THE FUTURE OF ADVANCED CARBON CAPTURE RESEARCH AND DEVELOPMENT

FIELD HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

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November 22, 2019

THE FUTURE OF ADVANCED CARBON CAPTURE RESEARCH AND DEVELOPMENT

FRIDAY, NOVEMBER 22, 2019

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:17 a.m., in the Waldorf Astoria Ballroom, Hilton University of Houston, 4450 University Dr., Houston, TX, Hon. Lizzie Fletcher presiding.

Present: Representatives Fletcher and Weber.

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES

HEARING CHARTER

The Future of Advanced Carbon Capture Research and Development
Friday, November 22, 2019
10:00 a.m.
Houston, TX

PURPOSE

The purpose of the hearing is to examine the state of advanced carbon capture, utilization, and storage (CCUS) technologies and practices in the United States and to determine how the Federal government can best accelerate this growing area of research in support of U.S. interests in energy security, environmental stewardship, and national security.

WITNESSES

- **Dr. Ramanan Krishnamoorti**, Chief Energy Officer, Professor of Chemical Engineering, University of Houston.
- **Dr. Jeffrey Long**, Faculty Senior Scientist, Materials Sciences Division, Lawrence Berkeley National Laboratory.
- **Mr. Greg Kennedy**, Senior Project Director, NRG Energy; and Director of Asset Management, Petra Nova Project.
- **Mr. Roger Dewing**, Director of Technology CCUS, Air Products and Chemicals Incorporated, Inc.
- **Mr. Nigel Jenvey**, Global Head of Carbon Management at Gaffney, Cline & Associates.

BACKGROUND:

Today in the United States, fossil energy sources account for over 77% of our total energy use and are responsible for approximately 76% of total U.S. anthropogenic greenhouse gas emissions, the vast majority of which are carbon dioxide (CO_2) based.[1,2] As a result, while U.S. national security and economic growth are reliant on continued access to these critical resources, there is growing interest in addressing CO_2 emissions generated by the use of fossil fuels.

Support of fundamental research to enable the development of emissions management and reduction strategies can play an important role in addressing this challenge. One leading opportunity to reduce emission is through carbon capture, utilization, and storage (CCUS) technologies. CCUS technologies involve the capture of CO_2 from fuel combustion or industrial

[1] U.S. Department of Energy, *FY 2020 Congressional Budget Request*, Vol. 3, Part 1, ENERY.GOV (March 2019), https://www.energy.gov/sites/prod/files/2019/04/f61/doe-fy2020-budget-volume-3-part-1_0.pdf.
[2] U.S. Energy Information Administration, *Energy and the environment explained*, EIA.GOV (Jun. 19, 2019), https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php.

processes to be either used for products and services, or deposited in permanent storage sites.[3] Carbon capture R&D involves novel compression technologies for fossil fuel-fired power plants and innovative gas separation technologies, including techniques like non-aqueous solvents, advanced membranes, and cryogenic processes in both the post-combustion and pre-combustion space.[4] Carbon capture R&D is supported by advanced computational tools that will help in material discovery and design of innovative system components.

Carbon utilization R&D often focuses on captured carbon use for various products and applications through the development of advanced catalysts, reactor systems, and efficient CO_2 conversion processes. Through research that explores opportunities to use carbon in industrial chemicals and polymers, mineralization to building products, and conversion to animal feed, there is the potential for carbon utilization to develop additional markets for fossil energy resources.[5]

Carbon storage R&D includes the development of technologies that can safely and permanently store captured CO_2 in geologic formations, particularly depleted oil and gas fields. Captured carbon can be stored in deep saline formations and injected for enhanced oil recovery (EOR) operations.[6] Simulation tools, characterization methods, and monitoring technologies have the potential to increase storage efficiency, reduce overall costs, and decrease subsurface uncertainties.[7]

By improving the performance and reducing the cost of these technologies, CCUS research can encourage the adoption and use of technologies to capture CO_2, and potentially increase its market potential.[8]

Houston, Texas

Houston, Texas, often called the "Energy Capital of the World", is home to 4,600 energy firms, employs nearly a third of U.S jobs in oil and gas extraction, and is uniquely positioned to lead in CCUS technology acceleration.[9] At this hearing, we will hear testimony from Dr. Ramanan Krishnamoorti, the Chief Energy Officer at the University of Houston (UH) who leads UH Energy, an umbrella for efforts across the University of Houston system to allow the university to serve as a strategic partner to the energy sector, and the CCUS industry both at home and abroad.[10]

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[3] International Energy Agency, *Carbon Capture, Utilisation and Storage*, IEA.ORG, https://www.iea.org/topics/carbon-capture-and-storage/ (last visited Nov. 20, 2019).
[4] *Ibid.*
[5] National Energy Technology Laboratory, *About Carbon Utilization*, NETL.DOE.GOV, https://netl.doe.gov/coal/carbon-utilization/about (last visited Nov. 20, 2019).
[6] U.S. Environmental Protection Agency, *Carbon Dioxide Capture and Sequestration: Overview*, EPA.GOV (Jan. 19, 2017), https://19january2017snapshot.epa.gov/climatechange/carbon-dioxide-capture-and-sequestration-overview_.html.
[7] U.S. Department of Energy, *Carbon Storage R&D*, ENERGY.GOV, https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-storage-rd (last visited Nov. 20, 2019).
[8] *About Carbon Utilization*, *supra* note 5.
[9] Great Houston Partnership, *Energy*, HOUSTON.ORG, https://www.houston.org/why-houston/industries/energy (last visited Nov. 20, 2019).
[10] University of Houston, *Research: Dr. Ramanan Krishnamoorti*, UH.EDU, https://uh.edu/uh-energy/research/krishnamoorti-ramanan.php (last visited Nov. 20, 2019).

We will also hear testimony from Mr. Nigel Jenvey, Global Head of Carbon Management at Gaffney, Cline & Associates who has decades of global fossil energy experience in technology, exploration, development, and production operations with major oil and gas operating companies in the Houston area and is an industry leader in CCUS technologies.[11]

DOE Office of Fossil Energy Research and Development

Within the jurisdiction of the Committee on Science, Space, and Technology, the Department of Energy (DOE) funds CCUS relevant fossil energy research. The DOE Office of Fossil Energy Research and Development (FER&D) supports applied research, development, demonstration, and commercialization activities for the advancement of technologies related to the reliable and environmentally sound use of fossil energy sources. In this capacity, FER&D conducts cross-cutting research on advanced fossil energy systems, and enables the development of innovative carbon capture, utilization, and storage (CCUS) technologies with application to both new and existing fossil fuel facilities. In fiscal year (FY) 2019, FER&D was funded at $740 million.[12]

Much of this research is carried out through DOE's world-leading national laboratories like the National Energy Technology Laboratory (NETL) in Pennsylvania, which is the Department's applied energy lab specifically dedicated to fossil energy research and development and a leader in developing CCUS technologies.[13] However, much of this applied research is supported by efforts throughout the national laboratory system, including the Department's Office of Science laboratories like Lawrence Berkeley National Laboratory (LBNL) in California.[14]

LBNL provides CCUS researchers with the necessary research infrastructure and expertise in advanced scientific computing and materials science that lay the foundation for innovative CCUS R&D. At this hearing, we will hear testimony from one of these researchers, Dr. Jeffrey Long, a Professor of Chemistry at the University of California Berkeley and Faculty Senior Scientist in the Materials Sciences Division at LBNL. Dr. Long's research focuses on the development of novel metal-organic frameworks (MOFs) for applications in hydrogen storage and CO_2 capture, a discovery that was enabled by Federal investments in fundamental science.[15]

Public-Private Partnerships

The U.S. fossil energy industry has an established history of leveraging DOE investments in R&D to achieve transformative technology breakthroughs. This tradition of successful public-private partnerships between DOE FER&D and the private sector has continued with the emerging U.S. CCUS industry.

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[11] Gaffney, Cline & Associates, *Authors: Nigel Jenvey*, GAFFNEY-CLINE-FOCUS.COM, http://gaffney-cline-focus.com/author/nigel-jenvey (last visited Nov. 20, 2019).
[12] *FY 2020 Congressional Budget Request*, *supra* note 1.
[13] National Energy Technology Laboratory, *Mission and Overview*, NETL.DOE.GOV, https://netl.doe.gov/about/mission-overview (last visited Nov. 20, 2019).
[14] Dan Krotz, *New Carbon Capture Membrane Boasts CO2 Highways*, LAWRENCE BERKELEY NATIONAL LABORATORY (Mar. 17, 2016), https://newscenter.lbl.gov/2016/03/17/carbon-capture-membrane/.
[15] The Long Group, *Metal-Organic Frameworks*, BERKELEY.EDU, http://alchemy.cchem.berkeley.edu/mofs/ (last visited Nov. 20, 2019).

One example of DOE's ongoing partnerships with the CCUS industry is NRG and JX Nippon's coal-powered Petra Nova plant in southwest Texas. After receiving a $190 million grant from DOE, NRG joined with JX Nippon in a 50/50 joint venture to finance the project, along with a joint venture with Hilcorp Energy to leverage the untapped potential of the West Ranch oil field.[16] Petra Nova is one of only two operating power plants utilizing carbon capture technology in the world, and it is the only such facility currently operating in the United States.[17]

Petra Nova captures approximately 90% of the CO_2 emitted from the flue gas slipstream of an existing coal-fired generating plant.[18] This captured carbon is then injected into mature local oil reservoirs to enhance West Ranch oil field production. Within the first 10 months of the start of operations in 2016, the Petra Nova plant has delivered more than 1,000,000 tons of captured carbon dioxide and boosted oil production 1,300 percent.[19]

Another DOE public-private partnership in CCUS is Air Products and Chemicals, Inc.'s carbon capture system located within the Valero Port Arthur Refinery in Port Arthur, Texas. Air Products is a public industrial gases and materials company with an international presence in CCUS technologies. In support of this innovative facility in Texas, DOE provided a total of $284 million, or 66% of the over $400 million project.[20]

The first project of its kind to begin operations at commercial scale, this facility captures CO_2 from steam methane reformers (SMRs), which is then transported by pipeline to Denbury Onshore's West Hasting Unit to assist in enhanced oil recovery. DOE has estimated that 1.6 to 3.1 million barrels of oil will be produced annually from this CO_2 application process.[21]

At this hearing we will hear testimony from Mr. Greg Kennedy, a Senior Project Director for NRG Energy, Inc. who serves as the Asset Manager for the Petra Nova Project, and from Mr. Roger Dewing, the Director of Technology CCUS at Air Products and Chemicals, Inc. who will highlight these important industry success stories and provide key insight into private sector needs for future Federal partnerships in CCUS and fossil energy technologies.

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[16] U.S. Department of Energy, *Petra Nova – W.A. Parish Project*, ENERGY.GOV, https://www.energy.gov/fe/petra-nova-wa-parish-project (last visited Nov. 20, 2019).
[17] Kenneth Dubin, *Petra Nova is one of two carbon capture and sequestration power plants in the world*, U.S. ENERGY INFORMATION ADMINISTRATION (Oct. 31, 2017), https://www.eia.gov/todayinenergy/detail.php?id=33552.
[18] NRG Energy, *Case Studies: Petra Nova*, NRG.COM, https://www.nrg.com/case-studies/petra-nova.html (last visited Nov. 20, 2019).
[19] *Ibid.*
[20] Air Products, *Air Products Signs Two Agreements to Move Texas Carbon Capture and Sequestration Project Forward*, AIRPRODUCTS.COM (May 26, 2011), http://www.airproducts.com/company/news-center/2011/05/0526-air-products-signs-two-agreements-for-texas-carbon-capture-and-sequestration-project.aspx.
[21] Air Products, *Air Products Celebrates Texas Carbon Capture Demonstration Project Achievement*, AIRPRODUCTS.COM (May 10, 2013), http://www.airproducts.com/Company/news-center/2013/05/0510-air-products-celebrates-texas-carbon-capture-demonstration-project-achievement.aspx.

Chairwoman FLETCHER. This hearing will come to order.

Without objection, the Chair is authorized to declare a recess at any time.

Good morning and welcome to today's field hearing, the Future of Advanced Carbon Capture Research and Development.

I am Lizzie Fletcher. I represent Texas' 7th congressional District, and I am delighted to be here with all of you this morning.

And I am going to turn the floor over to Mr. Weber for an opening statement. He's the Ranking Member of the Subcommittee.

Mr. WEBER. Well, good morning, and thank you, Chairwoman Fletcher. I'm excited to be back in Texas. I think I'd rather be here than just about anywhere. We're going to have the opportunity today to hear about ground-breaking new research and development in carbon capture technology.

Today's hearing is a chance for private-sector organizations to highlight their leading roles in fossil energy innovation through carbon capture, through storage, and through utilization technologies. The scope and range of technologies being pursued is as vast as the untapped oil and gas reserves right here in good old Texas.

Coal and natural gas, believe it or not, make up about 64 percent of the net electricity generation in the United States, and that number is expected to only dip to 58 percent by the year 2040. Simply put, the use of fossil fuels isn't going away anytime soon.

We have incredible domestic fossil energy resources, and our economic stability depends on the power that those resources produce.

So it should come as no surprise that a robust industry has developed right here at home focused on investing in the next generation of technologies to produce and use American fossil fuels more efficiently, more safely, and at a lower cost for American consumers.

In fact, I think I'm well within my rights to label Houston, Texas as the carbon capture capital of the world, and I would include my District 14 with that. We've seen incredible research and technology successes through a collaborative public-private partnership right here in our backyard, multiple partnerships.

One such example is Air Products, a production facility in my district right down the road in Port Arthur, Texas. This facility, which was sponsored in part by the Department of Energy (DOE), captures over 90 percent of the CO_2 from the product streams of two commercial-scale steam methane reformers and injects that carbon dioxide into the West Hastings oil field for enhanced oil recovery, which used to be in my district when I was a State Rep., back before I got demoted to Congress.

In return, Department of Energy has estimated that an additional 1.6 to 3.1 million barrels of oil will be produced annually from this CO_2 application process.

Now, let me put that in perspective for you all. Today's price of Texas West Intermediate Crude is $57 a barrel, OK? So that would mean, if it's 1.6 million to 3.1 million barrels of oil, that's a savings of $91,248,000. If it's at the higher number, 3.1 million, that would be a revenue stream of $176,793,000. It means jobs, it means economic stability, it means energy security. It is absolutely incredible to what we're trying to achieve.

Another example is the Petra Nova facility just a few miles southwest of here, a facility my colleagues and I will have a chance to visit this afternoon. This facility captures carbon dioxide from a coal-fired plant and then, much like the Air Products facility, routes that CO_2 to the West Ranch, which was in my district when I was a State Rep. It's about probably 35, 40 miles from here. They use it for enhanced oil recovery. Within the first 10 months of opening, this field saw oil production boost by 1,300 percent using enhanced oil recovery.

Let's do the math again. If you took those same number of barrels, if you took 1.6 million barrels, it goes up $91,248,000. That's unbelievable, the amount of difference in price. So it's incredibly important for us.

Additionally, the Department of Energy is making smart, targeted investments in early stage research to advance the next generation of production and emissions control technologies through the DOE Fossil Energy Research and Development, what we call FER&D, program.

Now, listen to these numbers. It's funded at $740 million. Remember the hundreds of millions of dollars from the one facility I just cited? Is this program paying off? You'd better believe it is. It's funded at $740 million, and it conducts research that supports clean, affordable, and efficient use of domestic fossil energy resources. The complex fossil energy resource challenges we face today will require an all-hands-on-deck approach: Academia, industry, the Department of Energy. They are the ideal partners. But I want to add one group to that, and that is the environmental groups. We ought to all work together to make sure this is working for the best possible outcome.

With support from the Department of Energy, the technology developed and deployed at facilities like Air Products and Petra Nova are reducing the emissions from local refineries and producing affordable American fuel to power our economy.

So that's basically it. I look forward to hearing about these partnerships from our witnesses today, and I want to thank all of our witnesses for testifying; and, Chairwoman, thank you for holding the hearing.

And I yield back.

[The prepared statement of Mr. Weber follows:]

Thank you, Chairwoman Fletcher. I'm excited to be back home in Texas and have the opportunity to hear about groundbreaking new research and development in carbon capture technology.

Today's hearing is a chance for private sector organizations to highlight their leading roles in fossil energy innovation through carbon capture, storage, and utilization technologies. The scope and range of technologies being pursued is as vast as the untapped oil and gas reserves here in Texas!

Coal and natural gas make up 64 percent of net electricity generation in the United States, and that number is expected to only dip to 58 percent by 2040. Simply put, the use of fossil fuels isn't going out of style anytime soon.

We have incredible domestic fossil energy resources, and our economic stability depends on the power they produce.

So it's no surprise that a robust industry has developed here at home focused on investing in the next generation of technologies to produce and use American fossil fuels more efficiently, more safely, and at a lower cost for American consumers. In fact, I think I am well within my rights to label Houston, Texas as the carbon capture capital of the world!

We've seen incredible research and technology successes through collaborative, public-private partnerships right here in our backyard. One such example is the Air Products production facility in my district, just down the road in Port Arthur.

This facility, which was sponsored in part by the Department of Energy, captures over 90 percent of the CO2 from the product streams of two commercial-scale steam methane reformers and injects that carbon dioxide into the West Hastings oilfield for enhanced oil recovery. In return, DOE has estimated that an additional 1.6 to 3.1 million barrels of oil will be produced annually from this CO2 application process.

Another example is the Petra Nova facility, just a couple miles southwest of here - a facility my colleagues and I will have the chance to visit this afternoon. This facility captures carbon dioxide from a coal-fired plant and then, much like the Air Products facility, routes the CO2 to the West Ranch oil field, also in my district, for enhanced oil recovery. Within the first 10 months of opening, this field saw oil production boost by 1,300 percent.

Additionally, the Department of Energy is making smart, targeted investments in early-stage research to advance the next generation of production and emissions control technologies through the DOE Fossil Energy Research and Development (FER&D) program.

Funded at $740 million in FY 2019, FER&D conducts research that supports clean, affordable, and efficient use of domestic fossil energy resources. The complex fossil energy research challenges we face today will require an all hands-on deck approach. Academia, industry, and the Department of Energy are the ideal partners to develop these solutions.

With support from DOE, the technology developed and deployed at facilities like Air Products and Petra Nova are reducing the emissions from local refineries, and producing affordable, American fuel to power our economy.

I look forward to hearing more about these partnerships from our witnesses today. I want to thank our all witnesses for testifying today, and the Chairman for holding this hearing.

Chairwoman FLETCHER. Thank you very much, Mr. Weber. I'm grateful for your work to bring us together for this hearing today on the future of advanced research and development on carbon capture, and it's fitting that we meet here in Houston.

I also thank the University of Houston and Dr. Khator for hosting us this morning.

Houston, as many of us in the room know, is a place of big ideas. It always has been. Perhaps more important, it is a place where big ideas become reality, and that is the subject of today's hearing, very big ideas that are becoming a reality right here in Houston.

Here in Houston, we know energy. When it comes to energy innovation, this is its home. Right now, we are experiencing an energy renaissance, one that has reduced costs and increased investment here and around the world.

Texas, as we all know, is the largest producer of oil and natural gas in the country. Texas is also the leader in developing wind energy in the country. We have installed 3-times as much wind power as the next leading State. And Texas is also the sixth leading State when it comes to solar power and solar energy capacity.

So, the other thing we know here in Houston is that climate change represents a real and growing threat. We are already experiencing its effects, and we know that reducing emissions is a key to addressing climate change.

The advances in technology that have transformed our energy economy have substantially reduced U.S. carbon emissions. Replacing coal-fired power plants with natural gas plants has contributed more to the reduction of domestic carbon emissions than any other effort.

Developing and utilizing more renewable energy sources is another critical part of our overall effort.

But we need to do more.

That is why I am glad that we are here today to talk about carbon capture research and development.

The Intergovernmental Panel on Climate Change "Special Report on Global Warming of 1.5 degrees Celsius" makes clear that the use of carbon capture technologies will be essential under just about any plausible scenario to sufficiently limit our global temperature increase.

Carbon capture, utilization, and storage (CCUS) provides an important pathway to meeting our energy needs and reducing our carbon emissions. While these technologies are promising, we need more research and development to reduce the costs of these technologies and to deploy them at the scale needed to meet our climate mitigation goals.

That's why I worked closely with my colleagues on our Committee, including our Committee Chairwoman, Representative Johnson, Subcommittee Chairman, Mr. Lamb, and Mr. Veasey from Fort Worth, to bring forward the *Fossil Energy Research and Development Act* to expand Department of Energy research, development, and demonstration programs, including carbon capture technologies for power plants, carbon utilization, carbon dioxide removal from the atmosphere, leak detection for methane, and identifying other novel approaches for light hydrocarbons produced during oil and gas shale production.

As we see consistently on this Committee, on the Science, Space, and Technology Committee overall, there is an important and valuable, and I would say essential, partnership between government, research institutions, and industry that is critical to advancing our efforts. And one of the things I appreciate most about this Committee is that consistently we have panels of witnesses from those various groups informing our work.

So I look forward to hearing from our expert witnesses today about how this important technology works and what the Federal Government can do to make smarter investments and assist in developments that ensure that we remain the global energy leader, and that we remain and become the global clean energy leader while addressing the challenges before us to reduce carbon emissions.

I want to thank you all for joining us here. I look forward to an excellent discussion.

I would also like to briefly recognize Dr. Renu Khator, President of the University of Houston, who is joining us this morning, for a few introductory remarks.

Thank you, Dr. Khator.

Dr. KHATOR. Thank you, Madam Chair, Members of the Committee. Welcome to the University of Houston. On behalf of our Board of Regents, our 74,000 students in the system, 46,000 students here on this campus, over 300,000 alumni, and a great, great, wonderful fleet of researchers here, I would like to welcome you all and thank you for choosing to come to the University of Houston. Your presence here means a lot.

I mean, I could talk a lot about the University of Houston, but that's not what I'm here for. But I just wanted to say that we being in Texas, first of all, take our responsibility toward higher education very seriously. We take responsibility for providing affordable education and access to a higher education, but at the same time also producing the intellectual capital that is necessary to solve some of the problems that you've just outlined.

