 floods"—to recover still more of the remaining oil. Suitable fields tend to be deep and at high pressures, causing CO_2 to function like a liquid that readily dissolves in the oil. Such fields also have a high degree of structural integrity, so that CO_2 floods move in a controlled, predictable fashion.

Commercial CO_2-EOR was pioneered in West Texas in 1972. In the ensuing 45 years, the U.S. independent oil and gas industry turned the practice into a robust and growing industry that accounted for approximately 4 percent of domestic oil production in 2014. The first two large-scale CO_2-EOR projects in the United States (SACROC and Crossett in West Texas) remain in operation today.

Capturing, compressing and transporting CO_2 via pipeline to an oilfield transforms CO_2 from a liability into a valuable commodity with remarkable properties and potential for enhancing oil production. When injected into an existing oilfield, CO_2 lowers the viscosity of the remaining oil, reduces interfacial tension, and swells the oil, thereby allowing oil affixed to the rock and trapped in pore spaces to flow more freely and be produced through traditional means.

Figure 4: How Carbon Dioxide and Water Can Be Used to Produce Residual Oil



*Miscible Zone = Injected CO_2 encounters trapped oil → CO_2 and oil mix → Oil expands and moves towards producing well

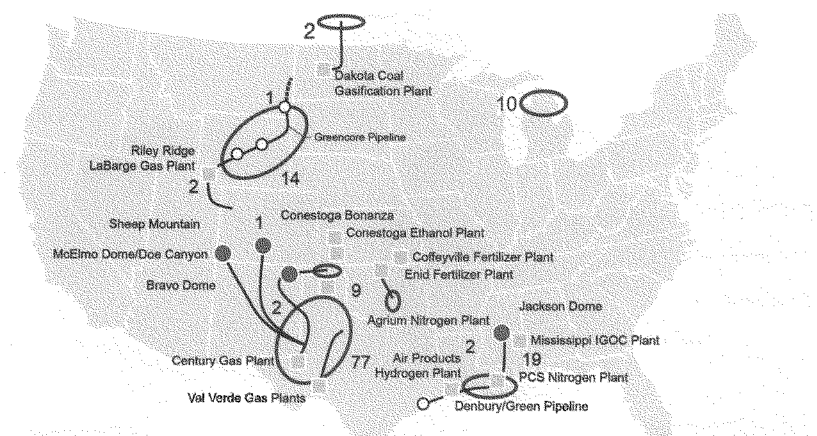
Source: National Energy Technology Laboratory, "Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution," March 2010.

A majority of injected CO_2 remains in the reservoir in the first pass; that CO_2 which does return to the surface with the produced oil is then separated, compressed, and re-injected. With standard operating procedures, this process results in only *de minimis* emissions (less than two percent) from what constitutes a closed-loop system from CO_2 source to oilfield sink.

Traditional production techniques yield one-third to one-half of the original oil in place. If oil companies could readily source ample CO_2 from pipeline networks to existing oilfields, operators would have the potential to extract a further 10-20 percent of the original oil resource. With access to CO_2, the same oilfield, with the same leases, drilling pads, extraction wells, and oil pipelines, would yield significantly more production.

However, insufficient access to CO_2 constrains long-term growth of EOR production. Two types of CO_2 supply the EOR industry, naturally occurring from geologic domes and man-made from industrial and power plant sources. The latter provides roughly one-fourth of the total volume of CO_2 purchased and injected by oilfield operators.

Figure 5: Current CO_2-EOR Operations & Infrastructure



139 Number of U.S. CO_2-EOR Projects
- Natural CO_2 Source
- Industrial CO_2 Source
- CO_2 Pipeline
- CO_2 Proposed Pipeline
- CO_2-EOR Region

U.S. regions with large-scale CO_2 pipeline systems currently in operation	Miles of Pipeline
Permian Basin *(W. TX, NM, and S. CO)*	2,320
Rocky Mountains *(N.CO, WY and MT)*	810
Gulf Coast *(MS, LA, and ETX)*	740
Mid-Continent *(OK and KS)*	480
Other *(ND, MI, Canada)*	215

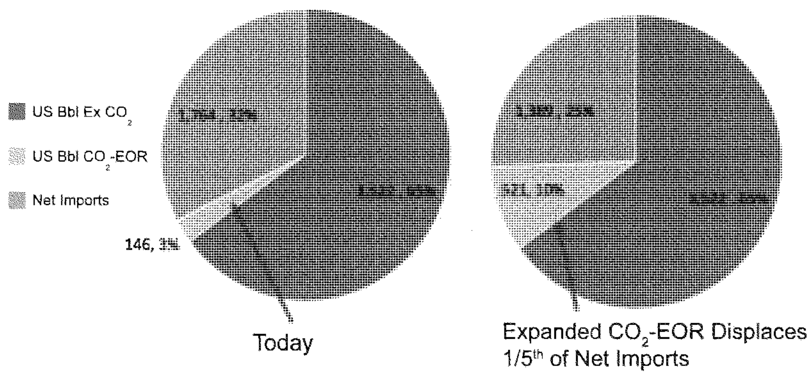
Source: U.S. Department of Energy, "Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure," April 2015.

The CO_2 first used in EOR was man-made and stripped from natural gas produced from fields in Texas and later in Wyoming. Today, Exxon's Shute Creek gas processing plant at the LaBarge gas field in Wyoming is the largest operating carbon capture facility in the world,[6] capable of separating over seven million tons of CO_2 per year and supplying a pipeline network and EOR fields spanning much of Wyoming and extending into Colorado.

Despite a long history of capturing, compressing and transporting man-made CO_2 for EOR, naturally occurring, but limited geologic CO_2 procured from underground domes now dominates the industry supply. For instance, CO_2 is transported via Kinder Morgan's Cortez pipeline—the world's largest—from McElmo Dome in southern Colorado across all of New Mexico, ultimately reaching the Permian Basin in Texas.

Taken together, natural and man-made CO_2 supplies about 79 million tons a year, supporting U.S. CO_2-EOR oil production of about 146 million barrels a year. **Increasing man-made CO_2 supplies by 150 million tons per year though expanded carbon capture and the buildout of five major pipeline corridors would increase annual U.S. EOR production by approximately 375 million barrels.**

Figure 6: New CO_2-EOR Reduces Oil Imports
Annual U.S. oil supply in millions of barrels/yr of crude and petroleum products. Excludes natural gas liquids, ethanol, and biodiesel. Source: U.S. Energy Information Agency 2016 Annual Energy Outlook, Table 11.

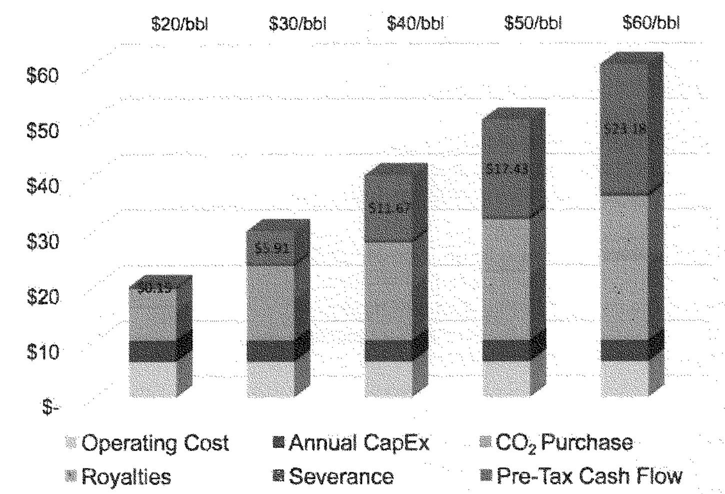


Since our nation still imports a net 1.76 billion barrels per year of foreign oil, a cost-competitive increase in U.S. domestic CO_2-EOR production of this magnitude could reduce our net imports by more than one-fifth.

CO_2-EOR can become a game changer for U.S. domestic energy production. According to 2013 analysis from the U.S. DOE's National Energy Technology Laboratory, the U.S. has the potential to produce an estimated 28 billion barrels of economically recoverable oil from conventional oil fields with today's industry best practices. Next-generation techniques have the potential to yield an estimated 81 billion barrels. For comparison, total U.S. proved reserves of oil stood at just under 40 billion barrels in 2014.

CO_2-EOR enhances our nation's energy and economic security by lessening our dependence on foreign oil, often imported from unstable and hostile areas, and reducing our trade deficit by keeping dollars currently spent on oil imports at work in the U.S. economy. Moreover, EOR operations remain relatively robust in the face of oil price declines triggered by foreign actors such as OPEC. Once the extensive infrastructure of wells, surface processing facilities, and CO_2 pipeline transport has been financed and constructed, an EOR operation is designed to operate and pay off its investors over 20 to 40 years, depending on the size of the field. An EOR operation has large initial investment costs compared to conventional onshore oil production, but very low cash costs of operation—and many of those cash costs, including royalties, severance taxes, and even CO_2 purchase costs, typically decline when oil prices fall. Thus, as shown in the chart below (Figure 7), an established EOR flood that has reached full operational levels may be able to cover day-to-day operating costs at oil prices as low as $20 per barrel.

Figure 7. Cash Flow at Various Oil Prices for CO_2-EOR Flood



In contrast, some newer technologies such as hydraulic fracturing can be very profitable, but require consistent re-investment in order to maintain oil production volumes. In an environment where oil prices have been driven to very low levels (e.g., because of actions by OPEC or other foreign actors), that reinvestment may not occur, and domestic oil production volumes begin to fall. Even with considerable and ongoing innovation and cost reductions in hydraulic fracturing, experts peg the break-even level for drilling new wells at a considerably higher range of $35-50 per barrel (depending on the particular site).

CO_2 Pipelines are Key to 21st Century Energy Infrastructure[7,8]

CO_2 from many man-made sources, especially from industrial processes with low costs of carbon capture, could readily supply oilfields with the right pipeline infrastructure in place. For example, ethanol and fertilizer plants emit CO_2 to the atmosphere that they would rather sell into a pipeline bound for an American oilfield. Even in the absence of regulatory requirements limiting CO_2 emissions, a number of industrial facilities located within reasonable proximity of oilfields have already been tapped. For example, fertilizer plants at Enid, Oklahoma, and Coffeyville, Kansas, were both close enough to oilfields to make the construction of short (~100 miles), small-diameter (~8 inch) pipelines feasible for CO_2-EOR.

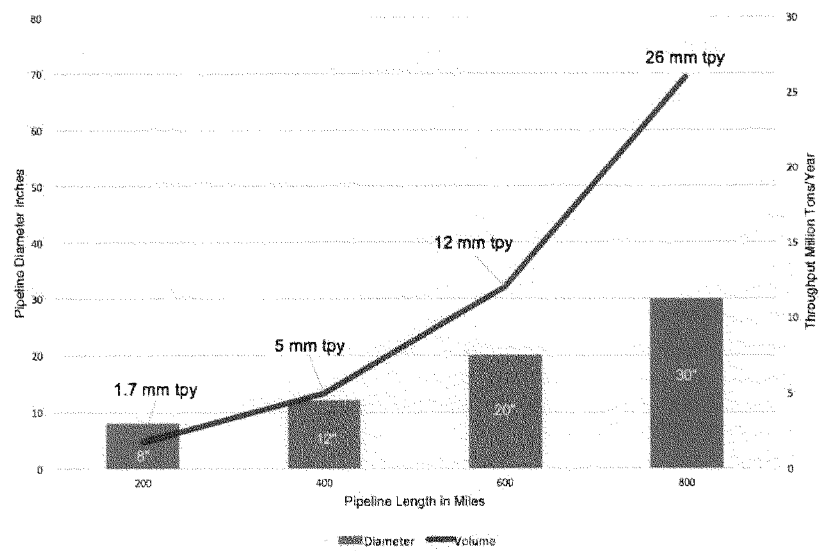
ADM (Archer Daniels Midland) captured 300,000 tons of CO_2 per year at its Decatur, Illinois, ethanol plant, and anticipates increasing capture capacity to 1.1 million tons per year —but that volume alone is not enough to make feasible the construction of a 600+ mile-long pipeline to reach large-scale EOR opportunities.[9] Thus, the CO_2 is being injected into a saline aquifer 7,000 feet below the plant. If a company like ADM could transport the CO_2, an entirely new revenue stream would emerge—in turn supporting the entire economic value chain of farmers, fertilizer makers, seed providers, and agricultural equipment manufacturers that supply ADM with its corn. Further, the global competitors of our ethanol producers, such as Brazil, currently lack the same extra revenue opportunity.

Like natural gas pipelines, building large, high-capacity CO_2 pipelines creates economies of scale and opportunities to realize major cost savings. The reason is simple. Pipelines are categorized by diameter (typically running as small as 8 inches up to more than 30 inches). The main cost of a pipeline—the tons of steel and miles of welds needed—is based on its *circumference* (i.e. the girth of the belt of steel it takes to go around the pipe as it is formed), which increases in direct proportion to the diameter. However, the capacity of the pipeline or, in this case, the volume of CO_2 it can transport, is based upon its cross-sectional *area,* which increases exponentially with diameter. Thus, doubling the diameter of the pipeline doubles the circumference, but quadruples the cross-sectional area and, therefore, quadruples the throughput capacity of the pipeline.[10]

So, by spending twice as much money to build a larger pipeline, an owner can get four times as much throughput capacity. Spending four times the money garners an even greater return—16 times the capacity.[11] The scale economies mean that pressurized gas can be moved long distances at reasonable tariffs, but only if pipelines are built at sufficiently large diameter to drive down capital cost per unit of CO_2 throughput capacity.

In simple terms, at today's expected oil prices (using estimates from futures markets or U.S. government forecasts), CO_2 will be worth roughly $25 per ton delivered to U.S. oilfields a decade from now. To make it worthwhile to capture and compress CO_2 at industrial and power plant sites far from those oil fields, the transport cost needs to be well under $25. For example, if the CO_2 is worth $25 at the oilfield, and it costs $10 to ship, $15 per ton remains to cover capture and compression costs and profit for an Iowa fertilizer plant or an Illinois ethanol distillery. If it costs $25 per ton just to move the CO_2, it will not be economical for a plant owner to capture, compress and transport CO_2. Instead, that plant owner will opt to vent the CO_2, no oil company will have an opportunity to buy it, and the potential oil production, job creation and emissions reduction benefits are all lost.

Figure 8. CO_2 Pipeline Diameter and Volume to Keep Transport Tariffs at $10/ton



Source: National Energy Technology Lab, "FE/NETL CO_2 Transport Cost Model," developed by Timothy Grant and David Morgan, 2014.

The chart above shows the pipeline size needed to drive down transport costs to $10 per ton—*the longer you build the pipe, the larger it must be to make sense economically:*

- To go only 200 miles[12] (far left of chart), with a $10 per ton tariff (transport fee), the pipeline can be eight inches in diameter and only needs to carry 1.7 million tons of CO_2 per year. (The total capital required is $150 million, or $750,000 per mile.)
- To go 800 miles (far right of chart), still keeping the tariff at $10, the pipeline needs to be expanded to 30 inches in diameter, carrying 26 million tons per year. (The total capital required is $2.4 billion, or $3 million per mile.)

From the first example to the second example above, the pipeline cost per mile quadruples from $750,000 per mile to $3 million per mile, but the capacity increases a staggering 16-fold, from 1.7 million to 26 million tons of CO_2 per year. An extraordinary economy of scale is realized. However, to obtain such savings in the real commercial world, the pipeline business deal becomes very complex. The pipeline developer must assemble a larger number of CO_2 suppliers, a larger number of oilfield customers, and a much greater sum of financing ($2.4 billion), all at once.

Rationale for Federal Involvement in CO_2 Pipeline Infrastructure Development

The potential for a major buildout of CO_2 pipeline infrastructure, together with the ramping up of industrial and power plant carbon capture, to deliver domestic energy production, jobs and environmental benefits on a truly national scale warrants a role for the federal government in supporting the financing of CO_2 pipeline infrastructure and in providing incentives for commercial carbon capture deployment.

Supersizing the capacity of the first CO_2 trunk pipelines constructed in states and regions not yet presently served by pipeline infrastructure capitalizes on the demonstrable cost-savings from economies of scale. Additionally, it will also de-risk and lower the cost of capital for tens of billions of dollars in private investment needed in carbon capture projects at industrial facilities and power plants, as well as in infrastructure required to prepare an oilfield for CO_2 injection and EOR.

Fortunately, private sector industrial CO_2 suppliers and oil industry customers can carry *most, but not all,* of the cost of a large capacity pipeline for a few years, while the remaining CO_2 suppliers and customers are identified. To illustrate, we use numbers similar to those in the chart in Figure 8:

- A small group of shippers needing to transport CO_2 800 miles, aggregating to only 12 million tons per year of volume, could make use of a large 30-inch diameter pipeline, instead of the smaller 20-inch line normally utilized for that volume. The 30-inch pipe can function at this smaller volume, even though it can carry much more—26 million tons per year (see the far right of pipeline bar chart above). The flexibility comes from a pipeline operator's ability to vary pressures—lower pressure for lower volumes, higher pressure for higher volumes.
- Until the rest of the suppliers and customers are recruited, the initial shippers, if unaided, would face a relatively high transport charge of $19 per ton—a level that would normally deter prospective shippers. However, once CO_2 shippers for the full 26 million tons per year have signed on, tariffs can fall to a more commercially attractive $10 per ton.
- However, accomplishing this favorable outcome for energy independence, jobs and the economy depends on finding an alternative to charging a prohibitive $19 per ton for the first shippers. To keep the initial shipping fee down to a more feasible $12 per ton, for instance, approximately $84 million per year in cash would be required during an assumed five-year period of operation before additional CO_2 suppliers and customers are brought on board (i.e., an expenditure of $500 million—including interest cost—would economically bridge the gap before the pipeline was filled to capacity).
- Finally, with the full complement of shippers (26 million tons per year) on board, a feasibly small repayment surcharge of $1.50 per ton would repay that $500 million bridge financing with interest.[13]

- Ultimately, a pipeline of this size could sell $650 million of CO_2 per year, driving EOR production of nearly $5 billion dollars of oil per year. More importantly the critical $500 million bridging investment created annual savings of $100 million per year in transportation costs.

The analysis of the Work Group suggests a critical supplementary role to private capital that the federal government is well-positioned to play. **Federal financial support could leverage substantially greater pipeline infrastructure capacity at a small proportion of total pipeline cost by financing the modest incremental expense of constructing increased capacity up front.** Federal taxpayers' infrastructure investment could then be recouped over time through minor tariff increases spread across many additional shippers added to the system as new carbon capture projects and EOR operations deploy and use the pipeline.

Under such an approach, all private sector participants—industry CO_2 suppliers, pipeline owners and EOR operators—come out financially ahead by constructing a higher-capacity pipeline with a modest federal financing component and adding shippers over time. By contrast, acting alone and building a smaller, optimized pipeline upfront would require permanently higher tariffs over the life of the project.

For its part, the federal government's incremental financing role for this CO_2 pipeline infrastructure would yield the extraordinary energy security, jobs, economic, fiscal and environmental benefits for our nation outlined at the beginning of this paper.

Additional Federal Recommendations

The State CO_2-EOR Deployment Work Group offers the following recommendations for a federal financing, siting and permitting role in CO_2 pipeline corridor development that enables construction of increased capacity upfront, potentially with options for states to supplement federal support. The Work Group urges the following:

- DOE should recognize long-distance CO_2 pipeline corridors as an "innovative" technology under the DOE Loan Program Office's funding available for Advanced Fossil Energy Projects. There has never been a long-distance (in excess of 200 miles) CO_2 pipeline constructed in the U.S. expressly to carry man-made CO_2 to oilfields, or one built with increased capacity to facilitate and accelerate future deployment of carbon capture and EOR projects.
  The Canadian energy powerhouse of Alberta is pursuing just such a supersized CO_2 pipeline, the Alberta Carbon Trunk Line, in partnership with industry and in consultation with First Nations and other key stakeholders. The Carbon Trunk Line benefits from a combination of provincial and federal government financial participation.
- The US Congress should expand the mission of USDOT's Transportation Infrastructure Finance and Innovation Act (TIFIA)[14] subordinated loan program to include CO_2 pipeline networks as part of its mission. This program has been used to spur innovative road and rail projects, such the Alameda Corridor Project to de-bottleneck freight movement from ports to railroads through the congestion of Los Angeles.

- Congress should authorize and direct federal agencies to play a supplementary role to private investors by financing additional capacity in strategic CO_2 trunk line projects until a sufficient customer base has been established to recoup the federal investment through tariffs.
  - In a historic example of the significant impact such a federal financing role can have, the federal government initially financed and owned the 1300 and 1500-mile oil pipelines (20 and 24-inch, respectively) from Texas to New England that eventually were privatized (sold for approximately $1.6 billion in today's dollars) and converted to natural gas pipelines as the Texas Eastern Transmission Corporation.[15] Those lines remain an important backbone of the U.S. energy system 75 years later.
  - To take another interesting example, once the federal Bonneville Power Administration had initially strung 1,000 miles of transmission lines between the Pacific Northwest and California, an enterprising group of utilities was able to piggyback on that federal investment by paying for capacity upgrades that greatly increased the lines' capacity.
- Pursuant to President Trump's January 24th executive order, Governors or heads of federal agencies should identify long-distance CO_2 pipelines as high-priority infrastructure projects for expedited environmental reviews and approvals.[16]
- The Administration should develop a more concerted federal policy[17] and require better coordination and consultation between federal agencies and with state, tribal and local governments and stakeholders regarding pipeline corridor siting and permitting. The development and utilization of designated pipeline corridors is a highly efficient and effective way to incentivize pipeline infrastructure development. Pipeline corridors are delineated primarily by siting them adjacent to existing infrastructure and in conformance with federal agency land use and planning documents. The benefits of utilizing designated corridors include: streamlined regulatory authorization, reduced environmental impacts, and increased constructability for project proponents.
- Federal land management agencies should:
  - Actively issue themselves right-of-way (ROW) grants that they will designate and manage as pipeline corridors on lands that they own or administer.
  - Allocate resources to complete National Environmental Policy Act (NEPA) analyses, which are required for ROW grants.
  - Develop their NEPA analyses at as close to project-level scale as possible. Fine scale analyses will allow the agencies to disclose the majority of impacts associated with building pipelines within the designated corridors. These robust analyses will allow pipeline projects to proceed with a much less costly and time-consuming authorization process.
  - Foster relationships to the greatest extent allowed by law with appropriate state, tribal and local governments, as well as industry, NGOs and other stakeholders, to ensure that designated corridors encompass all reasonably

foreseeable development scenarios. To formalize these cooperative relationships, memorandums or agreements should be developed to describe the roles and responsibilities of each partner.

Conclusion

American oil fields are poised to rapidly expand production through utilization of man-made CO_2 for enhanced oil recovery. This promise can be realized if the oil industry can gain access to large, secure volumes of CO_2, transported via pipeline networks and purchased from industrial facilities and power plants where that CO_2 would otherwise be emitted to the atmosphere and wasted.

The State CO_2-EOR Deployment Work Group recommends that President Trump and Congress incorporate the development of long-distance, large-volume CO_2 pipelines as a priority component of a broader national infrastructure agenda.

In particular, Congress and the President should, in consultation with states, tribal governments and key stakeholders, identify and foster the development of five priority CO_2 trunk pipelines. This would include support for planning, streamlined permitting, and financing to transport CO_2 to oilfields for EOR from industrial facilities and power plants not currently served by pipeline infrastructure.

Development and expansion of regional and national CO_2 pipeline networks, together with proposed tax credits and other financial incentives for industrial and power plant carbon capture, can support long-term production and use of America's abundant and affordable coal, oil and natural gas resources, put our nation further down the path of replacing imported oil and create high-paying jobs in energy-producing and industrial states and regions of the country, all while significantly reducing net carbon emissions.

Endnotes

1. Identifying and developing technology for enabling small producers to pursue the residual oil zone (ROZ) fairways in the Permian Basin San Andres. Final Report http://www.netl.doe.gov/file%20library/research/oil-gas/10123-17-final-report.pdf
2. In order to be eligible for LPO financing, a project must use fossil energy; avoid or store greenhouse gas emissions; be innovative; and provide a reasonable prospect of repaying the federal loan.
3. "...it is the policy of the executive branch to streamline and expedite, in a manner consistent with law, environmental reviews and approvals for all infrastructure projects, especially projects that are a high priority for the Nation, such as improving the U.S. electric grid and telecommunications systems and repairing and upgrading critical port facilities, airports, pipelines, bridges, and highways...upon request by the Governor of a State, or the head of any executive department or agency (agency), or on his or her own initiative, the Chairman of the White House Council on Environmental Quality (CEQ) shall, within 30 days after a request is made, decide whether an infrastructure project qualifies as a "high priority" infrastructure project...the Chairman of the CEQ shall coordinate with the head of the relevant agency to establish, in a manner consistent with law, expedited procedures and deadlines for completion of environmental reviews and approvals for such projects..." https://www.whitehouse.gov/the-press-office/2017/01/24/executive-order-expediting-environmental-reviews-and-approvals-high.
4. "The Secretary of Commerce, in consultation with all relevant executive departments and agencies, shall develop a plan under which all new pipelines, as well as retrofitted, repaired, or expanded pipelines, inside the borders of the United States, including portions of pipelines, use materials and equipment produced in the United States, to the maximum extent possible and to the extent permitted by law. The Secretary shall submit the plan to the President within 180 days of the date of this memorandum..." https://www.whitehouse.gov/the-press-office/2017/01/24/presidential-memorandum-regarding-construction-american-pipelines.
5. Some operators go directly to CO_2, where it is readily available and skip the waterflooding phase.
6. Information on the Shute Creek facility can be found at: https://www.globalccsinstitute.com/projects/large-scale-ccs-projects
7. "CO_2 EOR: A Model for Significant Carbon Reductions," L. Steven Melzer and C. Michael Ming, Paper Presented at the Symposium on the Role of EOR in Accelerating the Deployment of CCS, July 23, 2010, Massachusetts Institute of Technology. https://rfflibrary.wordpress.com/2011/05/25/role-of-enhanced-oil-recovery-in-accelerating-the-deployment-of-carbon-capture-and-sequestration/

8. A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide, Interstate Oil and Gas Compact Commission, December 31, 2011. http://groundwork.iogcc.ok.gov/node/987
9. Decatur to North Burbank Field (Chaparral) is about 600 miles. To Permian hubs (Denver City) is approximately 900 miles.
10. The surface area of a pipe (cylinder) = length x circumference = length x (2 x π x radius). The volume of a pipe (cylinder) = length x cross-sectional area = length x (π x radius^2).

Steel needed vs. volume of a one-foot long pipe					
Diameter	Radius = D/2	Area of steel plate needed to form the pipe = 12 inches x Circum-ference	Area vs. 2 inch diameter pipe	Volume of gas contained inside the pipe = 12 inches x Area	Volume vs. 2 inch diameter pipe
2 inch	1 inch	12 x 2 x 3.14 x 1 = 75.3 sq-in	1x	$12 \times \pi \times 1^2 = 37.7$ cubic-in	1x
4 inch	2 inch	12 x 2 x 3.14 x 2 = 150.8 sq-in	2x	$12 \times \pi \times 2^2 =$ 150.8 cubic-in	4x
8 inch	4 inch	12 x 2 x 3.14 x 4 = 301.4 sq-in	4x	$12 \times \pi \times 4^2 =$ 603.2 cubic-in	16x
16 inch	8 inch	12 x 2 x 3.14 x 16 = 602.8 sq-in	8x	$12 \times \pi \times 8^2 =$ 2,411 cubic-in	64x

11. The main cost that has to be recovered through transportation tariff rates charged to pipeline shippers is the annual financing charge based upon the original capital cost.
12. Note that in the chart we assume the pipeline climbs 4 feet per mile, since industrial sources in the Midwest (for example) are located at low elevations (for example, 1,000) feet, whereas much of the oil production region lies at altitudes 3,000 to 4,000 feet higher.
13. The repayment surcharge is relatively small because it is spread over the full 26 million ton per year customer base and extended over the full life of the pipeline.

14. The TIFIA program was modeled on the Alameda Corridor $400 million loan, though it is not clear that the actual loan was technically a TIFIA loan at the time. (Source: https://www.gpo.gov/fdsys/pkg/CHRG-107hhrg77859/html/CHRG-107hhrg77859.htm)
    TIFIA Eligibility - https://www.transportation.gov/buildamerica/programs-services/tifia/eligibility

    Any type of project that is eligible for Federal assistance through existing surface transportation programs (highway projects and transit capital projects) is eligible for the TIFIA credit program, including intelligent transportation systems (ITS). In addition, the following types of projects are eligible: international bridges and tunnels; intercity passenger bus and rail facilities and vehicles; publicly owned freight rail facilities; private facilitates providing public benefit for highway users; intermodal freight transfer facilities; projects that provide access to such facilities; service improvements on or adjacent ot the National Highway System; and projects located within the boundary of a port terminal under certain conditions.

    An eligible project must be included in the applicable State Transportation Improvement Program. Major requirements include a capital cost of at least $50 million (or 33.3 percent of a state's annual apportionment of Federal aid funds, whichever is less) or $15 million in the case of ITS. TIFIA credit assistance is limited to a maximum of 33 percent of the total eligible project costs. Senior debt must be rated investment grade. The project also must be supported in whole or in part from user charges or other non-Federal dedicated funding sources and be included in the state's transportation plan. Applicable Federal requirements include, but are not limited to Titles 23 and 49 of the U.S. Code, NEPA, Buy America provisions, and the Civil Rights and Uniform Relocation Acts. Qualified projects are evaluated by the Secretary against eight statutory criteria, including among others, impact on the environment, significance to the national transportation system, and the extent to which they generate economic benefits, leverage private capital and promote innovative technologies.
15. Big Inch definition on Wikipedia: https://en.wikipedia.org/wiki/Big_Inch
    The Big Inch and Little Big Inch, collectively known as the Inch pipelines, are petroleum pipelines extending from Texas to New Jersey, built between 1942 and 1944 as emergency war measures in the U.S. Before World War II, petroleum products were transported from the oil fields of Texas to the northeastern states by oil tanker. After the United States entered the war on January 1, 1942, this vital link was attacked by German submarines in the Operation Paukenschlag, threatening both the oil supplies to the northeast and its onward transshipment to Great Britain. The Secretary of the Interior, Harold Ickes, championed the pipeline project as a way of transporting petroleum by the more secure interior route.

    The pipelines were government financed and owned, but were built and operated by the War Emergency Pipelines company, a non-profit corporation backed by a consortium of the largest American oil companies. It was the longest, biggest and heaviest project of its type then undertaken; the Big and Little Big Inch pipelines were 1,254 and 1,475 miles (2018 and 2,374 kilometers) long, respectively, with

35 pumping stations along their routes. The project required 16,000 people and 725,000 short tons of materials. It was praised as an example of private-public sector cooperation and featured extensively in U.S. government propaganda.

After the end of the war, there were extended arguments over how the pipelines should be used. In 1947, the Texas East Transmission Corporation purchased the pipelines for $143,127,000, the largest post-war disposal of war-surplus property. The corporation converted them to transport natural gas, transforming the energy market in the northeast. The Little Big Inch was returned to carry oil in 1957. The pipelines are owned by Spectra Energy Partners and Enterprise Products and remain in use.

16. "...it is the policy of the executive branch to streamline and expedite, in a manner consistent with law, environmental reviews and approvals for all infrastructure projects, especially projects that are a high priority for the Nation, such as improving the U.S. electric grid and telecommunications systems and repairing and upgrading critical port facilities, airports, pipelines, bridges, and highways...upon request by the Governor of a State, or the head of any executive department or agency (agency), or on his or her own initiative, the Chairman of the White House Council on Environmental Quality (CEQ) shall, within 30 days after a request is made, decide whether an infrastructure project qualifies as a "high priority" infrastructure project...the Chairman of the CEQ shall coordinate with the head of the relevant agency to establish, in a manner consistent with law, expedited procedures and deadlines for completion of environmental reviews and approvals for such projects. https://www.whitehouse.gov/the-press-office/2017/01/24/executive-order-expediting-environmental-reviews-and-approvals-high.
17. USDOE, A Review of the CO_2 Pipeline Infrastructure in the U.S., DOE/NETL-2014/1681, April 21, 2015.

Oil and Gas, Natural Resources, and Energy Journal

Volume 3 | Number 4

November 2017

Siting Carbon Dioxide Pipelines

Tara K. Righetti

ONE J

Oil and Gas, Natural Resources, and Energy Journal

VOLUME 3 NUMBER 4

SITING CARBON DIOXIDE PIPELINES

TARA K. RIGHETTI[*]

* Associate Professor of Law, University of Wyoming College of Law, and Director of the academic program in Professional Land Management, University of Wyoming School of Energy Resources. This research was made possible through support from the University of Wyoming College of Law and the Charles Koch and David True Foundations. I received valuable comments on earlier drafts of this Article from Jason Robison and Kipp Coddington, and at the Junior Faculty Forum at the University of Wyoming College of Law and the Oil and Gas, Natural Resources, and Energy Journal symposium at the University of Oklahoma College of Law. Madeleine Lewis (J.D./M.A. 2018) provided excellent research assistance. The conclusions and findings reported here are those of the author and do not necessarily reflect the views of Koch and True Foundations or the University of Wyoming. Any errors or omissions are the sole responsibility of the author.

Introduction

Last fall, the subject of oil pipeline siting was thrust into the spotlight. Protesters and police and private security employed by the Dakota Access Pipeline clashed in full media view.[1] Social media accounts buzzed as constituents as diverse as activists, lawyers, nurses, and homemakers nationwide "checked in" at Standing Rock.[2] "Water Protectors" were profiled in *National Geographic* and *Vogue*.[3] Suddenly, it seemed,

1. Joshua Barajas, *Police Deploy Water Hoses, Tear Gas Against Standing Rock Protesters*, PBS NEWSHOUR (Nov. 21, 2016, 10:08 AM), https://www.pbs.org/newshour/nation/ police-deploy-water-hoses-tear-gas-against-standing-rock-protesters; Derek Hawkins, *Police Defend Use of Water cannons on Dakota Access Protestors in Freezing Weather*, WASH. POST (Nov. 21, 2016), https://www.washingtonpost.com/news /morning-mix/wp/2016/11/21/police-citing-ongoing-riot-use-water-cannons-on-dakota-access-protesters-in-freezing-weather/?utm_term=.d2a7f49bd01d.

2. Robinson Meyer & Kaveh Waddell, *Facebook is Overwhelmed with Check-Ins to Standing Rock*, THE ATLANTIC (Oct. 31, 2016), https://www.theatlantic.com/technology/archive/2016/10/facebook-is-overtaken-with-check-ins-to-standing-rock/505988/.

3. Rebecca Bengal, *The Water Protectors at Standing Rock Who Stood Against DAPL*, VOGUE (Mar. 8, 2017), https://www.vogue.com/projects/13528338/american-women-water-protectors-standing-rock-dakota-access-pipeline-protesters/; Saul Elbein, *These Are the Defiant "Water Protectors" of Standing Rock*, NAT'L GEOGRAPHIC (Jan. 26, 2017),

everyone had an opinion on oil pipeline siting, including the adequacy of state approvals and federal oversight. There was widespread outrage that private oil pipelines could be developed over the objections of the local landowners and stakeholders most impacted by disruptions to land use and potential spills.[4] Meanwhile, approximately 450 miles away and removed from the media frenzy, an application quietly proceeded for a federal right-of-way on a 16-inch carbon dioxide ("CO_2") pipeline.[5] This pipeline would tie into a larger network intended to transport anthropogenic CO_2 from a privately owned treatment plant to a larger trunk line where it would be transported to aging oil fields for injection as part of tertiary recovery operations.[6] In addition to the federal right-of-way, the pipeline company would require permission to cross private lands—permission it could likely obtain, if needed, through the exercise of eminent domain.

More than 5,000 miles of high-pressure pipelines carrying CO_2 traverse the western and southern United States primarily connecting natural and anthropogenic sources of CO_2 sources to mature oilfields for CO_2 enhanced oil recovery (CO_2-EOR).[7] The majority of CO_2 pipelines are point-to-point—connecting one privately held asset to another. CO_2 is not transported or delivered for general use by the public—it is neither a heating nor transportation fuel. Accordingly, the pipeline network has developed in a highly localized and organic manner connecting reliable sources of CO_2 to oilfields for CO_2-EOR.

However, there is a foreseeable need for a more flexible, integrated CO_2 pipeline network. It is anticipated that there will be significant growth in CO_2 transportation infrastructure in the coming decades. Demand for CO_2 for CO_2-EOR purposes is only anticipated to grow.[8] Additionally, should

https://news.nationalgeographic.com/2017/01/tribes-standing-rock-dakota-access-pipeline-advancement/.

4. Paul Parfomak, *Dakota Access Pipeline: Siting Controversy*, CRS INSIGHT (June 15, 2017), https://fas.org/sgp/crs/misc/IN10567.pdf.

5. Notice of Intent to Prepare an Environmental Impact Statement for the Proposed Riley Ridge to Natrona Project, Wyoming, 79 FR 32975 (Bureau of Land Management June 9, 2014).

6. *Id.*

7. *Annual Report Mileage for Hazardous Liquid or Carbon Dioxide Systems*, U.S. DEP'T OF TRANSP., PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMIN. (Nov. 1, 2017), https://www.phmsa.dot.gov/pipeline/library/data-stats/annual-report-mileage-for-hazardous-liquid-or-carbon-dioxide-systems [hereinafter DOT Mileage Report].

8. *See* Vello Kuuskraa & Matt Wallace, *CO_2-EOR Set For Growth as New CO_2 Supplies Emerge*, OIL & GAS J. (Apr. 7, 2014), http://www.ogj.com/articles/print/volume-

carbon capture, utilization, and storage (CCUS) be implemented more broadly as a climate-mitigation technology, transportation of additional volumes of CO_2 from anthropogenic sources to storage reservoirs will be necessary. Together, it is estimated that these technologies will necessitate between a three-fold and five-fold expansion of existing CO_2 transportation infrastructure within the United States in the next 30 years.[9]

The precise route of the pipelines may be impacted by a variety of factors under both state and federal law. Like oil pipelines and electric transmission lines, developers of CO_2 pipelines site infrastructure according to state law. Accordingly, state law determines whether, and under which circumstances, CO_2 pipeline companies may utilize eminent domain authority to acquire property along the pipeline route. States principally provide pipelines with this authority under two public interest justifications: 1) the development of natural resources; or 2) constructing and making available public access infrastructure through the imposition of common carrier requirements.

This paper analyzes the adequacy of the current regulatory framework for siting CO_2 pipelines with a goal towards building a CO_2 pipeline network that is flexible enough to serve both CO_2-EOR and CCUS purposes. Part I discusses carbon dioxide itself: its production and capture, its transport, and its current uses in CO_2-EOR and CCUS. Part II discusses state and federal regulations controlling the siting of CO_2 pipelines. Part III examines the process for permitting and acquiring right of way for CO_2 pipelines with a focus on state approaches to grants of condemnation authority to private developers of CO_2 pipelines. Specifically, the discussion compares the two principal methods states utilize to establish public interest for eminent domain for CO_2 pipelines. This exploration analyzes approaches adopted by states that utilize a public purpose justification based on natural resource development as contrasted with those requiring public use via common carriage mandates. Part III also considers the benefits and limitations of requiring common carriage, noting the unique technical and legal requirements of CO_2 transport for both CO_2-EOR

112/issue-4/special-report-eor-heavy-oil-survey/co-sub-2-sub-eor-set-for-growth-as-new-co-sub-2-sub-supplies-emerge.html.

9. *See* J.J. Dooley et al., *Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks*, 1 ENERGY PROCEDIA 1595 (2009), *available at* http://ac.els-cdn.com/S1876610209002100/1-s2.0-S1876610209002100-main.pdf?_tid=cc780e34-caec-11e7-ab6e-00000aacb361&acdnat=1510850585_ae8a579226bf4eab66cd391db3ffe9b7 ("Between 11,000 and 23,000 additional miles of dedicated CO_2 pipeline might be needed in the United States before 2050.").

and CCUS. Part IV examines state siting in a broader context. It considers whether the patchwork of state siting requirements is an insurmountable hurdle to a growing and adaptable CO_2 transportation network and discusses proposals for federal siting regulation. The paper concludes that, at least for the time being, state siting is appropriate given the localized nature of CO_2 pipeline development and its impacts on landowners and the environment. However, the paper suggests that a public goods approach to siting and justifying eminent domain is preferable. A public use approach resolves ambiguity regarding condemnation authority of CO_2 pipeline developers under current statutes and constitutional provisions drafted principally with oil or natural gas in mind. Further, through common carrier requirements it may be possible to assure that CO_2 pipeline infrastructure developed utilizing eminent domain for CO_2-EOR can later be integrated into a broader, national pipeline network to accommodate CCUS.

I. CO_2 – Capture, Transport, and Use

CO_2 is concurrently and variably considered a by-product,[10] a pollutant greenhouse gas (GHG) capable of threatening public health and subject to regulation under the Clean Air Act,[11] and a valuable commodity essential to improving oil production.[12] This would seemingly generate an obvious

10. *See* Maryam Takht Ravanchi & Saeed Sahebdelfar, *Carbon Dioxide Capture and Utilization in Petrochemical Industry: Potentials and Challenges*, 4 APPLIED PETROCHEMICAL RES. 63, 63-77 (May 2014). *See generally* Union Carbide Chems. & Plastics Tech. Corp. v. Shell Oil Co., 308 F.3d 1167 (Fed. Cir. 2002) (describing carbon dioxide as an "undesirable byproduct" of ethylene oxide production); Nat'l Union Fire Ins. Co. of Pittsburgh v. Terra Indus., Inc., 346 F.3d 1160, 1162 (8th Cir. 2003) ("Carbon Dioxide is a byproduct of fertilizer production.").

11. *See* Massachusetts v. EPA, 549 U.S. 497, 529 (2007) ("Carbon dioxide, methane, nitrous oxide, and hydrofluorocarbons are without a doubt 'physical [and] chemical . . . substances[s] which [are] emitted into . . . the ambient air.'"); *Overview of EPA's Proposed Endangerment and Cause or Contribute Findings for Greenhouse Gases Under the Clean Air Act*, U.S. ENVTL. PROT. AGENCY, (Apr. 17, 2009), http://epa.gov/climatechange/endangerment/downloads/determination.pdf. State statutes may also classify CO_2 as a pollutant. *See, e.g.*, N.H. REV. STAT. ANN. § 125-O:1 (West 2002); N.J. STAT. ANN. § 48:3-87(a)(2) (West 2008).

12. *See* MONT. CODE ANN. §§ 82-11-111(9), 82-10-301 through -302; (West, Westlaw through 2017 Sess.); OKLA. STAT. tit. 27A, § 3-5-101(1) (West 2010) ("Carbon dioxide is a valuable commodity to the citizens of the state, particularly for its value in enhancing the recovery of oil and gas and for its use in other industrial and commercial processes and applications."); Paul Parfomak & Peter Folger, *Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues*, CONG. RES. SERV. (2007), http://research.policyarchive.org/18606.pdf; *Best Practices for: Geologic Storage Formation Classification,*

synergy—GHG produced from the burning of fossil fuels could be captured, rather than emitted, and then stored underground as part of commercial CO_2-EOR operations.[13] Yet, despite shortages in CO_2 for CO_2-EOR operations,[14] this has rarely been the case historically.[15] Almost all of the CO_2 used in enhanced oil recovery is produced from natural sources underground,[16] and almost all the CO_2 generated by industrial processes and power generation is emitted into the atmosphere.[17] This paradox results from several reasons, including the fact that most anthropogenic CO_2

Understanding Its Importance and Impacts on CCS Opportunities in the United States, U.S. DEP'T OF ENERGY, NAT'L ENERGY TECH. LAB. (2010), https://www.netl.doe.gov/File%20Library /Research/Carbon%20Seq/Reference%20Shelf/BPM_GeologicStorageClassification.pdf.

13. Storage of CO_2 related to enhanced oil recovery operations is variously called associated storage and incidental storage. *See* MONT. CODE ANN. § 82-11-188; WYO. STAT. ANN. § 30-5-502; L. Steven Melzer, *Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery*, NAT'L ENHANCED OIL RECOVERY INITIATIVE (Feb. 2012), http://neori.org/Melzer_CO2EOR_CCUS _Feb2012.pdf (report prepared for the National Enhanced Oil Recovery Initiative, Center for Climate and Energy Solutions); J. Greg Schnacke et al., *Carbon Dioxide Infrastructure: Pipeline Transport Issues and Regulatory Concerns – Past, Present, and Future, Enhanced Oil Recovery: Legal Framework for Sustainable Management of Mature Oil Fields*, ROCKY MTN. MIN. L. FOUND. 10 (2015).

14. *See* Melzer, *supra* note 13, at 6 ("Depletion of the source fields and/or size limitations of the pipelines are now constricting EOR growth.").

15. *See* Bob Berwyn, *Wait, They're Drilling For CO_2 in Colorado?*, COLO. INDEP. (Mar. 15, 2010), http://www.coloradoindependent.com/151977/wait-theyre-drilling-for-co2-in-colorado; Philip M. Marston & Patricia A. Moore, *From EOR to CCS: The Evolving Legal and Regulatory Framework for Carbon Capture and Storage*, 29 ENERGY L.J. 421 (2008).

16. As of 2016, only eight EOR projects used anthropogenic CO_2, injecting an estimated total of 21 metric tons annually. *Compare* Carbon Capture & Sequestration Techs., *Commercial EOR Projects Using Anthropogenic Carbon Dioxide*, MASS. INST. OF TECH., http://sequestration.mit.edu/tools/projects/index_eor. html [hereinafter MIT Report] (last visited Nov. 16, 2017), *with* Guntis Moritis, *Special Report: EOR/Heavy Oil Survey: Point of View: SPE IOR Conference Chair Laments Lack of R&D Funds*, OIL & GAS J. (Apr. 19, 2010), http://www.ogj.com/articles/print/volume-108/issue-14/General-Interest/special-report-eor.html; *see also Enhanced Oil Recovery*, OFFICE OF FOSSIL ENERGY, http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery (last visited Nov. 28, 2017) (noting that there were "about 114 active commercial CO_2 injection projects that together inject over [75 metric tons] of CO_2" in the U.S. alone in 2010); Marston & Moore, *supra* note 15, at 424.

17. Compare the 21 metric tons captured in 2016 for reinjection, to the more than 2800 metric tons emitted by the Coal and Natural Gas sources in 2016. *See* MONTHLY ENERGY REV., U.S. ENERGY ADMIN 178-85 (2017), https://www.eia.gov/totalenergy/ data/monthly/ archive/00351706.pdf.

capture technologies have not innovated to efficiently and economically address supply needs.[18] Natural CO_2 is often purer and is less expensive to produce in sufficient volumes than the capture and processing of anthropogenic CO_2.[19] It may also be subject to less regulation.[20] However, this paradigm is unlikely to last. As natural reservoirs are depleted and tertiary recovery of oil becomes more prevalent, and as CO_2 capture technologies advance, an increase in the use of anthropogenic CO_2 will be necessary to meet CO_2 demand for EOR.[21] These technologies may become more commercially driven due to tax or other incentives.[22] Concurrently, the geologic injection and storage of anthropogenic CO_2 may be required in some instances due to, for example, regulation,[23] carbon pricing,[24] or

---

18. *See* Melzer, *supra* note 13, at 6. An exception is natural gas separation associated with natural gas production operations, which is economic in many situations where CO_2-EOR is also available.

19. *See* A. S. Bhown & B. C. Freeman, *Analysis and Status of Post-Combustion Carbon Dioxide Capture Technologies*, 45 ENVTL. SCI. TECH. 8624, 8624-32 (2011); Anand B. Rao & Edward S. Rubin, *A Technical, Economic, and Environmental Assessment of Amine-Based CO_2 Capture Technology for Power Plant Greenhouse Gas Control*, 36 ENVTL. SCI. TECH. 4467, 4467-75 (2002); Melzer, *supra* note 13, at 6 ("The new age of anthropogenic supplies of CO_2 has just not advanced to meet the supply shortages. The CO_2 cost gap between industrial CO_2 and the pure, natural CO_2 remains a barrier.").

20. *See* Arnold W. Reitze, Jr., *Federal Control of Carbon Capture and Storage*, 41 ENVTL. L. REP. NEWS & ANALYSIS 10796, 10808 (2011).

21. *See* Ian J. Duncan, *CO_2-EOR 101: An Overview of CO_2 Enhanced Oil Recovery*, ENHANCED OIL RECOVERY: LEGAL FRAMEWORK FOR SUSTAINABLE MANAGEMENT OF MATURE OIL FIELDS, ROCKY MT. MIN. L. FOUND. 7-3 (2015).

22. The currently existing 45Q tax credit (I.R.C. § 45Q) is insufficient to address current cost gaps. *See Siting and Regulating Carbon Capture, Utilization, and Storage Infrastructure, Workshop Report*, U.S. DEP'T OF ENERGY (2017), *available at* http://energy.gov/sites/prod/files/2017/01/f34/Workshop%20Report--Siting %20and%20Regulating%20Carbon%20Capture%2C%20Utilization%20and%20Storage%2 0Infrastructure.pdf. Amendments to 45Q have been proposed. *See* H.R. 3761, 115th Cong. (2017).

23. CCUS has been included in Step 1 of a top-down BACT analysis for GHGs. *See* Utility Air Reg. Grp. v. EPA, 134 S. Ct. 2427, 2448 (2014). However, EPA guidance specifies that its inclusion "does not necessarily mean CCS should be selected as BACT for such sources." *See* John-Mark Stensvaag, *Preventing Significant Deterioration Under the Clean Air Act: The BACT Determination – Part 1*, 41 ENVTL. L. REP. NEWS & ANALYSIS 11101, 11104 n.25 (2011) (citing U.S. EPA Office of Air and Radiation, PSD and Title V Permitting Guidance for Greenhouse Gases). EPA's Proposed New Source Rule Proposal for New, Modified, and Reconstructed Plants under CAA 111(b) also relied on the use of CCUS in establishing emissions limitations. *See* Michael. J. Nasi & Jacob Arechiga, *Greenhouse Gas Reduction Technologies for Power Generation*, RMMLF SPECIAL INST., CLIMATE

governmental imperatives[25] for geoengineering solutions to climate change.[26] As a result, it is likely that the capture of CO_2 from anthropogenic sources and its transport for both CO_2-EOR and CCUS will be of increasing importance in coming years.

The transport of CO_2 across long distances is critical to both improved oil recovery and climate mitigation through CCUS.[27] Sources of CO_2, whether natural or anthropogenic, are rarely co-located with established oil fields or appropriate subsurface storage complexes for geologic storage.[28] In order to deliver CO_2 to these end users, a pipeline network is required,

---

CHANGE LAW AND REGULATIONS: PLANNING FOR A CARBON-CONSTRAINED REGULATORY ENVIRONMENT, Appendix B (2015).

24. *See* Henriette Naims, *Economics of Carbon Dioxide Capture and Utilization—A Supply and Demand Perspective*, 23 ENVTL. SCI. & POLLUTION RES. INT'L 22226, 22231 (2016) ("If these [capture] costs can be reimbursed, e.g., through CO_2 utilization options or political incentives such as a carbon tax, then carbon capture could make economic sense.").

25. *See* J. Thomas Lane et al., *Carbon Sequestration: Critical Property Rights and Legal Liabilities – Real Impediments or Red Herrings?*; 32 E. MIN. L. FOUND. § 23.02 (2011), *available at* http://www.adv res.com/pdf/32nd%20Annual%20Institute %20of%20 EMLF %20Vol%202%20-%20FINAL%20Chapter%2023.pdf; Melzer, *supra* note 13, at 2.

26. CCUS continues to be promoted as one of the chief technologies available to combat climate change. *See Carbon Capture Utilization and Storage: Climate Change, Economic Competitiveness, and Energy Security*, U.S. DEP'T OF ENERGY (2016), http://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon %20Capture%20 Utilization%20and%20Storage_2016-09-07.pdf. ("There is international consensus that CCUS will play a critical role as part of an economically sustainable route to the emissions cuts needed to limit global warming to 2°C. In 2014, the Intergovernmental Panel on Climate Change (IPCC) concluded that without CCUS, the costs of climate change mitigation could increase by 138%, and further, that realizing a 2°C scenario may not even be possible without CCUS technologies."); *see also* R.K. Pachauri & L.A. Meyer, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: SYNTHESIS REPORT (2014), *available at* http://www.ipcc.ch/pdf/assessment-report /ar5/syr/SYR _AR5_FINAL_full_wcover.pdf; Stephen Pacala & Robert Socolow, *Stabilization Wedges: Solving the Climate Program for the Next 50 Years With Current Technologies*, 305 SCIENCE 968 (2004).

27. *See* Rickard Svensson et al., *Transportation Systems for CO_2 – Application to Carbon Capture and Storage*, 45 ENERGY CONVERSION & MGMT 2343, 2353 (2004); Dooley, *supra* note 9, at 1596; Paul Parfomak & Peter Folger, CONG. RES. SERV., RL34316, Pipelines for Carbon Dioxide (CO_2) Control: Network Needs and Cost Uncertainties (2008).

28. *See generally* Jerry R. Fish & Eric L Martin, TECHNICAL ADVISORY COMMITTEE REPORT: APPROACHES TO PORE SPACE RIGHTS, CAL. CARBON CAPTURE & STORAGE REV. PANEL (2010), http://www.climatechange.ca.gov/carbon_capture_review_panel/ meetings/ 2010-08-18/white_papers/Pore_Space_Rights.pdf.

often crossing several states and federal land.[29] An integrated and nationwide network may address concerns about CO_2 availability and reliability for CO_2-EOR and favorably impact economics for CCUS and captured anthropogenic CO_2.[30] However, unlike the massive growth of natural gas pipelines in the 20th century, CO_2 pipelines are unlikely to grow explosively or pervasively. Demand for CO_2 is highly localized and development is likely to progress through point-to-point, single use pipelines. An integrated backbone CO_2 pipeline infrastructure that is flexible enough to accommodate CO_2-EOR and CCUS uses is unlikely to develop organically. Accordingly, facilitating the expansion of CO_2 transportation networks in a manner that addresses economic needs, while promoting CCUS, presents unique legal challenges.

Exploration, Production, and Capture of CO_2

CO_2 can be produced from naturally occurring underground sources[31] or can be captured from industrial facilities, such as mining processing facilities or coal fired generation.[32] Natural CO_2 is produced from underground reservoirs that are typically called domes.[33] Known reservoirs of natural CO_2 exist in Colorado, Utah, New Mexico, and Mississippi.[34] These reservoirs contain high purity CO_2 that is suitable for use in CO_2-EOR with minimal processing.[35] Natural CO_2 reserves in the United States are substantial: as of 2012, known reservoirs of natural CO_2 were estimated to contain approximately 41 trillion cubic feet of CO_2.[36]

29. *See* John Gale & John Davison, *Transmission of CO_2—Safety and Economic Considerations*, 29 ENERGY 1319, 1319-28 (2004).

30. *See* Ioannis Chrysostomidis, et al., *Assessing Issues of Financing a CO_2 Transportation Pipeline Infrastructure*, 1 ENERGY PROCEDIA 1625, 1632 (2009).