Being in the top five petroleum engineering programs in the country, being ranked number one in the entrepreneurship program in the country, being ranked number one in transfer of technology of our professors into the real world when measured in terms of the revenue from IP, we ranked number one there as well, all of these things make sure that we have the ability that we could do it, we could find the solutions. And as I always say, we as an institution being in Houston never raise the ivory walls to begin with, so we have no problem in knocking them down, a very collaborative institution.

You will hear a lot from our energy advisory board members. They advise us, and they take us to the areas that we didn't think possible. But you will also hear from our chief energy officer. Anything we can do to advance the agenda as you have outlined, we are here as your University, and again being in Houston, being in Texas, we take it very, very seriously.

So thank you for being here. I hope you have a good time and enjoy the beautiful campus on this beautiful day.

Chairwoman FLETCHER. Thank you so much, Dr. Khator. I would like to second your comment. I think collaboration is something that we do very well here in Houston, and I'm pleased that so many of our Houston area delegation members are here today for the hearing.

If there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

[The prepared statement of Chairwoman Fletcher follows:]

Thank you, Mr. Weber. I am grateful for your work to bring us together for this hearing today on the future of advanced research and development on carbon capture, and it is fitting that we meet here in Houston.

Houston is a place of big ideas - it always has been. Perhaps more important, it is a place where those big ideas become realities. And the subject of today's hearing is a very big idea that is becoming a reality.

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Carbon capture, utilization, and storage provides an important pathway to meeting our energy needs and reducing our carbon emissions. While these technologies are promising, we need more research and development to reduce the costs of these technologies and to deploy them at the scale needed to meet our climate mitigation goals.

That is why I worked closely with my colleagues, including our Committee Chairwoman Johnson and Subcommittee Chairman Lamb and Mr. Veasey, to bring forward the *Fossil Energy Research and Development Act* to expand Department of Energy (DOE) research, development, and demonstration programs including carbon capture technologies for power plants, including technologies for coal and natural gas; carbon storage, including to develop and maintain mapping tools and resources that assess the capacity of geologic storage formations in the United States; carbon utilization, including to assess and monitor potential changes in the life cycle of carbon dioxide and other greenhouse gas emissions; advanced energy systems to reduce emissions from and improve the efficiency of fossil fuel power generation; developing and assessing methods to separate and recover rare earth elements from coal and byproduct streams; identifying the environmental, health, and safety impacts of methane hydrate development; carbon dioxide removal from the atmosphere; methane leak detection and mitigation; and identifying and evaluating novel uses for light hydrocarbons produced during oil and shale gas production.

As we see consistently on the Science, Space, and Technology Committee, there is an important and valuable partnership between government, research institutions, and industry that is critical to advancing this effort.

I look forward to hearing from our expert witnesses today about how this important technology works and what we in the federal government can do to make smarter investments and assist in developments that ensure that we remain the global energy leader and as the global clean energy leader, while addressing the challenges before us to reduce carbon emissions.I want to thank all of you here today for joining us for this hearing and I look forward to an excellent discussion.

[The prepared statement of Chairwoman Johnson follows:]

Good morning and thank you, Chair Fletcher, for holding today's hearing in Houston on the Department of Energy's efforts to advance carbon capture, utilization, and storage, or CCUS, technologies.

Historically, fossil fuels have served as the primary sources of U.S. energy as they provide reliable power at low costs. They have also been an important resource to the manufacturing sector, which relies on fossil fuel combustion to provide high-temperature heat needed for a variety of processes, including the production of cement and glass.

My home state of Texas has played an important role in the fossil fuel industry as the leading producer of crude oil and natural gas in the U.S. However, as our nation's priorities have evolved, we are now focused not only on using energy sources that provide low cost, dispatchable energy, but also on how the greenhouse gases produced by these sources are mitigated and managed.

That's why we must strengthen our investment in the Department of Energy's Office of Fossil Energy, which amongst other activities, supports research to reduce emissions that result from the production and use of fossil fuels. This includes the development of technologies such as carbon capture, utilization, and storage, and methane leak detection and mitigation. DOE's Fossil Energy Office has already been instrumental in advancing CCUS technologies, having heavily invested in one of the first commercial scale demonstrations of carbon capture and storage in the power sector at Petra Nova. Yet, there is much more to be done. To date, there has been relatively little research, development, and demonstration conducted on CCUS technologies applied to natural gas plants, an increasing energy source for our power sector, and industrial processes, which produce over 20% of U.S. greenhouse gas emissions. Moreover, many experts, including former DOE Secretary, Ernest Moniz, have highlighted the need to advance direct carbon capture technologies to manage existing, ambient carbon pollution.

For these reasons, I am a proud cosponsor of H.R. 3607, the bipartisan *Fossil Energy Research and Development Act of 2019*, which reauthorizes and expands these important research activities, and specifically enables DOE to conduct additional demonstration projects, like Petra Nova, that are critical for propelling the CCUS industry forward.

I look forward to discussing this legislation further and hearing from our distinguished group of witnesses today on the research investments we need to make our transition to a clean energy future possible. Thank you for being here this morning.

With that, I yield back.

Chairwoman FLETCHER. If there are no other statements, I will go ahead and recognize Mr. Weber to introduce our witnesses.

Mr. WEBER. Thank you, ma'am. But before I do, I want to echo Dr. Khator's remarks. She's being very gracious and very humble. As one of those 300,000 alumni from the University of Houston, I want to say for those of you who want to increase your Texas or your energy bona fides, they're still taking applications for continuing education, so we'll have people outside with clipboards to sign you up.

But seriously, thank you, Dr. Khator. We are just so grateful to be here today. Thank you. You bet.

So, our first witness today is Mr. Greg Kennedy, Senior Project Director of Petra Nova Asset Management at NRG Energy, and in this capacity he oversees the management of innovative carbon capture projects designed to capture and store 1.4 million tons of CO_2 per year.

I've actually done some math, Mr. Kennedy, on that. If the cost is $600 a ton—that's $840 million. If the cost is $94 a ton, as some are trying to get it down to that, that would be $131 million a year. So that's about a $700 million difference; unbelievable.

Mr. Kennedy has over 4 decades of project management experience overseeing commercial contracts, power origination operations, and other global special projects in the energy industry. Prior to joining Petra Nova project, he served as the Senior Project Director of all southeast assets for GenOn Energy.

Mr. Kennedy holds a bachelor of science and engineering degree from Purdue University and received his master of business administration from the University of Houston.

Did I mention they're still taking applications for the rest of you all?

[Laughter.]

Mr. WEBER. Next we're going to Dr. Jeffrey Long. Our next witness, Dr. Jeffrey Long, is a Faculty Senior Scientist at the Lawrence Berkeley National Laboratory. His research expertise and interest includes inorganic and materials chemistry, metal organic frameworks, catalysts and conductivity, and molecular magnetism.

Dr. Long has received extensive recognition throughout his career for excellence in both teaching and research in the energy field, including from Harvard University and UC-Berkeley.

Dr. Long, we need to add UH to that list, by the way.

He has also earned fellowships in the Office of Naval Research, the National Science Foundation, the Alfred P. Sloan Foundation, and the Bakar Fellows Program at UC-Berkeley. Dr. Long holds two Bachelor of Arts degrees from Cornell University in chemistry and mathematics and a Ph.D. in chemistry from Harvard University.

Welcome, Dr. Long; and, Mr. Kennedy, you too.

Dr. Ramanan Krishnamoorti is our next witness that we're going to welcome today, and he's the Chief Energy Officer of the University of Houston. He oversees UH Energy, a program that partners with the energy industry to build those technical leadership skills that Dr. Khator was talking about and develop those new technologies.

Since 1996, he has had a storied career in energy research at UH, receiving over $16 million for his innovative research in the energy field. When I read that I thought, man, you've been given a lot of money, but we all know it actually goes here to the school and we appreciate your stewardship of that.

The doctor has been recognized for his outstanding research and teaching in the field of prestigious institutions, including the University of Houston, the National Science Foundation, and the *Journal of Polymer Science*. Polymers are very big in my district, by the way.

He is also a Fellow of the Neutron Scattering Society and the American Physical Society.

Dr. Krishnamoorti received his bachelor of technology from the Indian Institute of Technology and holds a Ph.D. in chemical engineering from Princeton University.

Welcome, Doctor.

Next we'll go to Mr. Roger Dewing. Our next witness is the Director of Technology at the Air Products Technology Center, where he has led engineering teams in Europe, China, and in the U.S. After graduating from the University of Surrey with a bachelor degree in chemical engineering.

[Laughter.]

Mr. WEBER. He has completed the Graduate Training Program in the U.K., taking on assignments in oil refining as well as offshore drilling. He then served with British Gas PLC as a part of their LNG engineering team before joining the Air Products Technology Center in 1996. Man, that's 23 years ago.

Since beginning his career with Air Products, Mr. Dewing has built energy processing technology and knowledge transfer systems all around the world. His most recent project will support cryogenic process innovation and development in the Middle East.

So, welcome, Mr. Dewing. We're glad you're here.

Our next witness is Mr. Nigel Jenvey. He is the Global Head of Carbon Management at Gaffney, Cline & Associates where he helps industry professionals understand the value of carbon management, which is one of the reasons we're here today.

Prior to this role, he has held leadership positions for some of the largest energy companies in the world, including as head of Carbon Capture, Use and Storage for British Petroleum. In addition to his role at Gaffney, Cline & Associates, he is now the Coordinating Subcommittee Deputy Chair for the National Petroleum Council CCUS study, due to be completed in 2019.

Mr. Jenvey attended the University of Leeds, where he earned a bachelor of engineering degree in mining, like we were talking about, mining engineering, and he also holds a master of science in petroleum engineering from Imperial College, London.

Welcome, Mr. Jenvey.

With that, Madam Chair, I will yield back.

Chairwoman FLETCHER. Thank you very much, Mr. Weber.

As our witnesses should have been informed, you will each have 5 minutes for spoken testimony and hopefully summarizing the written testimony that you have already prepared. It is included in the record for the hearing. And when you've completed your 5 minutes each, then we will begin with questions from the Members, and each Member will have 5 minutes to question the panel. We'll do at least the first round of questions that way.

So, we will start with Dr. Krishnamoorti, if you would like to begin. Thank you.

TESTIMONY OF DR. RAMANAN KRISHNAMOORTI, CHIEF ENERGY OFFICER, PROFESSOR OF CHEMICAL ENGINEERING, UNIVERSITY OF HOUSTON

Dr. KRISHNAMOORTI. Thank you so much, Chairwoman Fletcher, Ranking Member Weber, and Members of the Committee. Thank you for being here at the University of Houston. We call it the energy university, and you'll see why.

Thank you for having me here today to talk about our approach to carbon management specifically at the intersection of fundamental science, new technology, and policy.

My name is Ramanan Krishnamoorti, as the Chairwoman indicated. I'm the Chief Energy Officer here and Professor of Chemical and Biomolecular Engineering.

Let me sort of set a context for this. Abundant, low-cost energy makes the world possible. Affordable and sustainable energy will be needed in ever-increasing quantities throughout the 21st century as our planet's human population grows by an additional 2 to 3 billion. Satisfying this need will be challenging. Adding to this challenge is the requirement that we must address energy-related climate change risks.

The University of Houston is uniquely positioned to play a leading role in delivering innovative solutions that will be required to address both of these global-scale imperatives. UH has committed itself to establish itself as the energy university, the university that will advance the science, technologies, and policies that underpin the energy transition while providing affordable energy for our entire planet's population.

At the University of Houston, located in the energy capital, we are committed to addressing the issue of carbon. A year ago we acted on this imperative that was brought to us by a broad group of stakeholders. My colleague Tracy Hester of the UH law school and I created the Center for Carbon Management in Energy, a center that's currently led by a former DOE official, Charles McConnell. It is our thesis that the energy industry is the only industry that operates at scale and is positioned to substantially reduce the annual addition of 36 gigatons of carbon dioxide and cumulative addition of 800 billion tons of carbon in the atmosphere. Moreover, we recognize that addressing the carbon challenge must be interdisciplinary, embracing the systems approach that addresses the present and the future.

Toward this, we have integrated scientific advances with technology innovations and, most importantly, connected them to regulatory, business, and public policy. In my written testimony I provided you a detailed analysis of the current challenges and opportunities in carbon management. I've emphasized the fact of the impact of UofH in providing innovative technological and policy strategies to address CO_2 and natural gas emissions. These twin challenges require innovative solutions, and they must address the immediate challenges and strategic long-term disruptive solutions.

Some prominent examples of these—I will go through three of them really quickly, in the interest of time. First, growing energy demand in emerging economies such as India presents an opportunity to address the twin challenges of access to affordable energy and addressing climate risk. A UofH project led by my renowned petroleum engineering colleague, Dr. Ganesh Thakur, who had an illustrious career at Chevron working in the Permian and doing some of the early stage CO_2 experiments there, has been working in collaboration with Oil India, Ltd. This is one of the publicly held companies in India in the state of Assam, and has demonstrated how CO_2 captured from nearby petrochemical plants can boost oil recovery in a nearby depleted oil field. This is a huge issue in a country like India where about 85 to 90 percent of their energy is being imported and their depleted oil fields stand as a national security and global instability challenge.

Second, we've been advancing cost-effective—and this is important—cost-effective direct air capture through the development of modular and intensified carbon capture technologies that are coupled with excess renewable energy that is unique to the State of Texas, and finding ways to appropriately deploy them on a distributed basis. Ongoing developments of membrane and electro-membrane technologies, along with integration into modular and intensified direct air capture units, is underway.

As a last example, going back to my chemical engineering basis here, the inherent stability of CO_2 means that many traditional processes for converting CO_2 to chemicals are highly energy intensive and hence produce additional carbon. In contrast, my colleagues in the Department of Chemical Engineering at UofH are using CO_2 both as a source of carbon as well as a source of active oxygen that can reduce the energy footprint of existing large-scale hydrocarbon conversion processes such as methane dehydrogenation. Such a process would result in continued monetization of natural gas liquids, as well as utilization of CO_2.

So, in conclusion, Members of the Committee, the University of Houston stands ready to address the most challenging problems facing our generation, providing affordable and reliable access to an ever-growing demand for energy and simultaneously addressing the energy-related climate change risk.

I thank you for the opportunity to provide testimony today and look forward to answering your questions. Thank you.

[The prepared statement of Dr. Krishnamoorti follows:]

Testimony of Dr. Ramanan Krishnamoorti, Chief Energy Officer, University of Houston

House Committee on Science, Space, and Technology, Subcommittee on Energy

Field Hearing: The Future of Advanced Carbon Capture Research and Development

November 22, 2019

Carbon Management: Intersection of Fundamental Science, New Technologies and Policy

The world is growing at an unprecedented pace and scale. The increased and reliable supply of safe, modern, and sustainable energy forms the basis of this transition. The demand for energy continues to grow, not only in the US but also globally, with the global population anticipated to reach more than 10 billion people, making it increasingly important to consider both the need for cheap and reliable energy and the environmental consequences of energy production and consumption.

This presents the dual challenge of our times – more energy that is cheap and reliable with fewer harmful emissions. Carbon management enables us to meet this challenge head-on and develop the opportunities it presents in a forward-looking manner. Two separate but related challenges need to be addressed to enable a sustainable energy future: rising anthropogenic carbon dioxide in the atmosphere and the increasing impact of natural gas related to venting, leaks, and flaring.

Human activities currently produce about 36 billion metric tons of CO_2 per year, with over 800 billion metric tons of CO_2 having been added to the atmosphere since the start of the industrial revolution. The size of the problem is evident. The energy industry is the only industry that operates at a scale and is positioned to substantially reduce the annual addition and the cumulative addition of carbon to the atmosphere. Integrating novel schemes to capture carbon from point and distributed sources, developing accretive processes to utilize and successfully sequester the carbon can be advanced only through the active engagement of the energy industry, writ large.

The Center for Carbon Management in Energy (CCME) at the University of Houston (UH) was established in January 2019 with the vision of powering the energy transition to a lowered carbon footprint. CCME and UH are partnering with industry and other thought leaders to lead impactful, multi-disciplinary change to technology, regulations and policy, involving science, business and law, as well as advancing education to develop a future-ready workforce ready to benefit the society at large. My colleague Tracy Hester from UH

Law Center, and I created this center in close engagement with our colleagues at UH, industry, and a broad group of stakeholders.

Significant advances have been made toward a diversified, lower emission energy portfolio. These include fuel switching from coal to natural gas in the power sector, increasing the efficiency of both the production and consumption of energy, enabling investment in renewable energy deployment, electrification of transportation, and developing novel technologies to capture carbon dioxide from the atmosphere while finding safe pathways for storage and utilization.

Obstacles to Expanding Carbon Capture Efforts

Currently, technical challenges prevent a rapid scale-up of CO_2 capture. However, economic and regulatory barriers are more consequential in preventing the growth of the CO_2 capture, utilization, and sequestration markets. As my colleagues Tracy Hester and Elizabeth George from the UH Law Center (UHLC) have written, CO_2 may be classified as a waste stream rather than a valuable commodity, which can prevent access to common carrier pipelines. What this means for the country, and specifically for Texas, is that there is more demand today for CO_2 than the capture and transportation infrastructure can provide.

Within the broader context of the US, there is:

- Significant potential for CO_2 storage in underground deep geological formations, as well as storage through enhanced oil recovery (EOR), including offshore capacity for storage and EOR. This, coupled with proximity to sources that produce CO_2, presents an opportunity to significantly reduce transportation costs and infrastructure requirements;
- Local wealth of intellectual capabilities and industrial know-how related to carbon management, especially carbon capture and sequestration through EOR, offering a unique and distinctive advantage;
- Nonetheless, legal and regulatory barriers exist, driven in part by the consideration of CO_2 as a waste product. The role and characteristics of injection wells change over the lifetime of the project, leading to classification issues, risk and liability, and pore space ownership issues.

In fact, CO_2 should be regarded as a valuable commodity with a variety of uses and applications that can close the carbon cycle in a manner that is technologically feasible and commercially viable while being self-sustaining in the long term. Disrupting the status quo means this misalignment needs to be addressed through stable and consistent policy changes. A well-defined cost of carbon is an effective instrument not just for achieving meaningful carbon reduction and environmental protection but would also drive technological innovation, spur new financial strategies to create new market opportunities, and foster continuous socioeconomic development.

The Cost of Carbon

Setting an economy-wide cost of carbon would offer a number of benefits, including:

- Political consensus, willingness, and certainty in support of carbon management and the opportunities it presents;
- A comprehensive and transparent price across all sectors of the economy and all components of different supply chains, in addition to a technology-agnostic approach toward impactful emissions reduction;
- System flexibility as it relates to compliance, border adjustability to avoid double accounting and ensure that the United Sates remains competitive with existing and emerging international costs of carbon;
- A level playing field that allows for new market opportunities and avenues for success for any and all efforts to reduce the carbon buildup, while de-risking market entry and/or upscaling and providing immunity to technological, financial, and legal institutions pioneering carbon management solutions;
- Tangible social benefits, which can help engage citizens and build broad-based public support for carbon management across communities.

Tax credits available through the reformed Section 45Q of the federal tax code, approved as part of the Bipartisan Budget Act of 2018, marked a significant advancement in this direction. It reinforces the principle that carbon management is not peripheral to the United States and that the energy industry will play a critical role as the carbon management landscape evolves, as well as supporting the belief that research, design, and development will drive carbon reduction efforts.

Earlier this year, the Department of the Treasury and the Internal Revenue Service invited public comments on issues arising from the implementation of Section 45Q. The measurement, monitoring, and verification of secure geological storage of qualified CO_2, the standard for measuring recapture of the benefits of the credit, guidance, and clarification on terms and definitions, understanding the boundaries of lifecycles, and understanding structures that can qualify as partners in a partnership for project developers and participating investors are all issues that remain to be addressed. UH and the CCME responded to the request for comments and these are presented in Appendix A.

Projects Are Already Underway

The reforms to Section 45Q have signaled a remarkable paradigm shift for carbon capture, wherein innovation stands to be rewarded and supported by the government. It is through such innovation, intensive research, and field-scale demonstrations across the United States over the last three decades that carbon capture technologies have advanced to their current status, positioning the nation to be a global leader in carbon management. There are no better examples of this deployment than what has been done in the Houston area – the Petra Nova project at the W.A. Parish power plant in Richmond, Texas, just southwest of Houston, which has developed a post-combustion carbon-capture unit coupled with a coal-fired power plant. The captured CO_2 is transported and used for enhanced oil recovery at the West Ranch oil field. As a second example, the NET Power facility in La Porte, a city along the Houston Ship Channel, is producing net-zero electricity from natural gas.

Building upon the lessons from these projects, well-designed and comprehensive policies can accelerate the scale of deployment and reduce the capital costs and the operating energy cost associated with CO_2 capture. The industry along with academia and the national laboratories, are working on possible solutions, including the replacement of absorbers with adsorption columns, advancing methods to separate oxygen from air that will be able to reduce capital costs and energy requirements.

Currently at the University of Houston we are:

- Advancing modular and intensified carbon-capture technologies for cost-effective and distributed deployment coupled with excess renewable electricity production for the case of direct air capture (DAC). Opportunities to identify better separation and release technologies along with process intensification and simultaneous capture and conversion of CO_2 are key areas of focus at UH. Ongoing development of membrane and electro-membrane technologies along with integration into modular and intensified DAC units, is underway;
- Exploring zero-emissions refining to lower and subsequently eliminate gaseous emissions, from process units, fuel headers, and overall plant operations. These gaseous emissions are the primary target for initial consideration. One of the significant areas of research being pursued at UH is the advancement of hydrogen as a source for industrial heating;

- Discovering new and beneficial uses of carbon. The inherent stability of CO_2 means that many traditional processes for converting CO_2 to chemicals are highly energy-intensive and hence, produce additional carbon. In contrast to traditional processing methods that focus exclusively on the direct conversion of CO_2 to value-added chemicals, my colleagues here in the Department of Chemical and Biomolecular Engineering are using CO_2 both as a source of carbon as well as a source of active oxygen that can reduce the energy footprint of existing large-scale hydrocarbon conversion processes such as ethane dehydrogenation;
- Developing new technologies using both computational and experimental work to create the coupled conversion of methane and CO_2 using a combination of low-temperature plasmas and catalysts;
- Advancing novel transportation mechanisms for captured CO_2 to utilize existing infrastructure and enable an international market that treats CO_2 as a gainful global commodity;
- Development of models, practices, and operations for the safe, reliable and permanent CO2 storage in geological formations including saline aquifers, depleted oil and gas reservoirs, and unconventional formations. Maximum storage potential estimation and monitoring of the impact of fluid storage on reservoirs, quantification of short- and long- term risks and detection of migration patterns are being advanced through the CCME, especially through our outstanding departments of Earth and Atmospheric Sciences and Petroleum Engineering.