31. *See* Duncan, *supra* note 21, at 3 (stating that "[n]aturally occurring CO_2 reservoirs exist in Colorado, New Mexico, and Mississippi").

32. *Id.* A third alternative, scrubbing CO_2 from the atmosphere, may eventually become available. *See* Robert Kunzig & Wallace Broecker, *Carbon Scrubbers: Taking CO_2 Out of the Air*, NEW SCIENTIST 34-37 (2009); Richard Schiffman, *Why CO_2 'Air Capture' Could Be Key to Slowing Global Warming*, YALE ENV'T 360 (May 23, 2016), http://e360.yale.edu/features/pulling_co2_from_atmosphere_climate_ change_lackner.

33. *See generally* Phil DiPietro et al., *A Note on Sources of CO_2 Supply for Enhanced-Oil-Recovery Operations*, SOC'Y OF PETROL. ENG'RS ECON. & MGMT. 69, 69-74 (2012).

34. *Id.*

35. *Id.*

36. *Id.* at 69-70.

Ownership and Leasing of CO_2

Natural CO_2 is found on both private and federal lands, including both private and federal split estate configurations. A split estate exists where different parties own the surface and mineral interests. "Split Estate Federal Minerals"[37] arose principally from reservations in patents issued under the land disposition acts of the early 20th century, including the Coal Land Acts,[38] Agricultural Entry Act,[39] and the Stock Raising Homestead Act.[40] By retaining the minerals Congress sought to preserve valuable public resources while simultaneously promoting efficient extraction of mineral resources and development of the arid west for both natural resource and agricultural purposes.[41] In the past one hundred years, whether these reservations include specific substances, such as gravel[42] or coal bed methane,[43] has been hotly contested, leaving ambiguity as to what precisely has been conveyed or retained.[44] Consistent with these cases, in the late 1970s and early 1980s, when production of natural CO_2 for CO_2-EOR purposes was gaining momentum, there was confusion as to whether CO_2

37. *See* 43 U.S.C. §§ 299, 301 (2012); DEP'T OF INTERIOR, BUREAU OF LAND MGMT., PUBLIC LAND STATISTICS, at 8 (2014), http://www.blm.gov/public_land_statistics/pls14/pls2014.pdf ("The term Split-Estate Federal Minerals refers to Federal mineral rights under private surface lands. These are patented lands with minerals reserved to the United States.").

38. 30 U.S.C. §§ 81, 83-85 (2012).

39. 38 Stat. 509, ch. 142, *as amended*, 30 U.S.C. § 121 et seq.

40. Stock-Raising Homestead Act, Pub. L. No. 64-290, 39 Stat. 862 (1916).

41. *See* Watt v. W. Nuclear, 462 U.S. 36, 47 (1983) ("While Congress expected that homesteaders would use the surface of SRHA lands for stock-raising and raising crops, it sought to ensure that valuable subsurface resources would remain subject to disposition by the United States, under the general mining laws or otherwise, to persons interested in exploiting them."); United States v. Union Oil Co. of Cal., 549 F.2d 1271, 1276 (9th Cir. 1977) ("When Congress imposed a mineral reservation upon the Act's land grants, it meant to . . . retain governmental control of subsurface fuel sources, appropriate for purposes other than stock raising or forage farming.").

42. *Id.* (holding that the gravel found on lands patented under the SRHA is a mineral reserved to the United States despite the fact that it would not have been considered a mineral at the time of the SRHA).

43. *See* Amoco Prod. Co. v. S. Ute Indian Tribe, 526 U.S. 865, 865 (1999) (holding that "[t]he term 'coal' as used in the 1909 and 1910 [Coal Land Acts] does not encompass CBM gas.").

44. *See Watt*, 462 U.S. at 62 (Powell, J., dissenting) (noting that by including gravel as a "mineral" within the reservation of the Stock Raising Homestead Act "only the dirt itself could not be claimed by the Government"); *Union Oil*, 549 F.2d at 1278 (noting that the patent under the SRHA "give[s] the owner much more than the surface, [it] give[s] him all except the body of the reserved mineral") (citation omitted).

was a "gas" as defined within these mineral reservations of "oil and gas."[45] The Department of Interior, citing the broad definition of gas in BLM regulations[46] and the general intent of the Congress to retain valuable mineral resources,[47] determined that the oil and gas reservations in land patents issued by the United States include CO_2.[48] This position was later confirmed in *Aulston v. United States*.[49] Thus, in addition to federal fee lands, CO_2 is federally owned on land with private surface and federal minerals retained pursuant to these reservations.

Federally owned CO_2 is considered a leasable mineral under the Mineral Leasing Act (MLA).[50] Like combustible and hydrocarbon gas, CO_2 on federal lands is produced by drilling and completing wells pursuant to oil and gas leases.[51] "Gas," as used in the MLA, is not restricted to hydrocarbons.[52] In fact, Bureau of Land Management definitions define "gas" as "any fluid, either combustible or noncombustible, which is produced in a natural state from the earth and which maintains a gaseous or rarefied state at ordinary temperatures and pressure conditions."[53] Noting specifically that helium, a non-hydrocarbon gas, was within the meaning of "gas" in the statute, the Tenth Circuit in *Aulston* held that CO_2 was a "gas" within the meaning of the MLA and thus could be extracted under the terms of an oil and gas lease.[54]

Where both surface and minerals are privately owned, a property-specific analysis is required to determine ownership of CO_2. If CO_2 is expressly granted or reserved, the language of the grant or reservation will control. However, where the conveyancing language is ambiguous, state

45. *See* Aulston v. United States, 915 F.2d 584 (10th Cir. 1990).

46. 30 C.F.R. § 206.151 (2017).

47. *Aulston*, 915 F.2d at 598 (citing *Union Oil*, 549 F.2d. at 1274-76).

48. *See* Robert D. Lanier, 93 Interior Dec. 66 (IBLA 1986); Rocky Mt. Min. L. Found., Law of Federal Oil and Gas Leases, § 9.03(3) (2017) (citing Memorandum from Reg'l Solicitor, Den. on Reservation of Carbon Dioxide Gas in Land Patent to the Colo. State Dir., Bureau of Land Mgmt. (July 2, 1979)).

49. 915 F.2d 584 (10th Cir. 1990).

50. *See generally* Aulston v. United States, 915 F.2d 584 (10th Cir. 1990).

51. *See generally* Atl. Richfield Co. v. Farm Credit Bank of Wichita, 226 F.3d 1138 (10th Cir. 2000); Comm'r of Gen. Land Office v. SandRidge Energy, Inc., 454 S.W.3d 603 (Tex. App.—El Paso 2014, pet. denied).

52. Ownership of and Right to Extract Coalbed Gas in Federal Coal Deposits, 88 Interior Dec. 538 (1981) (subsequently withdrawn).

53. 43 C.F.R. § 3000.0-5(a) (2017).

54. *See Aulston*, 915 F.2d 584, 591-99 (10th Cir. 1990) (citing Northern Nat. Gas Co. v. Grounds, 441 F.2d 704 (10th Cir. 1971)).

case law or statutory enactments may be determinative.[55] These approaches may variously look to the value of the substance,[56] its location and the degree of surface damage caused by the manner by which it can be reasonably extracted,[57] the substance's similarity to named minerals,[58] and the commonly understood meaning of the term at the time of the grant.[59] Some states like North Dakota have statutorily defined "minerals," although doing so has not necessarily resolved uncertainty for interpretation.[60] Despite abundant case law on the question, ambiguous mineral reservations or conveyances may still be unclear as applied to various substances—including CO_2.

Exploration and Production

State regulation of exploration activities and potential surface and environmental impacts of exploration are very similar to those for oil and gas. CO_2 is produced using methods similar to those used for hydrocarbon gas production. In fact, CO_2 domes may be discovered in the course of oil and gas exploration. Accordingly, state oil and gas conservation agencies may be authorized to create drill spacing units, permit new drilling, and unitize leases for purposes of CO_2 production.[61] Drilling for CO_2 results in

55. See Patrick H. Martin & Bruce M. Kramer, WILLIAMS & MEYERS OIL & GAS LAW, § 219 (2015); E. Wayne Thode, *Mines and Minerals – Meaning of the Word "Minerals" in a Grant or Reservation*, 27 TEX. L. REV. 726 (1949).

56. *See* Spurlock v. Santa Fe Pac. R.R., 694 P.2d 299, 304, 308 (Ariz. Ct. App. Div. 1 1984) (holding a "a reservation of 'all oil, gas, coal, and minerals whatsoever'" included "all commercially valuable substances separate from the soil"). This is substantially similar to the "manner of enjoyment" approach suggested by Professor Kuntz. *See* Eugene O. Kuntz, *The Law Relating to Oil and Gas in Wyoming*, 3 WYO. L.J. 107, 112-13 (1947); *see also* John S. Lowe, *What Substances are Minerals?*, 30 ROCKY MT. MIN L. INST. 2-1 (1984).

57. *See generally* Moser v. U.S. Steel Corp., 676 S.W.2d 99 (Tex. 1984); David A. Scott, *Determining Mineral Ownership in Texas After Moser v. United States Steel Corp. – The Surface Destruction Nightmare Continues*, 17 ST. MARY'S L.J. 185 (1985).

58. *See generally* State ex rel. Comm'rs Land Office v. Butler, 753 P.2d 1334 (Okla. 1987).

59. *See generally* Keith v. Kinney, 140 P.3d 141 (Colo. App. 2005); *Salzseider v. Brunsdale*, 94 N.W.2d 502 (N.D. 1959); *Atwood v. Rodman*, 355 S.W.2d 206 (Tex. Civ. App.—El Paso 1962); Mullinnix LLC v. HKB Royalty Trust, 126 P.3d 909 (Wyo. 2006).

60. N.D. CENT. CODE ANN. § 47-10-24 (West 1983); George E. Reeves, *The Meaning of the Word "Minerals"*, 54 N.D. L. REV. 419 (1978); Robert E. Beck, *"And Other Minerals" As Interpreted By the North Dakota Supreme Court*, 52 N.D. L. REV. 633 (1976).

61. *See* Bailey v. Shell W. E&P, Inc., 609 F.3d 710 (5th Cir. 2010); *see, e.g.*, MISS. CODE. ANN. § 53-1-3(d) (West 1995) (defining "gas" to include Carbon Dioxide and therefore putting CO_2 within the permitting authority of the state Oil and Gas Board); N.M. STAT. ANN. § 70-2-34(A) (West 2003) ("The oil conservatiou division shall adopt and

surface disturbances and can generate impacts to species, noise and light pollution, and other environmental externalities associated with the exploration and production of other gaseous underground resources. Appropriately, surface requirements for bonding, setbacks, and reclamation may also be similar to those mandated for oil and gas exploration.

Producing CO_2 as a byproduct from industrial processes and natural gas separation plants is an alternative to natural CO_2. Early CO_2-EOR projects, prior to the discovery of natural sources, used CO_2 from industrial facilities and natural gas separation plants. Although the processes are distinct, and the CO_2 itself is indistinguishable from that produced by natural sources, for purposes of this paper CO_2 sourced from these types of facilities are collectively referred to as "anthropogenic CO_2."[62] Anthropogenic CO_2 can be captured from the flue gas stream from existing sources such as natural gas, coal, and combined cycle power plants, and from energy intensive industrial processing facilities such as gas processing, coal gasification, combined cycle generation, and fertilizer production facilities.[63] Most currently available technologies capture from a flue through retrofits onto existing plants.[64] The cost of capture and the purity of CO_2 captured depend on the quantity of CO_2 in the flue and the method of generation, and estimates vary greatly.[65] While the potential volume of CO_2 that can be captured from these sources may exceed that available from underground reservoirs,[66] methods of capture can be expensive and the CO_2 captured may require additional processing to reach pipeline quality specifications. These specifications require removal of water and other impurities that

administer rules on the conservation, the production and the prevention of waste of carbon dioxide, helium and other non-hydrocarbon gases in the same manner as it regulates, conserves and prevents waste of natural or hydrocarbon gas.").

62. *See* Marston & Moore, *supra* note 15, at 428.

63. Duncan, *supra* note 21, at 3; Schnacke, *supra* note 13, at 287; Dipietro, *supra* note 33, at 1, tbl. 2-3.

64. Duncan, *supra* note 21, at 3; Rao & Rubin, *supra* note 19, at 4467.

65. Patrick Falwell & Brad Crabtree, *Understanding the National Enhanced Oil Recovery Initiative*, CORNERSTONE (2014), http://cornerstonemag.net/understanding-the-national-enhanced-oil-recovery-initiative/; *Developing a Pipeline Infrastructure for CO_2 Capture and Storage: Issues and Challenges*, ICF INTERNATIONAL, at 23 (2009), http://www.globalccsinstitute.com/publications/developing-pipeline-infrastructure-co2-capture-and-storage-issues-and-challenges [hereinafter ICF Report]; Kelly Thambimuthu et al., *Capture of CO_2*, IPCC SPECIAL REPORT ON CARBON DIOXIDE CAPTURE AND STORAGE (Bert Metz 2005); *CO_2 Pipeline Infrastructure*, INT'L ENERGY AGENCY, GLOBAL CCS INST., at 12, 14, 104 (2014), http://hub.globalccsinstitute.com/sites/default/ files/publications/ 120301/co2-pipeline-infrastructure.pdf.; Marston & Moore, *supra* note 15, at 433.

66. DiPietro, *supra* note 33.

contribute to corrosion during transportation or make the CO_2 unsuitable for EOR.[67] Perhaps due to these constraints, the majority of CO_2-EOR projects use natural CO_2. Only eight oil and gas fields presently utilize anthropogenic CO_2 for enhanced recovery operations.[68]

CO_2 Transportation

Once captured, CO2 is processed, dehydrated, pressurized, and transported via pipeline to end-users for CO_2-EOR.[69] According to data compiled by the Pipeline Hazardous Materials Safety Administration (PHMSA), as of 2016, there were over 5,100 miles of CO_2 pipelines in the U.S.[70] The majority of CO_2 pipelines were built to deliver CO_2 from reservoirs in New Mexico and Colorado for EOR operations in the Permian oil field in West Texas.[71] In addition to these states, demand for EOR has driven construction of significant CO_2 pipeline infrastructure in Wyoming, Mississippi, Louisiana, and Texas.[72] These pipelines are highly localized and field specific, and carry "both naturally-occurring CO_2 and anthropogenic CO_2 extracted or captured from industrial sources."[73] CO_2-EOR accounts for approximately 90 percent of total CO_2 transported, although additional end uses include manufacturing, such as soda bottling.[74]

Transportation of CO_2 by pipeline requires unique design and construction to address the pressure and temperature requirements for transport in a supercritical phase. CO_2 is transported in a supercritical dense-phase state at pressures ranging "from 1,200 to 2,700 psi"—pressures significantly higher than those used for the transport of natural gas.[75] Dense-phase gas has attributes that are both like a gas and a liquid.[76]

67. B. Wettenhall, et al., *The Effect of CO_2 Purity on the Development of Pipeline Networks for Carbon Capture and Storage Schemes*, 30 INT'L J. OF GREENHOUSE GAS CONTROL 197-211 (2014); Marston & Moore, *supra* note 15, at 434.

68. MIT Report, *supra* note 16.

69. Schnacke, *supra* note 13, at 10-6.

70. DOT Mileage Report, *supra* note 7.

71. Dooley, *supra* note 9, at 1596 (citing *Natural Gas Transmission Pipeline Annual Mileage Database*, U.S. DEP'T OF TRANSP., PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMIN., OFFICE OF PIPELINE SAFETY (2007), https://www.phmsa.dot.gov/ data-and-statistics/pipeline/annual-report-mileage-natural-gas-transmission-gathering-systems)).

72. *Id.*; Dooley, *supra* note 9, at 1596.

73. Schnacke, *supra* note 13, at 275.

74. *Id.* at 289 (citing Presentation, Lisa Bacanskas, *CO_2-EOR and EPA's Greenhouse Gas Reporting Program*, EPA Workshop: Introduction to Carbon Dioxide Enhanced Oil Recovery (CO_2-EOR) (June 11, 2013)).

75. *Id.* at 278.

76. *Id.*; Marston & Moore, *supra* note 15, at 426.

Because dense-phase CO_2 moves like a liquid, pumps, rather than compressors, are required to move it through the pipeline.[77] Compression to these pressures is itself energy intensive.[78] Since CO_2 cannot be burned to generate the energy necessary for compression, compression stations must be located near sources of electric power or natural gas.[79] Due to high pressures, CO_2 pipelines typically use thicker walled pipe than is used for natural gas pipelines.[80] Additional linings, claddings, and coatings may be necessary to manage corrosion risk.[81] Although possible, these unique construction specifications make requalification of existing natural gas pipelines for CO_2 unusual.[82]

End Uses of CO_2

CO_2 is considered a commodity for use in manufacturing, the food and beverage industry, and energy production.[83] The majority of CO_2 drilled, produced, and transported today is for use in oil fields for CO_2-EOR.[84] Conventional oil production may only produce as much as 80% or as little as 10% of the initial oil in place.[85] As pressure within the reservoir diminishes, oil remains trapped within the pore space.[86] Some of this stranded oil can be produced by the injection of CO_2 to mobilize flow of oil within the pore spaces towards a production well.[87]

EOR operations also result in underground storage of CO_2. As long as tertiary recovery operations continue, CO_2 is recycled and reinjected with only minimal losses throughout the process.[88] Approximately 90% of the total CO_2 injected will remain within the hydrocarbon reservoir, a process

---

77. Schnacke, *supra* note 13, at 278.

78. Marston & Moore, *supra* note 15, at 435.

79. *Id.* at 435-36; ICF Report, *supra* note 65, at 39.

80. *Id.*

81. *Id.*

82. *Recommended Practice: Design and Operation of CO_2 Pipelines*, DET NORSKE VERITAS, DNV-RP-J202, at 29 (Apr. 2010); Marston & Moore, *supra* note 15, at 430, 436, 450 (citing *Southern Natural Gas Co.*, 115 F.E.R.C. ¶ 62, 266 at P 1-3 (2006)).

83. Emitted CO_2 has also been classified as a "pollutant" under the Clean Air Act, whereas injected CO_2 for storage has been classified as a solid waste and may be considered a hazardous waste, if not injected under Class VI and within the scope of EPA's conditional exclusion. *See supra* note 11 and *infra* note 402.

84. Duncan, *supra* note 21, at 1.

85. *Id.*

86. *Id.* at 2.

87. *Id.*

88. Robert C. Ferguson, et al., *Storing CO_2 with Enhanced Oil Recovery*, ENERGY PROCEDIA 1, 1989-96 (2009); Schnacke, *supra* note 13, at 283.

that is referred to as "associated storage."[89] This storage accounts for the majority of anthropogenic CO_2 that has been sequestered to date.[90]

CO_2 can also be sequestered underground for CCUS to decarbonize fossil-fuel generation and mitigate climate change.[91] In this process, CO_2 is viewed as a waste rather than a commodity. CO_2 is captured from anthropogenic sources, such as coal and natural gas fired power plants or natural gas separation facilities, and injected underground for long term or permanent storage.[92] Sequestration requires rock formations with impervious layers and that are free of faulting to prevent the injected CO_2 from migrating or escaping into other formations, such as fresh water aquifers, or to the surface.[93] The underground reservoirs where CO_2 can be sequestered may be depleted oil or gas fields—hydrocarbon reservoirs that have already demonstrated secure containment of substances under pressure over a geologic time scale—or newly discovered non-hydrocarbon storage sites such as deep saline aquifers or coal seams.[94]

---

89. *Id.* (quoting *The Global Status of CCS: 2012*, GLOBAL CCS INST., at 147 (2012), http://hub.globalccsinstitute.com/sites/default/files/publications/47936/global-status-ccs-2012.pdf).

90. Marston & Moore, *supra* note 15, at 425 ("The amount of CO_2 that has been incidentally stored [as residual unrecoverable CO_2 injected for EOR] over the last several decades dwarfs the volumes injected by CCS pilot projects around the world.").

91. An exploration of the comparative merits and drawbacks of CCUS as a climate mitigation technology is beyond the scope of this article. *See* David Biello, *Can Carbon Capture Technology Be Part of the Climate Solution*, YALE ENV'T 360 (Sept. 8, 2014), http://e360.yale.edu/features/can_carbon_capture_ technology_be_ part_of_the_climate_solution; *Carbon Capture and Storage: The Solution of Deep Emissions Reductions*, INT'L ENERGY AGENCY (2015), https://www.iea.org/publications/freepublications/publication/ Carbon CaptureandStorageThesolutionfordeepemissionsreductions.pdf; Alexandra B. Klass & Elizabeth J. Wilson, *Climate Change Carbon Sequestration and Property Rights*, 2010 ILL. L. REV. 363, 371-72 (2010) [hereinafter Climate]; Jeff Tollefson, *Is The 2 Degree C World a Fantasy?*, NATURE (Nov. 24, 2015), http://www.nature.com/news/is-the-2-c-world-a-fantasy-1.18868; *Technology Roadmap: Carbon Capture and Storage*, INT'L ENERGY AGENCY, at 7 (2013), http://www.iea.org/publications/freepublications/publication /Technology RoadmapCarbonCaptureandStorage.pdf.

92. Academic literature refers to both CCUS and CCS, often using the terms interchangeably. However, there are differences between projects where CO_2 is exclusively stored and projects where CO_2 is utilized for EOR, or the production of chemicals or other industrial products. *See* Rosa M. Cuellar-Franca & Adisa Azapagic, *Carbon Capture, Storage, and Utilization Technologies: A Critical Analysis and Comparison of Their Life Cycle Environmental Impacts*, 9 J. OF CO_2 UTILIZATION 82-102 (Mar. 2015).

93. Nasi, *supra* note 23, at 9B-9.

94. Stefan Bachu, *Identification of Oil Reservoirs Suitable for CO_2-EOR and CO_2 Storage (CCUS) Using Reserves Databases, with Application to Alberta, Canada*, 44 INT'L

The U.S. Department of Energy (DOE) estimates that in the U.S. alone there is adequate sequestration capacity for geologic storage to contain more than 3,300 billion metric tons of CO_2.[95] Implementation of CCUS at the nationwide, commercial scale necessary to materially impact climate change will require CO_2 pipeline infrastructure to expand dramatically.[96] Development of even a small portion of these storage resources will require a significant expansion of CO_2 transportation infrastructure.[97] An explosion of construction, however, is unlikely. Thus far, implementation of CCUS technology has been exclusively through pilot projects with extensive government funding.[98] The DOE has provided billions of dollars for CCUS research, technology development, and pilot projects.[99] It is unknown whether, and to what extent, these technologies will be commercially adopted.

Pipelines developed for EOR will likely form the basis for a larger system to accommodate CCUS deployment. In fact, many depleted EOR assets may have additional carbon storage potential. Transitioning end-of-life EOR assets to permanent storage facilities requires navigation of complex and inconsistent regulatory permitting requirements and

---

J. OF GREENHOUSE GAS CONTROL 152-65 (Jan. 2016); Stephanie M. Haggerty, Note, *Legal Requirements for Widespread Implementation of CO_2 Sequestration in Depleted Oil Reserves*, 21 PACE ENVTL. L. REV. 197, 200-01 (2003).

95. U.S. DEP'T OF ENERGY, CARBON SEQUESTRATION ATLAS OF THE UNITED STATES AND CANADA 15 (2007).

96. Dooley, *supra* note 9, at 4; Paul Parfomak & Peter Folger, *Pipelines for Carbon Dioxide (CO_2) Control: Network Needs and Cost Uncertainties*, CONG. RES. SERV., RL34316 (Jan. 10, 2008).

97. Kevin Bliss, et al., *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide, Topical Report*, INTERSTATE OIL & GAS COMPACT COMM'N, at 32 (Sept. 10, 2010); Dooley, *supra* note 9, at 1957.

98. Peter Folger, *Carbon Capture and Sequestration: Research, Development, and Demonstration at DOE*, U.S. CONGRESSIONAL RES. SERV., RL42496 (Feb. 10, 2014); Climate, *supra* note 91, at 374; Marston & Moore, *supra* note 15, at 425, Nasi, *supra* note 23, at 9B-12.

99. Climate, *supra* note 91, at 307 (citing Steven D. Cook, *Carbon Capture, Storage to Get 2.4 Billion in Recovery Funds, Secretary Chu Announces*, 40 ENV'T REPT. 1164 (BNA) (May 22, 2009); U.S. DEP'T OF ENERGY, OFFICE OF FOSSIL ENERGY, FE IMPLEMENTATION OF THE RECOVERY ACT, *available at* http://energy.gov/fe/fe-implementation-recovery-act (last visited Aug. 1, 2017); *Carbon Capture Utilization and Storage: Climate Change, Economic Competitiveness, and Energy Security*, U.S. DEP'T OF ENERGY (Aug. 2016), https://energy.gov/sites/prod/files/2016/09/f33/DOE%20-%20Carbon %20Capture%20Utilization%20and%20Storage_2016-09-07.pdf.

adjustments to real property entitlements.[100] While these assets may permit utilization of existing pipeline infrastructure for at least some storage, in order to make maximum utility of available methods of capture and the reservoirs at each terminus, the unique needs and objectives of those technologies will need to be evaluated.[101]

The exact "size and configuration of the pipeline system" that will be required for CCUS will depend on a number of factors, including the demand and economics of EOR, fuel switching, and the timing, rate, and stringency of commercial adoption of CCUS technologies.[102] By all accounts, however, there will be significant expansion of CO_2 pipeline infrastructure between now and 2050.[103] Much of this infrastructure may be pieced together from pipelines developed for CO_2-EOR. Integration of these pipelines into a flexible, hybrid infrastructure that can accommodate CCUS requires consideration of the ways in which CO_2 pipelines are sited, constructed, and regulated today.

II. The Federal Regulatory Framework for CO_2 Transport

Unlike pipelines for natural gas, there is no federal regulatory framework for siting CO_2 pipelines or providing pipeline developers with eminent domain authority. Only safety is subject to comprehensive federal regulation. Rather, the design, routing, construction, and operation of CO_2 pipelines are regulated at the state level. Nonetheless, numerous federal laws and regulations influence CO_2 pipeline siting, design, or operation, particularly where pipelines cross state lands. These regulations introduce

---

100. A full exploration of these issues is beyond the scope of this article. *See* Patrick Falwell, *State Policy Actions to Overcome Barriers to Carbon Capture and Sequestration and Enhanced Oil Recovery*, CTR. FOR CLIMATE AND ENERGY SOLS., (Sept. 2013) (for the Industry Working Group of North America 2050); Elizabeth J. Wilson & David Gerard, CARBON CAPTURE AND SEQUESTRATION: INTEGRATING TECHNOLOGY, MONITORING AND REGULATION (Blackwell Publishing 2007); Marston & Moore, *supra* note 15.

101. *Id.* at 464 ("A CCS Pipeline for removing captured CO_2 from one or more power plants for permanent geologic storage is, in certain respects, the polar opposite of the EOR pipeline.").

102. Richard S. Middleton & Jeffrey M. Bielicki, *A Comprehensive Carbon Capture and Storage Infrastructure Model*, 1 ENERGY PROCEDIA, at 1611-16 (Feb. 2009); Dooley, *supra* note 9; *Id.* at 436.

103. Howard J. Herzog, *Scaling Up Carbon Dioxide Capture and Storage: From Megatons to Gigatons*, 33 ENERGY ECONOMICS 4, 597-604, 600 (2011); M.D. Jensen, et al., *A Phased Approach to Building a Hypothetical Pipeline Network for CO_2 Transport During CCUS*, ENERGY PROCEDIA 37, 3097-3104 (2013).

mechanisms for federal agencies to influence the siting of CO_2 pipelines in coordination with state regulatory agencies.