Between 2005 and 2017, fuel switching and a diversified energy mix in the United States resulted in emissions reductions of nearly 760 million metric tons, while delivering low-cost energy to US consumers. In other words, we achieved a 20% reduction in emissions within this time frame on a per capita basis. The vast majority of this decline can be attributed to the dramatic increase in natural gas production from shale, carbonate, and other tight geological formations.

The astounding growth in natural gas production in less than a decade is due to the sheer size and volume of the resources, rapid and continued improvements in technologies such as horizontal drilling and hydraulic fracturing, and the ability of producers to promptly respond to market signals by upscaling production and drilling intensity. That has positioned the US as the largest oil and gas producer in the world, with positive spillover effects such as a more robust domestic manufacturing industry and greater disposable income from reduced fuel costs.

We recognize that capturing emissions, however, only solves part of the challenge facing carbon management. Transportation and utilization form the remaining pillars. The Permian Basin is home to a majority of enhanced oil recovery (EOR) projects in the nation, given its number of large and mature oil fields amenable to CO_2 injection. The first few decades of CO_2-enabled EOR were supported by underground natural CO_2 source fields, but over time these fields have been depleted. In addition, size limitations of CO_2 carrying pipelines mean they are unable to support the demand for CO_2 in the region. Moreover, in the absence of an established carbon cost to incentivize capture, capturing industrial CO_2 remains financially unattractive when compared with naturally occurring CO_2.

Other utilization technologies including co-valorization with stranded methane and conversion of CO_2 to plastics and carbon nanomaterials are being advanced at UH. These are early stage ideas that are probing hard scientific questions, but they lie at the center of finding increasing societal value for both CO_2 and natural gas without impacting the environment.

Similarly, the deployment of carbon storage in the offshore, especially the Gulf of Mexico, depends on the availability of sufficient high-purity CO_2 captured from near-to-shore industrial sources. The challenge of sourcing can be easily and effectively resolved by optimized source-to-sink matching. Even though sources and at-scale sinks are present, the predominant challenge in connecting the two has been the high cost of transportation and the risks involved in deploying dedicated pipeline infrastructure for long-distance transport, especially for offshore pipelines. Therefore, novel transportation methods such as dual-use LNG and CO_2 ships that transport LNG one way and carry captured CO_2 on their return journey, could allow the CO_2 to be used for EOR at an appropriate location in proximity to the LNG source site. This is an effective way to reduce the bottlenecks surrounding sourcing of CO_2 and the high cost of transportation via pipelines. This means lessons from projects in the North Sea and extensive experience from the Permian Basin can be easily transferred to advance CO_2-based EOR in amenable offshore Gulf of Mexico fields and the broader objective of carbon management in the US.

Growing energy demand in emerging economies such as India presents an opportunity to analyze how carbon management can be developed in regions that will continue to predominantly rely on fossil fuels to meet their energy needs. A UH project, led by world-renowned petroleum engineer Dr. Ganesh Thakur in collaboration with Oil India Limited (OIL) in the Indian state of Assam, has demonstrated how CO_2 captured from nearby petrochemical plants can boost oil recovery in a nearby depleted oil field. Opportunities such as this present a fertile exploratory field for research and development, the avenues to acquire global lessons and develop integrated solutions for a low-carbon world.

	CO_2 Value Chain		
	Capture	Transportation	Utilization and Sequestration
Power Generation Hydrocarbon Exploration & Production Petrochemical Refining Chemicals and Fertilizers	Novel Capture Technologies: Adsorption; Selective Membranes; Modular & Distributed; Integration with Renewables Re-engineering Processes: Integration; Intensification	Pipeline Technologies: Materials, Corrosion & Leak Testing Shipping of CO_2: Technologies, Economics & Policies Compressors & Power Systems	Conversion: Fuels Chemicals Plastics Enhanced Oil Recovery: Conventional ROZ Unconventional Offshore Water Use & Recycle Geological Sequestration: Seismic, Acoustic, Modeling & Policy

Concerns Over Methane Emissions

This increase in energy production and demand has not been matched with a proportionate increase in transport infrastructure, however, specifically in the expansion of pipeline capacity. Fearing a market glut and restricted by the ability to transport natural gas to where it is needed, both domestically and for export, the venting, accidental leaking, and flaring of natural gas continues to challenge the sustainability of natural gas production and transportation.

While CO_2 is the most significant greenhouse gas (GHG), methane is 25 times more potent than CO_2 as a GHG on a 100-year time scale. Similar to the context of CO_2 in carbon management, methane emissions associated with natural gas flaring, venting, and leaks go beyond environmental protection and the health impacts associated with air quality. There is a compelling case for reducing methane emissions.

Natural gas is a valuable commodity with an existing market, ever-increasing domestic and local demand, and is of relatively low carbon-intensity when compared with other fossil fuels. Therefore, the more we reduce methane emissions, the larger the volumes of natural gas that will be available for consumption. Nonetheless, there is potential good news. We have technologically proven and relatively low-cost solutions that can deliver methane emissions reduction at scale. Implementing those solutions, however, has been hampered in part by the fact that most energy producers are unaware of their methane footprints, in part due to the lack of effective monitoring. That has translated to producers underestimating or sometimes incorrectly reporting their emissions. This is strongly indicative of a gap that can be bridged through policy interventions in the form of newer methane standards and reining in on emissions reporting.

Potential Solutions

In this direction, experts at the University of Houston are developing:

- New technologies to quantitatively monitor a broad range of highly distributed assets for natural gas leaks and economically implementing such technologies at field-scale by combining a variety of key advances, including the development of high-quality and high-fidelity sensors based on light and acoustic methods, wireless communications, data analytics, robotics, and automation;
- Sensor systems, deployment technologies, data analytics, artificial intelligence, and machine learning-based tools at the Hewlett Packard Enterprise Data Science Institute, along with robotics and automation focused on asset-integrity management;
- Chemistry and chemical engineering experts using molecular-scale modeling along with catalyst synthesis to macroscale process modeling and pilot-scale reaction engineering are addressing issues of hydrocarbon and CO_2 conversions through:
    - decomposition of methane,
    - methane conversion to methanol,
    - oxidative dehydrogenation of ethane,
    - partial oxidation of methane and ethane using CO_2, oxidative coupling of methane,
    - tri-reforming of methane, and
    - the use of non-thermal plasmas for the conversion of methane.
- Skid-based methane conversion technologies that can address gas-to-liquid technologies that are modularized and economically produce specialty liquids ranging from methanol to gasoline.

	Methane and Hydrocarbons	
	Emissions: Monitoring and Mitigation	Conversion and Monetization
Power Generation	Monitoring: (i) Remote Monitoring using Drones (ii) Distributed Acoustic Sensing Mitigation: (i) Pipeline Modeling (ii) Renewable Integration for Pneumatic Valves	Distributed Catalysis and Power Generation Conversion: Fuels (methanol) Chemicals Polymers & Materials Monetization: Gas Injection EOR
Hydrocarbon Exploration & Production		
Petrochemical Refining		
Chemicals and Fertilizers		

A Call to Act Now to Lead Carbon Management Globally

Plainly, the near-term challenge for carbon management is rapid deployment to benefit from economies of scale and reductions in cross-chain risks. Currently, we have reliable and commercially proven technology to mitigate the challenge; what we need are market-based solutions incentivized by economics, regulations, and policies that remain stable over time to accelerate early-stage development.

The critical piece of this puzzle, however, is understanding that the objective and nature of carbon management is based on long-term viability, operates on geological time scales rather than human time scales, and goes beyond emissions reduction and the sustainable energy transition. The local and global context of carbon management underpins:

1. Broader energy security and energy diversity to develop reliable and affordable energy options;
2. Preserving existing jobs while creating new opportunities for long-term employment without dislocating or disbanding the substantial technological, financial, intellectual, and social capital that has been invested in and also produced by our energy systems;
3. Minimizing disruption to the economy while ensuring energy access and safeguarding the rights of citizens;
4. Accountability and responsibility towards capacity building and inclusive participation of all stakeholders.

Higher education institutions have a central role in advancing carbon management. The examples of ongoing research and projects at the University of Houston that I have described today are focused on delivering measurable results through technological, financial, policy, and legal breakthroughs. At the heart of these capabilities is the exceptional quality of our academic faculty and researchers. We remain committed to serving the city of Houston, Texas, and the United States through our wide-ranging educational and research offerings, partnerships with local and global entities, and contributions to the community.

APPENDIX A

UNIVERSITY of HOUSTON | ENERGY

CC:PA:LPD:PR (Notice 2019-32)
Room 5203
Internal Revenue Service
P.O. Box 7604
Ben Franklin Station
Washington, D.C., 20044

Re: Request for Comments on Section 45Q Credit for Carbon Oxide Sequestration (Notice 2019-32)

The Treasury Department and the IRS requested comments on issues that should be addressed in regulations to implement section 45Q.

The government is to be commended for making this regulatory project a priority for the upcoming year. Congress has expressed a longstanding and expanding desire to enhance the incentives for carbon sequestration through the tax credit afforded in section 45Q. Section 45Q's predecessor was originally enacted in 2008 to provide a tax credit for sequestration of carbon dioxide,[1] and that prior provision was amended shortly thereafter in 2009.[2] After ten years of the allowance of a tax credit for sequestration of carbon dioxide, Congress, in 2018, expanded the scope of section 45Q so that the tax credit afforded under that provision applies to sequestration of carbon oxide and then substantially increased the amount of the tax credit for carbon oxide captured with equipment placed in service after 2017.[3] Congress also provided that certain applicable facilities would be entitled to the expanded benefits of the new section 45Q tax credit in certain events.[4] Thus, Congress has expressed a longstanding and growing desire to provide increasing levels of tax benefits to motivate carbon sequestration.

With the above backdrop in mind, it bears stating that the Treasury Department and the IRS have the responsibility to ensure that its guidance furthers the climate policy goals that Congress desires to promote through its enactment of section 45Q. In addition, it also bears stating that because the financial incentives provided by section 45Q are essential to creating a sufficient financial incentive for private citizens to voluntarily take-on the responsibility for investing in the climate change mitigation activities that Congress desires to promote, the Treasury Department's guidance with respect to Section 45Q is fundamental in terms of ensuring that the market activity that Congress wants to create does in fact get created.

UH Energy is an umbrella initiative for efforts across the University of Houston system to position the University as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, and research and development for needed innovations and new

[1] See enacted by § 115 of the Energy Improvement and Extension Act of 2008, Division B of Pub. L. No. 110-343 , 122 Stat. 3765, 3829 (October 3, 2008).
[2] See § 1131 of the American Recovery and Reinvestment Tax Act of 2009, Division B of Pub. L. 111-5 , 123 Stat 115 (February 17, 2009)
[3] See § 41119 of the Bipartisan Budget Act of 2018, Pub. L. No. 115-123 (February 9, 2018).
[4] See §45Q(f)(6).

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technologies. Strategically located in the energy capital of the world, UH Energy along with the Center for Carbon Management in Energy (CCME) has engaged with the energy industry to address the issue of managing carbon at a scale that is likely to significantly impact the carbon balance in the atmosphere.

This letter responds to the government's request for comments and addresses six areas to which further guidance and clarification are needed. Several of the comments are explicitly related to areas where the government asked for comments, but at least one of our comments was not explicitly requested. We request that the Treasury Department and the IRS consider all of our comments in its regulatory process. Our specific comments are as follows.

1. **Economic Substance Doctrine.**

   Section 45Q serves as important goal of creating market incentives for private citizens to affirmatively take steps to sequester carbon oxide into secure geological formations. Without such a tax credit, sufficient financial incentives likely would not exist for citizens on their own to engage in such an expensive endeavor. Congress has recognized this fact through its design of section 45Q. For taxpayers who sequester carbon oxide as part of a tertiary recovery operation, Congress expressed a desire to provide a substantial (albeit reduced) amount of section 45Q credit.[5] The taxpayer in the tertiary injection context has sequestered carbon oxide, but at the same time that taxpayer has received another compensating benefit, namely enhanced recovery of oil and gas through the tertiary development operations. So, the amount of the tax credit afforded to the taxpayer under section 45Q is meaningful but objectively much less than the tax credit afforded to taxpayers who sequester carbon oxide in a secure geological formation outside of the tertiary development context.

   Said differently, section 45Q provides taxpayers who sequester carbon oxide into a secure geological formation outside of the tertiary recovery context with a much higher tax credit amount.[6] The increased amount of tax credit for carbon sequestration where no tertiary recovery benefits are created makes sense because the sequestration of carbon oxide in the non-tertiary context necessarily means that the taxpayer will receive no anticipated revenue stream from that carbon sequestration activity. Carbon sequestration in the non-tertiary recovery context necessarily means that the taxpayer will incur solely financial costs to capture the carbon and to sequester it as the taxpayer will not receive any offsetting revenue

[5] See §45Q(a)(4); §45Q(b)(1)(A)(i)(II). The IRS provided set forth a table for the amount of the credit applicable to each year for purposes of section 45Q(a)(4) in Notice 2018-93, Sec. 3, 2018-51 I.R.B. 1041. The amount so established by year is also subject to indexation for inflation after 2026. See §45Q(b)(1)(A)(ii)(II).

[6] See §45Q(a)(3); §45Q(b)(1)(A)(i)(I). The IRS provided set forth a table for the amount of the credit applicable to each year for purposes of section 45Q(a)(3) in Notice 2018-93, Sec. 3, 2018-51 I.R.B. 1041. The amount so established by year is also subject to indexation for inflation after 2026. See §45Q(b)(1)(A)(ii)(I).

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for storing the carbon oxide molecules given that no enhanced recovery of a commercially marketable product (namely enhanced oil and gas recovery) arises in that context. Thus, the entirety of the financial incentive for engaging in carbon sequestration in the nontertiary scenario arises solely from the tax benefit of the allowable section 45Q credits, and Congress tacitly recognized this fact because it gave a larger tax credit benefit to motivate taxpayers to engage in carbon sequestration in that context and necessarily needed to do so as that activity does not create or produce a marketable product (namely no enhanced oil or gas is recovered in that context). The design of section 45Q, therefore, make perfect sense in terms of its calibration of the tax credit benefit to motivate taxpayers to engage in activities that promote climate mitigation policies that Congress wants to promote in a broad range of contexts. But even so, section 45Q's unique design features require the Treasury Department and the IRS to carefully consider how section 45Q's goals should be meshed with generally applicable federal tax principles like the economic substance doctrine.

In 2010, Congress codified the judicially created economic substance doctrine through the enactment of section 7701(o).[7] The judicially created economic substance doctrine provides the government with broad authority to disregard the tax benefits derived in transactions that have no economic substance apart from the tax benefits derived from engaging in the transaction.[8] In relevant part, section 7701(o)(1) provides that in the case of any transaction to which the economic substance doctrine is relevant, such transaction shall be treated as having economic substance only if the transaction changes in a meaningful way (apart from Federal income tax effects) the taxpayer's economic position and the taxpayer has a substantial purpose (apart from Federal income tax effects) for entering into such transaction. The above broad-based economic substance doctrine serves a legitimate purpose of preventing tax motivated transactions that frustrate Congress' desires.

But, application of that doctrine in the context of section 45Q would serve to frustrate Congress' desires, not promote them. In this regard, in the context of an allowance of the section 45Q tax credit in the context of nontertiary sequestration as envisioned under section 45Q(a)(3), there is no other derived financial benefit from the carbon sequestration activities apart from the federal income tax credit benefits afforded by section 45Q. The non-tax benefits for engaging in carbon sequestration are benefits derived by the society at large in the form of the positive climate change benefits derived from removing ambient carbon oxide from the atmosphere. This societal benefit is the substantial purpose that

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[7] For an more in depth consideration of the codification of the economic substance doctrine and its impact on the decided case law, see Bret Wells, *Economic Substance: How Codification Changes Decided Cases*, 10 FLORIDA TAX REV. 411 (2010)

[8] See e.g., See Coltec Indus., Inc. v. United States, 454 F.3d 1340 (Fed. Cir. 2006).

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Congress sought to further through its enactment and later expansion of the section 45Q tax credit, but as to the particular taxpayer engaged in the relevant carbon sequestration activity this societal benefit represents "an externality" as the taxpayer receives no direct financial benefit in the nontertiary storage context apart from the allowance of the tax credit for engaging in the carbon sequestration activities.

Thus, an important initial question for an appropriately functioning tax credit under section 45Q relates to when and to what extent will the economic substance doctrine be called upon to disallow tax benefits attributable to carbon sequestration activities that by their very nature are conducted solely to obtain the tax benefits of section 45Q. Section 7701(o)(5)(C) states that the determination of whether the economic substance doctrine were relevant to any particular transaction is to be made in the same manner as if section 7701(o) had never been enacted. Thus, if the economic substance doctrine was not relevant to a particular activity or investment prior to the enactment of section 7701(o), the IRS has recognized that it is still not relevant after the enactment of section 7701(o).[9]

Nevertheless, at present, the government has stated that the determination of when to apply the economic substance doctrine is to be done on a case-by-case basis, depending on the facts and circumstances of each individual case.[10] Moreover, the IRS has a ruling policy that it will not provide private rulings on the question of whether or to what extent the economic substance doctrine is relevant to a particular transaction.[11] Thus, at present, taxpayers who cannot meet the profit-motivation safe harbor indicated in section 7701(o)(2) are left with a significant level of uncertainty as to the manner and the extent to which the economic substance doctrine might be used to disallow tax credit benefits derived from carbon sequestration activities when the tax benefits of those activities are the principle reason the taxpayer was motivated to engage in carbon sequestration in the first place. In thinking about this issue, the Treasury Department and the IRS need to ensure that the application of generally applicable tax principles like the economic substance doctrine do not frustrate the goals of section 45Q or else taxpayers will not obtain the tax benefits that are necessary to motivate them to engage in the positive climate change mitigation efforts that Congress seeks to motivate them to conduct.

The Treasury Department and the IRS, therefore, need to provide guidance to indicate that the economic substance doctrine is not relevant to activities that are conducted under the auspices of section 45Q and then need to state that the generally applicable economic substance doctrine would not be used as a basis to disallow the availability of tax credits otherwise allowable under section 45Q. Clarity is needed because the economic substance

[9] See Notice 2010-62, 2010-40 IRB 411
[10] See Notice 2014-58, 2014-44 I.R.B. 746.
[11] See Rev. Proc. 2019-3, Sec. 3.02, 2019-1 IRB 130.

doctrine is an otherwise far-reaching doctrine that if applied to the section 45Q context would frustrate the Congressional intent to provide an explicit tax subsidy to motivate private citizens to engage in carbon sequestration activities that would not otherwise be pursued "but for" the allowance of the section 45Q tax credits. The legislative history to section 7701(o) provides significant support for the Treasury Department to provide the clarity along the lines advocated in this comment letter as the following explanation of the relevance of the economic substance doctrine makes plain:

> If the realization of the tax benefits of a transaction is consistent with the Congressional purpose or plan that the tax benefits were designed by Congress to effectuate, it is not intended that such tax benefits be disallowed. . . . Thus, for example, it is not intended that a tax credit (e.g.,
> section 42 (low-income housing credit), section 45 (production tax credit), section 45D (new markets tax credit), section 47 (rehabilitation credit), section 48 (energy credit), etc.) be disallowed in a transaction pursuant to which, in form and substance, a taxpayer makes the type of investment or undertakes the type of activity that the credit was intended to encourage.[12]

Section 45Q is not listed in the above non-exhaustive list of examples of where Congress' desire to promote some other policy goal would be subverted by the application of the economic substance doctrine. But, section 45Q provides an even clearer case for not applying the economic substance doctrine than several of the illustrative areas cited in the legislative history to section 7701(o) because section 45Q(a)(3) provides a tax benefit for an activity where no other financial gain is posited to exist apart from the tax credit benefits, and so this reality makes section 45Q a unique provision to which general tax principles must recognize as exceptional.

Guidance is needed in regulations because recent private rulings issued by the IRS evidence a reluctance by the agency to disclaim the relevance of the economic substance doctrine in situations where Congress' goals would seem to be frustrated by its application. In this regard, the IRS has on multiple occasions reserved on the issue of whether investments that generate tax benefits under the analogous area of section 45 implicated the economic substance doctrine even though section 45 is cited as an illustrative example for where the economic substance doctrine should not be applicable.[13] The IRS's refusal to rule on the

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[12] See Staff of the Joint Committee on Taxation, Technical Explanation of the Revenue Provisions of the "Reconciliation Act of 2010," as Amended, in Combination with the "Patient Protection and Affordable Care Act" (JCX-18-10, 2010), at 152, n.344.

[13] See PLR 20110500 (Feb. 4, 2011) (IRS refused to rule on whether or to what extent the economic substance doctrine was implicated by the taxpayer's investment in refined coal investment project that was eligible for tax credits under section 45(c)(7)); PLR 201105006 (Feb. 4, 2011) (same); PLR 201105002 (Feb. 2, 2011) (same)

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applicability or nonapplicability of the economic substance doctrine was left unexplained in those private rulings, and that's a problem. Consequently, in the context of this current regulatory project, the Treasury Department and IRS need to explicitly make clear that Congress' desire to encourage carbon sequestration activities solely or principally for tax reasons is what Congress envisioned and so by necessity the economic substance doctrine is inapplicable to activities conducted under the auspices of section 45Q. Again, Congress' allowance of a higher tax credit in the context of carbon sequestration into a non-tertiary formation provides tangible evidence of Congress' desire to motivate taxpayer behavior even when there is no other financial benefit in the carbon capture and sequestration context. Thus, given this reality, the economic substance doctrine cannot be applied in the carbon sequestration context as doing so would frustrate Congress' goal of using the tax system to provide the principal or sole financial incentive for taxpayers to engage in the carbon sequestration activities that otherwise would not be financially viable apart from the tax benefits.