Safety

Safety is the only aspect of CO_2 pipeline development that is subject to comprehensive federal regulation. PHMSA—part of the U.S. Department of Transportation—regulates the safety of interstate CO_2 pipelines[104] pursuant to the Hazardous Liquid Pipeline Safety Act of 1979 (HLPSA).[105] Through the Office of Pipeline Safety (OPS), PHMSA regulates the design, construction, pressure testing, operation, maintenance, corrosion control, and reporting requirements for hazardous liquid pipelines.[106] Department of Transportation regulations categorize CO_2 as a non-flammable gas hazardous material and not as a hazardous liquid. However, in 1988 Congress amended the HLPSA to require regulation of CO_2 pipeline facilities.[107] Accordingly, CO_2 pipelines are subject to the same safety regulations as hazardous liquid pipelines, rather than those applied to natural and other gas pipelines.[108]

States are largely preempted from adopting and imposing additional safety standards for interstate pipelines.[109] States can, however, accept responsibility for the safety regulation of intrastate CO_2 pipelines and can "participate in oversight of interstate pipelines" as "agents of the OPS" pursuant to delegation of HLPSA authority.[110] HLPSA permits state regulatory authority and responsibility for enforcement of HLPSA requirements either through certification pursuant to Section 60105(a) or by

104. CO_2 pipelines are defined as pipelines carrying at least 90% CO_2 molecules compressed to a supercritical state. 49 C.F.R. § 195.2 (2008).

105. 49 U.S.C. § 60101 (2006).

106. 49 C.F.R. §§ 190, 195-199 (2008).

107. An Act of October 31, 1988, Pub. L. No. 100-561, 102 Stat. 2805; Paul Biancardi & Lisa Bogardus, *An Introduction to Federal Pipeline Safety Regulations*, 38A ROCKY MTN. MIN. L. INST. 5 (1995).

108. Transportation of Carbon Dioxide by Pipeline, 54 Fed. Reg. 41912 (proposed Oct. 12, 1989) (to be codified at 40 C.F.R. pt. 195).

109. 49 U.S.C. § 60104(c) (2006); Olympic Pipe Line Co. v. City of Seattle, 437 F.3d 872 (9th Cir. 2006).

110. Robert R. Nordhaus & Emily Pitlick, *Carbon Dioxide Pipeline Regulation*, 30 ENERGY L.J. 1, 96 (2009) (citing 49 U.S.C. § 60105 (2006)). Intrastate pipelines are defined as those that both "start and stop" within a state boundary. *See* Pipeline Safety Reauthorization Act of 1988, Pub. L. No. 100-561, 102 Stat. 2805.

entering into agreements with the OPS.[111] A state must adopt the minimum federal regulations and must provide for injunctive and monetary sanctions similar to those authorized by federal pipeline safety laws to obtain certification.[112] All of the states with significant CO_2 pipeline infrastructure have obtained OPS certification to regulate some safety aspects of intrastate CO_2 pipelines.[113] Accordingly, state agencies may be responsible for functions such as inspection, accident investigation, and regulatory enforcement of intrastate hazardous liquid pipelines.[114]

In addition to administration of federal requirements, HLPSA permits states to impose additional requirements on intrastate hazardous liquid and CO_2 pipelines, provided that the additional or more stringent regulations are not inconsistent with federal regulations.[115] Pursuant to this authorization, several states have imposed specific requirements for CO_2 pipelines or for hazardous liquid pipelines in general. For example, Texas requires CO_2 operators to engage in additional public education and reporting, restricts siting near schools, and imposes additional corrosion control requirements.[116] Wyoming mandates specific casing and siting requirements for hazardous liquid pipelines facilities within the state highway system right-of-way,[117] and Oklahoma imposes additional notice

111. *Natural Gas Pipeline Safety*, COLO. DEP'T OF REGULATORY AGENCIES https://www.colorado.gov/pacific/dora/aboutgaspipelines (last visited Sept. 19, 2017); *Office of Conservation*, LA. DEP'T OF NAT. RES., http://www.dnr.louisiana.gov/ index.cfm/page/46 (last visited Sept. 19, 2017); *Pipeline Safety*, MISS. PUB. SAFETY COMM'N, http://www.psc.state.ms.us/pipeline /pipeline.html (last visited Sept. 19, 2017); *Pipeline Safety*, OKLA. CORP. COMM'N, TRANSP. DIV., http://www.occeweb.com /tr/PLSHome.htm (last visited Sept. 19, 2017); *Pipeline Safety*, R.R. COMM'N OF TEX., http://www.rrc.state.tx.us/ pipeline-safety/ (last visited Sept. 19, 2017); *Pipeline and Water*, WYO. PUB. SERV. COMM'N, http://psc.state.wy.us/ pscdocs/pipeline.html (last visited Sept. 19, 2017).

112. 49 U.S.C. § 60105 (2006).

113. *States Participating In the Federal/State Cooperative Gas and Hazardous Liquid Pipeline Safety Programs*, PIPELINE AND HAZARDOUS MATERIALS SAFETY ADMIN. (Nov. 25, 2014), https://www.phmsa.dot.gov/portal/site/PHMSA/menu item.6f23687cf7 b00b0f22e4 c6962d9c8789/?vgnextoid=60dc8f4826eb9110VgnVCM1000009ed07898RCRD&vgnextchannel=a576ef80708c8110VgnVCM1000009ed07898RCRD&vgnextfmt=print.

114. Nordhaus & Pitlick, *supra* note 110, at 96.

115. *Id.*

116. TEX. ADMIN. CODE tit. 16, §§ 8.301-8.315 (2017).

117. *WYDOT Rules and Regulations, Utility Accommodations Section*, WYO. DEP'T OF TRANSP., http://www.dot.state.wy.us/files/live/sites/wydot/files/shared /Management_ Services/utility%20accommodations%20section %20rules/utl10.pdf (last visited Sept. 19, 2017).

requirements for hazardous liquid pipeline developers.[118] Recommended practices suggest siting pipelines based on the likelihood and consequence of failure considering pipeline contents and human activity along the pipeline route.[119] Through these requirements states can semi-customize safety requirements to address local land use, political, geographic, and environmental considerations.

An Absence of Federal Siting Authority

There is no federal siting authority for CO_2 pipelines. CO_2 concurrently falls outside the scope of "natural gas" within the Natural Gas Act (NGA) and within the "gas" exclusion in the Interstate Commerce Act (ICA).[120] Accordingly, there is no authority for federal siting of CO_2 pipelines, other than issuance of rights-of-way for those on federal land.

Natural gas pipelines are sited according to the NGA. In 1938, Congress granted the Federal Power Commission (FPC), now the Federal Energy Regulatory Commission (FERC), authority for regulating transportation of natural gas in interstate commerce.[121] The NGA requires a certificate of public convenience and necessity from FERC for every new pipeline or pipeline extension for "the transportation in interstate commerce of natural gas"[122] and for the acquisition and operation of interests in natural gas pipelines.[123] Each step of the FERC process for obtaining a certificate of public convenience and necessity is designed to provide transparency, opportunities for public comment, and coordination between stakeholders, thus streamlining the siting process through consolidated information gathering and approvals.[124] This process facilitates consideration of local and national needs and impacts to either customers or the environment.[125] If granted, the pipeline company receives the right to use eminent domain for the pipeline's entire length.[126] Accordingly, although other state

118. OKLA. ADMIN. CODE tit. 32, § 165:20-7-2 (2015).

119. Design and Operation of CO_2 Pipelines, *supra* note 82, at 17.

120. Natural Gas Act of 1938 § 1, Pub. L. No. 75-688, 52 Stat. 821 (codified as amended at 15 U.S.C. § 717 (2012); Interstate Commerce Act, 49 U.S.C. §§ 1(4), 2, 3(1) (1887).

121. Natural Gas Act, 15 U.S.C. §§ 717c, 717h (1938); Alex B. Klass & Danielle Meinhardt, *Transporting Oil and Gas: U.S. Infrastructure Challenges*, 100 IOWA L. REV. 947 (2015).

122. Natural Gas Act, 15 U.S.C. § 717f(c) (1988).

123. *Id.* § 717f(c)(1)(a).

124. Klass & Meinhardt, *supra* note 121, at 1007.

125. *Id.*

126. 15 U.S.C. § 717f(c)(1)(a).

requirements may apply, natural gas pipelines are not required to navigate state siting and eminent domain requirements to obtain right-of-way.

The NGA does not define the term "natural gas."[127] CO_2 is gaseous at atmospheric pressures. However, it is transported via pipeline at high pressures that result in a phase change from gas to an "indeterminate" state that is neither solid, liquid, or gaseous—variously called "dense phase gas," "supercritical fluid," or a "dense vapor."[128] As a result, it was initially unclear whether the NGA applied to CO_2 pipelines. Accordingly, in anticipation of the development of several interstate CO_2 pipelines, Cortez Pipeline Company petitioned FERC for a jurisdictional determination of whether CO_2 was a natural gas under the statute.[129] FERC declined to make a determination based on the chemical composition of the gas[130] and determined that gas that was 98% CO_2 was not a "natural gas" as intended by Congress in the NGA.[131] Instead, FERC based its determination on the fact that the NGA was enacted by Congress to regulate a "burgeoning" and "defined industry" in order to "protect the consumers of a salable commodity from exploitation at the hands of the natural gas companies."[132] Concluding that the CO_2 transported was solely for the purpose of increasing the production of oil and would not be sold as fuel to the public, the Commission found that the proposed pipeline was "not within the NGA jurisdiction provided by the Commission."[133] In 2006, in *Southern Natural Gas Co.*, FERC reaffirmed its lack of jurisdiction, stating that CO_2 facilities were "exempt from jurisdiction under [ ] the NGA."[134]

Oil pipelines are also subject to federal regulation, although not federal siting, pursuant to the Interstate Commerce Act (ICA).[135] The ICA was passed in 1887 to address the growing problem of natural monopolies in railroads.[136] It required that railroads charge "just and reasonable rates"

127. *Cortez Pipeline Co.*, 7 FERC 61024 (Apr. 6, 1979) (stating that "[t]here appears to have been no attempt during the legislative debate over the NGA to address the problem of the ambiguity in the term natural gas") (internal citations and quotations omitted).

128. Schnacke, *supra* note 13, at 3.

129. *Cortez Pipeline Co.*, 7 FERC 61024 (Apr. 6, 1979).

130. *Id.*

131. *Id.*

132. *Id.* (citing FPC v. La. Power & Light Co., 406 U.S. 621, 631 (1972); Sunray Mid-Continent Oil Co. v. FPC, 364 U.S. 137, 147 (1960); Phillips Petroleum Co. v. Wisconsin, 347 U.S. 672 (1954); FPC v. Hope Nat. Gas Co., 320 U.S. 591, 610 (1944)).

133. *Id.*

134. *Maritimes & Ne. Pipeline, L.L.C.*, 115 FERC 61176 (2006).

135. ExxonMobil Oil Corp. v. FERC, 487 F.3d 945, 956 (D.C. Cir. 2007).

136. Am. Trucking Ass'ns v. Atchison, T. & S.F. Ry., 387 U.S. 397 (1967).

without regard to locality or distance and without preference to any individual product or shipper—thus establishing the baseline requirements for what is now referred to as "common carriage."[137] Oil pipelines were similarly "bedeviled" by monopolistic practices.[138] By 1904 Standard Oil transported more than 90% of the total oil transported in the United States.[139] In response to complaints of Standard Oil's monopolistic behavior and the resulting lack of access to interstate markets and price disparities, Congress passed the Hepburn Act of 1906 and expanded the regulatory responsibilities of the Interstate Commerce Commission (ICC) under the ICA to include oil pipelines.[140] Oil pipelines were thus subjected to common carrier requirements, including non-discriminatory access, regulation of rates and terms of service, and ICC approval of tariffs.[141]

Oil pipeline regulation was transferred to FERC with the passage of the Department of Energy Organization Act in 1977.[142] FERC authority over oil pipelines is notably different from its authority over natural gas pipelines. The authority it derives from the ICA is exclusively focused on assuring reasonable and nondiscriminatory access to oil pipelines; FERC does not regulate the siting, construction, expansion, or operation of oil pipelines and does not provide developers with nationwide powers of eminent domain along proposed pipeline routes. Accordingly, state law determines siting, permitting or certification, and a developer's rights to acquire land by eminent domain.

CO_2 is also excluded from FERC regulation under the ICA. The ICA initially applied to all persons engaged in "the transportation of oil or other commodity, except water and gas, by means of pipelines."[143] Similar to the NGA, the ICA leaves the term "gas" undefined. In 1981, in response to a request from Cortez Pipeline Co. and after public comment, the ICC, the predecessor regulatory agency to FERC, issued a final declaratory order.[144]

---

137. Interstate Commerce Act, 49 U.S.C. §§ 1(4), 2, 3(1) (1887).

138. Farmers Union Cent. Exch., Inc. v. FERC, 734 F.2d 1486, 1494 (D.C. Cir. 1984).

139. Klass & Meinhardt, *supra* note 121, at 959-60.

140. Valvoline Oil Co. v. United States, 25 F. Supp. 460 (W.D. Pa. 1938); Elizabeth Granitz & Benjamin Klein, *Monopolization by "Raising Rivals' Costs": The Standard Oil Case*, 39 J.L. & ECON 1 (1966); Jeff D. Makholm, et al., *The Politics of U.S. Oil Pipelines: The First Born Struggles to Learn from the Clever Younger Sibling*, 37 ENERGY L.J. 409, 410 (2016) (citing Pub. L. No. 59-337, 34 Stat. 584 (1906)).

141. Klass & Meinhardt, *supra* note 121, at 961.

142. *Id.* at 980 (citing JAMES H. MCGREW, FERC: FEDERAL ENERGY REGULATORY COMMISSION 227 (2d ed. 2009); 42 U.S.C. § 7172(b)).

143. *Valvoline Oil Co.*, 25 F. Supp. at 462.

144. *Cortez Pipeline Co.*, 45 Fed. Reg. 85,177 (1980).

The ICC also elected not to base its decision on the physical properties of CO_2. Instead, the ICC based its analysis on the original language in the Hepburn Act and legislative history regarding the exclusion of "natural or artificial" gas.[145] In a decision that it later affirmed, the ICC concluded the "all gas types classified by origin or source were excluded from [its] jurisdiction."[146]

Where a proposed CO_2 pipeline will cross federal land, the Bureau of Land Management (BLM) has authority to grant rights-of-way for CO_2 pipelines as a "natural gas" pursuant to the MLA.[147] In *Exxon Corp. v. Lujan*, Exxon challenged the grant of a right-of-way for a CO_2 pipeline under the MLA, asserting instead that the proper authority for issuing the right-of-way was the Federal Land Policy and Management Act (FLPMA).[148] BLM has authority under the MLA to grant right-of-way for "pipeline purposes for the transportation of oil, natural gas, synthetic liquid or gaseous fuels, or any refined product produced therefrom,"[149] whereas pipeline rights-of-way for water and any substance other than those covered by the MLA are issued pursuant to FLPMA.[150] The BLM determined that the term "natural gas" as used in the MLA was not limited to hydrocarbons and accordingly issued the right-of-way pursuant to the MLA.[151] Exxon argued that because carbon dioxide was not a hydrocarbon[152] and FERC had each previously determined that CO_2 was not a "natural gas" in *Cortez Pipeline*, the appropriate authority for issuing right-of-way was FLPMA.[153] The court affirmed BLM's decision, finding that FERC's determination was under a different statute and accordingly had "no bearing" on BLM's

145. Nordhaus & Pitlick, *supra* note 110, at 90.

146. Harry L. Reed, *The New Carbon Dioxide Pipelines: Revival of the Common Carrier at Common Law*, 12 OKLA. CITY U. L. REV. 103, 108 (1987) (citing ICC, Cortez Pipeline Company—Petition for Declaratory Order—Commission Jurisdiction Over Transportation of Carbon Dioxide by Pipeline, 45 Fed. Reg. 85,177 (1980); ICC, Cortez Pipeline Co.—Petition for Declaratory Order—Commission Jurisdiction Over Transportation of Carbon Dioxide, 46 Fed. Reg. 18,805 (1981)). Adam Vann & Paul W. Parfomak, *Regulation of Carbon Dioxide Sequestration Pipelines: Jurisdictional Issues*, U.S. CONGRESSIONAL RES. SERV., RL343070, at 2 (Apr. 15, 2008); Schnacke, *supra* note 13, at 10-18.

147. Exxon Corp. v. Lujan, 970 F.2d 757, 761 (10th Cir. 1992).

148. *Id.* (The crux of this dispute concerned whether or not Exxon would be required to operate its pipeline as a common carrier.)

149. 30 U.S.C. § 28(a)185.

150. 43 U.S.C. § 1761(a)(2).

151. *Lujan*, 970 F.2d at 761.

152. *Id.* at 760. Hydrocarbon refers to a chemical composition including both hydrogen and carbon, whereas CO_2 is a combination of carbon and oxygen.

153. *Cortez Pipeline Co.*, 7 FERC 61024 (Apr. 6, 1979).

interpretation. Given the many definitions of "natural gas" within the federal regulations, including some within the Department of Interior, the court found that BLM's interpretation that CO_2 was a "natural gas" was not unreasonable.[154] Accordingly, CO_2 pipelines crossing federal land are sited by BLM pursuant to the MLA.

Opportunities for Federal Input in State Siting Processes

Despite the lack of federal siting and eminent domain authority, the National Environmental Policy Act (NEPA), the Clean Water Act (CWA), the National Historic Preservation Act (NHPA), and the Endangered Species Act (ESA), among others, may provide opportunities for federal agencies to influence on CO_2 pipeline siting. These opportunities are most abundant where the pipeline crosses federal lands or waterways—as is often true in the western United States. For example, Denbury's proposed Riley Ridge to Natrona project in Wyoming required the grant of a 212-mile right-of-way, 76% of which crossed federal lands administered by five BLM field offices.[155] Although not requiring a full assessment of the entire pipeline project, thus far the project has required section 106 review, ESA consultation, and preparation of an EIS. These processes may increase public awareness about CO_2 pipeline projects, enhance consideration of potential impacts, and influence siting decisions made pursuant to state law.

NEPA

NEPA may provide an opportunity for federal agencies to conduct additional environmental analyses, facilitate public participation, and contribute oversight to state siting processes. NEPA requires the preparation of an environmental assessment (EA) or an Environmental Impact Statement (EIS) for any major federal action that will significantly affect the quality of the human environment prior to the irreversible or irretrievable commitment of resources.[156] Construction of a CO_2 pipeline, particularly one of adequate size for CCUS, across federal lands could have

---

154. *Lujan*, 970 F.2d at 757.

155. *Riley Ridge to Natrona Project, Project Description*, BUREAU OF LAND MGMT., https:// eplanning.blm.gov/epl-front-office/projects/nepa /64342/77065/85578/ RRNP_ Project_Description.pd (last visited Sept. 19. 2017).

156. 42 U.S.C. § 4332(2)(C). "Major federal action" is defined at 40 C.F.R. § 1508.18 (1977). "Significantly" is defined at 40 C.F.R. § 1508.27. *See also* Metcalf v. Daley, 214 F.3d 1135, 1141 (9th Cir. 2000).

significant environmental impacts.[157] Unless the pipeline could be built within a pipeline corridor or otherwise qualify for a categorical exclusion,[158] BLM would be required to conduct an EA or EIS prior to issuing a right-of-way.[159] The analysis would prompt consideration of multiple alternatives—including a no action alternative—and could prompt the integration of mitigation measures.[160] While not mandating a specific outcome,[161] the NEPA process provides opportunity for stakeholder and agency input on proposed projects that require right-of-way or other major federal action.

NEPA's application to pipelines crossing only private land is more limited. In order to trigger NEPA, there must be a "major federal action."[162] Private actions may become subject to NEPA where the project is subject to federal control or requires a federal authorization, funding, or permit.[163] These analyses are limited to the proposed action, and would be unlikely to trigger a NEPA review of the entire pipeline project and route.[164] Although it is possible for an otherwise private project to become "federalized" if the federal government has "actual power to control the project," the cumulative effect of decisions, such as PHMSA approval of a safety plan or

157. Arnold W. Reitze Jr., *Carbon Capture and Storage Program's NEPA Compliance*, 42 ENVTL. L. REP. NEWS & ANALYSIS 10853, 10856 (2012); *See DOI-BLM-WY-D010-2017-0087-EA Riley Ridge Development Project*, BUREAU OF LAND MGMT., https://eplanning.blm.gov/epl-frontoffice/eplanning/planAndProjectSite.do?metbod Name=dispatch ToPatternPage&currentPageId=115957 (last visited Sept. 19, 2017).

158. 40 C.F.R. §§ 1501.4(a)(2), 1508.4 (1977); 42 U.S.C. § 15942 (2005).

159. *Fuel Safe Wash. v. FERC*, 389 F.3d 1313, 1317 (10th Cir. 2004); Mont. Wilderness Ass'n v. Fry, 310 F. Supp. 2d 1127, 1146-47 (D. Mont. 2004); Arnold W. Reitze, Jr., *The Role of NEPA in Fossil Fuel Resource Development and Use in the Western United States*, 39 B.C. ENVTL. AFF. L. REV. 283 (2012); Zeke J. Williams & Steven K. Imig, *EOR on Federal Lands, Enhanced Oil Recovery; Legal Framework for Sustainable Management of Mature Oil Fields*, ROCKY MTN. MIN. L. INST. 6-20 (May 6-7, 2015).

160. Nat'l Envtl. Policy Act Handbook H-1790-1, 6.6, 6.8.4, BUREAU OF LAND MGMT. (Jan. 2008).

161. Vt. Yankee Nuclear Power Corp. v. NRDC, 435 U.S. 519, 558 (1978); Hammond v. Norton, 370 F. Supp. 2d 226 (D.C. Cir. 2005).

162. 40 C.F.R. § 1508.18.

163. Ka Makani 'O Kohala Ohana Inc. v. Water Supply, 295 F.3d 955, 960 (9th Cir. 2002).

164. Sierra Club v. Bostick, 787 F.3d 1043 (10th Cir. 2015).

Fish and Wildlife Service issuance of a biological opinion, are unlikely to reach that threshold.[165]

Section 404 Permits

Federal permits are frequently required for water and wetland crossings on otherwise private projects.[166] The Army Corps of Engineers issues permits for discharge of dredge or fill materials under Section 404 of the Clean Water Act.[167] Section 404 requires a permit for any "utility line"—defined as including "any pipe or pipeline for the transportation of any gaseous, liquid, liquescent, or slurry substance for any purpose"—crossing requiring discharge of dredge or fill material into waters of the United States.[168] Due to the expansive geographic scope of the program, almost any pipeline project will require a 404 permit.[169] The level of environmental analysis includes a range of possibilities based on the type of permit required.[170] Permits issued under Section 404 are categorized as either general (nationwide) or individual.[171] General permits evaluate a category of activities having minimal cumulative impacts.[172] Although general permits "undergo a stringent pre-approval evaluation process that involves a comprehensive environmental assessment under NEPA and also public notice and comment," the process does not involve substantive findings related to each discrete project.[173] Individual water or wetland crossings with potentially significant impacts trigger a more extensive 404 permitting process.[174] These projects are evaluated under public interest review based

165. Sierra Club v. U.S. Army Corps of Eng'rs, 64 F. Supp. 3d 128, 149 (D.C. Cir. 2014) (citing Citizens Alert v. EPA, 259 F. Supp. 2d 9, 20 (D.D.C. 2003), *aff'd* 102 Fed. App'x 167 (D.C. Cir. 2004)).

166. Solid Waste Agency v. U.S. Army Corps of Eng'rs, 531 U.S. 159 (2001).

167. Greater Yellowstone Coal. v. Flowers, 359 F.3d 1257, 1266 (10th Cir. 2004).

168. 33 U.S.C. § 1344; (1987); 77 Fed. Reg. 10,271-72 (Feb. 21, 2012).

169. Eric Biber & J.B. Ruhl, *The Permit Power Revisited: The Theory and Practice of Regulatory Permits in the Administrative State*, 64 DUKE L. J. 133, 162 (2014).

170. *Id.* at 171.

171. Sierra Club v. U.S. Army Corps of Eng'rs, 990 F. Supp. 2d 9, 19 (D.D.C. 2013) (citing 33 U.S.C. §§ 1344(a), (e) (for general permits) and 33 C.F.R. §§ 323 and 325 (2013) (for the application and review requirements of specific permits)).

172. Nat. Res. Def. Council v. Costle, 568 F.2d 1369, 1380-82 (D.C. Cir. 1977); 33 C.F.R. § 330.1; 40 C.F.R. § 230.7 (2015).

173. *Sierra Club*, 990 F. Supp. 2d. at 19 (citing 33. U.S.C. § 1344(e)); Biber & Ruhl, *supra* note 169, at 167. For linear projects like utility lines, each crossing of a waterway is considered to be a "single and complete project" as long as these crossings are "separate and distant." *See* Sierra Club v. Bostick, 787 F.3d 1043 (10th Cir. 2015).

174. 40 C.F.R. § 230.

on environmental criteria and require the consideration of alternatives and incorporation of compensatory mitigation.[175] Neither of the 404 processes requires a consolidated environmental review of the entire project.[176] The 404 permitting process may provide a vehicle for public and federal input on siting relative to specific projects and the attachment of specific conditions and mitigation requirements within state law siting.[177] However, the efficacy of the permitting program to address cumulative consideration of environmental impacts from private land projects has been criticized.[178]

NHPA Consultation

National Historic Preservation Act (NHPA) procedures may also provide avenues for federal input on pipeline siting. The NHPA's consultation and review process is designed to avoid or minimize, to the extent possible, harm to historic properties where "the area of potential effects" from a proposed project "may result in changes in the [property's] character or use."[179] The NHPA requires federal agencies to consult with the Advisory Council on Historic Preservation and other consulting parties prior to taking an action[180] that may affect a site "included in or eligible for inclusion" in the National Register.[181] Sites may include "traditional cultural properties" that, due to their association with the cultural history, practice, or traditions of Native American groups, rural communities, or particular cultural groups within urban neighborhoods, "are important in maintaining the continuing cultural identity of the community."[182] Were a proposed pipeline project to

175. *Individual Permits*, U.S. ARMY CORPS OF ENG'RS, FT. WORTH DIST., http:// www.swf.usace.army.mil/Missions/Regulatory/Permitting/IndividualPermits.aspx (last visited Sept. 19, 2017).

176. *Sierra Club*, 990 F. Supp. 2d. at 34.

177. Dave Owen, *Little Streams and Legal Transformations*, 2017 UTAH L. REV. 1, 24 (2017).

178. Lucy Allen, *Making Molehills out of Mountaintop Removal: Mitigated "Minimal" Adverse Impacts in Nationwide Permitting*, 41 ECOLOGY L.Q. 181 (2014).

179. 36 C.F.R. § 800.2 (2000). Changes in character can result from direct, indirect, short-term, long-term, or cumulative effects.

180. Lee v. Thornburgh, 877 F.2d 1053, 1056 (D.C. Cir. 1989) (stating that "[t]he NHPA is aimed solely at discouraging federal agencies from ignoring preservation values in projects they initiate, approve funds for, or otherwise control").

181. Historic places can be nominated by agencies, individuals, preservation groups and historic societies, and, if they are deemed to meet the eligibility criteria, may be listed in the National Register. 54 U.S.C.A. § 302104.

182. Patricia L. Parker & Thomas F. King, *Guidelines for the Evaluation and Documentation of Traditional Cultural Properties*, NAT'L REG. BULL. 38 (1990), http://www.nps.gov/nr/publications/bulletins/nrb38/. Native American religious concerns

impact historic or cultural properties,[183] an agency would have to engage in the NHPA consultation process. Like NEPA, an agency's obligations under the NHPA are procedural and not outcome driven.[184] The process does not guarantee the preservation of historically or culturally significant properties, provided that the consultation process is adequate.[185] Accordingly, the utility of the NHPA to influence CO_2 pipeline siting will vary based on the location and scope of the project and level of public engagement.