Thus, forthcoming guidance by the Treasury Department should indicate that taxpayers who make investments in carbon capture equipment and then uses that carbon capture equipment to sequester the captured carbon oxide will be entitled to a tax credit under section 45Q and will be treated as being engaged in the active conduct of a trade or business regardless of whether or not those carbon sequestration activities ever generate a financial profit apart from the tax benefits derived from the tax credit allowed under section 45Q. In order for Congress' goals to promote carbon sequestration to be realized, forthcoming regulations should make plain that the ongoing cost associated with the conduct of these carbon sequestration activities should be deductible under section 162 and then should make plain that the ability to claim a tax credit under section 45Q will not be disallowed by reason of the economic substance or business purpose doctrines as long as those carbon capture and sequestration activities are actively conducted in the manner Congress desired to promote through the enactment of section 45Q. Applying the business purpose doctrine and the economic substance doctrine in the context of carbon sequestration activities would frustrate the fundamental policy goals that section 45Q was designed to promote.

2. Secure geological storage. For both section 45Q(a)(3) and (4), the captured carbon must be sequestered into a secure geological formation. Section 45Q(f)(2) provides that the Treasury Department, in consultation with the Administrator of the Environmental Protection Agency, the Secretary of Energy, and the Secretary of the Interior, shall establish regulations for determining adequate security measures for the geological storage of qualified carbon oxide. In furtherance of that regulatory directive, Sec. 3.01 of Notice 2019-83 specifically asked for comments on two matters:

   - Are there technical criteria different from or in addition to those provided in the EPA's GHGRP that should be used to demonstrate secure geological storage? Are

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there existing guidelines, standards, or regulations that could be used to demonstrate secure geological storage such as those developed by the International Organization for Standardization (ISO)?

- Should EPA's GHGRP rules continue to be the reporting requirements for purposes of § 45Q, and should an approved MRV Plan from the EPA be received before any §45Q credit can be claimed? Are there any viable alternatives to the subpart RR reporting requirements, such as third party, Department of Energy, or State certification?

As to the first bulleted item, we believe that the government should be open to standards developed by the International Organization for Standardization.[14] We believe that the IRS and EPA should not foreclose the opportunity to be certified by a nongovernmental organization such as ISO.

However, the caution we would like to provide to the Treasury Department and the IRS is that the science is quickly evolving in this arena. Significant discoveries and learning are occurring in terms of carbon sequestration and carbon capture. As a result, any regulatory guidance in this area should not be static and should recognize that best practices and standards are going to evolve. Given this reality, forthcoming regulations should allow certification of a formation as "geologically secure" under safe harbor provisions but then should provide a means to satisfy that criteria under a facts and circumstances test through certification by the EPA, an appropriate state government authority, or through a rigorous nongovernment organization such as the ISO certification process. The regulatory grant of authority under section 45Q(f) is broad, and the Treasury Department should exercise its broad authority under section 45Q(f) to ensure that its regulations provide clarity on what will be considered a secure geological formation but then provide a facts and circumstances test that could be utilized for potential future developments.

As to the second bulleted item, we recognize that the Treasury Department has a legitimate concern that adequate proof should exist that the sequestered carbon oxide has been appropriately secured before a tax credit is allowable under section 45Q. The Treasury Department also is right to understand that other agencies or nongovernmental organizations are likely better positioned to address the specific technical issues related to whether the captured carbon molecules have been stored in a secure geological formation. However, even though the Treasury Department and the IRS need administrable regulations on issues outside of its areas of particular expertise, the regulations nevertheless should take a balanced approach. As long as adequate proof of sequestration into a secure

[14] See International Organization for Standardization, Carbon dioxide capture, transportation and geological storage — Carbon dioxide storage using enhanced oil recovery (CO2-EOR), ISO/FDIS 27916 (2018).

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geological formation exists, then the Treasury Department should not bar the allowance of a tax credit under section 45Q simply because of a procedural foot fault when the taxpayer has complied with the substantive directive to which section 45Q is aimed.

Thus, we believe that the government's disallowance of section 45Q tax credits in the fact pattern set forth in FSA 20183701f (May 3, 2013) is overly harsh if the facts in that ruling were such that the taxpayer could have demonstrated that the carbon dioxide had been sequestered into a secure geological formation. The fact that EPA had not pre-approved the taxpayer's sequestration plan as of the time of the taxpayer's filing of its tax return represents a "foot fault" that by itself should not bar the allowance of tax credits under section 45Q. To state that such proof must exist as of the time of the taxpayer's filing of the original tax return represents a procedural trap for the unwary that frustrates the legitimate goals of ensuring that a tax credit is provided to those taxpayers who in fact have substantively engaged in the activity that Congress desired to promote, namely the capture and sequestration of carbon oxide so that it does not become ambient. The intent of the statute and the public policy goal is to ensure that sequestered carbon oxide is placed in a secure geological formation. Certainly, confirmation from an agency with appropriate oversight should be obtained. However, conditioning the availability of the tax credit afforded under section 45Q upon the pre-approval by the EPA sets forth an extra compliance hurdle that potentially limits the tax credit benefits to taxpayers who have engaged in the activity that Congress desires to promote.

In our view, forthcoming regulations should provide a safe harbor that indicates that pre-approval from the EPA of the taxpayer's carbon sequestration plan and compliance with that pre-approved plan would provide certainty that the taxpayer's activities are compliant with section 45Q's substantive requirements, but that should not be the sole means of demonstrating compliance. Absent prior EPA approval of the taxpayer's carbon sequestration plan, the taxpayer should have the burden of proof to demonstrate that its captured carbon was sequestered into a secure geological formation under a facts and circumstances analysis. In this regard, the taxpayer should be given an opportunity to have a fact-finding by the EPA, state agency, or relevant nongovernmental agency to determine whether its carbon oxide molecules have been appropriately stored in a secure geological formation. If the taxpayer can satisfy this burden of proof under a facts and circumstances analysis that relies on the expertise of another agency, then the taxpayer should be afforded with an opportunity for such a determination as doing so allows the taxpayer the opportunity to claim the tax benefits that Congress intended to provide.

3. Recapture of Tax Credit. Pursuant to section 45Q(f)(4), taxpayers must recapture the benefit of any credit allowable under section 45Q(a) with respect to any qualified carbon oxide that ceases to be captured, disposed of, or used as a tertiary injectant in a manner consistent with the requirements of section 45Q.

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In Sec. 3.02 of Notice 2019-32, the government asks for comments on the applicable standard that should be utilized to determine whether and to what extent a tax credit should be recaptured. In addition, the government asked for comments specifically on rules for the determination of whether a formation is a secure geological storage when carbon oxide is used as a tertiary injectant.

In our view, the recapture period should simply be the normal period for the statute of limitations for a tax return plus any extensions.[15] The existing limitations period that generally applies to tax returns already provides an appropriate balancing of interest between the taxpayer's desire for repose and the government's need for ensuring appropriate enforcement.

In terms of the standards for determining recapture, we note that the EPA is charged with oversight that includes the ongoing monitoring, reporting, and validation over whether carbon oxide has been captured and for determining whether the sequestered carbon oxide has ceased to be securely stored. Thus, the IRS should look to the EPA or, where appropriate, to a state agency charged with oversight over such facilities. The EPA or appropriate state agency with oversight over these formations should provide safe harbor guidance on the anticipated amount of carbon oxide that is likely to be re-released back into the atmosphere in a tertiary development project. Thus, once the EPA has certified that a formation is a secure formation and provided guidance on what amount of carbon oxide molecules is likely to be re-released in the context of tertiary activities, then that determination should be presumptively accepted pending contrary evidence provided either by the taxpayer, the EPA, or state agency that exercises oversight over the sequestration of carbon oxide.

However, notwithstanding the above safe harbor, the taxpayer should be able to provide scientific evidence to either the EPA or appropriate state regulatory agency to demonstrate that the amount of carbon oxide that has actually been re-released is less than what the EPA safe harbor guidelines anticipated for the taxpayer's tertiary activities. Thus, in our view, the regulations should provide a safe harbor to which taxpayers can rely and then provide a mechanism for taxpayers to demonstrate that the actual carbon oxide release was in fact lower than the safe harbor threshold.

4. Definition of Terms: Carbon Capture Equipment and Qualified Facility. In Sec. 3.03 of Notice 2019-32, the government asked whether guidance is needed to further clarify terms and definitions appearing in section 45Q, such as carbon capture equipment, qualified

[15] See §6501(a).

carbon oxide, direct air capture facility, qualified facility, tertiary injectant utilization, or lifecycle greenhouse gas emissions.

We believe that clarification of these terms would be beneficial to both taxpayers and the government. In particular, the government should clarify the definition of "qualified facility" and "carbon capture equipment." A "qualified facility" is the industrial facility that is the source of the qualified carbon oxide and will often be owned by a party that is different from the taxpayer that will own the "carbon capture equipment." The IRS definition should understand that there is likely to be many different types of facilities and that facilities may have been retrofitted over time. The government should then make clear that the relevant party entitled to claim a tax credit under section 45Q is the taxpayer who owns the carbon capture equipment whether or not that party owns the qualified facility that emitted the carbon oxide.

5. Party Entitled to the Credit. The reality for many arrangements is that multiple parties will be involved in the carbon sequestration process. Except in the case of the largest companies, it is likely to be the case that a carbon sequestration activity will include differing parties that perform one or more of the following functions: (a) one party will emit the carbon oxide at a qualified facility, (b) another party will invest in carbon capture equipment at that facility and will separately own and operate that carbon capture equipment to capture carbon oxide molecules (hereafter referred to as the "Carbon Capture Partnership"), (c) a different party may agree to transport the sequestered carbon oxide molecules through its pipeline to a storage facility, and (d) a final party may own a storage facility and will take custody over the transported captured carbon oxide molecules and then inject those molecules into a secure geological formation.

   Throughout each of these steps in the carbon capture and sequestration supply chain, contractual arrangements will likely exist that set forth the performance obligations of each party and the representations and warranties for each party in terms of its duty of care for ensuring that the captured carbon oxide molecules are not re-released back into the atmosphere. Investors into the entity that owns the carbon capture equipment may well be financial investors that provide the capital for the activities performed by the Carbon Capture Partnership but otherwise may be passive partners. Ownership of the carbon oxide molecules may well pass from the Carbon Capture Partnership to the next party in the supply chain indicated above. In other arrangements, the carbon oxide molecules may remain owned by the Carbon Capture Partnership throughout the transportation and/or injection process and the role of intervening parties may simply be to act as agents with respect to the transport and injection of the carbon oxide molecules for and on behalf of the Carbon Capture Partnership. And, with respect to the carbon oxide molecules that are transported to the injection site, the carbon oxide molecules may be commingled with other carbon oxide molecules that were captured elsewhere by a different Carbon Capture

Partnership, and this commingling would necessarily occur if the carbon oxide molecules are placed into a common carrier pipeline for transportation to a common disposal site.

Forthcoming regulatory guidance needs to be nuanced enough to envision these expected and recurring business complexities but at the same time must also be transparent enough to be administrable for taxpayers and the government.

In Sec. 3.06, 3.07, and 3.09 of Notice 2019-32, the government requested comments on the following:

> .06 Under § 45Q(f)(3)(A), the credit is attributable to the person that captures and physically or contractually ensures the disposal, utilization, or use of the qualified carbon oxide as a tertiary injectant. The Treasury Department and the IRS seek comments on the types of contractual arrangements that investors anticipate with parties who capture or dispose or utilize qualified CO. What are common terms of contracts ensuring the disposal, utilization, or use of qualified CO as a tertiary injectant? What should result if such terms are determined to be insufficient?
> .07 What factors should be considered in determining the time and manner of the election under § 45Q(f)(3)(B) to transfer the § 45Q credit to a person that disposes of the qualified carbon oxide, utilizes the qualified carbon oxide, or uses the qualified carbon oxide as a tertiary injectant? If such an election is made, what issues should be considered regarding the transfer of the § 45Q credit?
> .09. Is guidance needed concerning structures in which project developers and participating investors would be respected as partners in a partnership generating a § 45Q credit? Further, is guidance needed on allocating the credit and recapture of the credit among the partners in a partnership?

We view each of the above three requests as presenting a common issue of what substantive requirements must be satisfied for a taxpayer to be entitled to the tax credit allowed under section 45Q, and so forthcoming guidance should designate one party in these complex supply chains that by default is entitled to the benefits of the tax credit afforded by section 45Q. We recognize that the government needs clear rules so that multiple parties do not submit competing claims of entitlement over the same section 45Q tax credit for the sequestered carbon oxide molecules. We also recognize that several parties in this supply chain have contributed significantly towards the ultimate sequestration of the capture carbon oxide molecules.

In our view, we believe that the government should provide clear guidance starting with when an investor into the Carbon Capture Partnership will be respected as a true partner and then extends that guidance to identifying which party in the entire carbon sequestration supply chain is entitled to claim the section 45Q credits. We believe that such guidance should follow the below framework.

First, as to an investor's right to claim an allocable share of tax credits as a partner in a Carbon Capture Partnership that invests and operates carbon capture equipment, the government needs to provide guidance on when it will respect that financial investor's role as a partner in the Carbon Capture Partnership and when the government will claim that the financial investor is not entitled to be treated as a partner in the Carbon Capture Partnership. To begin with, there is a concern about whether a tax partnership can exist when no expected revenue is going to be generated from the Carbon Capture Partnership's activities. For situations where carbon capture equipment is constructed and operated and the eventual disposition of the sequestered carbon is into a nontertiary formation, the Carbon Capture Partnership will make capital investments into carbon capture equipment and then will incur costs to operate that equipment and then will likely have to pay other counterparties for the cost of transporting and disposing of the captured carbon oxide molecules. The Carbon Capture Partnership may have no revenues from these operations in the context envisioned by section 45Q(a)(3). The only financial benefit derived from the Carbon Capture Partnership in the nontertiary context is again solely the tax credits allowable under section 45Q.

The Supreme Court has indicated that the existence of a partnership for tax purposes depends upon a consideration of all of the facts and circumstances and a determination of whether the parties acted in good faith and with a business purpose to join together to conduct the business of the enterprise.[16] Unfortunately, the determination of whether a valid partnership arrangement exists is one where the courts have used differing tests.[17] For the government's part, the IRS has announced a fifteen factor test for determining whether a partnership is one that would be respected for tax purposes.[18] What is more, the Treasury Department has broad authority to disregard partnership transactions that violate the goals and purposes of subchapter K.[19] The government therefore needs to provide guidance on how a partnership that incurs only costs and does not expect to generate positive revenue nevertheless would be deemed to be a valid partnership that is engaged in an ongoing business for the purpose that Congress designed it to conduct. Congress wants to create a market for carbon capture activities and not simply apply a tax regime on an existing market that exists for nontax reasons. In important instances, section 45Q is attempting to create a market where none existed before. This reality has profound

[16] See Commissioner v. Culberton, 337 U.S. 733 (1949).
[17] See Bradley T. Borden, *The Federal Definition of Tax Partnership*, 43 HOUS. L. REV. 925 (2006).
[18] See Rev. Proc. 2002-22, 2002-1 C.B. 733.
[19] See Treas. Reg. §1.701-2.

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implications as to the manner in which general tax principles are to be applied in the unique context of section 45Q.

Second, as an additional issue, the government should also define what level of risk is necessary for an investor to possess in order to be respected as a partner in a Carbon Capture Partnership. In this guidance, the government needs to recognize that the Carbon Capture Partnership will receive contractual protections from the downstream counterparties who take-over responsibility for transporting and disposing of the captured carbon oxide molecules and for its injection into a secure geological formation. Those contractual protections may also provide indemnity protection if the downstream counterparty fails to act in accordance with their contractual obligations. Those contractual arrangements may also include audit and inspection rights along with the right to receive documentation to indicate that the carbon oxide molecules were properly sequestered into a secure geological formation.

The government's successful litigation in *Historic Boardwalk Hall, LLC v. Commissioner*[20] creates concern over what residual partner-level risk must exist for an investor to be considered a partner in a partnership that conducts activities entitled to obtain a tax credit. In *Historic Boardwalk Hall, LLC v. Commissioner*, the government successfully disallowed rehabilitation tax credits otherwise allowable under section 47 that had been allocated to an investor in a partnership because the court found (at the government's urging) that the particular investor (Pitney Bowes) lacked a meaningful stake in either the success or failure of the underlying partnership activities and thus was not a bona fide partner in that endeavor; thus even though the underlying partnership had engaged in the rehabilitation activities that were intended to be incentivized by Congress, the benefits of the section 47 rehabilitation tax credits were disallowed as the investor in that partnership had simply purchased tax credits and was not a bona fide partner with business risk. The IRS has cited its victory in *Historic Boardwalk Hall* as a basis to disallow monetization structures utilized in the context of section 45 production credits, claiming that the monetization strategies that were posited in the rulings had crossed a line so as to cause the investor to not be viewed as a partner with business risk but simply was an investor who had attempted to purchase tax credit benefits.[21] The investor, according to the government's audit position in those rulings, must be in form and substance a partner with an appropriate interest in the partnership's business activities in order to be entitled to claim the tax credits.

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[20] See Historic Boardwalk Hall, LLC v. Comm'r, 694 F.3d 425, 462–63 (3d Cir. 2012).
[21] See TAM 201729020 (July 21, 2017) (concluding that the parties structured a financial transaction in which Taxpayer facilitated the improper sale of §45 tax credits to an investor with the consequence that the Investor was not entitled to claim the tax credits arising from partnership's activity).

The government's victory in *Historic Boardwalk Hall* had a chilling effect on the tax credit market,[22] and so the IRS in Rev. Proc. 2014-12 provided a safe harbor for when it would not contest an outside investor's entitlement to claim tax credits as a partner in a partnership that conducts the credit-eligible activities.[23] Given that the government has already asserted that its litigating position in *Historic Boardwalk Hall* would be applicable to investors that seek tax credits outside the context of the tax credits that were the subject of that particular litigation, the Treasury Department should expand its safe harbor guidance set forth in Rev. Proc. 2014-12 to provide specific safe harbor guidance for section 45Q so that a partner's status as a partner in a Carbon Capture Partnership is respected and the allocation of tax credits to that partner would not be challenged. As part of that expanded guidance, in terms of making this safe harbor applicable to carbon sequestration, the government should provide affirmative guidance on what contractual protections can exist between the Carbon Capture Partnership and a party that is obligated to assume responsibility for transporting the captured carbon oxide and then to dispose of it into a secure geological formation. Specifically, the IRS should affirmatively state that a prohibited guarantee does not exist if the party responsible for disposing of the carbon oxide warrants that it did in fact dispose of the carbon oxide in a secure geological formation and agrees to indemnify the Carbon Capture Partnership if the EPA or another appropriate agency contests that determination. In a vast number of scenarios, it is unlikely to be the case that the Carbon Capture Partnership will own a secure geological formation. Thus, in many situations, the Carbon Capture Partnership will ask for assurances that the party that will inject the carbon oxide molecules does in fact own a secure geological formation. Contractual representations, warranties, and indemnities with respect to the status of the formation should not create a concern under *Historic Boardwalk Hall*, and forthcoming regulations should make this point plain.

Third, in terms of which party should be entitled to claim the benefits of section 45Q, we believe that forthcoming regulations should provide a default rule that the owner of the carbon capture equipment is the appropriate party to claim the tax credit under section 45Q. However, forthcoming regulations should allow the Carbon Capture Partnership to elect to transfer or assign some or all of the section 45Q credit in whole or in party to another party in the carbon capture supply chain if both parties make a joint election that is binding on both parties. The IRS should develop a form that would be attached to the tax returns of both parties that would set forth how the tax credit would be claimed by each of the parties, and the parties should be bound by the allocation set forth in the joint form. The joint filing of duplicate forms with tax returns of both of the relevant taxpayers would provide the IRS with the means to confirm that the transfer of any section 45Q credit to the other party was

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[22] See Richard M. Lipton, New Rehabilitation Credit Safe Harbor—Limiting Historic Boardwalk Hall, 120 J. Tax'n 128 (March 2014).
[23] See Rev. Proc. 2014-12, Sec. 4, 2014-1 C.B. 415.

appropriate and each party consistently reports its share of the tax credits in accordance with the joint election. In our view, this assignment of credit should be an annual election. But importantly, absent a joint election to which the Carbon Capture Partnership joins in making, the Carbon Capture Partnership should be designated as the party that would be entitled to the full amount of the section 45Q credit under the default rule.

The above default rule and election procedure, in combination, would ensure that the Carbon Capture Partnership would be entitled to claim the tax credit allowable under section 45Q. The above framework would provide certainty under the default rule that the partners in the Carbon Capture Partnership would not be disgorged of the section 45Q credit absent the consent of the Carbon Capture Partnership. The ability to assign a portion of the section 45Q credits would allow other parties in the supply chain to obtain value for their participation and contribution without requiring that compensation to be in the form of cash. But having said all of this, the above framework also provides a clear and administrable framework for determining the party entitled to the credit and provides a mechanism to ensure that parties take consistent tax positions with respect to their share of the tax credit.

6. Beginning of Construction. To be eligible for the section 45Q benefits, taxpayers must commence construction on qualifying projects before January 1, 2024. In Sec. 3.08 of Notice 2019-32, the government asks whether guidance is needed on what constitutes beginning of construction.

   The Treasury Department and the Service have published extensive guidance on what constitutes the beginning of construction of a qualified facility under section 45(d). In the context of section 45(d), the government provided two tests for determining when construction of a qualified facility has begun.[24] Under the first test, the beginning of construction can be commenced by beginning physical work of a significant nature (Physical Work Test). Alternatively, under the second test, a taxpayer may establish the beginning of construction by meeting the safe harbor provided (Five Percent Safe Harbor). Both methods require that a taxpayer make continuous progress towards completion once construction has begun (Continuous Construction Test). In the section 45(d) context, the government supplemented these tests with a safe harbor (the Continuity Safe Harbor) that addresses what level of continuous activity must be met in order for construction to be viewed as ongoing.[25] In 2014, the government provided further clarifications to the Physical Work Test.[26] And, in 2015, the government extended the period for the Continuity Safe Harbor by an additional year.[27] Also in 2016, the government further modified the

[24] See Notice 2013-29, 2013-1 C.B. 1085.
[25] See Notice 2013-60, 2013-2 C.B. 431.
[26] See Notice 2014-46, 2014-2 C.B. 520.
[27] See Notice 2015-25, 2015-1 I.R.B. 814.