FWS Consultation

Finally, pipeline siting may be influenced by species and habitat preservation concerns for threatened or listed species, including federal and state habitat protection and mitigation requirements. Federal laws such as the Endangered Species Act,[186] the Migratory Bird Treaty Act,[187] and the Bald and Golden Eagle Protection Act,[188] among others, prohibit developers from activities that are likely to result in a "take" or disturbance of a protected species and impose both civil and criminal penalties for violations.[189] Before undertaking activities likely to result in take, pipeline developers must consult with the Fish and Wildlife Service as part of NEPA or to obtain a Section 10 Incidental Take Permit and develop a habitat

---

would be evaluated pursuant to the American Indian Religious Freedom Act of 1978, 42 U.S.C. § 1996 (1978).

183. NHPA compliance may be part of a NEPA record, but can apply to projects qualifying for a categorical exclusion. Nat'l Envtl. Policy Act Handbook H-1790-1, *supra* note 160, at 4.1.

184. Monumental Task Comm., Inc. v. Foxx, 157 F. Supp. 3d 573, 590 (E.D. La. 2016) (citing Coliseum Square Ass'n, Inc. v. Jackson, 465 F.3d 215, 224 (5th Cir. 2006) (quoting Bus. & Residents All. of E. Harlem v. Jackson, 430 F.3d 584, 591 (2d Cir. 2005) ("The NHPA is procedural in nature. . . . It does not itself require a particular outcome, but rather ensures that the relevant federal agency will, before approving funds or granting a license to the undertaking at issue, consider the potential impact of that undertaking on surrounding historic places.") (internal citations and quotations omitted))).

185. Standing Rock Sioux Tribe v. U.S. Army Corps of Eng'rs, 205 F. Supp. 3d 4, 8 (D.D.C. 2016).

186. 16 U.S.C. §§ 1531, 1537(a), 1538-1544 (2014).

187. *Id.* §§ 703-711 (1998).

188. *Id.* § 668 (1972).

189. Roberto Iraola, *The Bald and Golden Eagle Protection Act*, 68 ALB. L. REV. 973, 992 (2005). For a list of other procedural requirements pertaining to the environmental impacts of agency actions, see Nat'l Envtl. Policy Act Handbook H-1790-1, *supra* note 160, at App. 1.

conservation plan.[190] Based on Fish and Wildlife Service conclusions, pipelines may be required to reroute or implement other "reasonable and prudent alternatives" to avoid effects to protected species or as conditions attached to an incidental take statement.[191] Pipeline developers, in coordination with agencies, may also agree to voluntary conservation measures through public-private conservation agreements or letters of commitment.[192] State conservation measures and species management plans, such as those put in place for protection of the greater sage-grouse in Wyoming and Nevada, may impose other siting limitations or habitat mitigation requirements.[193] For example, Wyoming's Greater Sage-Grouse Core Area Strategy limits surface disturbances in core habitat area through a disturbance cap of 5%, a density limit of not more than one per square mile, and a prohibition of surface disturbances within 0.6 miles of any active sage-grouse lek.[194] These habitat and conservation requirements can significantly impact pipeline siting. For example, Denbury's Greencore Pipeline route was modified in order to conform to a number of species protection mandates including those for the greater sage-grouse, raptors, and the mountain plover.[195]

Procedural requirements contained in numerous environmental laws provide opportunities for federal influence in pipeline siting. In some cases, the reviews required may be significant. These mechanisms invite participation from a diverse group of stakeholders and prompt consideration of federal interests and environmental impacts. Environmental laws thus provide a framework within which pipeline developers and agencies can

---

190. 16 U.S.C. § 1536(b)(a)(2)(A).

191. Ctr. for Biological Diversity v. U.S. Fish & Wildlife Serv., 807 F.3d 1031, 1037 (9th Cir. 2015) (citing 16 U.S.C. § 1536(b)(1)(B)(3)(A) (1988)).

192. *Id.* Although these voluntary public-private conservation plans may be necessary to obtain agency permission for construction, an agency may not rely on voluntary measures to approve a pipeline. Benjamin Hanna, *The Ninth Circuit Constrains Non-Enforceable Public-Private Endangered Species Conservation Agreements*, 41 B.C. ENVTL. AFF. L. REV. E. SUPP. 42 (2014).

193. For an example of some of the restrictions, see *Wyoming Pipeline Corridor Initiative Plan of Development*, WYO. PIPELINE AUTH., App. B (May 2014), https://www.wyopipeline.com/wp-content/uploads/2014/06/WPCI_POD_may_2014.pdf (last visited Sept. 20, 2017).

194. Kristina Fugate, *One Bird Causing a Big Conflict: Can Conservation Agreements Keep Sage Grouse Off the Endangered Species List?*, 49 IDAHO L. REV. 621 (2013); *Wyoming Governor's Executive Order 2011-5, Greater Sage-Grouse Core Area Protection*, WYO. EXEC. DEP'T, https://www.nrc.gov/docs/ML1301/ML13015A702.pdf.

195. *Greencore Pipeline Project*, DENBURY, http://www.denbury.com/operations/ rocky-mountain-region/COsub2-sub-Pipelines/default.aspx (last visited Sept. 20, 2017).

work together to address national and environmental concerns in a manner that complements state siting processes.

III. Siting Under State Law: The Condemnation of Pipeline Easements

The majority of CO_2 pipeline routing is dependent on state law.[196] State laws may authorize siting authorities,[197] establish set back,[198] permitting, or industrial siting requirements,[199] and create mechanisms for local government participation.[200] Most significantly, state law establishes whether and for what purposes CO_2 pipeline developers may utilize eminent domain authority to acquire property along the pipeline route.

Eminent domain, the power to take private property for public use, is essential to the ability of a sovereign, including the federal and state governments, to fulfill government functions and promote the public welfare.[201] The Fifth Amendment of the United States Constitution[202] recognizes the right of a sovereign to take private property subject to two conditions: it must be for a "public use" and "just compensation" must be paid in return.[203] States are similarly constrained in their ability to take property by the Fourteenth Amendment and by public use provisions within state constitutions.[204]

The public use requirement arose from concerns that an unrestricted right in the government to take property would be subject to private influence resulting in a threat to private rights.[205] Coerced transfers to private parties

196. Fish & Martin, *supra* note 28 at 4; Nordhaus & Pitlick, *supra* note 110, at 100.

197. WYO. STAT. ANN. § 37-5-101 (2011).

198. TEX. ADMIN. CODE tit. 16, §§ 8.301-8.315 (2017).

199. KY. REV. STAT. § 278.714 (2014); OR. REV. STAT. § 469 (2010).

200. COLO. REV. STAT. §§ 24.65.1-101 through 108 (2017).

201. DONALD WORSTER, UNDER WESTERN SKIES: NATURE AND HISTORY IN THE AMERICAN WEST 130 (1992).

202. U.S. CONST. amend. V.

203. *Id.* A discussion of the various manners of calculating just compensation for pipeline rights-of-way is beyond the scope of this article.

204. Chicago Burlington & Quincy R.R. v. City of Chicago, 166 U.S. 266, 241 (1897).

205. JACK N. RAKOVE, ORIGINAL MEANINGS: POLITICS AND IDEAS IN THE MAKING OF THE CONSTITUTION 314-15 (1996); Daniel B. Kelly, *The Public Use Requirement in Eminent Domain Law: A Rationale Based on Secret Purchases and Private Influence*, 92 CORNELL L. REV. 1, 10 (2006) (citing Clark v. Nash, 198 U.S. 361, 369 (1905); Errol Meidinger, *The Public Uses of Eminent Domain: History and Policy*, 11 ENVTL. L. 1, 17-18 (1980-1981)).

for private use were viewed as inconsistent with due process of law.[206] Accordingly, the public use limitation was drafted to restrict coerced property transfers "for the private use of another" to those that would be available for "use by the general public."[207] Consistent with this interpretation, early American applications of eminent domain were predominantly to general government functions—such as the construction of town halls, court houses, and other public buildings or buildings for the public welfare—and to "build roads and provide hydropower to grist mills widely used by local populations."[208] These takings were seen as consistent with the public use requirement because the resultant project would either be publicly owned or, if privately owned, would be available for use by the public.[209] This view pervaded up until the end of the 19th century.[210] However, as technological innovations and modes of production innovated, courts increasingly permitted the extension of eminent domain authority to private corporations for private purposes.[211] New towns and homesteads were springing up in the American West, fueled by booms and busts in coal, oil, timber, and uranium.[212] Cities were rapidly developing too; and, with development came new public health hazards associated with overcrowding and dilapidated tenement housing.[213] Soon, it seemed, land was needed not only for roads to landlocked parcels or mills, but for mines

206. Missouri Pac. Ry. Co. v. Nebraska, 164 U.S. 403, 417 (1896); Matthew P. Harrington, *"Public Use" and the Original Understanding of the So-Called "Takings Clause,"* 53 HASTINGS L.J. 1245 (2002).

207. Kelly, *supra* note 205, at 10 (citing Mt. Vernon-Woodberry Cotton Duck Co. v. Ala. Interstate Power Co., 240 U.S. 30, 32 (1916) (Holmes, J.)).

208. Meidinger, *supra* note 205, at 2.

209. Wendell E. Prichett, *The "Public Menace" of Blight: Urban Renewal and the Private Uses of Eminent Domain*, 21 YALE L. & POL'Y REV. 1, 9 (2003).

210. Kelly, *supra* note 205, at 10 (citing RICHARD A. EPSTEIN, TAKINGS: PRIVATE PROPERTY AND THE POWER OF EMINENT DOMAIN 178 (1985) (stating that "[t]he nineteenth century view, abstractly considered, was that it was a perversion of the public use doctrine to acquire land by condemnation for these purposes")).

211. Prichett, *supra* note 209, at 9.

212. PATRICIA NELSON LIMERICK, SOMETHING IN THE SOIL: LEGACIES AND RECKONINGS IN THE NEW WEST 19 (2000); Gary Liebcap, *The Assignment of Property Rights on the Western Frontier: Lessons for Contemporary Environmental and Resource Policy*, 67 J. OF ECON. HIST. 2 (2007).

213. Norwood v. Horney, 853 N.E.2d 1115 (Ohio 2006); Hudson Hayes Luce, *The Meaning of Blight: A Survey of Statutory and Case Law*, 35 REAL PROP. PROB. & TR. J. 389 (2000); Prichett, *supra* note 209.

and more urban needs such as the elimination of blight.[214] Initial constructions that interpreted the public use limitation as requiring actual use by the public proved inadequate to advance legislative goals as applied to these new purposes. Thus, judicial interpretations of the public use limitation evolved in response.[215] Takings where the use advanced "public values" or was for the "comfort, convenience, and prosperity of the people" soon withstood judicial review.[216]

The division between these interpretations exists today. There are two judicial tests principally used to define "public use."[217] The first is a narrow interpretation—requiring that the end use of the property taken must be open to actual use by the public or some subset thereof.[218] The construction of roads, the creation of parks and public spaces, and other public infrastructure projects such as pipelines and railroads have all been found to satisfy this narrow requirement of "use by the public."[219] The second approach encompasses a broad scope of uses and property interests where the taking yields some general public benefit—be it revenue generation, jobs, tax base, or development of industry.[220] Projects benefiting from this approach include economic redevelopment,[221] mineral or agricultural

214. *Id.* at 25 (citing N.Y. City Housing Auth. v. Muller, 1 N.E.2d 153, 154 (N.Y. 1936)); Strickley v. Highland Boy Gold Mining Co., 200 U.S. 527, 531 (1906).

215. Only South Carolina adheres strictly to the requirement that property must be available for occupation or use by the public. *See* Karesh v. City Council, 247 S.E.2d 342, 345 (S.C. 1978); Lynda J. Oswald, *The Role of Deference in Judicial Review of Public Use Determinations*, 39 B.C. ENVTL. AFF. L. REV. 243, n.163 (2012).

216. Thomas W. Merrill, *The Economics of Public Use*, 72 CORNELL L. REV. 61, 72 (1986) (citing Cass R. Sunstein, *Naked Preferences and the Constitution*, 84 COLUM. L. REV. 1689 (1984)); Prichett, *supra* note 209, at 9 (citing HARRY SCHEIBER, THE ROAD TO MUNN: EMINENT DOMAIN AND THE CONCEPT OF PUBLIC PURPOSE IN THE STATE COURTS, IN LAW IN AMERICAN HISTORY 329, 370, 386 (Donald Fleming & Bernard Bailyn 1971)); Meidinger, *supra* note 205, at 24.

217. Alexandra B. Klass, *The Frontier of Eminent Domain*, 79 COLO. L. REV. 651, 663-64 (2008); Kelly, *supra* note 205, at 2-3, 11; Merrill, *supra* note 216, at 67.

218. Dayton Gold & Silver Mining Co. v. Seawell, 11 Nev. 394 (1876); Rindge Co. v. Los Angeles Cty., 262 U.S. 700, 707 (1923); Merrill, *supra* note 216, at 67-68.

219. Klass, *supra* note 217, at 656 (citing Philadelphia Clay Co. v. York Clay Co., 88 A. 487 (Pa. 1913)).

220. Merrill, *supra* note 216, at 64.

221. Kelo v. City of New London, 545 U.S. 469 (2005); Elizabeth F. Gallagher, Note, *Breaking New Ground: Using Eminent Domain For Economic Development*, 73 FORDHAM L. REV. 1837 (2005).

development projects,[222] and other purposes that promote "economic expansion."[223] Most courts, including the U.S. Supreme Court, have adopted the more expansive interpretation, thus deferring to legislative determinations of public use. [224] While not establishing an "authoritative delimitation," courts look instead to the various factors influencing historical development of the public use.[225]

The majority of states have no legislation specifically addressing the siting of CO_2 pipelines. This owes to the private nature of CO_2 transportation. Unlike oil, electricity, or natural gas, there are not broad public markets for CO_2—it is neither a generation nor transportation resource.[226] Thus, development has progressed along narrow corridors in a handful of states with either CO_2 sources or EOR. Were development to expand beyond these areas for CCUS or other purposes, states siting new infrastructure would assess public use for CO_2 pipelines under existing state frameworks for eminent domain.

The few state statutes that grant eminent domain authority for CO_2 pipelines may provide insight to how public purpose questions will be resolved. These statutes typically require that public purpose is established in one of two ways: either the pipeline will produce a public benefit by advancing the development of natural resources within the state,[227] or the pipeline will be available for "use by the public" through operation as a common carrier.[228] An analysis of the two predominant approaches provides an opportunity for deeper exploration of the public purpose requirement as applied to CO_2 transportation.

222. Mont. Talc Co. v. Cyprus Mines Corp., 748 P.2d 444 (Mont. 1987); Tanner v. Treasury Tunnel, Mining & Reduction Co., 35 Colo. 593 (1906).

223. Corey J. Wilk, *The Struggle Over the Public Use Clause: Survey of Holdings and Trends, 1986-2003*, 39 REAL PROP. PROB. & TR. J. 251 (2004); Merrill, *supra* note 216 (noting even acquisition of a football team's intangible contract rights could be a public use).

224. Norwood v. Horney, 853 N.E.2d 115, 132-33 (Ohio 2006); Merrill, *supra* note 216, at 68 (citing United States *ex rel.* TVA v. Welch, 327 U.S. 546, 551-52 (1946)).

225. Cty. of Essex v. Hindenlang, 114 A.2d 461, 467 (N.J. App. Div. 1955), *appeal dismissed*, 132 A.2d 807 (N.J. 1957); Oswald, *supra* note 215.

226. *Cortez Pipeline Co.*, FERC 61024 (Apr. 6, 1979).

227. *See infra* notes 246-63 and accompanying text.

228. N.D. CENT. CODE § 49-19-01(1) (2007); TEX. NAT. RES. CODE §§ 111.002(6) (2007), 111.019(a) (1993).

CO_2 for a Public Purpose: Natural Resource Development Takings

The concept of "natural resource development takings"[229] refers to private oil, gas, and mining companies' "power of eminent domain under state constitutions or state statutes to take private property to develop coal, oil, or other natural resources."[230] These public purpose justifications exist almost exclusively in the American West and are deeply rooted in the history of frontier expansion.[231] Development of the west was fueled by private exploitation of natural resources: timber, water, mineral, wildlife, grass, and hydrocarbon.[232] Eager to grow their populations and economies, western states' territorial legislatures sought to advance these purposes by embedding authority to take private property as necessary for natural resource development purposes within state constitutions. Accordingly, many western state constitutions authorize eminent domain for "private takings" to promote the extractive industries through the development of roads, flues, ditches, canals, tramways, and other necessary infrastructure.[233]

States sought to serve a public purpose through the creation and growth of a resource based state economy. Through the encouragement of industry states endeavored to assure their future prosperity—jobs and wealth—and encourage the expansion and development of communities that were attendant with those industries.[234] It was commonly believed that natural resources would be the sole source of development. Considering the possibility of a coal severance tax in the Wyoming Constitution, one legislator expressed that once the coal was exhausted Wyoming would "have nothing left but a howling wilderness."[235] With these principles memorialized in states' constitutions and statutes,[236] western landowners, mineral developers, and courts' concepts of property and public use

229. Klass, *supra* note 217, at 652.

230. *Id.* at 651.

231. *Id.*

232. PATRICIA NELSON LIMERICK, THE LEGACY OF CONQUEST (1987).

233. Klass, *supra* note 217, at 667-68.

234. *Id.* at 660-61; Patricia Limerick, *The Complicated History of Extraction in Colorado*, DENVER POST (Jan. 15, 2015, 10:37 AM), http://www.denverpost.com/2015/01/15/limerick-the-complicated-history-of-extraction-in-colorado.

235. T.A. LARSON, HISTORY OF WYOMING 252 (2d ed. 1978).

236. Klass, *supra* note 217, at 657-61, n.25.

developed in a way that was more permissive of the acquisitiveness inherent to private "natural resource takings" than in eastern states.[237]

Traditionally, states have benefited from the "extreme judicial deference" afforded to the public use limitation.[238] The result, as Professor Klass has noted, is an "absence of meaningful judicial review of natural resource development companies' contentions that the taking of private property to support development of natural resources is for a public use."[239] Due to strong grants of constitutional and statutory authority, and the deference to state legislatures in establishing these purposes, the public purpose of almost any taking of private property to serve expansion and development of the extractive industries is presumed.[240] The wide latitude given to state legislatures has led many scholars, at least prior to *Kelo*, to declare the public use clause "moribund."[241]

A number of states grant developers of CO_2 pipelines eminent domain authority based on statutes grounded in the concept of natural resource development. These grants may be general, giving CO_2 pipelines condemnation authority without regard to the end use.[242] Others address CO_2 as necessary to enhanced oil recovery[243] or underground carbon storage,[244] or include CO_2 within general statutory or constitutional grants for pipelines or mineral development.[245] Consistent with historic values, these grants advance the "great public interest in an imminent need for

237. *Id.* at 657-59 (citing GORDON M BAKKEN, ROCKY MOUNTAIN CONSTITUTION MAKING 1850-1912, at 30-32 (1987) (noting that not all westerners ascribed to this philosophy)).

238. *Id.* at 661 (stating that "[c]ourts in the Interior West responded to public use challenges with strong language upholding the right of private industry to exercise the power of eminent domain as a 'public use' without the need for any oversight by local, county, or state political bodies"); Merrill, *supra* note 216, at 65; Oswald, *supra* note 215, at 251-58.

239. Klass, *supra* note 217, at 661.

240. *Id.* at 661-69, (citing Mont. Talc Co. v. Cyprus Mines Corp., 748 P.2d 444, 447-48 (Mont. 1987) ("In present day Montana, as in Wyoming, once a private taking is found to be within a broadly-defined statutory or constitutional public use, there is little further role for a court in reviewing whether the exercise of the taking power is in fact in the interests of the public.").

241. Prichett, *supra* note 209, at 2.

242. KY. REV. STAT. ANN. §154.27-100 (2014); N.M. STAT. ANN. § 70-3-5 (1993).

243. 220 ILL. COMP. STAT. ANN. 75/5 (2013); MISS. CODE ANN. § 11-27-47 (1984).

244. 220 ILL. COMP. STAT. ANN. 75/5 (2013); LA. STAT. ANN. § 30:23 (2008); LA. STAT. ANN. § 19:2(10) (2012).

245. As discussed in notes 238-247, condemnation effectuated based on statutes authorizing mineral development may preclude utilization of those CO_2 pipelines for CCUS.

energy"[246] and promote economic growth through the extraction of mineral or other natural resources, including CO_2.

Natural Resource Development as Public Purpose

Idaho, Wyoming, and Colorado advance natural resource takings through constitutional provisions granting condemnation authority to private developers for mining purposes.[247] The Idaho Constitution declares mining to be a public use in a particularly expansive provision that includes "the drainage of mines, or the working thereof, by means of roads, railroads, tramways, cuts, tunnels, shafts, hoisting works, dumps, or other necessary means to complete development, or any other use necessary to the complete development of the materials resources of the state."[248] The Colorado and Wyoming constitutions each provide that "[p]rivate property shall not be taken for private use . . . except for . . . reservoirs, drains, flumes, or ditches on or across the lands of others for agricultural, mining, milling, domestic or sanitary purposes."[249] Historically, these provisions have been used by mining companies for access and transportation facilities, as well as for land, lumber, and construction materials,[250] and upheld based on the public interest in exploiting resources and making new markets.[251]

Constitutional natural resource takings provisions have been interpreted to encompass a range of uses beyond those specifically enumerated within the provision. Instead courts have focused on states' broader intent to promote natural resource development. For example, the Wyoming Supreme Court has included oil and gas exploration and production activities within the term "mining" as used in Article I, section 32 of the Wyoming Constitution and the Wyoming Eminent Domain Act.[252] Rejecting a strict interpretation, the court found that oil and gas development was encompassed in the term "mining" based on its historical categorization as a mineral, early exploration techniques referring to oil and

246. Coronado Oil Co. v. Grieves, 603 P.2d 406 (Wyo. 1979).

247. COLO. CONST. art II, § 14; WYO. CONST. art. 1, § 32; WYO. STAT. ANN. § 1-26-815 (2007).

248. IDAHO CONST. art. I, § 14.

249. WYO. CONST. art. I, § 32. Despite nearly identical constitutional provisions, Colorado courts have taken a much more restrictive approach, limiting the application of its private necessity provision solely to landlocked parcels. *See* Larson v. Sinclair Transp. Co., 284 P.3d 42 (Colo. 2012).

250. Meidinger, *supra* note 205, at 30 (citing Dayton Gold & Silver Mining Co. v. Seawell, 11 Nev. 294, 411 (1876)).

251. Klass, *supra* note 217, at 661.

252. Coronado Oil Co. v. Grieves, 603 P.2d 406, 441 (Wyo. 1979).

gas wells as mines, and consistency with the purpose of the provision to "facilitate the development of [the] state's resources."[253] The result was a significant extension of authority to private oil and gas companies. Uses that fall within those enumerated in section 32 are presumed "by constitutional edict" to have "the force and effect of a public use," thus satisfying the public purpose requirement of the Wyoming Eminent Domain Act.[254]

Based on this expansive reading of the term "mining," CO_2 production and its associated transportation may also fall within the broad scope of Wyoming's natural resource taking authority. Categorization of one substance, for example natural gas, is not dispositive as to the categorization of another.[255] Whether a specific project falls within the legislative declarations of public use requires an analysis of the project and material within its geographic and historical context. There are no precise analogs for CO_2 pipelines or production. CO_2, like natural gas, is gaseous at atmospheric pressures and can be extracted via wells under the terms of oil and gas leases. However, technical definitions may be less persuasive than considerations of history and purpose.[256] While CO_2 is like other extractive activities that benefit from Wyoming's natural resource takings provision in that it brings economic benefits to the state through encouragement of energy and generation of revenue, it is unique in that its production is a fairly recent development and is not limited to drilling or other techniques

253. *Id.*

254. *Id.* (citing Grover Irrigation & Land Co. v. Lovella Ditch, Reservoir & Irrigation Co., 131 P. 43 (Wyo. 1913)). A CO_2 pipeline would still need to satisfy other provisions of the act, including demonstrating that it is a "petroleum or other pipeline compan[y]" and that the project was located so as to balance the greatest public good and private injury and that the intended property was necessary for the project. *See* WYO. STAT. ANN § 1-26-504(a) (2013); WYO. STAT. ANN § 1-26-814 (1981); WYO. STAT. ANN § 1-26-815 (2013). Eminent domain has been used at least once in Wyoming for purposes of obtaining right of way for a CO_2 pipeline. However, the issue in that case was calculation of compensation under the Wyoming Eminent Domain Act and not a determination of public purpose. *See* Barlow Ranch Ltd. P'ship v. Greencore Pipeline Co., 301 P.3d 75 (Wyo. 2013).

255. Merrill, *supra* note 216, at 94 (citing Kaiser Steel Corp. v. W. S. Ranch Co., 467 P.2d 986, 988 (N.M. 1970)) (noting that coal mining may be governed by one rule, metal mining by another).

256. *Cortez Pipeline Co.*, 7 FERC 61024 (Apr. 6, 1979); Exxon Corp. v. Lujan, 970 F.2d 757 (10th Cir. 1992).

like mining. Thus, CO_2 pipelines may not benefit from the rich history that served the condemnor in *Coronado*.[257]

State statutes detail the legal processes to condemn property and which entities have authority to condemn.[258] These statutes may limit the scope of condemnation authority for natural resource development. Accordingly, determination of whether and, if so, how CO_2 pipeline developers are authorized to use eminent domain requires a state specific analysis. A survey of state statutes, regulations, and procedures goes beyond the scope of this Article. However, a look at Colorado's grant of condemnation authority to pipelines provides insight to the types of interpretation issues that are likely to arise. Colorado's eminent domain laws grants condemnation authority to "telegraph, telephone, electric light power, gas, or pipeline compan[ies]"[259] and to "pipeline[s] for the transmission of power, water, air, or gas for hire to any mining or mining claim or for any manufacturing, milling, mining, or public purpose."[260] Despite Colorado's broad constitutional natural resource takings provision, Colorado courts have precluded oil pipelines from using eminent domain on the basis that they are neither "pipeline companies" within the meaning 38-5-105, nor do they transport "water, air, or gas" as required by 38-4-102.[261] CO_2 pipelines may fall within the scope of these statutory authorizations based on the classification of CO_2 as "gas." However, as noted elsewhere, CO_2 is transported in a pseudo-liquid state, thus complicating that determination.[262] A pipeline company could also demonstrate that the CO_2 was transported to a "mining claim" or for "mining" or another public purpose.[263] Unlike Wyoming, Colorado courts have not considered whether the term "mining" includes operations for oil and would thus encompass EOR operations. A developer could also advance arguments that CO_2 transportation by pipeline is for a public purpose—be it climate mitigation or natural resource

257. Failing to establish CO_2 production itself as mining, a potential condemnors could also argue that CO_2 transportation as part and parcel of enhanced oil recovery would fall within the courts prior expansive reading of the term "mining."

258. A sampling of these statutes is listed in Klass, *supra* note 217, at n.25.

259. COLO. REV. STAT. § 38-5-105 (2017).

260. *Id.* § 38-4-102.

261. Larson v. Sinclair Transp. Co., 284 P.3d 42 (Colo. 2012)

262. *See supra* note 127 and accompanying text.