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Continuity Safe Harbor and the Physical Work Test and provided that the Continuity Safe Harbor Test would be presumptively met if a facility is placed in service by the calendar year that is no more than four calendar years after the calendar year during which construction of the facility began.[28] In 2017, the government further modified the guidance it provided as to the Continuity Safe Harbor and modified other guidance as well.[29]

The above brief review of the government's guidance in the section 45(d) context demonstrates that the government has already expended considerable effort to set forth what constitutes the beginning of construction in an analogous tax credit situation. In our view, forthcoming regulations should simply rely on that existing guidance and extend that guidance to the section 45Q context. We commend the government for the diligence and detailed work it has already incurred in order to provide helpful and clear guidance for taxpayers.

However, we do note two areas where section 45Q should have differing guidance. In our view, the Continuity Safe Harbor should envision a longer period of time than just the four-year period specified in Notice 2016-31 when applied to section 45Q projects. The development of carbon sequestration equipment is ongoing and evolving, and prototypes are being developed and tested. Depending on the type and nature of the carbon capture equipment, these installation projects may be more extensive and require a longer construction period than would normally exist for a project contemplated under section 45(d). Thus, we would encourage the government to allow for a longer presumptive period under the Continuous Safe Harbor Test for a project constructed under the auspices of section 45Q than is currently envisioned in the section 45(d) guidance. As a second point, we think that the Continuity Safe Harbor Test should contemplate that a delay in a project due to the lack of an immediately available pipeline connection should be an excludible disruption in the context of a section 45Q project.[30] Carbon capture equipment will need to be connected to a pipeline that is capable of transporting the captured carbon oxide molecules to an injection site. The timing for construction and completion of pipelines might be subject to unexpected delays due to permitting and other matters that are outside the control of the entity that invests in the carbon capture equipment. Section 4.02 of Notice 2016-31 contemplates various excludible disruptions, and that guidance should be expanded to include delays or disruptions in construction caused due to the lack of an immediately available pipeline connection.

[28] See Notice 2016-31, 2016-1 C.B. 1025.
[29] See Notice 2017-04, 2017-4 I.R.B. 541.
[30] See Notice 2016-31, Sec. 4.02, 2016-1 C.B. 1025.

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We commend the Treasury Department and the IRS for its detailed list of questions in Notice 2019-32. That notice evidences a real desire by the government to grapple with the substantive questions that must be addressed, and the notice on its face demonstrates that the government has given considerable thought to the policy issues that are at stake. We appreciate the opportunity to have provided comments as part of the Treasury Department's and IRS's regulatory guidance process. Should you have any further questions or would like to discuss our comments more thoroughly, please do not hesitate to context the signatories of this letter.

Sincerely,

Bret Wells

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July 4th, 2019

Via Electronic Transmission

CC:PA:LPD:PR (IRS Notice: 2019-32)
Room 5203
Internal Revenue Service
P.O. Box 7604
Ben Franklin Station
Washington, DC 20044

Re: Comments on Notice 2019-32, Credit for Carbon Dioxide Drawdown and Carbon Oxide Sequestration

To Whom It May Concern,

On behalf of UH Energy we are pleased to submit comments in support of Notice 2019-32 for the Request on Comments on Credit for Carbon Dioxide Drawdown and Carbon Oxide Sequestration.

UH Energy is an umbrella for efforts across the University of Houston system to position the university as a strategic partner to the energy industry by producing trained workforce, strategic and technical leadership, and research and development for needed innovations and new technologies. We're located in the energy capital of the world and believe that the section 45Q credits, in their current form, will transform the landscape for the carbon management industry in the US. However, for effective and at-scale carbon dioxide drawdown it is essential to develop global solutions. Our recommendations of treating carbon dioxide as a global commodity and adopting a dual-use shipping system for its multinational trade can position US as a world leader across the carbon management, enhanced oil recovery for hydrocarbon resources, and marine transport industries.

We thank you for your time and for considering our recommendations for Notice 2019-32. We will be happy to provide further clarifications or comments if you have any questions.

Sincerely,

Ramanan Krishnamoorti
Chief Energy Officer
UH Energy, University of Houston

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Executive Summary
The current status of considering and treating carbon dioxide (CO_2) as a waste product is hindering large scale deployment of carbon management. In contrast, CO_2 is, in fact, a valuable commodity with multiple uses and applications that can close the carbon cycle in a manner that is technologically feasible, commercially viable while being self-sustaining in the long-term. However, the commercially viable sources and uses of CO_2 are in geographically and internationally disparate areas. Moreover, since CO_2 is an atmospheric component and rapidly equilibrates across the globe, the capture of CO_2 in any part of the world must be considered as a valuable resource to address carbon management. Therefore, we suggest that multinational CO_2 trade should be encouraged and incentivized to match commercially viable sources and uses.

Among the many uses of CO_2 is its ability to act as a tertiary injectant to enhance oil and gas production. However, not all sites of oil and gas production are viable for tertiary recovery. Identifying sites that are mature and past primary and secondary methods of recovery is crucial for optimized source to use matching for CO_2-based enhanced oil recovery (EOR). Having identified a viable geological site for use of CO_2, it is important to establish the miscibility and wettability of the CO_2 to achieve higher recovery ratios and to ensure that CO_2 does not leak back to the surface. For CO_2-based EOR that warrants these targets, CO_2 has to be available where it's needed. The cost of capture is a critical determinant for CO_2 availability, which in turn depends on the concentration of CO_2 at the capture site and the source of the emissions at the said site. Point source capture sources such as fertilizer plants offer the lowest cost with the highest concentration of CO_2 in the captured stream; while distributed air capture has the lowest concentration and highest costs of capture.

The last and critical link between sources and uses is the transportation of CO_2. CO_2 can be moved between sources and sinks over the lifetime of projects only if efficient, effective, and low cost transportation options exist. To debottleneck the challenges of high costs and risks for the transportation of captured CO_2 multinational trade of CO_2 needs to be addressed. Section 45Q provides the necessary pathways to accelerate the same.

We have examined the commercial viability of dual-use shipping system utilizes vessels which transport exported LNG from the US and carry captured CO_2 on their return journey from the destination of delivery. This can expedite long-distance transport and multinational trade of CO_2 without the costs and risks of conventional pipeline-based transport. This CO_2 can be utilized as a tertiary injectant in amenable fields in the offshore US where CO_2 for EOR is required but scarce, and pipelines are financially intensive or their deployment is fraught with strategic risks. The advantages of a dual-use shipping system are manifold, and discussed in detail in the response.

Background

Reforms to tax credits for carbon dioxide sequestration were passed by Congress in early 2018. Through broad bipartisan support as part of a larger bill- the FUTURE Act (Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions Act), the reforms are more commonly known as the 45Q tax credit. They are aimed at driving investment in large-scale commercial deployment of carbon management methods. The reformed section 45Q credits are characterized by the following-

- Increases the credit amounts for qualified facilities
- Expands the end-uses for which captured CO_2 may be used
- Modifies the requirements for the amount of CO_2 that must be captured
- Allows certain new industrial facilities, including direct air capture facilities to qualify for the credit if construction begins before 2024
- Allows qualified facilities to claim the credit for 15 years, beginning on the date the equipment was originally placed in service

CO_2 as a global commodity - Why moving CO_2 from one country to another should qualify for Section 45Q?

Curbing emissions as well as removing carbon from the atmosphere is critical for the mitigation of anthropogenic emissions. Although, without large-scale deployment of carbon management techniques, which allow carbon to be a profitable commodity as against its current status as a waste product, the mitigation of emissions at scale with climate targets is unlikely.

Countries vary in their geological storage capacity or the ability to utilize CO_2 as a tertiary injectant due to limited viable fields. Many nations have sequestration potentials well over their rates of emission; while other high emitting nations which are projected to emit at current or higher levels lack comparable capacity for the sequestration of these emissions, even if they were to capture their emissions. Resultantly, it would either be technologically infeasible to sequester the captured carbon from these countries or be commercially unviable to continue capturing CO_2 in the long run. Allowing carbon to be traded as a physical commodity between nations resolves this challenge. Moreover, carbon dioxide takes about two years to level out and disperse globally in the atmosphere. Moving carbon through trade from one country to another, which would otherwise equilibrate through the global atmosphere regardless, and sequestrating it can mitigate the imbalance between sources of emissions and viable carbon sinks amongst different nations. Even though sources and at-scale sinks are present, the predominant challenge in connecting the two has been the high cost of transportation and the risks involved in deploying dedicated pipeline infrastructure for long-distance transport, especially for offshore pipelines.

Why is dual-use shipping important?
As discussed above, transporting CO_2 via pipelines has proven expensive or prohibitive for projects. The current pricing structure suggests that transport costs constitute 12-16% of the total cost of carbon management projects that are based on carbon capture, utilization, and storage techniques for point-source capture. However, these estimates are highly project specific; depending on the distance and mode of delivery the costs can escalate to about 40% of total costs for some cases. Adopting a dual-use shipping mechanism can eliminate a bulk of this cost to allow economically feasible transportation of CO_2 over long distances. Dual-use shipping utilizes vessels that transport LNG one way and carry captured CO_2 on their return journey, allowing the CO_2 to be used for EOR at an appropriate location in proximity to the LNG source site. Specifically for the purpose of section 45Q, transporting CO_2 via dual-purpose ships that carry LNG from the US and CO_2 back to the US on its return journey will allow the CO_2 to be then utilized as a tertiary injectant for enhanced oil recovery (EOR). This would-

- Eliminate the cost of operating an empty ship on its return journey
- Optimize sources to use coordination and transporting CO_2 over long distances at a fraction of the current costs
- Accelerate the development of multiple parallel projects based on demand and supply and eliminate the need for dedicated infrastructure that results in sunk costs at the end of the project's lifetime
- Provide a market for CO_2 mitigation
- Provide secure and permanent locations for utilizing CO_2
- Transform the pricing structure for carbon management by eliminating any potential regulatory support for transportation of CO_2 and focus regulatory support for carbon capture and carbon utilization and storage.

With fuel costs making up about 60% of operational expenses, an empty vessel on the return journey is a lost commercial opportunity. Fuel consumption for a cargo-free vessel is only about 25%-30% less than that for a laden LNG vessel. For a 250,000 m3 LNG vessel that consumes about 220 tons of bunker fuel per day. If the vessel were to be used for dual-use shipping and forgo the 30% reduction in fuel consumption by loading it with CO_2 – at $440 per ton for bunker fuel and assuming a one-way journey of 14 days–more than 300,000 tons of CO_2 could be transported at $1.5 per ton. From a logistical perspective, CO_2 is often produced at points close to LNG offloading, for example at refineries or chemical plants in close proximity to the shore. On the other hand, CO_2 demand for EOR is close to sources of natural gas as well. At this price of transportation, logistical convenience, matching supply with demand, and with the added value of fossil fuel recovered through EOR, dual-use shipping can accelerate large-scale deployment of carbon management. Global energy related CO_2 emissions for 2018 were ~33 Gt. If even a tenth of this were to be utilized for EOR through multiple parallel projects, the revenue from additional oil produced (at an average of 2.5 barrels per ton of CO_2 and priced at $59 per barrel) is a robust

$4.4 trillion dollars in revenue for the industry, along with carbon-negative fossil fuel production. This can advance multi-national partnerships between

- Those who produce fossil fuels in the US and export LNG outside of the US
- Those who capture carbon outside of the US and import LNG from the US.

What does utilization mean for carbon management?

Geological storage without utilization, which does not result in a commercial end-use of carbon dioxide, would remain a cost center despite the credits applied through section 45Q. In contrast, carbon management can be made a commercially viable and self-sustaining opportunity only through utilization. While the carbon management industry is not mature enough to settle on a single end-use approach for now, utilization provides pathways for carbon management which are environmentally safe and benign, allows trade beyond small niche markets, and guarantee long-term stability. Hence, the carbon cycle can be closed in a commercially and environmentally profitable manner. Trading as a commodity would also make assigning ownership, liability, and benefits more efficient since firmly established and well-documented international trade rules will apply to the movement of CO_2 via dual-use vessels.

What would this mean for carbon management?

A dual-use shipping system enables a least cost pathway for advancing carbon management by creating modifications within existing frameworks and infrastructure. The system also relies on mature industry experience from the oil and gas industry for the utilization of CO_2 as a tertiary injectant for EOR, and marine industry for transport while notably advancing the relatively immature carbon capture industry. In the process, carbon is traded as a profitable commodity, which would not need incentives in the long-run.

Recommendations- What needs to be addressed for Section 45Q?

We need to consider multi-national trade and storage as part of the guidelines for Section 45Q. For this:

- The definition of qualifying carbon dioxide and qualifying facility need to include specifications on imported CO_2 as well as on applicable dollar amount and payout mechanism for the said CO_2.
- Since the qualifying facility in a dual-use shipping system will be located outside of the US, joint ventures and MoU which have a US based partner should qualify for the credits as applicable in Section 45Q. The definition of qualifying facility should also be expanded to include provisions for the applicable dollar amount to be shared amongst multiple parties and/or investors. Further guidance is needed on the structure of such partnerships and potential contractual agreements.

- Standards established by the World Trade Organization (WTO) can be employed to supplement determining the amount of qualified carbon dioxide when transported using dual-use vessels. Inventory analysis and management are established marine industry practices which can supplement lifecycle greenhouse emissions analysis under section 45Q. This would require the expansion of reporting guidelines to include WTO standards.
- Greenhouse Gas Reporting does not include guidelines on utilization through means other than EOR. Guidance is required on how qualified carbon, qualified facility, and subsequent credits be determined for utilization processes as mentioned in section 45Q(f)(5)(A).

Appendix A

Terms and Definitions
For the purpose of this document,
1)The term "qualified carbon oxide" means—
(A) Any carbon dioxide or other carbon oxide which
(i) Is captured from an industrial source by carbon capture equipment which is originally placed in service on or after the date of the enactment of the FUTURE Act of 2018,
(iii) Is measured at the source of and verified at the point of disposal, injection, or utilization
Or
(B) in the case of a direct air capture facility, any carbon dioxide which
(i) Is captured directly from the ambient air
(ii) Is measured at the source of capture and verified at the point of disposal, injection, or utilization.

2) The term "taxpayer" means any person subject to a tax under the applicable law.

3) The term "tertiary injectant" means any injectant, other than a hydrocarbon injectant which can be recovered which is used as a part of a tertiary recovery method. The term "hydrocarbon injectant" includes natural gas, crude oil, and any other injectant which is comprised of more than an insignificant amount of natural gas or crude oil.

5) The term "calendar year" means a period of 12 months ending on December 31.

6) The term "direct air capture facility" means any facility which uses carbon capture equipment to capture carbon dioxide directly from the ambient air.

7) The term "applicable dollar amount" shall be an amount equal to—
(i) for any taxable year beginning in a calendar year after 2016 and before 2027—
a) the dollar amount established by linear interpolation between $22.66 and $50 for each calendar year during such period
b) the dollar amount established by linear interpolation between $12.83 and $35 for each calendar year during such period, and

(ii) for any taxable year beginning in a calendar year after 2026—
(a), an amount equal to the product of $50 and the inflation adjustment factor for such calendar year determined under section 43(b)(3)(B) for such calendar year, determined by substituting "2025" for "1990", and (II) an amount equal to the product of $35 and the inflation adjustment factor for such calendar year determined under section 43(b)(3)(B) for such calendar year, determined by substituting "2025" for "1990".

8) The term Class VI wells means wells that are used to inject CO_2 into deep rock formations. This long-term underground storage is called geologic sequestration. Geologic sequestration refers to technologies to reduce CO_2 emissions to the atmosphere and mitigate climate change.

9) Greenhouse Gas Reporting Rule
The US EPA mandates reporting of greenhouse gases (GHG) from sources that emit 25,000 metric tons or more of carbon dioxide equivalent (CO_2e) per year in the United States. However, the rule, 40 CFR 98, published on October 30, 2009, does not include smaller sources or sectors such as agricultural or land use change. The program is more commonly referred to as the Greenhouse Gas Reporting Program (GHGRP) and is aimed at providing a comprehensive understanding of the sources of GHGs and to guide development of policies and programs to reduce emissions. 40 CFR 98 applies to direct greenhouse gas emitters, fossil fuel suppliers, industrial gas suppliers, and facilities that inject CO_2 underground for sequestration or other reasons.

According to the EPA, suppliers of CO_2 (subpart PP) covers facilities that capture CO_2 from industrial sources and processes or extract it from natural CO_2-bearing formations for supply into the economy. Underground injection of CO_2 (subpart UU) covers facilities that inject CO_2 underground for enhanced oil and gas recovery (EOR), acid gas injection/disposal, carbon storage research and development (R&D), or for any other purpose other than geologic sequestration. Geologic sequestration of CO_2 (subpart RR) provides a mechanism for facilities to monitor and report to EPA amounts of CO_2 sequestered. Facilities submit a plan for monitoring, reporting and verifying CO_2 sequestered underground. Once the plan is approved, facilities report basic information on CO_2 received for injection, data related to the amounts of CO_2 sequestered, and annual monitoring activities.

For subpart PP, suppliers of CO_2 consist of the following:

- Facilities with production process units that capture and supply CO_2 for commercial applications that capture and maintain custody of a CO_2 stream in order to sequester or otherwise inject it underground.
- Facilities with CO_2 production wells
- Importers of bulk CO_2, if total combined imports of CO_2 and other GHGs exceed 25,000 tons of CO_2 equivalent (CO_2e) per year.
- Exporters of bulk CO_2, if total combined exports of CO_2 and other GHGs exceed 25,000 tons CO_2e per year.

This source category does not include entities that store CO_2 through geologic sequestration or above ground storage; use CO_2 in enhanced oil and gas recovery; transport or distribute CO_2; purify, compress, or process CO_2; or import or export CO_2 in equipment.

The subpart RR source category comprises a well or group of wells that inject a CO_2 stream for long-term containment in subsurface geologic formations. All wells permitted as Class VI by the

Underground Injection Control (UIC) program meet the definition of this source category. Under subpart RR, facilities that conduct geologic sequestration by injecting CO_2 for long-term containment in subsurface geologic formations are required to:

- Report basic information on CO_2 received for injection.
- Develop and implement an EPA-approved site-specific MRV plan
- Report the amount of CO_2 geologically sequestered using a mass balance approach and annual monitoring activities.

Geologic sequestration research and development (R&D) projects will be granted an exemption from subpart RR. A project is eligible for the subpart RR R&D exemption if it will investigate practices, monitoring techniques, injection verification or is engaged in other applied research that will enable safe and effective long-term containment of a CO_2. To receive a subpart RR R&D exemption, the reporter must submit to EPA information on the planned duration of CO_2 stream in subsurface geologic formations, including research conducted as a precursor to long-term storage. Facilities that receive an R&D exemption from subpart RR are not exempted from any other source category of the GHG Reporting Program including subpart UU.

Under subpart UU, all other facilities that inject CO_2 underground such as for enhanced oil and gas recovery or any other purpose, are required to:

- Report basic information on CO_2 received for injection
- Facilities that report under subpart RR for a well or group of wells are not required to report under subpart UU for that well or group of wells.
- Facilities that conduct enhanced oil and gas recovery are not required to report geologic sequestration under subpart RR unless
    - the owner or operator chooses to opt-in to subpart RR

      or,
    - the facility holds a UIC Class VI permit for the well or group of wells used to enhance oil and gas recovery
- Geologic sequestration R&D projects will be granted an exemption from subpart RR. Projects receiving a subpart RR R&D exemption are required to report basic information on CO_2 received under subpart UU.

11) Monitoring, Reporting, and Verification Plan (MRV Plan)
Facilities that are subject to Subpart RR and are issued a final Underground Injection Control (UIC) permit (any class) on or after January 1, 2011 are required to submit a Certificate of Representation 60 days prior to submission of a proposed Monitoring, Reporting, and Verification (MRV) plan or Research and Development (R&D) project exemption request.

12) The term "carbon management" means human efforts to reduce anthropogenic carbon dioxide from the atmosphere, and permanently and safely sequester it.

How does the credit apply?
The value of the credit that can be claimed is based on:

- Method of use and disposal of qualified carbon
- Date of carbon capture equipment is put on service

For facilities placed in service prior to February 9, 2018, credits can be claimed by those who capture qualified carbon oxide from a qualified facility in a taxable year beginning after October 3, 2008, and meet all of the other requirements of section 45Q. For qualified facilities placed in service after February 8, 2018, the credit is available to those who own the carbon capture equipment and meet all of the other requirements of section 45Q.

For carbon capture equipment originally placed in service at a qualified facility before February 9, 2018,

(i) the credit amount is either

(A) $20 per metric ton of qualified CO_2 and is captured and disposed of in secure geological storage and is not

(1) used as a tertiary injectant in a qualified EOR project and disposed of in secure geological storage
(2) utilized through
(i) the fixation of such qualified carbon oxide through photosynthesis or chemosynthesis, such as through the growing of algae or bacteria,
(ii) the chemical conversion of such qualified carbon oxide to a material or chemical compound in which such qualified carbon oxide is securely stored,
(iii) the use of such qualified carbon oxide for any other purpose for which a commercial market exists (with the exception of use as a tertiary injectant in a qualified enhanced oil or natural gas recovery project)

Or

(B) $10 per metric ton of qualified CO_2 and is captured by the taxpayer, used by the taxpayer as a tertiary injectant in a qualified EOR project, and is used as

(1) for a qualified EOR project and disposed of in secure geological storage
(2) utilized in a manner as described above in (A) (iii) (Section 45Q (f) (5))

ii) For any taxable year beginning in a calendar year after 2009, section 45Q provides for an equal amount of the product of the credit amount and the inflation adjustment factor for the said calendar year.

Ramanan Krishnamoorti

Ramanan Krishnamoorti holds the position of chief energy officer at the University of Houston since February 2013, leading the university's efforts to establish energy-centered partnerships on an industry and university level to address the world's most pressing energy challenges. He is a professor of chemical and biomolecular engineering and has courtesy appointments as a professor of chemistry and professor of petroleum engineering. Previously, until July 2017, Krishnamoorti served as Interim Vice Chancellor for Research and Technology Transfer for the UH System and Interim Vice President for Research and Technology Transfer for UH, a role he assumed in April 2015. In these roles he had oversight responsibilities for the Division of Research, and various centers and institutes that report to the Division of Research. During his tenure at the University of Houston, he has served as a department chair of the UH Cullen college of engineering's chemical and biomolecular engineering department, and associate dean of research for engineering,

Krishnamoorti obtained his bachelor's degree in chemical engineering from the Indian Institute of Technology Madras and doctoral degree in chemical engineering from Princeton University in 1994.

Chairwoman FLETCHER. Thank you, Dr. Krishnamoorti.
Dr. Long?

TESTIMONY OF DR. JEFFREY LONG, FACULTY SENIOR SCIENTIST, MATERIALS SCIENCES DIVISION, LAWRENCE BERKELEY NATIONAL LABORATORY

Dr. LONG. Chair Fletcher, Ranking Member Weber, distinguished Members of the Committee, thank you for inviting me. My name is Jeffrey Long, and I'm the Faculty Senior Scientist at Berkeley Lab and a Professor at the University of California-Berkeley.

Fossil fuels will continue to supply the majority of global energy for many years to come, making it crucial that we invest in carbon capture technologies that will stem the buildup of greenhouse gases in our atmosphere. Support for basic scientific research plays a vital role in this quest. I will present a case study that underscores this point.

I'm a Director of a DOE-funded Energy Frontier Research Center, the Center for Gas Separations. Our goal is to create new materials that enable the efficient separation of gas mixtures, with particular emphasis on separations that reduce carbon dioxide emissions from power plants.

Toward this end, we synthesize new porous solids known as metal organic frameworks or, affectionately, MOFs. These materials behave as sponges capable of soaking up vast quantities of a specific gas molecule such as carbon dioxide. MOFs are particularly powerful for such applications owing to their controllable structure and their extremely high internal surface areas. Indeed, just one gram of a MOF in amounts similar to a cube of sugar can have a surface area greater than a football field.

Consequently, if designed properly, a small amount of a MOF can remove an enormous amount of carbon dioxide from the exhaust gas produced by fossil fuel combustion.

Working within our center, we serendipitously discovered that certain MOFs can capture carbon dioxide through an unprecedented switch-like mechanism. What's particularly exceptional about these materials is that CO_2 capacity is highly sensitive to temperature such that one can envision using them in a system where CO_2 can be captured and then released in pure form with minimal energy input.

It's important to emphasize that intensive collaboration among a team of talented scientists with diverse backgrounds, as well as access to unique federally funded facilities such as the Advanced Light Source at Berkeley Lab, were essential to gaining an understanding of why these materials behave in this unexpected manner.

Our discovery led to a DOE ARPA-E (Advanced Research Projects Agency—Energy) project that enabled us to further optimize the materials for efficient removal of CO_2 from a power plant flue gas. We showed that the capture and release of carbon dioxide could be accomplished using much smaller temperature changes than required for other technologies. This strategy eliminates the need to divert high-value, high-temperature steam away from electricity production, avoiding a large increase in the cost of electricity.

In the course of these efforts, we also showed that variance of the MOFs could be efficient for the removal of CO_2 from other gas mixtures, including biogas, natural gas, and even directly from air.

This research led in 2014 to the formation of a startup company, Mosaic Materials, in which for full disclosure I have a financial interest. Acceptance into Cyclotron Road, an incubator program at Berkeley Lab, enabled a demonstration of how the new technology might be deployed at scale. This then led to success in raising venture capital, and Mosaic Materials is now actively pursuing the commercial production of MOFs for integration within numerous CO_2 separation processes.

Substantial government support has been raised to facilitate these efforts, including from the DOE for carbon capture from power plants, from the Navy for efficiently scrubbing CO_2 from submarine atmospheres, and from NASA (National Aeronautics and Space Administration) for CO_2 capture and life support applications.

The company has further succeeded in forming strategic partnerships with other companies with an interest in carbon capture, including Exxon Mobil.

Berkeley Lab is now leading a project funded through the National Energy Technology Laboratory in which we're working with Mosaic Materials and an engineering company called Svante to carry out a pilot demonstration at a coal-fired power plant. Here, use of the MOF in a unique rotating bed system can achieve quick capture-release cycle times and reduce energy consumption. Ultimately, it's envisioned that widespread commercial deployment of such technology could result in a dramatic reduction of the costs and energy associated with carbon capture as it necessarily becomes implemented across the globe.

The discovery of new carbon capture MOFs would not have been possible without basic research support at numerous stages. If we're to halt global warming, it is essential that we continue to champion and even increase such support for basic science. Moreover, we need to invest intensively in accelerating the most promising new discoveries toward technology realization. This is a difficult, slow, and expensive process but one that is of vital importance to our future.

Again, thank you for inviting me. I look forward to answering any questions you may have.

[The prepared statement of Dr. Long follows:]

Stimulating New Carbon Capture Technologies through Basic Research

Jeffrey R. Long, Faculty Senior Scientist, Lawrence Berkeley National Laboratory
and Professor of Chemistry and Chemical & Biomolecular Engineering,
University of California, Berkeley

House Science Committee Field Hearing on Carbon Capture Science and Technology
Friday, November 22, 2019
The University of Houston

Chairman Johnson, Ranking Member Lucas, and distinguished Members of the Committee. Thank you for inviting me to testify today and for your interest in carbon capture science and technology development. My name is Jeffrey Long and I am a Faculty Senior Scientist at the Lawrence Berkeley National Laboratory and a Professor at the University of California, Berkeley. My testimony is my own and does not necessarily reflect the views of the U.S. Department of Energy, Berkeley Lab, or the University of California.

Fossil fuels are projected to continue to supply the majority of global energy for at least the next several decades, and thus, in addition to the fervent pursuit of renewable energy technologies, it is critical to invest in carbon capture technologies that will stem the buildup of greenhouse gases in our atmosphere. Support for basic scientific research plays a vital role in the quest for efficient, economical carbon capture technologies needed for the well-being of life on our planet. Here, I present a case study that underscores this point.

I serve as Director of a Department of Energy-funded Energy Frontier Research Center (EFRC), the Center for Gas Separations (www.cchem.berkeley.edu/co2efrc), which is based in Berkeley. The goal of our center is to create new materials that enable the energy-efficient separation of gas mixtures, as required for the cleaner use of fossil fuels and for reducing industrial emissions. Particular emphasis is placed on separations that can reduce carbon dioxide (CO_2) emissions from power plants and lower the cost of large-scale gas separations performed in industry and agriculture. Toward this end, we create new porous solid materials known as metal–organic frameworks (MOFs). These materials behave as finely-tuned sponges, capable of soaking up vast quantities of a specific gas molecule, such as CO_2. MOFs are particularly powerful for such applications, owing to their chemically controllable structure and their extremely high internal surface areas. Indeed, just one gram of a MOF, an amount similar to a cube of sugar, can have a surface area greater than that of a football field. Consequently, if designed properly, a small amount of MOF can serve to remove an enormous amount of CO_2 from a gas mixture, such as the exhaust gas produced upon combusting fossil fuels.

Working with a team of scientists in the Center for Gas Separations, we serendipitously discovered that certain MOFs can capture carbon dioxide in a cooperative fashion, similar to how hemoglobin is known to bind and release oxygen in the body. In these unprecedented materials, an initial reaction with CO_2 sets off a chain reaction that causes the uptake of more and more CO_2 molecules, rapidly filling the pores of the solid. Importantly, the MOFs exhibit a specific affinity for binding CO_2 over other gas molecules, such as nitrogen (N_2) and oxygen (O_2), which are the other main components of a flue gas created upon burning fossil fuels. What is particularly exceptional about these materials is that the uptake of CO_2 depends critically upon temperature and pressure, such that, with judicious separation process design, one can envision using them in a system where CO_2 can be captured and then released in pure form for utilization or sequestration with minimal energy input. It is important to emphasize that intensive collaboration among a team of talented scientists with diverse backgrounds, the cornerstone of the EFRC program, was essential to gaining an understanding of why these materials behave in this unexpected manner. Beyond the instrumental role of the EFRC program, our research was aided substantially by access to national laboratory resources, such as at the Advanced Light Source and The Molecular Foundry at Lawrence Berkeley National Laboratory (LBNL).

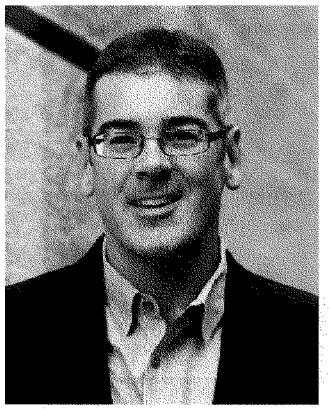
Our discovery subsequently led to a Department of Energy ARPA-e project focused on learning how to adjust the CO_2 adsorption properties of the new materials, enabling us to customize them for efficient removal of CO_2 from a power plant flue gas. In the course of these efforts, we also generated a number of variants of the materials that are highly efficient for the removal of CO_2 from other gas mixtures, including biogas, natural gas, and even directly from air. The resulting solids all exhibit high capacities for CO_2—even in the presence of water vapor—and a single sample of material can be reused hundreds of times for the removal of carbon dioxide from large volumes of gas. Importantly, this recycling requires only small changes in temperature and gas pressure, and the materials can capture more than five times the amount of CO_2 trapped by state-of-the-art aqueous amine solutions currently used in industry. Ultimately, these MOFs have the potential to separate CO_2 from mixtures with minimal energy input, and for example could achieve carbon capture from a flue gas using only low-value heat in a power plant. This strategy would eliminate the need to divert high-temperature steam away from power production to carbon capture, avoiding a large increase in the cost of electricity, which is a common critique of other carbon capture technology designs.

The potential applications of these MOFs led to the formation of a start-up company, Mosaic Materials, Inc. (mosaicmaterials.com), in 2014. Significantly, in its initial stages, the company was the first project accepted into the Cyclotron Road incubator program (www.cyclotronroad.org) at LBNL, which enabled a demonstration of how the new carbon capture technology might be deployed at scale. This led to success in raising venture capital, and Mosaic Materials is now actively pursuing the development, optimization, and large-scale commercial production of these materials for integration within numerous carbon dioxide separation processes, including its efficient, low-cost removal of CO_2 from air, biogas, natural gas, and flue gases. The company has already developed straightforward, inexpensive, and scalable methods for the production of key MOFs in a variety of forms and in particular has demonstrated the capacity and potential of the materials for performing carbon dioxide separations. More than $7M in government support has been raised to facilitate these efforts, including from the Department of Energy for carbon capture from coal-fired power plants, the Navy for efficiently scrubbing CO_2 from submarine atmospheres, and NASA for CO_2 capture in life support applications associated with space travel. The company has further succeeded in forming a number of strategic partnerships with other companies with an interest in carbon capture, including ExxonMobil.

LBNL is now leading a project in which Mosaic Materials is working with Svante, Inc. (svanteinc.com) to carry out a pilot demonstration at a coal-fired power plant (the National Carbon Capture Center in Wilsonville, Alabama) that incorporates the MOF technology within a unique rotating bed system to achieve large capture rates with quick process cycle times and reduced energy consumption—equating to high performance with reduced cost. Additionally, we are working with the National Energy Technology Laboratory on the multi-institutional Carbon Capture Simulation for Industry Impact ($CCSI^2$, www.netl.doe.gov/coal/carbon-capture/ccsi2) program to compare implementation of this MOF technology with existing carbon capture technologies. This program is also investigating other processes where these unique MOF materials might be employed to achieve key separations, with the ultimate goal of identifying the most efficient and economical means of deploying the materials in a capture process. It is expected that there will be wide-spread commercialization of these exceptional materials in industry and power generation sectors, resulting in a dramatic reduction in the cost and energy associated with carbon capture as it necessarily becomes implemented across the globe.

Ultimately, the discovery of these unprecedented new carbon capture materials would not have been possible without basic research support at numerous stages—through larger programs such as the EFRCs and smaller programs, such as those spearheaded by national laboratories. If we are to halt global warming, it is essential that we continue to champion and even increase such support for basic science. Moreover, we need to invest intensively in accelerating the most promising new discoveries toward technology realization. This is a difficult, slow, and expensive process, but one that is of vital importance to our future.

Again, thank you for inviting me to testify at this important hearing. I look forward to answering any questions that you may have.



Jeffrey R. Long, Ph.D.

Jeffrey R. Long is a Professor of Chemistry and Chemical & Biomolecular Engineering at the University of California, Berkeley and a Faculty Senior Scientist in the Materials Sciences Division at Lawrence Berkeley National Laboratory. He served as Chair of the Division of Inorganic Chemistry of the American Chemical Society in 2012 and as a founding Associate Editor of the journal *Chemical Science*, and he is presently Director of the Center for Gas Separations. In 2014, he co-founded Mosaic Materials, Inc., a company devoted to the development of metal-organic frameworks for low-energy gas separations. His 320 publications have received more than 62,000 citations, and his recent awards include election to the American Academy of Arts and Sciences and the 2019 American Chemical Society F. Albert Cotton Award in Synthetic Inorganic Chemistry.

Chairwoman FLETCHER. Thank you, Dr. Long.
Mr. Kennedy?

TESTIMONY OF MR. GREG KENNEDY, SENIOR PROJECT DIRECTOR, NRG ENERGY, AND DIRECTOR OF ASSET MANAGEMENT, PETRA NOVA PROJECT

Mr. KENNEDY. Thank you. Madam Chairwoman, Ranking Member, and Committee Members, I am honored to be here today testifying on carbon capture and utilization and sharing NRG's perspective on the role that carbon capture can play in reducing greenhouse gas emissions.

My name is Greg Kennedy, and I'm Senior Project Director for NRG Energy, a large, publicly traded, competitive power company, and I serve as President of Petra Nova. At the outset I'd like to provide some context for what it means to be competitive in the electricity sector. It means that NRG is not a utility with rates determined by regulators. We do not have captive ratepayers from whom we can recover costs or a guaranteed rate of return. Our shareholders bear the risk tied to the plants that we build and operate and investments that we make to support those plants, including our investment in the Petra Nova project.

This morning I want to focus on carbon capture utilization and storage and NRG's experience at Petra Nova, the only commercial-scale CCUS project in the United States. Petra Nova is the largest post-combustion carbon capture project in the world, and it was completed on time and on budget.

Petra Nova captures CO_2 from NRG's WA Parish power plant located southwest of Houston, Texas. We use amine-based post-combustion technology to capture 90 percent of the CO_2 from a 240-megawatt-equivalent slipstream of flue gas from one of the coal units at the plant. When operating at 100 percent, over 5,200 short tons of CO_2 are captured each day. The captured CO_2 is then dried, cooled, compressed, and transported 81 miles via pipeline to the West Ranch oil field, where it is injected to enhance oil recovery and ultimately sequestered.

To help finance and achieve the technological goals of the project, the NRG partnered with JX Nippon, a global oil and gas company, in a 50/50 joint venture. Additionally, Petra Nova formed a joint venture with Hilcorp Energy, a privately held oil and gas company, to use enhanced oil recovery to increase oil production at the West Ranch oil field. We are parties to a third partnership as well, and one that is very important to this Committee. Petra Nova would not exist without support from the U.S. Department of Energy, which provided a $190 million cost-shared grant to defray the project's approximately $1 billion price tag.

Petra Nova became operational on December 29, 2016, and as of the end of October the plant has delivered approximately 3.6 million tons of captured CO_2, equivalent to pulling almost 700,000 cars off the road for a year. From an engineering perspective, the project has been a success, and the technology works.

As with any first-of-a-kind effort, we have learned several lessons. We have gained a valuable and detailed understanding of the challenges presented by scaling up carbon capture to commercial scale: The impact of location-specific considerations such as ambient temperature, any capital and operating costs, along with options to reduce or manage both.

Working with our technology provider, Mitsubishi Heavy Industries, we have encountered and solved a variety of challenges. What we have learned has, of course, been shared with the Department of Energy and provides valuable insights for the next generation of CCUS projects. We encourage the Committee to position the Federal Government as a more active partner in making projects work from both an engineering and business perspective. Strengthening these public-private partnerships is critical, because if a commercial-scale demonstration is not also financially viable, it will be the first and last.

One way to strengthen these partnerships would be ongoing collaboration between the DOE's R&D (research and development) efforts, technology providers, and potential project investors to work through technology challenges. Petra Nova was a 10X scale-up of a post-combustion demonstration project in Alabama. Future projects will likely be a further scale-up in size, and whether this results in larger equipment or multiple trains of similar-sized equipment, this will likely create new challenges to keep costs down.

I would also encourage this Committee to collaborate with the tax-writing committee to ensure that the 45Q tax credit is implemented in a way that provides flexibility around, eligibility for, and receipt of the credit. These initiatives will help to continue advancing commercial-scale CCUS projects by facilitating technology improvements to drive capital and operating costs lower, the ability to sell CO_2 at a competitive price, and access to tax credits can improve project economics.

We encourage the Committee to remain engaged both on the challenges to reduce carbon emissions and to deploy the technologies needed to solve that challenge. At NRG, we are committed to be part of that solution.

I thank you for the opportunity to appear this morning, and I'm happy to answer any questions that the Committee may have. Thank you.

[The prepared statement of Mr. Kennedy follows:]

NRG Energy, Inc.
804 Carnegie Center
Princeton, NJ 08540

November 22, 2019
TESTIMONY of MR. GREG KENNEDY
Senior Project Director of Asset Management (Petra Nova)
before the
U.S. House of Representatives Committee on Science, Space, and Technology

Hearing to receive testimony on CCUS

Chairwoman Johnson, Ranking Member Lucas, members of the Committee, I am honored to appear today to testify on the issue of carbon capture, utilization and storage and, what we can do as a Country, using market forces and public-private partnerships, to reduce greenhouse gas emissions.

My name is Greg Kennedy, and I'm a Senior Project Director of Asset Management for NRG Energy, Inc., a large, publicly traded competitive power company. My role is to serve as the asset manager for the Petra Nova project and in that capacity, also serve as the President of Petra Nova Parish Holdings and its subsidiary companies. Currently, I also serve as the President of TCV Pipeline, LLC, the entity that owns the 81-mile CO_2 transportation pipeline between the Petra Nova project and the West Ranch oilfield.

What does it mean to be a competitive power company in the electricity sector? It means that NRG is not a rate-regulated utility and, therefore, does not have captive ratepayers from whom we can recover costs or a guaranteed rate of return on the capital that we invest. We have to earn our customers. And our shareholders – not our customers – bear the risks associated with the power plants and other projects that we build and operate and the investments that we make to support those plants, including our investment in the Petra Nova project.

Our company is proud to be a leader in acting to reduce carbon emissions – even in the absence of a comprehensive, federal approach. We have embarked on that effort by establishing science-based greenhouse gas emission reduction targets to reduce our carbon emissions 50% by 2025 and net zero by 2050. We provide granular and public disclosure of our progress towards meeting those targets. And we are making the business decisions that are required to meet those targets in a way that provides consumers with the affordable, reliable and increasingly cleaner electricity they want while generating a return for our shareholders.

I am pleased to be here today sharing not only what we have done as a company, but what we believe the federal government can do as well, to facilitate broader participation – from energy companies and consumers alike – in the actions that are needed to reduce carbon emissions. This morning, I will focus my testimony specifically on carbon capture, utilization and storage and NRG's experience with Petra Nova. I will be providing some background on Petra Nova, discussing the lessons we have learned, underscoring the importance of public-private partnerships, and sharing a few policy ideas.

I. Background on Petra Nova

Petra Nova captures carbon dioxide from NRG's WA Parish power plant, which is located southwest of Houston, Texas. The Parish plant has ten coal-fueled and natural gas-fueled units and has a total capacity of 3,653 MW, which makes it one of the largest power plants in the Country. Petra Nova uses an amine-based post-combustion technology to capture 90% of the carbon dioxide from a 240 MW equivalent slipstream of flue gas from Unit 8, a coal-fired unit. The captured carbon dioxide is then dried, cooled, compressed and transported 81 miles via pipeline to the West Ranch oilfield where it is injected to enhance oil recovery and ultimately sequestered in the subsurface geology of the field.

To help finance and achieve the technological goals of the project, NRG partnered with JX Nippon—a global oil and gas company—in a 50/50 joint venture. Additionally, Petra Nova formed a joint venture with Hilcorp Energy, a privately held oil and gas exploration company, to leverage the untapped potential of the mature West Ranch oilfield. Given Petra Nova's ownership in the oilfield, oil revenues, not the sale of CO_2, are necessary to service the project's debt and fund going forward costs.

Petra Nova would not exist without its partnership with the U.S. Department of Energy, which provided a $190 million cost-shared grant to defray the approximately $1 billion price tag for the Petra Nova partners' investment in the carbon capture facility and their share of the oilfield improvements.

Petra Nova became operational on December 29, 2016. I am very proud of the development of the project, which resulted in the system coming online, on budget and on schedule. Since starting operations, the plant has captured 3,700,000 tons of carbon dioxide used for enhanced oil recovery providing the dual benefit of removing CO_2 from the atmosphere while boosting the production of domestic oil and the United States' goal of energy independence.

In 2017, Petra Nova received recognition as both the Project of the Year and the Coal-Fired Project of the Year, awarded by Power Engineering. Overall, the project represents an accomplishment for cleaner energy today and a proven vision for how we can enhance sustainable coal-powered technology for the future. This achievement has captured interest from all over the world as we and the Department of Energy have hosted hundreds of visitors each year from both industry and government, including members from both the U.S House of Representatives and Senate.

II. Technical and Economic Advancements in Commercial Scale CCUS

As with any first-of-a-kind effort, we have learned several lessons from Petra Nova. Specifically, we have gained a valuable and more detailed understanding of the challenges presented by scaling up carbon capture to commercial scale; the impact of location-specific considerations, such as the effects of ambient temperatures; and the costs – both capital and operating costs – along with options to reduce or manage both.

Petra Nova is the only U.S. facility capturing CO_2 in large quantities (over 1 million tons per year) from a fossil-fueled power plant. In the United States, small-scale pilot projects have been more typical. As you would expect, an increase in scale necessitates technical solutions to accommodate unique design challenges. Working with our technology provider, Mitsubishi Heavy Industries America, we have encountered and solved for a variety of challenges.

For example, maintaining the proper temperatures in the process is critical for the amine to capture and subsequently release the CO_2. The use of amines to capture CO_2 has been well proven in other applications; however, the large scale of the Petra Nova project combined with the previously mentioned high ambient conditions created the need for numerous large heat exchangers, both plate-and-frame and shell-and-tube designs, to properly control temperatures inside the process. While both styles of heat exchangers have been used successfully for many years in industrial applications and in the presence of amines, the projects designers had to work diligently to ensure the long-term viability of the exchangers while providing the needed cooling capacity.