263. Colorado courts have not considered whether the term "mining" includes oil production.

production. Whether those uses constitute a sufficient public use would ultimately be determined by the judiciary.[264]

While advancing many of the same public benefits, CO_2 fits imperfectly within the historical context of constitutional natural resource development takings provisions. Statutory provisions regarding the authority and procedures granted to natural resource companies for eminent domain are likewise ambiguous when applied to CO_2 pipelines. Accordingly, while natural resource development takings provisions have been interpreted broadly and given extensive judicial deference, the extent to which CO_2 pipeline developers can avail themselves of these provisions is unclear.

To the Last Drop: EOR as a Public Purpose

A number of states grant eminent domain authority specifically to CO_2 pipeline developers for the purpose of encouraging enhanced oil recovery.[265] This approach is a refinement of the general natural resource development approach to establishing public purpose. In these states, CO_2 is not viewed as the primary resource itself but is rather an ancillary product necessary for production of another natural resource: oil.

State legislatures adopting this approach establish public purpose through increased petroleum production.[266] For example, Louisiana's

264. COLO. CONST. art. II, § 15 ("[W]henever an attempt is made to take private property for a use alleged to be public, the question whether the contemplated use be really public shall be a judicial question, and determined as such without regard to any legislative assertion that the use is public.").

265. LA. STAT. ANN. § 19:2(10); MISS. CODE ANN. § 11-27-47. Kentucky provides eminent domain to carbon dioxide transmission pipelines for "sale, storage, or carbon management." *See* KY REV. STAT. § 154.27-100. North Dakota and Texas provide broader grants of condemnation authority without regard to the end use but, as discussed *infra* at notes 295-309, tie condemnation authority to common carrier status.

266. This article does not address the merits of putting in place policies that facilitate increasing oil recovery rather than transitioning to renewable energy. However, social cost associated with climate change may be a limiting factor in public use determination. In at least one case, *Merrill v. City of Manchester*, the court stated that "if social costs exceed probable benefits, the project cannot be said to be built for a public purpose." 499 A.2d 216, 237 (N.H. 1985). For analysis of the evolving metrics for calculating the social cost of carbon in regulatory and NEPA analyses, see Daniel A. Farber, *Coping with Uncertainty: Cost-Benefit Analysis, the Precautionary Principle, and Climate Change*, 90 WASH. L. REV. 1659 (2015); Michael Greenstone, et al., *Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation*, 7 REV. ENVTL. ECO & POL'Y 23 (2013); Ted Hamilton, *The Virtues of Uncertainty: Lessons From the Legal Battles Over the Keystone XL Pipeline*, 18 VT. J. ENVTL. L. 222, 249-53 (2016); Mark Squillace & Alexander Hood, *NEPA, Climate Change, and Public Lands Decision Making*, 42 ENVTL. L. 469 (2012).

statute provides that the state, corporations, or limited liability companies may expropriate private property for "the piping or marketing of carbon dioxide for use in connection with a secondary or tertiary recovery project for the enhanced recovery of liquid or gaseous hydrocarbons."[267] Similarly, Mississippi's statute advances enhanced oil recovery within the state as the public purpose for the exercise of eminent domain by CO_2 pipeline developers.[268] New Mexico, while not specifying that CO_2 within pipelines must be used for enhanced oil recovery, grants eminent domain authority to pipeline developers pursuant to its oil and gas chapter, indicating a relationship to those purposes.[269]

CO_2-for-EOR provisions blur the already fuzzy distinctions between natural resource development takings and economic development takings.[270] Economic development takings originated in the 1920s as part of the urban renewal movement's efforts to eliminate the public health and safety hazards associated with slums and blight.[271] Over time, the scope of economic development expanded to include the creation of jobs, increases in tax base or revenues, and community revitalization—all of which were found to constitute permissible public purposes.[272] Recently, however, the

267. LA. REV. STAT. ANN. § 19:2(10) (2012). Incidentally, Louisiana's statute also provides expropriation rights for operations related to storage of carbon dioxide underground. *Id.* § 30:1108 (2009).

268. MISS. CODE ANN. § 11-27-47 (1984). Use of eminent domain is limited to pipelines for carbon dioxide for "use in connection with secondary or tertiary recovery projects located within the state of Mississippi for the enhanced recovery of liquid or gaseous hydrocarbons." A proposed bill, HB 907 (2016), would have required CO_2 pipelines to operate as common carriers, but did not pass. *See* H.B. No. 907, MISS. LEGIS., *available at* http://billstatus.ls.state.ms.us/documents/2016/pdf/HB/0900-0999/HB0907IN.pdf (last visited Sept. 21, 2017). In 2017, a similar effort failed. H.B. 1449, MISS. LEGIS., *available at* https://legiscan.com/MS/bill/ HB1449/2017.

269. N.M. STAT. ANN. § 70-3-5 (1993). Nordhaus & Pitlick, *supra* note 110, at 98 (citing 1983-1986 Op. Att'y Gen. N.M. 146 (1984)).

270. Klass, *supra* note 217, at 652.

271. George Lefcoe, *After Kelo, Curbing Opportunistic Tif-Driven Eonomic Development*, 83 TUL. L. REV. 45, 50-51 (2008); Hudson Hayes Luce, *The Meaning of Blight: A Survey of Statutory and Case Law*, 35 REAL. PROP. PROB. & TR. J. 389 (2000), Ilya Somin, *The Grasping Hand: "Kelo v. City of New London" and the Limits of Eminent Domain*, 29 FLA. B.J. 66, 80-86 (2016).

272. Berman v. Parker, 348 U.S. 26 (1954); City of Shreveport v. Chanse Gas Corp., 794 So. 2d 962, 973-74 (La. Ct. App. 2001); Poletown Neighborhood Council v. City of Detroit, 304 N.W.2d 455, 459-60 (Mich. 1981); City of Duluth v. State, 390 N.W.2d 757 (Minn. 1986); D. Benjamin Barros, *Nothing "Errant" About It: The* Berman *and* Midkiff *Conference Notes and How the Supreme Court got to* Kelo *With Its Eyes Wide Open*, PRIVATE PROPERTY, COMMUNITY DEVELOPMENT, & EMINENT DOMAIN (2008); Patricia E.

Supreme Court revived the question of whether private takings to further economic development activities constitute public use.[273] In *Kelo v. City of New London*, the Court found that economic development was a "traditional and long accepted function of government,"[274] and, deferring to legislative determinations that general increases in tax base and economic revitalization were public purposes, upheld a taking for those purposes.[275] The public was less convinced, resulting in a tide of legislative action to limit the use of eminent domain for private economic development purposes.[276]

CO_2-EOR undeniably generates economic benefits to the state through the maximization of recoverable reserves. Nationwide, DOE estimates that CO_2-EOR could increase domestic oil reserves by 87.1 billion barrels.[277] This additional recovery has significant economic benefits. For example, EOR has the potential to revitalize state economies by generating significant state revenues from severance and income taxes and royalty and provide high-compensation employment opportunities.[278] Although general economic benefits may inure to the state or its citizens, except where development occurs on state or federal land, the profits these operations yield are private.

EOR is similar in many ways to economic redevelopment. In response to the *Kelo* decision, many states have enacted anti-*Kelo* or post-*Kelo* laws through statutes or constitutional amendments, disclaiming economic redevelopment as a public purpose.[279] Public purpose arguments based

---

Salkin & Lora A. Lucero, *Community Redevelopment, Public Use, and Eminent Domain*, 37 URB. LAW. 201 (2005).

273. Kelo v. City of New London, 545 U.S. 469 (2005).

274. *Id.* at 484.

275. *Id.*

276. Michael J. Coughlin, *Absolute Deference Leads to Unconstitutional Governance: The New For a New Public Use Rule*, 54 CATH. U. L. REV. 1001 (2005); Steven J. Eagle & Lauren A. Perotti, *Coping with Kelo: A Potpourri of Legislation And Judicial Responses*, 42 REAL PROP. PROB. & TR. J. 799 (2008); Anastasia C. Sheffler-Wood, *Where Do We Go From Here? States Revise Eminent Domain Legislation in Response to Kelo*, 79 TEMP. L. REV. 617 (2006).

277. Klaas T. van 't Veld & Owen R. Philips, *The Economics of Enhanced Oil Recovery: Estimating Incremental Oil Supply and CO_2 Demand in the Powder River Basin*, 3 ENERGY J. 31, 32 (2011) (citing Kuuskraa & Ferguson, *Storing CO_2 with Enhanced Oil Recovery*, DEP'T OF ENERGY, NAT'L ENERGY TECH. LAB. (2008)).

278. Melzer, *supra* note 13, at 6.

279. County of Wayne v. Hathcock, 684 N.W.2d 765 (Mich. 2004); Eagle & Perotti, *supra* note 276.

exclusively on EOR may be vulnerable to these same criticisms.[280] EOR is more similar to the "upgrading" of property of which Justice O'Connor was so skeptical in her *Kelo* dissent.[281] In the context of the tertiary recovery operations for which the majority of CO_2 is needed, the economic resource has already been at least partially developed. The developer will not be "shut in and deprived of the opportunity to exploit" his valuable resources.[282] Rather, condemnation of private property is desired in order to increase the profitability and yield of existing resources.

Despite these similarities, natural resources takings have been more-or-less insulated from the wave of post-*Kelo* reforms aimed at limiting the ability of political subdivisions or private parties to take private property for economic redevelopment.[283] That owes in part to the differing historical contexts behind these public purpose justifications. Economic redevelopment takings originated in the 1920s with the movement to eliminate the public health hazards associated with blight,[284] and accordingly the extension of that authority to take property for the purpose of increasing tax revenue was perceived by the public as an overreach. On the contrary, the history of natural resource takings indicates that the high grading of property in order to encourage industrial and agricultural development was precisely the purpose of these constitutional provisions. Natural resource takings were intended to establish new industries, promote exploitation of land and natural resources, and encourage the growth of emerging economies.[285] Though perhaps less existential to western states'

280. Klass, *supra* note 217, at 676-77, 681-700.

281. *Id.* at 672 (citing *Kelo*, 545 U.S. at 503 (O'Connor, J., dissenting) ("Nothing is to prevent the state from replacing any Motel 6 with a Ritz Carlton, any home with a shopping mall, or any farm with a factory.")).

282. Coronado Oil Co. v. Grieves, 603 P.2d 406, 411 (Wyo. 1979).

283. Colorado, Wyoming, and Louisiana have all imposed harsh limitations on the ability of the state to take property for economic development purposes; however, these limitations may not extend to natural resource takings. *See* LA. CONST. ART. VI § 21 (creating the industrial use exception, "Assistance to Local Industry"); LA. STAT. ANN. § 19:2 (permitting expropriation by certain corporations and limited liability companies); UTAH CODE ANN. § 78-34-1 (West 2002 & Supp. 2007), as amended by S.B. 117, 2006 Leg., Gen. Sess. (2006)) (noting exceptions specifically for natural resource development purposes; Eagle and Perotti, *supra* note 276 (citing ALASKA STAT. § 09.55.240(a) (2006), as amended by H.B. 318, 24th Leg., Reg. Sess. (2006)); Klass, *supra* note 217, at 675-76. North Dakota's constitutional amendment, which limits all takings except for those by common carriers or public utilities, is a notable exception. *See* N.D. CONST. art. I, § 16 (as amended by Measure 2) (2006).

284. Lefcoe, *supra* note 271; Luce, *supra* note 213; Somin, *supra* note 271.

285. Norwood v. Horney, 853 N.E. 2d 1115, 1132-33 (Ohio 2006) (citing *The Public Use Limitation on Eminent Domain: An Advance Requiem*, 58 YALE L.J. 599, 600 (1949); Philip

economies today, the continued expropriation of property for those purposes still falls within the scope of the original constitutional and statutory provisions.

Public Use: CO_2 Pipelines as Common Carriers

A second category of statutes adheres to a more traditional "public use" justification for eminent domain. Some states that have enacted these statutes, such as North Dakota, Montana, and Colorado, may also have natural resource takings provisions within their state constitutions but have limited the scope of that authority through the imposition of common carrier requirements. These requirements authorize private companies to take private property for utilitarian use, provided that they consent to "provide necessary services without discrimination and at reasonable rates."[286]

Courts have confirmed that the "public use" requirement is satisfied where privately owned pipelines are required to operate as common carriers. In *Vardeman v. Mustang Pipeline Company*, a landowner challenged that the purpose of the pipeline was not a public use.[287] The court found that the public use requirement was satisfied both because the pipeline would be used "in a manner determined by the legislature to be a public use"—the movement of "a petroleum product . . . from the producing areas to areas where it can be used"—and because the designation as a common carrier also established use for a public purpose.[288]

Several states and the federal government adopt the common carrier approach with respect to CO_2 pipelines.[289] These statutes authorize condemnation for CO_2 pipelines provided that the pipelines are operated as common carriers. Common carriers provide non-discriminatory access to

Nichols Jr., *The Meaning of Public Use in the Law of Eminent Domain*, 20 B.U. L. REV. 615, 617 (1940)) ("In America's nascent period, there was an abundance of unclaimed land, limited government activity, and little controversy over the use of eminent domain to develop land and natural resources.").

286. Meidinger, *supra* note 205, at 22.

287. Megan James, *Checking the Box is Not Enough: The Impact of Texas Rice Land Partners v. Denbury Green Pipeline-Texas, LLC and Texas's Eminent Domain Reforms on the Common Carrier Application Process*, 45 TEX. TECH L. REV. 959, 987 n.283-84 (citing Vardeman v. Mustang Pipeline Co., 51 S.W.3d 308, 310 (Tex. App.—Tyler 2001, pet. denied)).

288. *Id.*

289. Pipelines receiving right of way pursuant to the MLA are required to act as common carriers. 30 U.S.C. § 185(r) (2006).

pipelines at established tariffs, thereby opening their pipelines to public use.[290] While these carriers can establish specifications that require all CO_2 transported through them to be of pipeline quality,[291] they must willing to carry product for anyone meeting those specifications. As such, by conferring eminent domain authority under this condition, states assure that the infrastructure itself is available for use by the public thus encouraging the growth of industry. Common carrier requirements may also foster efficiencies. As infrastructure expands, these nondiscriminatory access and regulated rate pipelines may help avoid duplicative routes or facilities by promoting development of a core backbone infrastructure by providing access to existing point-to-point pipelines. Further, by lowering barriers to entry, common carrier requirements may facilitate more widespread implementation of CCUS or transitions from CO_2-EOR to incremental storage operations.

Common Carriers and Pipelines

Common carrier requirements evolved from the assumption that in order to counteract adverse behavior, companies enjoying a natural monopoly should be required to "serve all comers at fair rates."[292] The hallmark requirements of common carriage are that the carrier must offer nondiscriminatory access to unrelated parties at fair and reasonable rates.[293] Common carrier requirements are found across a broad spectrum of industries providing "public goods," including public utilities, telecommunications companies, airlines, taxicabs, cruise ships, canal operating companies, and oil pipelines.

The Hepburn Act, passed in 1906, requires oil pipelines to operate as common carriers, regardless of whether eminent domain was utilized in obtaining right of way.[294] Prior to its passage, monopolistic behavior by the Standard Oil Trust, which controlled nearly all the oil pipelines in the country, limited the ability of Kansas refineries to ship crude out of state.[295]

290. Reed, *supra* note 146, at 104.

291. Bliss, *supra* note 97; Marston & Moore, *supra* note 15, at 442, 448.

292. Richard Posner, *Natural Monopoly and Its Regulation*, 21 STAN. L. REV. 548, 607 (1968) (citing Am. Trucking Ass'ns v. Atchison, 387 U.S. 397, 406-07 (1967)); Reed, *supra* note 146.

293. Belle Fourche Pipeline Co., 28 FERC 61,150, 61,281 (1984); Posner, *supra* note 292; Klass & Meinhardt, *supra* note 121, at 960.

294. 34 Stat. 584 (1906); 49 U.S.C. § 1 et seq.; Leonard L. Coburn, *The Case for Petroleum Pipeline Deregulation*, 3 ENERGY L.J. 225, 229 (1982); Klass & Meinhardt, *supra* note 121, at 960.

295. *Id.*

In order to obtain access to its pipelines, Standard Oil required that producers first sell oil to it at its set price.[296] The Hepburn Act assured equitable treatment of producers and shippers by amending the ICA and extending ICC authority to oil pipelines.[297] Regulatory provisions of the ICA required nearly all pipelines to "charge just and reasonable rates for their service; provide and furnish transportation upon reasonable request; establish reasonable through routes with other carriers; and establish just and reasonable rates for through transportation."[298] The only exception was for "a pipeline engaged solely in transporting oil from its wells across a state line to its own refinery for its own use."[299]

With the exception of pipelines receiving a right of way across federal lands pursuant to the MLA, CO_2 pipelines are not subject to federal common carrier requirements.[300] However, a number of states statutorily require CO_2 pipelines, or pipelines generally, to operate as common carriers.[301] These statutes establish processes and requirements for developments that are intended for use by the public. For example, North Dakota imposes universal common carrier requirements.[302] Were Colorado's constitutional or statutory provisions for condemnation found to extend to CO_2 pipelines,[303] those pipelines would be required to act as common carriers by carrying CO_2 "for hire."[304] Similarly, Montana and Texas impose common carrier requirements only on those CO_2 pipeline companies utilizing the power of eminent domain. The following three

296. United States v. Ohio Oil Co., 234 U.S. 548 (1914).

297. Coburn, *supra* note 294, at 229 (citing Staff of Subcomm. on Antitrust and Monopoly of the Senate Comm. on the Judiciary, *Oil Company Ownership of Pipelines*, 95th Cong., 2d Sess., 99 (Comm. Print 1978)).

298. *Id.* at 230 (citing 49 U.S.C. §§ 1(5), 1(4)) ("The Interstate Commerce Act was recodified without substantive change by Pub. L. 95-473 (Oct. 17, 1978), 92 Stat. 1337, 49 U.S.C. § 10101 et seq.").

299. *Id.* at 562 (citing Pipe Line Cases, 234 U.S. 548 (1914)).

300. Natural gas pipelines crossing federal land were originally obligated to act as common carriers but were exempted in 1953. *See* William A. Mogel & John P. Gregg, *Appropriateness of Imposing Common Carrier Status on Interstate Natural Gas Pipelines*, 25 ENERGY L.J. 21, 42 (2004).

301. COLO. REV. STAT. ANN. §§ 38-4-102, 38-4-105 (2017); KY. REV. STAT. ANN. § 278.470 (2014); MONT. CODE. ANN. §§ 30-70-102(20), 69-13-101 (West 2007); N.D. CENT. CODE ANN. §§ 49-19-01(1), 49-19-08 (West 2007); OKLA. STAT. ANN. tit. 52 §§ 23, 24, 56; TEX. NAT. RES. CODE. ANN. § 111.019 (West 2015).

302. N.D. STAT. ANN. § 49-19-01(1) (West 2007).

303. *See supra* notes 259-264 and accompanying text.

304. COLO. REV. STAT. ANN §§ 38-4-102, 38-4-105 (West 2017).

examples demonstrate differing approaches to common carrier requirements as applied to CO_2 pipelines.

North Dakota imposes strict common carrier requirements on CO_2 pipelines via both constitutional and statutory provisions. A citizen-initiated constitutional amendment passed in response to the *Kelo* decision provides that "[p]rivate property shall not be taken for the use of, or ownership by, any private individual or entity, unless that property is necessary for conducting a common carrier or utility business."[305] North Dakota also statutorily defines any party transporting natural gas via pipeline "for hire or for sale" within the state, "the right of way for which is granted or secured . . . through the exercise of the right of eminent domain" as a common carrier.[306] North Dakota goes further by defining any entity "engaged in the business of transporting crude petroleum, gas, coal, or carbon dioxide by pipelines" as a pipeline common carrier.[307] As such, pipeline operators must submit to the jurisdiction of the North Dakota Public Service Commission, which, among other things, establishes and enforces rates and regulates tariffs.[308] Accordingly, all CO_2 pipelines in North Dakota must operate as common carriers, whether or not eminent domain is used to acquire right of way.

Montana grants eminent domain authority only to common carrier pipelines but does not require all pipelines to operate as common carriers.[309] Montana law defines a common carrier pipeline as one that transports by pipeline "carbon dioxide from a plant or facility that produces or captures carbon dioxide" but excludes "pipelines that are limited in their use to the wells, stations, plants, and refineries of the owner."[310] This provision would require some CO_2 pipelines transporting anthropogenic CO_2 to operate as a common carrier but would exclude pipelines transporting only natural CO_2.[311] In a provision that mimics the Hepburn Act "Uncle Sam"

305. N.D. CONST. art. I, § 16.
306. N.D. CENT. CODE § 49-19-01(3).
307. *Id.* § 49-19-01(1).
308. *Id.* § 49-19-17.
309. MONT. CODE §§ 30-70-102(20), 69-13-101.
310. *Id.* § 69-13-101(3)(a).
311. Plant or facility is defined as "a facility that produces a flow of carbon dioxide that can be sequestered or used in a closed-loop enhanced oil recovery operation. This does not include wells from which the primary product is carbon dioxide." *Id.* § 15-6-158(2)(g).

exception,[312] Montana also excepts point-to-point pipelines where both the CO_2 source and the end use are owned by the same party.[313]

Texas takes a similar approach but does not distinguish based on either the source or end use of the pipeline. Private pipelines are permitted for any source or use of CO_2, however, the use of eminent domain obligates a CO_2 pipeline to operate as a common carrier.[314] Although no permit is required prior to construction, the Texas Railroad Commission must designate the pipeline as a common carrier.[315] To do so, the pipeline must notify the Commission of its proposed route and establish whether or not the pipeline will be available for use by the public through the filing of a T-4 permit application and a P-5 Organization Report.[316] The developer must declare itself to be a common carrier, provide the Texas Railroad Commission with a letter agreeing to be subjected to Chapter 111 of the Natural Resource Code, and publish a tariff prior to exercising eminent domain.[317] However, mere willingness to serve other customers is not enough to exercise eminent domain; the court in *Denbury Green Pipeline-Texas, LLC v. Texas Rice Land Partners, Ltd.* clarified that there must also be a reasonable probability that the pipeline will actually be used by the public.[318] Consistent with the proposition that landowners should not be deprived of their property for purely private use, the developer must demonstrate that

312. Coburn, *supra* note 294, at 231.

313. MONT. CODE ANN. § 69-13-101e(3) (West 2013).

314. TEX. NAT. RES. CODE ANN. § 111.019(b) (West 2011); Amanda Buffington Niles, Comment, *Eminent Domain and Pipelines in Texas: It's as Easy as 1, 2, 3 – Common Carriers, Gas Utilities, and Gas Corporations*, 16 TEX. WESLEYAN L. REV. 271 (2010).

315. TEX. NAT. RES. CODE ANN. §§ 111.002(6), 111.020(d) (West 2011).

316. *Form T-4, Application for Permit to Operate a Pipeline in Texas*, R.R. COMM'N OF TEX. (Dec. 15, 2011), *available at* http://www.rrc.state.tx.us/forms/forms/gs/T-4Permit.pdf; *Pipeline Eminent Domain and Condemnation Frequently Asked Questions*, R.R. COMM'N OF TEX., http://www.rrc.state.tx.us/about/faqs/eminentdomain.php (last visited Apr. 23, 2012).

317. TEX. NAT. RES. CODE ANN. §§ 111.002(6), 111.014 (West 2011); Cavarrio Carter, *System Check: Balancing Texas's Need for Natural Resources Exploration with Texas Landowner Rights in Light of Texas Rice Land Partners v. Denbury Green Pipeline Texas*, 2 LSU J. ENERGY L. & RES. 309, 318 (2014); James, *supra* note 287, at 971.

318. Denbury Green Pipeline-Texas, LLC v. Tex. Rice Land Partners, Ltd, 510 S.W.3d 909 (Tex. 2017) (stating that there must also be a reasonable probability "that the pipeline will at some point after construction serve the public by transporting gas for one or more customers who will either retain ownership of their gas or sell it to parties other than the carrier").

the pipeline will not be "limited in [its] use to the wells, stations, plants, and refineries of the owner."[319]

Texas' approach equates common carriage with public use.[320] Once a pipeline has demonstrated that it will serve as a common carrier, it does not have to make any additional showing regarding the public purpose of the pipeline.[321] Accordingly, whether the pipeline will mitigate climate change, provide CO_2 for the beverage industry, or be used for EOR is irrelevant. The operation of the pipeline as a public good is itself indicative of public purpose. In a subsequent decision, the Texas Supreme Court clarified that the state's requirement does not mandate that a pipeline serve a substantial public purpose but rather that it establishes a reasonable probability of public use.[322]

Pipelines for CCUS: Public Purpose v. Use by the Public

The growing demand for EOR and investment and research towards CCUS indicate that there will be increased development of CO_2 pipelines in coming decades.[323] As new CO_2 pipelines expand across the country, private landowners nationwide will be expected to yield their property towards those ends. CO_2 pipelines intended for CCUS may not be able to rely on traditional natural resource development justifications of public purpose to obtain condemnation authority. This challenge illustrates the limitations of public purpose arguments based solely on extraction and contributes to the dialogue on whether property taken by private companies should be made available to some "possession, occupation, and direct enjoyment by the public."[324] Resolution of these issues will influence where pipelines are located, how they are operated, and the extent to which they can be integrated into a broader network to serve both EOR and climate-change mitigation uses.

Many of the traditional public purpose justifications for natural resource development are ill fitting as applied to CO_2 pipelines for CCUS, absent

319. *Id.*; Richard F. Brown, *Oil, Gas, and Mineral Law*, 66 SMU L. REV. 1003, 1027-28 (2013).

320. Dave Player, *Eminent Domain, Denbury, and the Keystone XL Pipeline*, 8 TEX. J. OIL GAS & ENERGY L. 177, 179-183 (2013); Montana J. Ware, Note, *Private Takings in Texas: Defining Public Use after Kelo*, 12 TEX. J. OIL GAS & ENERGY L. 259, 270 (2017).

321. Vardeman v. Mustang Pipeline Co., 51 S.W.3d 308 (Tex. App.—Tyler 2001, pet. denied).

322. *Denbury*, 510 S.W.3d at 917.

323. Dooley, *supra* note 9.

324. Klass, *supra* note 217, at 662.

associated EOR operations. Although non-EOR-CCUS may offset the environmental externalities of natural resource development, it does not, in itself, result in either the expansion of tax revenue or the development or production of natural resources. Accordingly, many of the statutes and constitutional provisions that have enabled use of condemnation for CO_2 pipelines related to the production of CO_2 or for EOR would be insufficient with respect to pipelines for carbon storage alone.

If natural resource takings provisions are narrowly interpreted as serving a public purpose solely by advancing resource extraction through the elimination of holdouts,[325] CO_2 pipelines for CCUS hardly fit within those confines. However, these constitutional provisions can also be interpreted as an intentional effort to broaden the eminent domain authority granted to private industry as a means for facilitating natural resource development towards the general end of economic prosperity.[326] Viewed in this light, it is feasible to argue that CCUS serves these same public purposes by decarbonizing fossil energy generation, thus resulting in an avoided cost from climate-related harms and potentially costly new emissions regulations.

The challenge of applying natural resource development takings provisions to CO_2 pipelines for CCUS illustrates the limitations inherent in public purpose justifications based entirely on the end use of the substance produced or transported. Whereas condemnation for CO_2 transportation as a resource or as necessary to "mining" would be nearly presumed to serve a public purpose, condemnation for CO_2 pipelines intended for CCUS may be constrained by the public purpose limitation. While little would prevent a pipeline developer from making a pipeline available for transport for purposes of CCUS *after* construction,[327] the law is opaque as to whether pipelines could be constructed with CCUS as the principal end. Due to the fact that the permanent storage reservoir might not be co-located with the

325. Coronado Oil Co. v. Grieves, 603 P.2d 406 (Wyo. 1979); Dayton Gold & Silver Mining v. Seawell, 11 Nev. 394 (1876) ("[T]he entire people of the state are directly interested in having the future developments unobstructed by the obstinate action of any individual or individuals.").