Additionally, information gathered from operating projects can assist engineers in understanding how advanced solvents and sorbents will perform over time. For example, understanding their rate of degradation and the impact on both the carbon capture system components and process efficiency can provide valuable insights for the next generation of carbon capture.

The project has also generated valuable information that could be useful to the committee and future developers, given Petra Nova's location on the Gulf Coast, ambient conditions, the use of Powder River Basin coal, and the geology for enhanced oil recovery unique to the Gulf Coast.

At the West Ranch oilfield, we are gaining experience regarding how an EOR flood performs by tracking and evaluating information such as the amount of gas required to produce a barrel oil (commonly called the gas-to-oil ratio); the pressure needed for the CO_2 to properly mix with the oil (called minimum miscibility pressure or MMP); the proper spacing for injection and production wells; the timing to alternate between injecting water and CO_2 and the amounts for each (a process called "water-alternating-gas" or WAG); the impact of unique reservoir characteristics; and the balance between capital and operating expenditures and production. An example of a specific R&D effort at West Ranch is the partnership between the oilfield partners and Japanese companies to pilot new membrane technologies to remove methane from recycled CO_2 and to determine if it can be deployed at commercial scale.

We would expect that for CCUS to be commercially successful in the future, it will be important for power generators to partner with oil companies in the form of a "fence line" sale of CO_2. The likelihood of producers and consumers of CO_2 to transact under such terms will improve as greater economies are realized to lower the cost of delivered CO_2.

III. The Role of Partnerships

We are fortunate to have partnered with the federal government to further the science and economics of CCUS. In terms of technical expertise and financial support, it is certain that without public-private partnerships for large-scale applications of developing technologies, projects like Petra Nova don't happen.

We hope that the Country proliferates CCUS projects, and that Petra Nova can provide a foundational piece of the knowledge required to do so. But we think there is more the government can do, and more that the DOE can do, to recognize the importance of remaining a partner. So, I'd like to pivot from policy and commercials lessons learned to a handful of new or additional ideas that we believe the committee should consider as it considers funding for ongoing research and development for CCUS.

IV. Policy Concepts.

Consistent with doing more to sustain partnerships between the federal government and the private sector for projects like Petra Nova, I would like to offer some policy ideas as the committee contemplates building upon the important policies of carbon reduction.

One option for ongoing support of projects like Petra Nova would be to amend the underlying authorities for the Department of Energy's Loan Programs Office to allow them to refinance debt associated with projects that are subject to a public-private partnership. Such a change would recognize that as technologies are proven at commercial scale, they become less risky. Improving the financing terms and conditions tied to project debt could provide a shot in the arm to projects that are not only working to demonstrate technologies but also to prove that they can operate profitably. This is particularly important in a state like Texas, which has a very competitive electricity market, and for companies like NRG that have no captive ratepayers from whom costs can be recovered or rates of return that are oftentimes guaranteed by public service commissions in other markets.

We encourage the committee to position the federal government as a more active partner in making projects work, from both an engineering and business perspective. Strengthening these public-private partnerships is critical, because if a commercial-scale demonstration is not also commercially viable, no one will build more of them.

One way to strengthen these partnerships would be on-going collaboration between the DOE's R&D efforts, technology providers, and potential project investors to work through technology challenges. By processing a 240 MW equivalent slip stream of flue gas, Petra Nova was a 10X scale-up of a post-combustion demonstration project in Alabama. This scale-up required an 8,000-horse power flue gas fan to draw flue gas from the host coal unit, a 300-foot tall absorber tower, a 26,000-horse power compressor, and 17 plate and frame heat exchangers, some of which are the largest frames made by our suppliers. Future projects will likely be a further scale-up in size and whether this results in larger equipment or multiple trains of similar size equipment, this will likely create new challenges to keep costs down.

Lastly, I would encourage members of this committee to collaborate with your colleagues at the tax-writing committees to ensure that the 45Q tax credits are implemented in a way that both recognizes the existence of an already operational facility like Petra Nova and provides flexibility in how eligibility for and receipt of the credit can be kept flexible.

V. Conclusion

In summary, several items are needed for "at-scale" CCUS: (a) technological advancements to drive capital and operating costs lower, (b) alignment between CCUS and EOR operators to sell CO_2 at competitive prices, and (c) flexible mechanisms to access to 45Q tax credits. Parallel to your efforts in looking at the technological challenges, we also support the current efforts of other Government agencies in looking at improving access to 45Q tax credits.

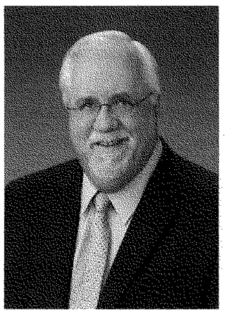
We applaud the committee for remaining engaged not only on the challenge of carbon reduction but also on advancing the programmatic authorities needed to demonstrate technologies capable of solving that challenge. At NRG, we are committed to being a part of that solution, we thank you – again – for the opportunity to appear this morning, and I am happy to respond to any questions that the committee may have.

Petra Nova

nrg | JX

PETRA NOVA Carbon Capture

Greg Kennedy



Mr. Greg Kennedy is a Sr. Project Director for NRG Energy, Inc. and serves as the Asset Manager for the Petra Nova Project. In that capacity, Mr. Kennedy also serves as the President of Petra Nova Parish Holdings, LLC and its subsidiary companies. Additionally, Mr. Kennedy serves as the President of TCV Pipeline, LLC. Mr. Kennedy is responsible for the management of Petra Nova's assets and the many commercial agreements needed to manage the carbon capture project. Mr. Kennedy has over 40 years of industry experience. Mr. Kennedy has a Bachelor of Science degree from Purdue University and a Masters in Business Administration from the University of Houston.

Chairwoman FLETCHER. Thank you, Mr. Kennedy.
Mr. Dewing?

TESTIMONY OF MR. ROGER DEWING, DIRECTOR OF TECHNOLOGY CCUS, AIR PRODUCTS AND CHEMICALS, INC.

Mr. DEWING. Madam Chairwoman, Ranking Member, and Members of the Committee, I appreciate the opportunity to testify before you today. First, I want to commend the leadership of this Committee for exploring the promise of carbon capture technology and its importance to global energy.

I'd like to start by outlining how Air Products believes carbon capture and storage, or CCS, projects may develop over the next few years. I'll highlight how important these projects could be in reducing carbon dioxide emissions to the atmosphere whilst maintaining global energy supplies.

Many of the current proposed CCS projects revolve around the production and utilization of hydrogen. Hydrogen, we believe, may be an enabler for many CCS projects. If current hydrocarbon fuels, from natural gas to coal, are converted to hydrogen and carbon dioxide, or CO_2, and if the carbon dioxide is captured and stored, then the produced hydrogen can be considered to have been produced emission-free. This hydrogen is often referred to as "blue hydrogen."

Using hydrogen to distribute and store energy has some significant benefits. It can be used as the fuel for power generation in turbines. It can be used for transportation in fuel cells. It can be distributed to industry clusters to de-carbonize energy-intensive industries. Excess hydrogen can also be stored for use when demand is high. It can therefore be complementary to green energy projects such as solar or wind, providing a backup supply of energy when needed.

However, CCS projects will only become a reality if you can ensure two fundamental questions can be answered: Where will the CO_2 go? And who will pay for it to be captured and stored? I will explore the answers to these questions again in a moment.

Within Air Products I'm currently setting up a group to further develop our CCS technology. We're recruiting scientists and engineers in the U.S. into our head office in Pennsylvania and elsewhere in the world. This is to meet the need for greater sustainability in global industrial projects.

Air Products' initial interest in CCS started in 2005 when these types of projects were being led by large power generation companies. However, global interest diminished with the recession of 2008. But that interest is returning with a slightly different focus. Current proposals seem to be for a large group of projects feeding a single CO_2 storage solution. The U.S., Canada, EU, and China are leading that renewed interest.

The U.S. is the market leader for CCS projects and associated technology. Currently, over half the operating CCS projects around the world are in the U.S. There are already hundreds of miles of super critical CO_2 pipelines moving large quantities of CO_2 for enhanced oil recovery. And also, the U.S. has the Federal 45Q tax credits providing financial incentives to capture that CO_2. I would argue that this credit may not be enough on its own, but it is ahead of many other countries who have nothing in place at the moment.

Among the current CCS projects operating is Air Products' Port Arthur facility here in Texas. It originally produced hydrogen and steam for the refinery locally, but since a retrofit in 2013 it also captures 1 million metric tons of CO_2 a year, and it's been operating for 6 years. The project was partially funded by the DOE, which allowed us to develop our CO_2 Vacuum Swing Adsorption technology that can flexibly capture CO_2 from processed gases. Air Products also installed equipment for the compression and drying of that CO_2 so that it could be delivered to a local Denbury pipeline for EOR (enhanced oil recovery). We were also able to reconfigure the facility such that it provides the same industrial gas products to our customers.

The capture project is still operating and is a success because it answers those two fundamental questions I posed earlier: Where the CO_2 will go? And who will pay for it to be captured and stored? First, the Denbury CO_2 pipeline, used to supply CO_2 for EOR, was only 13 miles away, so there was a home for the CO_2. Second, the DOE funded the project, the 45Q tax credits, and the fact that CO_2 has a value for EOR made the project financially sensible.

Looking to the future, Air Products is actively seeking more projects like Port Arthur. That experience gives us a proven reference for designing and operating CCS projects. It is likely that many of the next projects may be of similar scope. Retrofits of existing hydrogen facilities lend themselves to capturing significant CO_2 at modest capital cost.

Air Products' recent acquisition of Shell and GE gasification technologies should offer another opportunity to develop CCS projects. Gasification technology converts a broad range of hydrocarbon feeds into hydrogen-rich synthesis gas. It is then possible to capture the CO_2 from this gas for storage. This means fuels such as coal can be used for energy supplies with theoretically no CO_2 emissions to the atmosphere.

Some final thoughts. The use of fossil fuels, as we said, will continue for many years to come, and CCS will allow this to continue while still meeting CO_2 emission targets. CCS means that heavier carbon-rich fuels may still be used to provide energy without the associated heavy burden of atmospheric CO_2. CCS projects are in operation today, so the technology to capture and store CO_2 already exists. There are no technology barriers to the projects, but further research will be essential to reduce costs and improve efficiency. This will make more projects feasible when the two fundamental questions are asked and answered.

Thank you for the opportunity to present Air Products' perspective on CCS issues, and I hope that with the continued support of the DOE that many more CCS projects like our Port Arthur facility will become reality. Thank you.

[The prepared statement of Mr. Dewing follows:]

United States House of Representatives

Committee on Science, Space and Technology

November 22, 2019

Field Hearing on the
"The Future of Advanced Carbon Capture Research and Development"

Testimony of
Roger A. Dewing
Air Products and Chemicals, Inc.

Mr. Chairman, Ranking Member and members of the Committee, I appreciate the opportunity to testify before you today. My name is Roger A. Dewing, Director of Technology, CCUS, at Air Products and Chemicals, Inc.

First, I want to commend the leadership of this Committee for exploring the promise of carbon capture technology and its importance to global energy.

I'd like to start by outlining how Air Products believes Carbon Capture and Storage, or CCS, projects may develop over the next few years. I'll highlight how important these projects could be in reducing carbon dioxide emissions to the atmosphere whilst maintaining global energy supplies.

Many of the current proposed CCS projects revolve around the production and utilisation of hydrogen. Hydrogen may be the enabler for many CCS projects. If current hydrocarbon fuels, from natural gas to coal, are converted to hydrogen and carbon dioxide, or CO_2, and if the carbon dioxide is captured and stored, then the produced hydrogen can be considered to have been produced emission-free. This is being referred to as "Blue Hydrogen."

Using hydrogen to distribute and store energy has some significant benefits. It can be used as the fuel for power generation in turbines. It can be used for transportation using fuel cells. It can be distributed to industry clusters to decarbonise energy intensive industries.

Excess hydrogen can be stored for use when demand is high. It can therefore be complementary to green energy projects such as solar or wind, providing a backup supply of energy when needed.

However, CCS projects will only become a reality if you can you answer two fundamental questions. Where will the CO_2 go, and who will pay for it to be captured and stored. I will explore these questions again in a moment.

Within Air Products I'm currently setting up a group to further develop our CCS technology, recruiting scientists and engineers into our U.S. head office in Pennsylvania and elsewhere. This is to meet the need for greater sustainability in global industrial projects.

Air Products' initial interest in CCS started in 2005 when these types of projects were being led by large power generation companies. However, global interest diminished with the recession of 2008. Interest is returning, but with a different focus. Current proposals are for a group of multiple projects feeding a separate single CO_2 storage solution. The US, Canada, EU, and China are leading this renewed interest.

The U.S. is the market leader for CCS projects and associated technology. Currently, over half the operating CCS projects around the world are in the U.S. There are already hundreds of miles of supercritical CO_2 pipelines moving large quantities of CO_2 for enhanced oil recovery known as EOR, and the federal 45Q tax credits provide financial incentives to capture CO_2. I would argue that this credit may not be enough on its own, but it is ahead of other countries who have yet to put this important funding in place.

Among the current CCS projects operating is Air Products' Port Arthur facility, here in Texas. It originally produced hydrogen and steam for refinery customers, but since a retrofit completed in 2013, it also captures 1 million metric tonnes per year of CO_2. The project was partially funded by the DOE which allowed us to develop our CO_2 Vacuum Swing Adsorption technology that can flexibly capture CO_2 from the process gas. Air Products also installed equipment for the compression and drying of the CO_2 so that it could be delivered to a local Denbury-owned CO_2 pipeline for EOR. We were also able to reconfigure the facility such that it still provides the same industrial gas products to our customers.

This capture project is still operating and is a success because it answers those two fundamental questions I posed earlier, where will the CO_2 go and who will pay for it to be captured and stored. First, the Denbury CO_2 pipeline, used to supply CO_2 for EOR, was only 13 miles away, so there was a home for the CO_2. Secondly, the DOE funding for the project, the 45Q tax credits, and fact that CO_2 has a value for EOR meant the project made financial sense.

Looking to the future, Air Products is actively seeking more projects like Port Arthur. That experience gives us a proven reference of designing and operating CCS projects. It is likely that many of the next projects may be of similar scope. Retrofits of existing hydrogen facilities lend themselves to capturing significant CO_2 at modest capital cost.

Air Products' recent acquisition of Shell and GE gasification technologies should offer another opportunity to develop CCS projects. Gasification technology converts a broad range of hydrocarbon feedstock into hydrogen rich synthesis gas. It is then possible to capture the CO_2 from this gas for storage. This means fuels such as coal can be used for energy supplies, with theoretically no CO_2 emissions to the atmosphere.

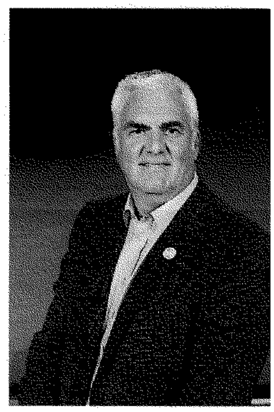
We also plan to extend the proven technology deployed at Port Arthur to increase capacity and improve its efficiency and reliability.

Some final thoughts. The use of fossil fuels will continue for many years to come and CCS will allow this to continue whilst still meeting CO_2 emission targets. CCS means the heavier carbon rich fuels may still be used to provide energy without the associated heavy burden of atmospheric CO_2 emissions.

CCS projects are in operation today, so the technology to capture and store CO_2 already exists and is reliable. There are no technology barriers to projects, but further research will be essential to reduce costs and improve efficiency. This will make more projects feasible when the two fundamental questions are asked and answered.

Thank you for the opportunity to present Air Products' perspective on CCS issues and I hope that with the continued support of the DOE that many more CCS projects like our Port Arthur facility will become reality.

Roger Dewing, Director of Technology for Carbon Dioxide Capture, Utilization and Storage (CCUS)



Roger graduated from the University of Surrey, UK, with a bachelor's degree in Chemical Engineering in 1988. He joined the Italian EPC, Snamprogetti, on their UK graduate training program, then joined British Gas plc as part of their LNG engineering team.

Since joining Air Products in 1996 Roger has worked in a variety of technology areas, leading Engineering teams in Europe, China and US. Significant career highlights include the technology development for multi-train Air Separation facilities, Hydrogen Steam Methane Reformer projects, novel Helium extraction processes, cryogenic syngas purification facilities, and a rare gas extraction facility in Saudi Arabia.

In 2017 Roger transitioned from the Global Technology Manager for cryogenic processes to undertake the development of the Air Product Technology Center located in the Dhahran Techno Valley, Saudi Arabia, building a world class organization to support Air Products businesses in the Middle East.

Roger has recently been appointed as the Director of Technology for CCUS, leading the recruitment and development of a new team. The objective is to increase the level of Air Products participation in sustainability and GHG mitigation projects by seeking to accelerate the technology development for Carbon Dioxide capture, purification, utilization and storage.

Chairwoman FLETCHER. Thank you, Mr. Dewing.
Mr. Jenvey?

TESTIMONY OF MR. NIGEL JENVEY, GLOBAL HEAD OF CARBON MANAGEMENT, GAFFNEY, CLINE & ASSOCIATES

Mr. JENVEY. Good morning, Chair Fletcher, Ranking Member Weber, distinguished Members of the Committee. I sincerely thank you for the opportunity to talk to you today and provide some perspectives that I have on capture and storage. Gaffney, Cline & Associates provides independent and trusted technical, commercial, and strategic advice to the oil and gas industry. A key pillar of our carbon management practice includes the assessment of the range of carbon solutions that are available to avoid, replace, reduce, offset, or sequester greenhouse gas emissions to assure continued compliance and competitiveness in a constantly evolving global energy market.

While there is no silver bullet to carbon management, per se, carbon capture, use, and storage is widely considered a vital carbon solution or clean energy technology that is available today. But according to the International Energy Agency, it is not on track for meeting the world's sustainable development goals. My objective today is to convey my experience on how continued U.S. technology and capability leadership will expand deployment domestically and internationally.

Amine-absorption CO_2 capture technology is proven today for use at commercial scale, as you've heard from Mr. Kennedy from Petra Nova. The original patent for this, a process for separating acidic gases, was filed in 1930. The technology is capital intensive due to its large scale and complexity, along with the significant energy and maintenance costs for operation. While cost and performance improvements have been achieved over time, this is now reaching fundamental limitations in the thermodynamics of the regeneration energy needed for the amines. Cost reductions are therefore stalling.

Other newer technology types, some of which you've heard about here today, include cryogenic, absorption, membranes, and process systems that have been researched, developed, and in some cases demonstrated at commercial scale over the last decade.

Typically, these technologies require less capital and have lower energy demands to operate. While some hold promise, deployment on commercial power plants or large-scale industrial facilities, of course, still has a significant amount of risk for investors due to the total as-spent cost and long-term operational performance uncertainties.

A novel approach has therefore materialized—we've heard it from colleagues here today—where some of these newer technologies are being demonstrated at much smaller scales. Sometimes they are being combined into hybrid systems or integrated with renewable power and heat sources. Innovation at this small modular scale carries less risk, reducing cycle times to success or failure. While they are currently less mature, these innovations could result in potential breakthroughs in cost that with further support and time potentially move back into power and large-scale industry applications.

We now understand that CCUS is a versatile carbon solution in that it can greatly reduce CO_2 emissions from existing energy, industrial infrastructure, and the atmosphere. However, since there is no panacea for CO_2 capture technology to address all CO_2 emissions, a diversified technology program is therefore needed.

I have personally worked in CCUS since 2004 on technology and projects across the world and have found unequivocally the U.S. to be the world leader in CCUS research, development, demonstration, and deployment. This is evidenced by consistent congressional support, over 20 years for the Department of Energy to lead and support public-private collaboration on science and technology, an established regulatory framework, over 5,000 miles of installed CO_2 pipelines, over 40 years of CO_2 enhanced oil recovery experience, over 80 percent of the world's installed CCUS capacity, and world-leading policy support with the 45Q tax credit.

However, the rest of the world is catching up, with 12 of the next 15 projects in advanced development located outside of the U.S., according to the Global CCS Institute.

Over the last year I have therefore had the honor and pleasure to serve as Deputy Chair to the CCUS Study Coordinating Subcommittee of the National Petroleum Council. This study was undertaken at the request of Secretary Perry and is due to report out on December 12, 2019. While, of course, I cannot comment on the specifics of this pending report, we have developed a roadmap for deployment at scale that will ensure continued U.S. leadership. A differential feature of the study has been to assess the costs of capture, transport, and storage to the largest 80 percent of all U.S. stationary sources. This, therefore, underpins our identification of the level of value necessary to enable deployment, builds the case for ongoing RD&D (research, development, and demonstration) across the entire CCUS value chain, and enables assessment of the economic benefits: jobs, economic competitiveness, and energy security.

The resulting recommendations have been laid out in three phases to achieve deployment at scale and are categorized into financial incentives, supportive legal and regulatory frameworks, technology and capability, and stakeholder engagement themes. I offer to revert to this Committee to provide further details of this study at a later date, should you be interested.

In conclusion, the U.S. is well positioned to lead the world with its experience, technology, and capability. Continued public-private commitments to RD&D investment are essential.

Thank you once again for your time today, and I would be happy to answer any of your questions.

[The prepared statement of Mr. Jenvey follows:]

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Testimony of Nigel Jenvey

Global Head of Carbon Management

Gaffney, Cline & Associates, Inc.

Field Hearing: The Future of Advanced Carbon Capture Research and Development

Subcommittee on Energy of the House Committee on Science, Space and Technology

United States House of Representatives

November 22, 2019

Good Morning Chair Fletcher, Ranking Member Weber, members of the Committee...I sincerely thank you for the opportunity to testify before you today. My name is Nigel Jenvey and I work for Gaffney, Cline and Associates here in Houston, Texas as Global Head of our Carbon Management Practice.

Gaffney, Cline & Associates (GCA) was established in 1962, and provides technical, commercial, and strategic advice to the oil and gas industry. GCA operates worldwide from three main offices, in Houston, London, and Singapore, supported by regional offices in Buenos Aires, Sydney and Dubai.

Our new Carbon Management practice is specifically designed to meet our client's technical, strategic, and commercial needs to assess carbon & climate risks and opportunities to their business. This provides trusted, third party due diligence to our clients in their evaluations, reporting requirements, permit applications, and financial transactions.