326. *See* Potlatch Lumber Co. v. Peterson, 88 P. 426, 431 (Idaho 1906) (holding that "a complete development of the material resources of our young state could not be made unless the power of eminent domain was made broader than it was in many of the Constitutions of the several states of the Union" because to hold otherwise would be "to defeat the development of the great natural advantages, resources and industrial opportunities.").

327. Kevin L. Cooney, *A Profit for the Taking: Sale of Condemned Property After Abandonment of the Proposed Public Use*, 74 WASH. U. L. Q. 751 (1996) (citing Mainer v. Canal Auth., 467 So. 2d 989, 993 (Fla.1985)).

EOR use, these limitations could be problematic, particularly for development of spur lines for the last mile. Accordingly, natural-resource development justifications of public purpose unnecessarily constrain development of an integrated CO_2 transportation network precisely at a time where maximum flexibility and expansion are needed.

As others have suggested, the natural resource development justification for public purpose is ripe for reconsideration in light of changing public needs.[328] A historical narrative characterizes the relationship of American attitudes and the physical environment as moving through three distinct phases: 1) fear; 2) conquest and mastery through maximum economic utilization; and, 3) appreciation and preservation.[329] Although reality was more nuanced than this linear model suggests,[330] historical approaches to interpreting public use clauses throughout the 19th and early 20th centuries largely align with this model, with courts considering public purpose in light of changing norms and historical use.[331] Yet, modern analyses of public purpose as it relates to natural resource purposes are firmly rooted in the rhetoric of conquest and utilization,[332] even whereas public attitudes towards nature have reoriented towards conservation, integration, and restraint.[333] Accordingly, as Professor Klass has suggested, the forced reallocation of property rights to promote natural resource development seems increasingly inconsistent with the evolving economies of western states towards emphasis on conservation and tourism, the protection of surface rights, and concerns about climate change and the social costs of carbon.[334]

Climate-Change Mitigation as Public Purpose

Climate-change mitigation may soon qualify as a public purpose independent of natural resource development.[335] There is a "general consensus that climate change poses a threat to human health and the

328. Klass & Meinhardt, *supra* note 121, at 689.
329. Limerick, *supra* note 212, at 172-73.
330. *Id.*
331. *Norwood*, 853 N.E.2d at 1129-30.
332. *Coronado*, 603 P.2d at 411.
333. Klass, *supra* note 217, at 679.
334. *Id.* at 679, 680, 689.
335. Samantha J. Hepburn, *Ownership Models for Geological Sequestration: A Comparison of the Emergent Regulatory Models in Australia and the United States*, 44 ENVTL. L. REP. NEWS & ANALYSIS 4, 10310, 10313 (2014) (citing Climate, *supra* note 91, at 417).

environment," as well as significant threats to private property.[336] Addressing these threats is one of the country's critical needs, and despite public perceptions to the contrary, likely provides specific benefits within the individual states.[337] As states and the federal government move to address the impacts of climate change or to reduce emissions, whether climate-change mitigation constitutes a public purpose is likely to be of critical importance.

This question is already being considered in the context of CCUS. CCUS will require not only land for pipelines but significant subsurface property rights necessary for sequestration.[338] It is generally acknowledged that existing statutes permitting eminent domain for gas storage are likely insufficient to acquire subsurface rights necessary for CCUS.[339] Accordingly, regulatory initiatives for CCUS and legislative declarations of pore space ownership have been shaped by the background landscape of eminent domain. In fact, the Interstate Oil and Gas Compact Commission (IOGCC) model statute proposes eminent domain as a tool to acquire subsurface property for CCUS.[340] In addition to other natural-resource based approaches to establishing public purpose, both Louisiana and Kentucky have passed legislation designating carbon storage as a public

336. Climate, *supra* note 91, at 424-25; Holly Doremus, *Climate Change and the Evolution of Property Rights*, 1 UC IRVINE L. REV. 1091 (2011).

337. Nadja Popovich, et al., *How Americans Think About Climate Change, in Six Maps*, N.Y. TIMES (Mar. 21, 2017), https://www.nytimes.com/interactive/2017/03/21/ climate/how-americans-think-about-climate-change-in-six-maps.html; Square Butte Electric Co-op v. Hilken, 244 N.W.2d 519, 524 (N.D. 1976).

338. Delissa Hayano, *Guarding the Viability of Coal and Coal-fired Power Plants: A Road Map for Wyoming's Cradle to Grave Regulation of CO_2 Sequestration*, 9 WYO. L. REV. 139, 141 (2009) (citing Steven L. Bryant, *Geologic CO_2 Storage – Can the Oil and Gas Industry Help Save the Planet?*, 54 ROCKY MTN. MIN. L. INST. 2-1, 2-8 (2008)); Tara Righetti, *Correlative Rights and Limited Common Property in the Pore Space: A Response to the Challenge of Subsurface Trespass in Carbon Capture and Sequestration*, 47 ENVTL. L. REP. NEWS & ANALYSIS 10420 (May 2017).

339. Mark A. de Figueiredo, *Property Interests and Liability of Geologic Carbon Dioxide Storage, A Special Report to the MIT Carbon Sequestration Initiative*, LAB. FOR ENERGY AND ENVT. 12-14 (Sept. 2005).

340. *Storage of Carbon Dioxide in Geologic Structures: A Legal and Regulatory Guide for States and Provinces*, INTERSTATE OIL AND GAS COMPACT COMM'N, TASK FORCE ON CARBON CAPTURE AND GEOLOGICAL STORAGE (2007); Tracy J. Logan, *Carbon Down Under – Lessons from Australia: Two Recommendations for Clarifying Subsurface Property Rights to Facilitate Onshore Geologic Carbon Sequestration in the United States*, 11 SAN DIEGO INT'L L.J. 561, 596-598 (2010); Larry Nettles & Mary Conner, *Carbon Dioxide Sequestration – Transportation, Storage, and Other Infrastructure Issues*, 4 TEX. J. OIL GAS & ENERGY L. 27, 36-37 (2009).

purpose.[341] Although courts have traditionally afforded extensive deference to legislative declarations of public purpose, these designations may not be dispositive as to judicial interpretations of states' constitutional provisions.

In some states, however, there may be insufficient political initiative to declare CCUS or climate mitigation as a public purpose. In fact, at least two states, Wyoming and Oklahoma, have expressly provided that nothing within their carbon capture and sequestration statutes creates a right to use eminent domain for CCUS.[342] These provisions do not necessarily preclude developers of CO_2 pipelines from obtaining condemnation authority under other provisions of law.[343] However, an express statement of the legislature against utilization of eminent domain for CCUS—at least in the context of unitization of subsurface rights—may challenge arguments that pipelines for CCUS is within broader declarations of public purpose.

At least one case has analyzed issues that tangentially relate to use of eminent domain for climate change. In *Borough of Harvey Cedars v. Karan*, a New Jersey borough successfully condemned a landowner's beachfront strip for the construction of protective sand dunes.[344] Sand dune protection is pertinent to coastal climate adaptation projects.[345] In fact, the National Oceanic and Atmospheric Administration's U.S. Climate Resilience Toolkit describes sand dunes as "natural infrastructure" that towns can protect or enhance to reduce damage from "rising sea levels."[346]

---

341. KY. REV. STAT. ANN. § 154.27-100 (2014); LA. STAT. ANN. § 30:1108 (2009).

342. OKLA. STAT. tit. 3 § 5-106(d); WYO. STAT. ANN. § 35-11-316 (West 2009).

343. Oklahoma grants eminent domain authority to oil pipelines for transport of "petroleum, liquid or liquefiable hydrocarbons and chemicals" and to natural gas pipelines. OKLA. STAT. ANN. tit. 52 §§ 51-67, 21-35. It is unknown whether CO_2 pipelines would fall within either of these provisions. Oklahoma requires both oil and natural gas pipelines to be common carriers.

344. Borough of Harvey Cedars v. Karan, 70 A.3d 524 (N.J. 2013); Robert R.M. Verchick, *Culture, Cognition, and Climate*, 2016 ILL. L. REV. 969, 1018 (citing 70 A.3d at 1017-18).

345. *Id.*; Andrew Romano, *The Day Climate Change Ruined Our Lives*, NEWSWEEK (Mar. 25, 2013, 4:45 AM), http://www.newsweek.com/day-climate-change-ruined-our-lives-62931. On the issue of compensation, see Joshua Ulan Galperin, *Raisins and Resilience: Elaborating Horne's Compensation Analysis with an Eye to Coastal Climate Change Adaptation*, 35 STAN. ENVTL. L.J. 3, 4-6 (2016).

346. Caitlyn Kennedy, *Beachfront Q&A: Talking About Dunes, Development, Storms, and Sea Level Rise*, CLIMATE.GOV (Oct. 28, 2013), https://www.climate.gov/news-features/features/beachfront-qa-talking-about-dunes-development-storms-and-sea-level-rise; *Restoring Natural Dunes to Enhance Coastal Protection*, U.S. CLIMATE RESILIENCE TOOLKIT, NAT'L OCEANIC AND ATMOSPHERIC ADMIN. (Jan. 17, 2017), https://toolkit.climate.gov/case-studies/restoring-natural-dunes-enhance-coastal-protection.

The dispute in *Borough of Harvey Cedars* concerned the determination of just compensation for an easement necessary to construction of protective sand dunes.[347] The municipality's right to acquire easements through its statutory powers of eminent domain for the construction of the sand dunes does not appear to have been questioned. In fact, the public benefits of the storm-protection project are discussed only as to whether it conferred a special benefit upon the property owners.[348] The benefits of protective sand dunes are much more localized and causally related to the property taken, and accordingly fall more closely within traditional public purposes than atmospheric GHG reduction strategies. Accordingly, although *Borough of Harvey Cedars* does not establish acceptance of climate change as a public purpose, it indicates that condemnation is already being used to acquire property necessary for climate-change mitigation projects. Further, the partial takings issues addressed in *Borough of Harvey Cedars* are likely to be a critical issue should eminent domain be used for condemnation of subsurface pore space.[349]

The transportation of CO_2 is a critical component of the vast infrastructure necessary to CCUS, and thus CO_2 pipelines have the potential to serve an important public purpose. Even were CCUS or climate-change mitigation accepted as a public purpose in its own right, success of CCUS on a national scale will require access to a greater interstate pipeline network. The incremental construction of trunk and spur lines for EOR pipelines could develop into the foundation for an national CO_2 pipeline network, but only if others can make use of that infrastructure. Absent common carrier requirements, infrastructure constructed using eminent domain to serve EOR purposes will not be available to "use by the public" through access by other producers or shippers in the same area. Thus, CCUS project proponents wishing to connect existing networks with new sources of captured CO_2 may suffer the same limits on access to market as early oil producers, hindering development of an integrated national pipeline network available for public use. Where used as an alternative to natural resource development justifications of public purpose, public use requirements thus serve a dual purpose in assuring future access to infrastructure built using eminent domain and eliminating limitations based on the natural resource end uses of CO_2 transported. Presently, those

347. *Borough of Harvey Cedars*, 70 A.3d 524; Bianca Iozzia, *Putting a Price Tag on an Ocean View: The Impact of Borough of Harvey Cedars v. Karan on Partial Taking Valuations*, 25 VILL. ENVTL. L.J. 501 (2014).

348. *Borough of Harvey Cedars*, 70 A.3d 524.

349. Climate, *supra* note 91, at 420.

limitations may preclude development of pipelines intended for CCUS, whereas stand-alone public use requirements would permit their development provided that they too operated as common carriers. Accordingly, where states elect to grant condemnation authority to CO_2 pipeline developers, approaches that require availability for use by the public may be preferable to those that focus solely on the end use of the product transported.

IV. Adequacy of the Current Regulatory Framework

The cost of pipeline construction[350] and unavailability of an integrated, open-access CO_2 pipeline network have been identified as among the major obstacles to widespread implementation of CCUS or greater deployment of EOR technologies. Concerns about inconsistent regulation between states and monopolization are cited as major impediments to its development. In response, many have suggested that a federal siting process is needed. This part evaluates the adequacy of the current regulatory framework to facilitate development of a nationwide integrated CO_2 pipeline network and suggests that many of the monopolization concerns identified could be overcome through state integration of common carrier requirements.

Proposals for a Federal Siting Framework

CO_2 pipelines are planned, constructed, and financed based on the specific characteristics of both the source and the end use—in almost all cases for EOR.[351] Accordingly, construction of CO_2 pipelines is likely to unfold in a slow and geographically limited manner as new industrial facilities, EOR operations, and CCS-enabled power plants are brought online. Early development of natural gas and oil pipelines, and of electric transmission lines, progressed in much the same way. In each case, an initial, localized build-out of infrastructure was accomplished through state

---

350. Cost estimates for CO_2 pipeline construction range from $70,000 to $126,000 per inch-diameter/mile. Joseph Essandoh-Yeddu & Gürcan Gülen, *Economic Modeling of Carbon Dioxide Integrated Pipeline Network for Enhanced Oil Recovery and Geologic Sequestration in the Texas Gulf Coast Region*, 1 ENERGY PROCEDIA 1, 1602-10 (2009); Tim Grant, et al., *Carbon Dioxide Transportation and Storage Costs in NETL Studies*, U.S. DEP'T OF ENERGY, NAT'L ENERGY TECH. LAB. (May 2014); Sean T. McCoy & Edward S. Rubin, *An Engineering-Economic Model of Pipeline Transport of CO_2 with Application to Carbon Capture and Storage*, GREENHOUSE GAS CONTROL, 219-29 (2008). An inch-diameter/mile is a cost estimate tool based on the cost per inch of diameter of pipe over a mile.

351. Schnacke, *supra* note 13, at 286.

regulation and private enterprise.[352] As the industry grew and expanded, federal regulation or backstop authority eventually became necessary to overcome geographic barriers or market failures.[353]

CO_2 pipelines may follow this well-worn path. Concerns about monopolization, among other problems, have led a number of scholars to conclude that federal regulation of CO_2 pipeline siting is needed.[354] Suggested frameworks include a model based upon the Natural Gas Act, federal common carrier requirements similar to those imposed on oil pipelines, FERC backstop authority, or the creation of an opt-in option for federal siting.[355] Each of these proposals seeks to address the inefficiencies of inconsistent state regulations and the risk of monopoly control.

Although federal regulation may eventually be required, it may not be needed yet. In the natural gas context, federal siting contributed to faster permitting, ease in obtaining right of way, and price stability.[356] However, these efficiencies came with new costs, such as "high rates, barriers to entry, stymied productivity, technological change, and management quality."[357] Thus, where state approaches appear to be sufficient, premature imposition of federal siting authority may impose unnecessary costs.[358]

States are better equipped to establish public participation and consider significant local concerns about safety, land use, and impacts to property and environment.[359] Further, under state siting rules, pipeline infrastructure has grown steadily, including a number of interstate pipelines and market participants. Those very pipelines are likely to form the backbone of the CO_2 transportation infrastructure that will ultimately be required. A

352. Alexandra B. Klass & Jim Rossi, *Reconstituting the Federalism Battle in Energy Transportation*, 41 HARV. ENVTL. L. REV. 423, 436 (2017).

353. Climate, *supra* note 91.

354. Policy Brief: Regulating Carbon Dioxide Pipelines for the Purpose of Transporting Carbon Dioxide to Geologic Sequestration Sites, CCS REG. PROJECT 3, 5 (2009).

355. Joel Mack & Buck Endemann, *Making Carbon Dioxide Sequestration Feasible: Toward Federal Regulation of CO_2 Sequestration Pipelines*, 38 ENERGY POL'Y 735, 739-42 (2010); Cyrus Zarraby, *Regulating Carbon Capture and Sequestration: A Federal Regulatory Regime to Promote the Construction of a National Carbon Dioxide Pipeline Network*, 80 GEO. WASH. L. REV. 950 (2012); Nordhaus & Pitlick, *supra* note 110, at 98-100.

356. Bliss, *supra* note 97.

357. *Id.*

358. Nordhaus & Pitlick, *supra* note 110, at 100-01 (citing Hearing on S. 2323 and S. 2144 Before the S. Comm., 110th Cong. (2008) (testimony of Hon. Joseph T. Kelliher, Chairman, FERC) [hereinafter "Kelliher Testimony"]).

359. Klass & Rossi, *supra* note 352, at n.148.

preemptive disruption in siting processes could drive away the only capital currently being invested in CO_2 transportation.

Proposals for federal siting have arisen in response to concerns that the incremental piecing together of CO_2 pipelines for EOR may later preclude or deter use and access to infrastructure for CCUS. Common carrier requirements in state eminent domain and siting processes may address many of these concerns. Common carrier requirements are consistent with historical understandings of public use, and will assure that the EOR-driven development of CO_2 pipelines today will later be available to serve CCUS or other carbon-mitigation industries. By doing so, states can concurrently promote development of an accessible and integrated pipeline infrastructure and avoid upsetting what has thus far seemed to be a workable paradigm.

The Monopoly Concern

All pipelines are considered natural monopolies.[360] The investment and time required to permit and build long distance pipelines, particularly interstate pipelines, is significant. Once built, pipelines present an opportunity to exert market power and extract secondary rents.[361] While nothing de facto prevents others from entering the market, "the costs of entering the market are so high [due to the fixed cost of building a pipeline] that it is most efficient for only one firm to serve a given geographical region."[362]

Prior to the Hepburn Act and NGA, both the oil and natural gas industries were characterized by control and consolidation of infrastructure in the hands of a few companies. Consumers and producers alike complained of monopolization.[363] In response, Congress enacted federal regulation. In the case of the NGA, the purpose was to protect consumers from market dominance, prevent discrimination against unaffiliated entities, and provide rate stability.[364] While not imposing common carrier requirements, the NGA granted FERC's predecessor, the Federal Power Commission, jurisdiction to assure that rates were "just and reasonable" and

360. Nat'l Fuel Gas Supply Corp. v. FERC, 468 F.3d 831, 834 (D.C. Cir. 2006); *see also* ALFRED E. KAHN, ECONOMICS OF REGULATION: INSTITUTIONAL ISSUES: PRINCIPLES AND INSTITUTIONS 199-23 (1971).

361. Merrill, *supra* note 216, at 85.

362. *Nat'l Fuel Gas Supply*, 468 F.3d at 834.

363. Klass & Meinhard, *supra* note 121, at 994.

364. Mack & Endemann, *supra* note 355, at 738; *see also* Assoc. Gas Distribs. v. FERC, 824 F.2d 981 (D.C. Cir. 1987).

that pipelines did not discriminate through "undue preferences."[365] The Hepburn Act addressed similar concerns through the imposition of federal common carrier requirements and rate regulation by the ICC.[366]

CO_2 pipelines are vulnerable to the same market manipulations. In fact, almost all of the large scale CO_2 trunk lines in the United States today are controlled by subsidiaries of three companies: Denbury Resources, Kinder Morgan, and Occidental Petroleum.[367] Further, unlike oil, CO_2 is not transportable by other means. Although conditions that might tend to create a natural monopoly are present, it is unclear to what extent closely held control of the transportation infrastructure impacts shipper access to pipelines or pricing of CO_2 to downstream EOR consumers. Affordable access to CO_2 has been identified as the "single largest challenge to the development of a thriving CO_2-based EOR industry in Wyoming."[368] However, it is unclear whether, or to what extent, high CO_2 prices result from lack of supply, insufficient capacity, or rent seeking by pipeline companies.

Similarly, it is unknown if pipeline control by a small number of market participants results in discriminatory access. At least one producer in Mississippi has asserted that access to CO_2 pipelines in the state is restricted through submarket pricing, limiting production and trapping reserves.[369] In Louisiana and Mississippi,[370] neither of which imposes common carrier requirements on CO_2 pipelines, one company controls all of the CO_2

---

365. 15 U.S.C. §§ 717(b), 717d(a), 717c, 717d, 717f(c)(1)(a); *see also* Natural Gas Act Amendment of 1947, Pub. L. No. 80-245, 61 Stat. 459.

366. Granitz & Klein, *supra* note 140; Klass & Meinhardt, *supra* note 121, at 961.

367. Matthew Wallace, et al., *A Review of the CO_2 Pipeline Infrastructure in the U.S.*, U.S. DEP'T OF ENERGY (Apr. 21, 2015).

368. Dag Nummedal, et al., *Enhanced Oil Recovery in Wyoming: Prospects and Challenges*, UNIV. OF WYO. 1 (June 15, 2003), https://www.uwyo.edu/acadaffairs/_files/docs/eorfinal.pdf

369. Clay Chandler, *Investor: Legislation Would Free Up Millions of Barrels of Miss. Oil*, CLARION LEDGER (Feb. 18, 2015, 9:43 AM), http://www.clarionledger.com/story/money/ business/2015/02/18/investor-legislation-free-millions-barrels-miss-oil/23610935/; Mark A. Worthey, *Worthey: Company Has Grip on Mississippi's CO_2*, CLARION LEDGER (Apr. 2, 2015, 12:30 PM) http://www.clarionledger.com/story/opinion/ 2015/04/02/worthey-company-grip-mississippis-co/70833934/.

370. LA. STAT. ANN § 30:1107 (2009) (providing that issuance of a certificate of public convenience and necessity shall not "[c]ause any . . . transporter of carbon dioxide for storage to become, or be classified as, a common carrier or . . . [subject] such carbon dioxide to storage transporter to any duties, obligations, or liabilities as a common carrier").

transportation infrastructure.[371] In contrast, in Texas, where common carriage is required to exercise eminent domain, at least two companies operate major trunk lines, and an even greater number of companies operate smaller scale distribution systems.[372] On its face this would indicate the existence of a natural monopoly in states without common carrier requirements. The experience in the Rocky Mountain Region, however, tells a different story; in Wyoming, where common carriage is not required, a number of companies operate both trunk and spur lines.[373] Accordingly, the efficacy of common carrier requirements in assuring more market participation or access is likewise unclear.

A Return to Public Use

States can facilitate development of infrastructure that may later prove compatible with CCUS through the imposition of common carrier requirements on pipeline developers utilizing eminent domain. This approach, similar to what has been adopted in Texas, establishes public use through the creation of infrastructure available for use by the public. As the litigants in *Texas Rice Partners* asserted, there is something about CO_2 transportation that *feels* private—particularly where, as many CO_2 pipelines are, such pipelines are constructed and operated principally, if not exclusively, for the transportation of CO_2 owned and used by the same party. A public use approach establishes a public benefit through the availability of the infrastructure to the public—thus encouraging new development, exploration, and uses of CO_2 where such infrastructure is located. Public use, as distinguished from public purpose, limits opportunities for monopoly and "secondary rent seeking" through the creation of public goods.[374] By reducing barriers to entry, common carrier requirements may reduce concerns about unfair pricing to both unaffiliated CO_2 producers and consumers for EOR.

The use of eminent domain for projects that are available to public use may be more defensible under both state and federal constitutional protections of private property. As discussed in Part III, the public purpose justifications for siting CO_2 pipelines—for natural resource development or

371. DiPietro, *supra* note 33.

372. *Id.*

373. Matthew Wallace, et al., *A Review of the CO_2 Pipeline Infrastructure in the U.S.*, U.S. DEP'T OF ENERGY (Apr. 21, 2015).

374. Merrill, *supra* note 216, at 73 (citing R. EPSTEIN, PRIVATE PROPERTY AND THE POWER OF EMINENT DOMAIN (1985)) ("Public goods are those that possess both jointness in supply and impossibility of exclusion.").

EOR—are based exclusively on the end use of the product transferred. Many of these statues are ambiguous as applied to CO_2, which may or may not constitute a "gas" or "natural resource" within the terms of those statutes. Further, changing views on climate, growing interests in recreation and tourism, and increasing land values leave natural resource extraction justification of public use vulnerable to criticism. Even were states to adopt legislation declaring transportation for CCUS a public purpose, those pipelines would similarly be limited—granting access to a closed set of market participants to transport a product for a defined purpose. Transitions to renewable energy and other market shifts may make CCUS uncompetitive as a decarbonization strategy for the power sector, thus rendering the public purposes advanced by laws authorizing condemnation for CO_2 pipelines on that basis obsolete.[375] The result is a rigid infrastructure that promotes monopolization and discourages innovation, rather than one that promotes creation of public goods in the form of pipelines to offer nondiscriminatory access to all potential future users.

A public access approach to siting addresses these limitations, although an imposition of common carrier requirements on pipelines developed without the use of eminent domain does not seem necessary. Like North Dakota, the Hepburn Act imposed federal common carrier requirements on all pipelines—regardless of how right of way was obtained.[376] Doing so was necessary to upend an entrenched monopoly characterized by uncompetitive practices resulting in stranded assets and limited access to market.[377] This sort of retroactive reallocation of property does not seem necessary. In at least two of the three geographic areas where CO_2 pipeline infrastructure exists, there are already a number of competitive market participants owning and operating CO_2 pipelines.[378] If common carrier requirements were linked only to the use of eminent domain—as they are in Montana and Texas—pipelines developed entirely on private land with private capital through voluntary agreement with landowners could be privately operated for the exclusive use of the owner(s).

---

375. *Expect the Unexpected: The Disruptive Power of Low-carbon Technology*, CARBON TRACKER INITIATIVE (Feb. 2017), http://www.carbontracker.org/wp-content/uploads/2017/02/Expect-the-Unexpected_CTI_Imperial.pdf.

376. Klass & Meinhardt, *supra* note 121, at 961; *see supra* notes 305-308 and accompanying text.

377. United States v. Ohio Oil Co., 234 U.S. 548 (1914); Klass & Meinhardt, *supra* note 121, at 961.

378. *See supra* notes 372-373 and accompanying text.

Challenges of CO_2 Common Carriage

Common carrier requirements are criticized as resulting in a paucity of public goods. Precisely because they are open to public use and do not convey a monopoly or unique advantage on the holder, common carrier requirements may deter investments resulting in scarcity.[379] Historically, both oil and natural gas companies opposed common carrier requirements.[380] These companies argued that common carrier requirements impermissibly subject private investment to public use, or would deter investments in infrastructure.[381] Yet, neither state nor federal regulatory siting or rate regulation requirements have resulted in an underdevelopment of pipeline infrastructure for oil or natural gas.[382] Similarly, although implementation challenges certainly exist,[383] development of CO_2 pipelines has not been forestalled by common carrier requirements in Texas, Colorado, Montana, and on federal lands.[384]

Curtailment and Single-Customer Pipelines

In order for common carrier requirements to work within the current industrial organizational structure, they must be consistent with the made-to-measure manner of pipeline development for EOR.[385] This raises two primary issues: curtailment and single-customer pipelines. CO_2 pipelines are designed with both a specific quantity of supply and a specific quantity of need/capacity at each terminus. Accordingly, common carrier requirements that result in curtailment—in order to make available capacity downstream—may create uncertainty as to whether there will be sufficient capacity to justify either capture costs or to adequately support the downstream EOR purposes.[386] For example, disparate common carrier requirements could result in bottlenecks driven by downstream oversubscriptions, thus making the pipeline unsuitable to an upstream

379. Miceli, Thomas J., *Free Riders, Holdouts, and Public Use: A Tale of Two Externalities*, 148 PUBLIC CHOICE 105-117 (2011); Klass & Meinhardt, *supra* note 121, at 992; Merrill, *supra* note 216, at 73.

380. Klass & Meinhardt, *supra* note 121, at 992.

381. *Id.*

382. *Id.* at 1016.

383. Schnacke, *supra* note 13, at 307-13.

384. It is unclear how BLM has implemented its MLA common carrier obligations in existing pipelines. *See* Sam Kalen, *Thirst for Oil and the Keystone XL Pipeline*, 46 CREIGHTON L. REV. 1, 21 (2012).

385. Schnacke, *supra* note 13, at 313.

386. Zarraby, *supra* note 355, at 969.

facility's capture needs.[387] Further, if a private developer of a CO_2 pipeline cannot be assured that it will have sufficient CO_2 for its EOR operations[388] or offloading capacity for captured CO_2, the pipeline may be difficult to finance.[389] In response to these issues, both a 2010 interagency task force established by President Obama and the IOGCC/SSEG CO_2 Pipeline Transport Task Force concluded that the apportionment practices under the oil pipeline framework were unworkable with the dedicated business models for CO_2 transport.[390] Accordingly, an effective CO_2 pipeline network—and any common carrier requirements attached thereto—will likely need to provide a mechanism for sources to reserve capacity.[391]

The made-to-measure nature of most CO_2 pipelines also creates the likelihood that many pipelines may be single-customer in the early stages of development.[392] As Mack and Endemann note, this may make common carrier requirements more difficult to satisfy. However, although criticized by landowners, the reasonable likelihood of a future public use standard articulated by the court in *Texas Rice Partners* may be sufficient. Pipeline companies would not necessarily need contracts from multiple generators or storage/EOR companies, provided that such use could be reasonably contemplated at some point in the future. While this may be sufficient, the standards for establishing common carriage may differ from state to state, creating uncertainty as to whether pipelines can rely on access to eminent domain. A requirement that a pipeline affirmatively establish the existence of multiple suppliers prior to construction could create an insurmountable obstacle to early-stage infrastructure development.

Pipeline Gas Specifications

Pipeline gas specifications may limit existing pipelines' utility to other shippers. Pipeline specifications for gas composition are critical to the safety and operation of the pipeline—the presence of other chemical

387. *Id.* at 968.

388. Exxon Corp. v. Lujan, 730 F. Supp. 1535, 1537 (D. Wyo. 1990) ("In order for tertiary recovery operations to be successful, a steady, constant, and uninterrupted supply of carbon dioxide is needed.").

389. Mack & Endemann, *supra* note 355, at 739. Challenges of common carrier requirements as applied to oil pipelines may provide insight to these issues. *See* Jeff. D. Makholm, et. al., *The Politics of U.S. Oil Pipelines: The First Born Struggles to Learn from the Clever Younger Sibling*, 37 ENERGY L.J. 409, 422 (2016).

390. Schnacke, *supra* note 13, at 311 (citing *Report of the Interagency Task Force on Carbon Capture and Storage*, OFFICE OF FOSSIL ENERGY (Aug. 2010)).

391. *Id.* at 311-12 (citing Bliss, *supra* note 97, at 15).

392. Mack & Endemann, *supra* note 355, at 741.

components within the CO_2 stream can lead to corrosion or impact miscibility pressures.[393] For example, material concentrations of either nitrogen or methane can preclude dense phase operations and oxygen can lead to corrosion.[394] Accordingly, pipeline specifications recommend dewatering and removing impurities at the inlet to the pipeline.[395]

Not only is dehydration and removal of certain impurities important for preventing corrosion, different downstream uses also require different qualities of gas. For example, the food and beverage industry has higher requirements than EOR.[396] Components like nitrogen in CO_2 may adversely impact suitability of CO_2 streams for EOR, whereas other chemicals within CO_2 may result in damage to industrial equipment.[397] Storage operators and EOR operators alike would need to consider the specific chemical and geologic characteristics of the target formation to avoid undesired interactions.[398] Due to these diverse considerations, gas specifications are tailored to fit the commercial requirements of the downstream project for which it is built.[399] CO_2 sources entering the pipeline would need to meet those specifications.[400] These specifications could result in limited utility of certain pipelines to other shippers or downstream users. Accordingly, uniform specifications, while promoting an integrated network, may be prohibitively costly and inefficient relative to certain sources or uses.[401]

The source and chemical components of CO_2 entering the pipeline may also subject pipeline and downstream users to additional regulatory requirements. For example, storage and injection pipeline operators would also be careful to avoid including any CO_2 stream containing components that might fall outside EPA's Conditional Exclusion from the Resource

393. TOWLER ET AL., INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE: SPECIAL REPORT ON CARBON CAPTURE AND SEQUESTRATION (2008); Z.X. Zhang, et al., *Optimization of Pipeline Transport for CO_2 Sequestration*, 47 ENERGY CONVERSION AND MANAGEMENT 6, 702-15 (2006); Bliss, *supra* note 97; ICF Report, *supra* note 65, at 42.

394. *Id.*

395. *Recommended Practice: Design and Operation of CO_2 Pipelines*, DET NORSKE VERITAS 20 (Apr. 2010); Yoon-Seok Choi, et al., *Effect of Impurities on the Corrosion Behavior of CO_2 Transmission Pipeline Steel in Supercritical CO_2 – Water Environments*, 44 ENVIRON. SCI. TECH. 9233-9238 (2010).

396. Henriette Naims, *Economics of Carbon Dioxide Capture and Utilization – A Supply and Demand Perspective*, 23 ENVTL. SCI. POLLUTION RES. 22,226, 22,232-35 (2016).

397. Marston & Moore, *supra* note 15, at 449; Recommended Practice, *supra* note 395.

398. Marston & Moore, *supra* note 15, at 435.

399. *Id.* at 448.

400. *Id.* at 448-49.

401. Bliss, *supra* note 97, at 18-21.

Conservation and Recovery Act (RCRA).[402] Similarly, pipelines may also prohibit introduction of CO_2 into the pipeline in order to avoid perceived project delays resulting from greenhouse gas reporting requirements under the EPA's Subpart RR rules.[403] Occidental has successfully complied with Subpart RR in order to obtain the 45Q tax credit in two CO_2-EOR projects—suggesting that such requirements are not an insurmountable obstacle. However, critics have suggested that downstream users may be concerned that comingled CO_2 would become subject to additional plan approval and reporting requirements, thus requiring assurance from pipeline companies.[404] Accordingly, CO_2 pipeline specifications may exclude certain upstream sources to avoid the potential of subjecting the entire stream to GHG Reporting Requirements or RCRA.

Inconsistent Rates

A final concern regarding state imposition of common carrier requirements on interstate CO_2 pipelines is the likelihood of inconsistent rates along various pipeline segments. The establishment and publication of non-discriminatory rates is a hallmark of common carriage and is subject to state economic regulation.[405] In a state directed common carrier model, each state would establish its procedures and requirements for rate regulation.[406] For example, Texas authorizes the Railroad Commission to establish rules for CO_2 tariffs, whereas in Montana the Public Service Commission regulates rates.[407] Due to varying procedures and policies, there is a strong possibility for differential rates along segments of an interstate pipeline.[408] Resulting implementation challenges may limit the efficacy of requirements in providing actual pipeline access and result in uncertainties for pipeline

402. Hazardous Waste Management System: Conditional Exclusion for Carbon Dioxide (CO_2) Streams in Geologic Sequestration Activities, 40 C.F.R. §§ 9, 20, 261 (Jan. 3, 2014).

403. Jonas J. Monast, et al., *A Cooperative Federalism Framework for CCS Regulation*, 7 ENVTL. ENERGY L & POL'Y J. 2, 15 (2012); Mandatory Reporting of Greenhouse Gases: Injection and Geologic Sequestration of Carbon Dioxide, 75 FR 75,060-01 (Dec. 1, 2010) (codified at 40 C.F.R. §§ 72, 78, 98 (2013)); WENDY B. JACOBS, GLOBAL CLIMATE CHANGE AND U.S. LAW, chs. 17, 19-20 (2014); Marston & Moore, *supra* note 15, at 470.

404. *Siting and Regulating Carbon Capture, Utilization, and Storage Infrastructure, Workshop Report*, U.S. DEP'T OF ENERGY (Jan. 2017); Marston & Moore, *supra* note 15, at 455; Schnacke, *supra* note 13, at 307-09.

405. Nordhaus & Pitlick, *supra* note 110, at 99.

406. Mack & Endemann, *supra* note 355, at 739.

407. MONT. CODE ANN. § 69-13-102 (West 2013); Nordhaus & Pitlick, *supra* note 110, at 96 (citing TEX. NAT. RES. CODE ANN. § 111.014 (West 1977)).

408. Mack & Endemann, *supra* note 355, at 739.

developers and customers.[409] This concern may be mitigated to a limited extent by rate dispute resolution by the Surface Transportation Board, an agency within Department of Transportation.[410] The STB has jurisdiction over interstate common carrier transportation, including some pipelines for commodities "other than water, gas, or oil."[411] Although its authority has not been tested with respect to CO_2 pipelines and STB could disclaim jurisdiction, a government accounting office report found that the STB had jurisdiction to resolve rate discrimination disputes.[412] This authority would note assure uniform rates across state lines, but rather that rates were reasonable and non-discriminatory.[413] Accordingly, if a shipper brought a case to the board and the STB agreed to take up the issue, it is unclear how disputes would be resolved.

Implementation

The integration of reserve capacity and specific made-to-measure pipeline gas specifications into tariff agreements and terms of service could undermine the actual utility of CO_2 pipelines as common carriers, adding costs to both upstream shippers and downstream users.[414] Determinations of pipeline quality gas, rate consistency, and reserve capacity present challenges that will need to be considered in tariff agreements and assessed to assure that the result is not so specific as to preclude actual access by other shippers. Accordingly, common carrier requirements should be developed in consultation with industry to assure compatibility with existing pipeline business models and to avoid disruption to CO_2-EOR operations.[415]

State agencies play an important role in balancing these considerations. State regulatory agencies, such as infrastructure authorities or oil and gas conservation or public service commissions, have experience siting oil pipelines and would have regulatory authority over the permitting and

409. *Id.*

410. Nordhaus & Pitlick, *supra* note 110, at 90-91, 99.

411. *Id.* at 90 (citing 49 U.S.C. §15301(a) (2006)).

412. Monast, *supra* note 403, at 24; Nordhaus & Pitlick, *supra* note 110, at 90-93 (citing Phyllis F. Scheinberg, Assoc. Dir., Transp. Issues, Issues Associated with Pipeline Regulation by the Surface Transp. Bd., Testimony Before the Subcomm. on Surface Transp. and Merchant Marine Infrastructure Safety and Security, U.S. Senate, Gov't Accountability Office (Mar. 31, 1998)).

413. Nordbaus & Pitlick, *supra* note 110, at 99.

414. Marston & Moore, *supra* note 15, at 455.

415. Workshop Report, *Siting and Regulating Carbon Capture, Utilization, and Storage Infrastructure*, U.S. DEP'T OF ENERGY, at 43 (Jan. 2017).

unitization of CCUS facilities and EOR operations. These agencies may be better equipped than federal regulators to balance the additional cost of uniform standards or curtailment with the state interest in making infrastructure truly accessible for use by the public.

The majority of states do not have laws specifically addressing siting or eminent domain for CO_2 pipelines. In the absence of EOR activities within the state, there has been no urgency to adopt specific legislation. Accordingly, whether a CO_2 pipeline can obtain eminent domain authority and under which conditions requires an analysis of whether such pipelines fall within existing authority for intrastate natural gas and oil pipelines or natural resource development.[416] However, as EOR operations extend into new areas—for example, Ohio and Pennsylvania—and as CCUS plays an increasingly larger role in the national climate change dialogue, state legislatures will have to consider statutes for siting CO_2 pipelines.[417] Eminent domain is likely essential to development of both intrastate and interstate pipelines and will thus be a core component of any such siting legislation.[418] Accordingly, legislatures will have a new opportunity to make a determination between public purpose and public use. By imposing common carrier requirements on CO_2 pipelines utilizing eminent domain, states can play an important role in assuring that the CO_2 pipelines built today can later be integrated into a CO_2 pipeline network that will serve both EOR and CCUS needs.

Common carrier requirements could also be integrated into the eminent domain laws for states with existing siting rules and operating CO_2 pipelines. For example, New Mexico, Wyoming, Mississippi, and Louisiana all permit use of eminent domain for CO_2 pipelines but do not require common carriage. These statues could be modified going forward. However, doing so may prove difficult. Failed efforts to enact common carrier legislation in Mississippi in 2014 and 2016 indicate that there may be a lack of political will for those changes or that efforts may face opposition from entrenched interests.[419] Additionally, retroactive imposition of common carrier requirements on pipelines not currently carrying product

416. Klass & Meinhardt, *supra* note 121, at 1027.

417. MORGAN, ET AL., CARBON CAPTURE AND SEQUESTRATION: REMOVING THE LEGAL AND REGULATORY BARRIERS (2012).

418. *Id.*

419. Miss. H.B. No. 907 (2016); Clay Chandler, *Pipeline Carrier Bill Dies Quietly*, CLARION LEDGER (Feb. 15, 2014). http://www.clarionledger.com/story/news/ politics/2014/ 02/16/-pipeline-carrier-bill-dies-quietly/5522159/.

for other shippers—nor indicating a willingness to do so—could raise constitutional concerns.[420]

Limitations of the State Siting Approach

The current state siting approach is subject to a number of limitations that may need to be resolved as the industrial organization and pipeline configuration grows to accommodate CCUS.[421] A long distance CO_2 pipeline would require a multiplicity of state and local approvals, each with potentially different requirements for eminent domain, common carriage, rate regulation, and stipulations.[422] The resulting patchwork may introduce uncertainty and inefficiency, thus diminishing economies of scale and limiting access to capital.[423] Further, as pipelines expand into new regions, states may block pipelines that would go through their sovereign territory but are unpopular either because they serve politically unsupported purposes or would not materially serve customers or industries within the state.[424] A majority of states have neither CCUS nor EOR operations and thus would have little incentive to subject private landowners in the state to eminent domain for an activity perceived as having little local relevance.[425] While the existence of several interstate CO_2 pipelines indicates that these challenges have not precluded development thus far,[426] the lessons of the Keystone XL pipeline, the Constitution natural gas pipeline, and the Plains & Eastern Clean Line caution not to discount that possibility.[427] Although CO_2 pipelines are unlikely to be characterized by rapid expansion relating from new sources of supply or exponentially increasing demand, additional regulation at the state and federal level may be necessary to address these obstacles as the need for interstate pipelines grows. Even then,

420. United States v. Ohio Oil Co., 234 U.S. 548, 561 (1914).

421. Industrial organizational structures for CCUS are unlikely to mimic those for EOR, thus, as those new configurations come on line, the administrative regulation of access to pipelines may again require consideration. *See* M. A. de Figueiredo, et al., *Regulating Carbon Dioxide Capture and Storage*, MIT CTR. FOR ENERGY & ENVTL. POL'Y RES. (2007).

422. Mack & Endemann, supra note 355, at 739.

423. *Id.* at 739; Nordhaus & Pitlick, *supra* note 110, at 98; Zarraby, *supra* note 355, at 968.

424. *Id.*; Klass & Rossi, *supra* note 352.

425. For examples of these challenges in the transmission context, see Alexandra B. Klass & Elizabeth J. Wilson, *Interstate Transmission Challenges for Renewable Energy: A Federalism Mismatch*, 65 VAND. L. REV. 1801, 1084, 1858-75 (2012).

426. For example, the northern Rockies CO_2 pipeline network crosses Colorado, Utah, Wyoming, and Montana, see Nemmedal, *supra* note 368; Wallace, *supra* note 367, at 15.

427. Klass & Rossi, *supra* note 352; Player, *supra* note 320.

comprehensive federal siting may not be the optimal approach. For example, as scholars have suggested in the transmission and oil pipeline contexts, these challenges may open pathways for non-binary state and federal cooperation or for limited federal intervention in state pipeline siting: for example, through interstate compacts,[428] backstop siting authority,[429] or the establishment of interstate pipeline corridors.[430]

Despite these limitations, for the time being the current state siting approach is preferable to a federal siting framework. While there is a strong and growing national interest in CCUS as a component of broader federal climate policy, presently, almost all CO_2 pipeline construction is occurring in the context of CO_2-EOR. These oil and gas production activities have traditionally been regulated by state conservation agencies, which permit operations and create unities for EOR and which are well equipped to make the types of balancing determinations related to tariffs and common carrier requirements that will be required. Further, CO_2 pipelines' design, construction, and operation, and impacts to the environment and to landowners are predominately local. Thus, it is appropriate for state legislature to make these important determinations regarding land use, private property, and public purpose.

V. Conclusion

There is no federal siting framework for CO_2 pipelines. Accordingly, state law determines whether and under which conditions private entities developing CO_2 pipelines may utilize eminent domain. States thus far have provided this authority under two public purpose justifications: natural

---

428. Klass & Rossi, *supra* note 352, at 486; Alexandra B. Klass & Jim Rossi, *Revitalizing Dormant Commerce Clause Review for Interstate Coordination*, 100 MINN. L. REV. 129, 145 (2015); Bliss, *supra* note 97, at 50.

429. Nordhaus & Pitlick, *supra* note 110, at 101 (citing 16 U.S.C. § 824p (2005)); Klass & Rossi, *supra* note 352, at 455-56. Congress provided federal backstop authority for transmission lines based on concerns related to grid reliability and energy security, concerns not present for CO_2 pipelines.

430. State CO_2-EOR Deployment Work Group, *21st Century Energy Infrastructure: Policy Recommendations for Development of American CO_2 Pipeline Networks*, GREAT PLAINS INST. (Feb. 2017); *Siting and Regulating Carbon Capture, Utilization and Storage Infrastructure*, U.S. DEP'T OF ENERGY 26 (Jan. 2017) (describing Wyoming's Pipeline Corridor Initiative); Matt Fry, Testimony Before the Subcomm. on Env't and Public Works (Sept. 13, 2017), *available at* https://www.epw.senate.gov/public/_cache /files /6/5/652f109b-c33c-4054-bcb6-d92d5a825666/BB8B2C37209CB099AE276F7 46FDE9458.fry-testimony-09.13.2017.pdf.

resource development and the creation of physical infrastructure available for use by the public.

The anticipated expansion of CO_2 pipelines provides a fresh opportunity for consideration of the public purpose requirement in light of changing social norms, public needs, and new technologies. The historically adequate public purposes of natural resource and economic development may hinder development of an integrated and accessible CO_2 pipeline network that can accommodate growing demand for both EOR and CCUS. Given anticipated needs for CO_2 pipelines for CCUS, a public use approach is preferable. This approach may assure that new pipelines developed for CO_2-EOR will be available for use by other shippers. Further, a public use approach clarifies condemnation authority of CCUS pipeline developers by resolving interpretation problems related to provisions that link eminent domain to extractive natural resource development.

The imposition of common carrier requirements within a state siting framework provides opportunities to promote growth and flexibility within the commercially driven CO_2 pipeline industry. This approach, however, leaves important structural and implementation issues to be resolved regarding the application of common carrier requirements to existing infrastructure, coordination between agencies across many levels of government, and disparate pipeline gas specifications and state regulations. These challenges provide a valuable opportunity for industry and state legislatures to collaboratively and proactively advance solutions that appropriately balance commercial concerns, the property rights of landowners, and the public interest.

Ten Teams From Five Countries Advance To Finals Of $20M NRG COSIA Carbon XPRIZE

Finalists Reimagine Carbon and Will Demonstrate CO2 *Conversion Tech Under Real-World Conditions*

NEW YORK (April 9, 2018) — XPRIZE, the world's leader in designing and managing incentive competitions to solve humanity's grand challenges, today announced the 10 teams advancing to the final round in the **$20M NRG COSIA Carbon XPRIZE**. This four-and-a-half-year global competition challenges teams to transform the way the world addresses carbon dioxide (CO2) emissions through breakthrough circular carbon technologies that convert carbon dioxide emissions from power plants into valuable products.

The 10 finalists, each taking home an equal share of a $5 million milestone prize, were revealed today at Bloomberg New Energy Finance's *Future of Energy Summit* in New York City.

Ranging from carbon capture entrepreneurs and start-ups to academic institutions and companies that have been tackling the challenge for more than a decade, the finalists hail from five countries and have already demonstrated conversion of CO2 into a wide variety of products, such as enhanced concrete, liquid fuels, plastics and carbon fiber. The universe of potential CO2-based products crosses a variety of energy sectors, industrial processes and consumer products. Each finalist team passed a first round evaluation based on the amount of CO2 converted into products, as well as the economic value, market size and CO2 uptake potential of those products.

"These teams are showing us amazing examples of carbon conversion and literally reimagining carbon. The diversity of technologies on display is an inspiring vision of a new carbon economy," said Dr. Marcius Extavour, XPRIZE senior director of Energy and Resources and prize lead. "We are trying to reduce CO2 emissions by converting them into useful materials, and do so in an economically sustainable way."

The NRG COSIA Carbon XPRIZE finalists were chosen from a field of 27 semifinalists by an independent judging panel of eight international energy, sustainability and CO2 experts. The competition is divided into two parallel tracks with five teams competing in each:

The **Wyoming Track** includes five teams that will demonstrate conversion of CO2 emissions at a coal-fired power plant in Gillette, WY:

- **Breathe** (Bangalore, India) – Led by Dr. Sebastian Peter, the team is producing methanol, a common fuel and petrochemical feedstock, using a novel catalyst.
- **C4X** (Suzhou, China) – Led by Dr. Wayne Song and Dr. Yuehui Li, the team is producing chemicals and bio-composite foamed plastics.
- **Carbon Capture Machine** (Aberdeen, Scotland) – Led by Dr. Mohammed Imbabi, the team is producing solid carbonates with applications to building materials.
- **CarbonCure** (Dartmouth, Canada) – Led by Jennifer Wagner, the team is producing stronger, greener concrete.
- **Carbon Upcycling UCLA** (Los Angeles, CA, USA) – Led by Dr. Gaurav Sant, the team is producing building materials that absorb CO2 during the production process to replace concrete.

The **Alberta Track** includes five teams that will demonstrate conversion of CO2 emissions at a natural gas-fired power plant in Alberta, Canada:

- **C2CNT** (Ashburn, VA, USA) – Led by Dr. Stuart Licht, the team is producing carbon nanotubes.
- **Carbicrete** (Montreal, Canada) – Led by Dr. Mehrdad Mahoutian, the team is producing cement-free, carbon-negative concrete that uses waste from steel production as an alternative to traditional cement.
- **Carbon Upcycling Technologies** (Calgary, Canada) – Led by Apoorv Sinha, the team is producing enhanced graphitic nanoparticles and graphene derivatives with applications in polymers, concrete, epoxies, batteries and pharmaceuticals.
- **CERT** (Toronto, Canada) – Led by Dr. Alex Ip of the Sargent Group at the University of Toronto, the team is producing building blocks of industrial chemicals.
- **Newlight** (Huntington Beach, CA, USA) – Led by Mark Herrema, the team uses biological systems to produce bioplastics.

To win a place in the finals, the semifinalist teams had to demonstrate their technologies at pilot scale at a location of their choosing. Over the course of a 10-month period, semifinalist teams were challenged to meet minimum technical requirements and were first audited by independent verification partner Southern Research. Teams were then evaluated by the judges based on how much CO2 the team converted into products; the economic value, market size, and CO2 uptake potential of those products; the overall CO2 footprint of their process; as well as energy efficiency, materials use, land use, and water use.

In the finals, teams must demonstrate at a scale that is at least 10 times greater than the semifinals requirements at one of two purpose-built industrial test sites. Teams competing in the Wyoming track will test their technologies at the Wyoming Integrated Test Center (ITC), a cutting-edge carbon research facility in Gillette, WY, USA, co-located with the Dry Fork Station coal power plant. Teams competing in the Alberta track will test their technologies at the Alberta Carbon Conversion Technology Centre, a new carbon conversion research hub co-located with the Shepard Energy Centre natural gas power plant in Calgary, Alberta, Canada.

"We're excited to support these teams as they scale up and start demonstrating under real-world conditions at the industrial test centers. This is the final, most ambitious stage of this prize competition," added Extavour.

The NRG COSIA Carbon XPRIZE is a part of XPRIZE's growing portfolio of Energy and Resources prizes and long-term vision for accelerating revolutionary energy technologies to help move the world towards a clean, abundant energy future.

For the latest information about the competition structure, important dates, and the finalist teams please visit **carbon.xprize.org**.

About XPRIZE
XPRIZE, a 501(c)(3) nonprofit, is the global leader in designing and implementing innovative competition models to solve the world's grandest challenges. XPRIZE utilizes a unique combination of gamification, crowd-sourcing, incentive prize theory and exponential technologies as a formula to make 10x (vs. 10%) impact in the grand challenge domains facing our world. XPRIZE's philosophy is that—under the right circumstances—igniting rapid experimentation from a variety of diverse lenses is the most efficient and effective method to driving exponential impact and solutions to grand challenges. Active competitions include the Lunar XPRIZE, $20M NRG COSIA Carbon XPRIZE, the $15M Global Learning XPRIZE, the $10M ANA Avatar XPRIZE, the $7M Shell Ocean Discovery XPRIZE, the $7M Barbara Bush Foundation Adult Literacy XPRIZE, the $5M IBM Watson AI XPRIZE, the $1.75M Water Abundance XPRIZE and the $1M Anu and Naveen Jain Women's Safety XPRIZE. For more information, visit **www.xprize.org**.

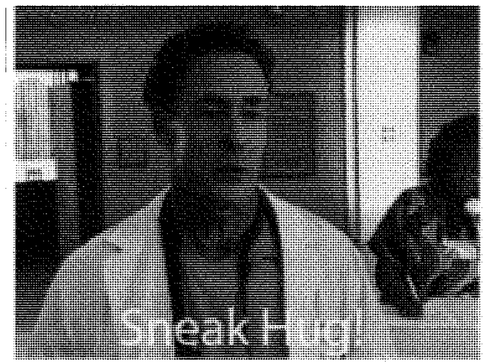
About NRG
NRG is the leading integrated power company in the U.S., built on the strength of our diverse competitive electric generation portfolio and leading retail electricity platform. A Fortune 500 company, NRG creates value through best in class operations, reliable and efficient electric generation, and a retail platform serving residential and

commercial businesses. Working with electricity customers, large and small, we implement sustainable solutions for producing and managing energy, developing smarter energy choices and delivering exceptional service as our retail electricity providers serve almost three million residential and commercial customers throughout the country. More information is available at www.nrg.com. Connect with NRG Energy on Facebook and follow us on Twitter @nrgenergy.

About COSIA

Canada's Oil Sands Innovation Alliance (COSIA) is a unique alliance of oil sands producers focused on accelerating environmental performance in Canada's oil sands. COSIA enables collaboration and innovation between big thinkers from industry, government, academia and the wider public to improve measurement, accountability and performance in the oil sands across our environmental priority areas of greenhouse gases, land, water and tailings. COSIA members search the world for solutions to our toughest problems. And we have some of the best minds on the planet working on technologies to enable responsible and sustainable development. To date, COSIA has shared 981 distinct environmental technologies and innovations that cost over $1.4 billion to develop. Visit us at www.cosia.ca.

Amy's notebook: one bipartisan thing



Giphy

Axios' Amy Harder has this observation...

Partisanship is default in Washington these days, but exceptions do exist, like this one:

Driving the news: Julio Friedmann, former top official in President Obama's Energy Department now working on carbon capture technologies, testified to Congress this week at the request of Sen. John Barrasso, Republican chairman of the Environment Committee. Last year, he testified to Congress at the invitation of Sen. Tom Carper, the panel's top Democrat.

Our thought bubble: It's exceedingly rare for an expert to be invited to testify by lawmakers from both parties in such a close time period.

One level deeper: Republicans like carbon capture technology because it furthers the development of fossil fuels in a carbon-constrained world. Some more liberal Democrats and climate advocates like it because fossil fuels are so prevalent in society, it'll be hard to tackle climate change without this type of technology.

What's next: After passing legislation earlier this year expanding a key tax credit for the technology, the same bipartisan group of lawmakers are at it again with a new bill that further supports permitting of such projects, on which Friedmann testified.

Our prediction: Congress doesn't do much actual legislating in an election year other than on essential issues like spending, but if anything has a shot at passing, this would be it.