A key pillar of our offering includes the assessment of the range of carbon solutions that are available to avoid, reduce, replace, offset or sequester Greenhouse Gases or CO_2 equivalent emissions in a cost-effective, time-based manner to ensure continued compliance and competitiveness in a constantly evolving global energy market.

While there is no silver-bullet to Carbon Management, Carbon Capture, Use and Storage (CCUS) is widely considered a vital carbon solution or clean energy technology that is available today, but according to the International Energy Agency reports on Tracking Clean Energy Progress, it is not on track for meeting the world's sustainable development goals. My objective today is to convey some of my experience on how continued U.S. technology and capability leadership will expand deployment domestically and internationally.

Historically most CCUS projects in the United States have been performed due to the commercial synergy that exists between the costs of transporting high concentration CO_2 that is vented from gas processing and ammonia production, to locations where revenues are available from large-scale use in Enhanced Oil Recovery (EOR) projects. With market-forces supplemented by 45Q tax credits having effectively developed most of these options, and recent 45Q tax credit enhancements laying a pathway to potentially add high concentration CO_2 from ethanol plants and include saline formation storage, additional CCUS technology and further deployment has focused on CO_2 capture from lower concentration sources.

A traditional view has been to focus on volume, with CO_2 capture from combustion based emissions at large-scale existing sources such as power plants. The CO_2 concentration in the flue gas from these plants typically ranges between 4-13% and is at or close to atmospheric pressure. Commercially available amine-based absorption technology is therefore capital intensive due to its large scale and complexity, along with significant energy and maintenance costs for operation. While cost and performance improvements have been achieved over time, they are now reaching fundamental limitations in the thermodynamics of the regeneration energy needed by the amine based solvents used in this process that has been in existence since the original patent for "A process for separating acidic gases" was filed by R.R. Bottoms in 1930. Cost reductions are therefore stalling.

An alternative approach has been to consider lower cost options, with CO_2 capture from a combination of process and combustion based emissions at medium-scale existing sources in industries such as cement, steel, and refining/petrochemicals. The CO_2 concentration in applicable streams from these plants typically ranges between 16-45%, and coupled with the potential for higher pressures, the size of capture equipment can be smaller, lowering the capital costs. However additional costs of integration of CO_2 capture equipment into these industrial processes, and lower economies of scale due to smaller sources, has not resulted in the significantly lower costs hoped for with currently available technology.

Other newer technology types include cryogenic, adsorption, membranes, and process systems that have been researched, developed and in some cases demonstrated at commercial scale over the last decade. Typically these technologies require less capital and have lower energy demand to operate than the incumbent commercially available technology. While some hold promise, deployment on commercial power plants or industrial facilities still has a significant amount of risk for investors due to total as spent cost and long term operational performance uncertainties.

A novel approach has therefore materialized, where some of these newer technologies are being demonstrated at much smaller-scales, with CO_2 capture from stationary emissions sources or directly from the air. Sometimes they are being combined into hybrid systems, or integrated with renewable power and heat sources. Innovation at this small, modular scale carries less risk, reducing cycle times to success or failure. While they are currently less mature, these innovations could potentially result in breakthroughs in cost that with further support and time potentially move back into power and large-scale industry applications.

We now understand that CCUS is a versatile carbon solution, in that it can greatly reduce CO_2 emissions from existing energy, industrial infrastructure, and the atmosphere. However, since there is no panacea for CO_2 capture technology to address all CO_2 emissions, a diversified technology program is therefore needed.

I have personally worked in CCUS since 2004 on technology and projects across the world, and have found unequivocally the U.S. to be the world leader in CCUS research, development, demonstration and deployment (RDD&D). This is evidenced by consistent congressional support over 20 years for the Department of Energy to lead and support public-private collaboration on science and technology, an established regulatory framework, over 5,000 miles of installed CO_2 pipelines, over 40 years of CO_2 EOR experience, over 80% of the world's installed CCUS capacity, and world leading policy support with the 45Q tax credit.

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In conclusion, the U.S. is well-positioned to lead the world with its experience, technology and capability. Continued public-private commitments to RD&D investment are essential.

Thank you once again for your time today and I would be happy to answer any questions you may have.

Nigel Jenvey

Global Head of Carbon Management

Gaffney, Cline & Associates

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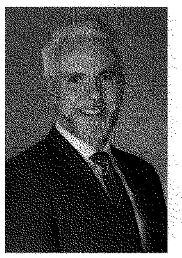
Gaffney, Cline & Associates



Nigel has over 23 years of global oil and gas industry experience in technology, exploration, development and production operations with major oil and gas operating companies. He is an industry leader in Carbon Management and expert in Carbon Capture, Use and Storage (CCUS) having previously held roles such as the chair of the CO2 Capture Project, chair of the North American CCS Association, and program chair of the Society of Petroleum Engineers CCUS Technical Section. At Gaffney, Cline & Associates, Nigel leads the new global Carbon Management practice to help customers understand the wide variety of options available that will ensure continued business success through the energy transition. Nigel graduated from Imperial College, London with a Master's degree in Petroleum Engineering, and from The University of Leeds, UK with a Bachelor's degree with honors in Mining Engineering. Nigel now lives in Houston, Texas with his wife and 2 children.

Chairwoman FLETCHER. Thank you very much, Mr. Jenvey.

At this point we will begin our first round of questions for our witnesses, and I will start by recognizing myself for 5 minutes. I do want to follow up on your offer and your comments, Mr. Jenvey, about the path forward, and your recommendations. I think this Committee would very much appreciate getting a copy of the recommendations as soon as they are available.

That kind of gave us a preview of the question that I'd like to put to everyone who is here about what it is that we can do to assist in this effort, because we sit before you as Members of Congress. This is the Science, Space, and Technology Committee, and this is the Energy Subcommittee. This is an issue that we are very focused on, and so I have a ton of questions. Five minutes will not cover all of them. We may get to do another round and, of course, would love to continue the conversation as we go.

But one particular question in your written testimony, Mr. Jenvey, was about the potential for use of these carbon capture technologies to reduce emissions in other industries such as cement or steel and petrochemicals. So, can you talk a little bit about how carbon capture technologies differ, how the designs differ with other applications, as opposed to the ones that have been designed for coal-fired power plants or natural gas plants?

Mr. JENVEY. Thank you. So, there are definitely synergies between the types of technologies, the fundamental building blocks that those technologies use, whether it's absorption, adsorption processing, or whether it's pre-combustion or post-combustion. So there is some ability to transfer from one industrial setting to another, but each is different. I think, as Mr. Kennedy pointed out earlier on, of course, they have environmental, atmospheric, different changes where they're actually operated. The stream compositions are different for the amount of CO_2 that's contained within them. Usually in the industrial processes there are process emissions, which tend to have higher concentration of CO_2, as opposed to combustion emissions from power plants or furnaces and heaters, which is a lower concentration of CO_2. But then again, those streams also have other gases, other contaminants in them that also have to be dealt with.

So there's a lot of synergy between the different technologies. But as I said, there's really no panacea that's safe for all different types of applications. Generally, cost of capture is related to CO_2 concentration in the stream, and therefore that really is a focus in order to spot the early opportunities, the low-hanging fruit, to be able to target those and find the right technology that can be applied.

Chairwoman FLETCHER. And as a quick follow up, are you aware of any planned or existing projects that work on carbon capture on some of these other processes right now?

Mr. JENVEY. There's one that's in the public domain that's going on over in Europe. It's one of those advanced projects in development that's capturing from a biogas site in Norway, and also a cement plant in Norway.

Chairwoman FLETCHER. Thank you very much.

Like I said, 5 minutes goes very quickly, so I have limited time.

But, Dr. Krishnamoorti, I also wanted to touch on your testimony. You mentioned that carbon dioxide is inherently stable, meaning that it requires a lot of energy to convert carbon dioxide to other chemicals for potential carbon utilization applications. Some of my colleagues in Congress, some who serve on this Committee with us, have expressed a similar skepticism about carbon utilization for this very reason.

So given that processing carbon dioxide is such an energy-intensive process, is it reasonable to expect that we will have a booming market for products that utilize carbon in the future? What would those products look like? Can you talk about that?

Dr. KRISHNAMOORTI. Sure, and this is the power of chemistry. Even though it is such a stable molecule, there are clever ways to not necessarily take it back to carbon and oxygen but take it to transitionary states where you can get it to happen at a much lower energy price and therefore be able to utilize it. This is some of the work that I was talking about where my colleagues are working with taking carbon dioxide, finding ways to apply catalysis to it, getting it to now be a co-reactant with methane and natural gas liquids to convert it into useful fuels; for instance, methanol. Co-plasma is a technology that we have been starting to deploy to take carbon dioxide with methane and with other lighter hydrocarbons to convert into methanol and other higher hydrocarbons. These take much less energy.

Clever chemistry works beautifully. This is what we've done for 150 years.

Chairwoman FLETCHER. Terrific.

With the few seconds I have remaining, I think we're all familiar with the use for enhanced oil recovery. Are there other, besides what you've touched on, other existing or potential uses for carbon dioxide that you see as part of this process?

Dr. KRISHNAMOORTI. Some of the ones that hit the headlines are things like we can make plastics. We can use it in cement production. But those, when you look at the scale, are very small.

Perhaps the one place which is really attractive is taking carbon dioxide and making fuel, making gasoline. That is a target that is ripe for the picking. Catalysis is available. It's a matter of reducing cost and getting it to be comparable to extracting from the ground and getting the natural gasoline.

Chairwoman FLETCHER. Thank you very much, Dr. Krishnamoorti.

My time has expired. That's what the little lights tell us. So we will move on, and I will now recognize Mr. Weber for 5 minutes.

Mr. WEBER. This is for all witnesses, so we'll start here and go down.

I'm very supportive of advanced renewable energy technologies and clean energy technologies, like nuclear energy, for example. It is clear to me that fossil fuels will be an important part of the U.S. energy portfolio for years to come.

Since many of you have touched on this issue in your prepared testimonies and remarks, I'm interested to know what each of you say to those who would believe that we should not invest in clean energy R&D for the fossil fuel sector and instead funnel all of our research and development money into renewable energy technologies. What do you think about that?

Dr. KRISHNAMOORTI. We've given it a lot of thought. Being in Houston, being a partner with many of the industries here, we believe that there are no silver-bullet solutions. It's an all-of-the-above strategy that has to operate. We believe that the fossil industry, it is not the hydrocarbon that is the problem. It is what comes out of that tailpipe is perhaps the problem.

And even that we dispute. We think that there are critical ways in which CO_2 can be utilized, and therefore should not be considered even a waste. I think there's a really interesting way to perhaps find a way to use that CO_2 and be economically advantaged.

So the short answer, absolutely not that we should be picking the technology solutions. I think we identify the challenge, which is we need to be protecting the environment.

Mr. WEBER. Thank you. So we'll coin a new phrase today based on that. The old phrase, "When life gives you lemons, make lemonade"——

Dr. KRISHNAMOORTI. Make margaritas.

[Laughter.]

Mr. WEBER. Make margaritas. It's 5 o'clock somewhere.

But the new phrase is, "When life gives you CO_2, make energy."

Dr. Long?

Dr. LONG. Yes, I agree with my colleague. I'd also add that the task of converting all of this energy infrastructure to renewable sources, there's no way we can do it without taking decades, particularly in developing countries where they will also use the cheapest source of fuel.

In addition, even if we could convert immediately to renewable sources of energy, we have the problem of the current CO_2 levels in our atmosphere, and a lot of projections of not increasing temperatures on our planet involve CO_2 capture from air. So we need to pursue this technology for many different uses.

Mr. WEBER. Thank you.

Mr. Kennedy?

Mr. KENNEDY. Yes, just echoing the same comments that were made. Renewables are very important. But, as you mentioned, fossil energy is not going to go away anytime soon. So to the extent that we can continue the R&D efforts to negate some of the impact of those fossil fuels, I think we're all better off by doing that.

Mr. WEBER. Well, they're still developing horizontal fracking and drilling and becoming better and better and better at that, and I would postulate that also they are getting at capturing all the things that come out of that process.

Mr. Dewing?

Mr. DEWING. I think we've proven that we can store CO_2 for the long term, thousands of years, underground. That's where the fossil fuels came from. We can return it there safely and take the benefit of the fossil fuel energy for the foreseeable future, and I think we need to, to maintain the world's energy requirements.

Mr. WEBER. Mr. Jenvey?

Mr. JENVEY. Definitely it's not a race to renewables. It's really a race to lower emissions in energy.

Mr. WEBER. Good point.

Mr. JENVEY. And, of course, fossil fuels and thermal power generation is a great partner to renewables within the grid, providing flexible backup to intermittency that naturally occurs within those renewable energy forms. So really it's about a partnership and an all-of-the-above energy solution. Of course, cost is a major consideration for consumers between the choices that there are within the energy supply.

Mr. WEBER. Thank you.

I've just got a couple of minutes left, so I'm going to go back to you, Mr. Dewing. In your prepared testimony, I like how you highlighted these questions: Where will the CO_2 go? You just mentioned underground for thousands of years. And who will pay for it? Now you and Mr. Kennedy have both explored various answers to these questions this morning. But since we are on the Science Committee, we want to hear more about the science of this process.

So first, from an industry perspective, I'd like to hear more from both of you about the technical challenges associated with the placement of captured CO_2. In your opinion, what are the major barriers associated with this end, of getting the CCUS pathway that can be addressed with our help through basic research and development?

Mr. Kennedy, we'll start with you.

Mr. KENNEDY. Yes, sure, and thank you. Let me just give you a few examples of the technical challenges that I think would be helpful through additional R&D: The behavior and impact of amines in large-scale carbon capture projects and equipment, including the degradation rates and the effect on carbon capture systems; the effects of higher operating temperatures on critical equipment. As was mentioned, location matters. Given the ambient conditions here in the Houston area, cooling capacity is a very, very important part of the process. We use some of the largest heat exchangers that manufacturers make. So it's very important to continue the R&D efforts to improve upon that.

Optimizing vessel sizes. We have some very large vessels that were done in our first-of-a-kind facility. Additional R&D to drive capital out to see if you can right-size or properly size those vessels.

Then outside of our technology, just expanding technologies: Capture of waste CO_2 from other large sources, including natural gas, direct air; and then also furthering our knowledge in EOR, looking at unconditional reservoirs and different geologies and how CO_2 interacts in those.

Mr. WEBER. [Inaudible.]

Mr. DEWING. I think the key issue we face is the efficiency of removal. If you're using lots more energy to remove that CO_2, then it's running away with you. So we have processes that work where we've got an absorption process that we think is a well beater, and we're looking forward to do that. We want to improve that. We have heat exchange issues as well. Some of the temperatures, we're experiencing some of the approaches on those heat exchanges need a lot of development, too. So we'd like help with investment to continue to improve our efficiency, improve the processes.

Mr. WEBER. Thank you, Madam Chair. I yield back.

Chairwoman FLETCHER. Thank you, Mr. Weber.

I'll now recognize Mr. Cloud for 5 minutes.

Mr. CLOUD. Thank you. This is an exciting topic. I'm really happy that you all are here to talk about these important issues. The world's demand for energy is growing. I have always believed that the solution to the challenges we face is advancements in technology rather than us all retreating from the industrial age. So it's exciting to see the developments that are happening.

Mr. Kennedy, I'm really amazed, first of all, to hear that a project was done on time and on budget. So if you could, first of all, give us a manual on that, that would be applicable across a number of spheres. But in all seriousness, there was a project I think in Kemper County, Mississippi where the government invested almost $400 million that ended up being wasted. So what was the difference in the success that happened at Petra Nova? How can we be effective in investing the taxpayer dollars to get the desired results?

Mr. KENNEDY. Yes, sure, and they (Kemper) had a totally different technology. So, what was successful for us? Number one, like I mentioned, was a scale-up of a demonstration project, so there was some history that the technology actually works. Ninety percent of our engineering was done prior to starting construction, so there were not a lot of scope changes. We had phenomenal partners. We basically formed a consortium with our technology provider and our contractor and did a single EPC contract. So they worked together on meeting the needs that we had in our turnkey project. A lot of those I think were very helpful to get us to where we got to.

Mr. CLOUD. And, Mr. Krishnamoorti—I hope I said that right—I really appreciated a lot of how you phrased this in the need to have research that gets this to a market-based approach. I think as far as moving us into the future, that's the best approach, as opposed to a heavy hand of regulatory environment. Of course, we'll need some light touch there probably, but in the sense of what technologies, what research areas need to be done? What are the areas that we need to focus on that will get this to market viability? And maybe all of you can lean into this a bit.

Dr. KRISHNAMOORTI. Sure. We believe that a large part of this is on the capture side, and we want to look at point source capture as being the first and foremost place where we can do this work. You heard from Petra Nova; they have done some very interesting things.

The other story in the Houston area, which has got another very large natural gas-based power plant that has developed new technology that is ready for the commercial world, is something that you hear about. Net Power, they have done some pretty amazing work. That's the kind of technology that needs to be scaled up.

Mr. WEBER. Repeat their name again?

Dr. KRISHNAMOORTI. Net Power. They are in Pasadena, Texas, and they've demonstrated at 50 megawatts what they can do to capture CO_2. They need to scale up. We need to find ways to get that technology ready for the marketplace.

Likewise, I believe distributed sources are something that we've got to look at. We've got abundant renewable electricity available that is not being utilized. How do we get that to be utilized and produce CO_2 in places where it can be used? Right now, there is more demand for CO_2 in the State of Texas than available piped CO_2. The big challenge is pipeline, and that's something that can be addressed by a light touch of regulation, change CO_2 from being a waste product to being a critical material that can create economic value.

Mr. CLOUD. That was going to be my next question, if the infrastructure existed or what needs there were in helping us to make it to that.

Dr. KRISHNAMOORTI. Yes. Going to common carrier pipeline will relieve enormous challenges today in the CO_2 market, and that will mean you'll get to see a lot more of these planned activities being done at scale. And the more we can do things at scale, we can make this cheaper.

Yes, we're doing a lot of things in the science and engineering world that will be disruptive, but that's 5, 10, 15 years out. We need things to happen now to make it viable for the future. Thank you.

Mr. CLOUD. Now, one of the great successes I see here is that in this case the investment went to technologies that went to practical applications. Do you all have any suggestions for that? Because a lot of times we'll invest in research, we'll have these breakthroughs, they make it to the journals, but they don't make it to practical application. Do you all have any suggestions for how we can be more effective nationwide in getting the research dollars that produce the breakthroughs that actually make it to the sphere of application?

Dr. LONG. Yes, you're absolutely right. There's a huge valley of death between fundamental discovery of some new possible technology and demonstration. One thing that does try to address that is ARPA-E. I think it's something we need a lot more of. There's a disconnect between the scientist doing the fundamental research and engineers who know how to build a practical device. We need to bridge that gap with funding, get those scientists and engineers together.

Chairwoman FLETCHER. Thank you very much, Mr. Cloud. I appreciate that.

We were just conferring that this Committee has passed the reauthorization of the ARPA-e bill through our Committee, and we're hoping that it will come to the floor very soon. So I was just checking on the timing on that, so thank you very much.

I will now recognize Dr. Babin for 5 minutes.

Mr. BABIN. Thank you, Madam Chair. Thank you, University of Houston. And thank you, expert witnesses, for being here today.

I'm privileged to have this opportunity today to bring this hearing down, help bring this hearing down to our great State, where we get a chance to show off southeast Texas and see firsthand the innovative new technologies that are revolutionizing the way that we produce energy. Texas has always played a huge role in America's energy economy, and I believe that Houston is the epicenter of that.

I represent the 36th District. We have more petrochemical refining facilities than anywhere else in the entire country. So I think that there's not a better place to roll this new technology out. We also have some of the busiest ports in the world.

Mankind benefits so greatly when science can solve a lot of our problems. For instance, turning an over-abundance of production of CO_2, and turn that into an advantage to help produce more energy and have a cleaner environment.

So my first question is, how do we roll out these new technologies here in Houston to improve the efficiency and quality of our energy production? Specifically, what are the technological barriers to commercialization, and how can the Department of Energy effectively partner up with industry? As briefly as possible. And, Mr. Kennedy, I'd like to ask that of you first, please, sir.

Mr. KENNEDY. Yes, sure. As I mentioned in my testimony, the private-public partnerships are very important. The technology is very, very expensive. So I think the effort today is to look at the second- and third-generation of carbon capture facilities without technology, look for ways to make those more cost-effective for people to invest in them.

Mr. BABIN. Right. OK, thank you.

And then Dr. Long?

Dr. LONG. Yes. Again, we have ARPA-e to try to bridge this gap. It's not enough. As someone working in fundamental science making discoveries, it's really sad to see when no one recognizes or takes up the challenge of how do we build something out of that, something practical. That's not something my lab does. We need partners. DOE should really encourage that partnership of taking a quaint new discovery just to the next step of a bench-scale engineered test. This could be a kilogram of materials. But that step is missing. We need more funding of that.

Mr. BABIN. OK. Thank you very much.

Now I'd like to ask the next question. Carbon capture technologies help us to more efficiently produce energy and helps us to create cleaner energy, as we mentioned, but addressing climate change is not a one-country problem. We see time and time again when other countries, like China and India for example, disregard the effects of their pollution. This is a global issue, there's no question about it. Do you see collaboration opportunities with countries like China and India where we can profit off of our innovative technology while they become cleaner countries at the same time? What collaboration opportunities do you see?

I'd like to start over with Dr. Krishnamoorti.

Dr. KRISHNAMOORTI. Well, in my testimony I talked about a collaboration with Oil India specifically on the issue of capturing CO_2 and putting it for EOR. There are other opportunities. For instance, we've developed some coal gasification technology in this country that is remarkable. It will probably never see the light of day here in this country, but given the need for energy, given the need for doing it environmentally conscious, how do we find a way to partner with countries like China and India to really deliver that coal gasification technology?

Mr. BABIN. Absolutely.

Mr. Dewing, if I could ask that of you?

Mr. DEWING. We already have a project where we partner with a Chinese company to gasify coal to make a synthesis gas. So we're already working together. We have gasification technology. We have CO_2 capture technology. China is showing an interest in CO_2 capture and sequestration. So a lot of that work is already in progress, and Air Products is actively working with Chinese partners.

We have a project for dry reforming where we reform the CO_2. So that's with the research organization Shanghai, and we're collaborating with them.

So I think there are lots of opportunities certainly in China, and we're exploring India as well. So it's happening already.

Mr. BABIN. And then Mr. Jenvey, if you could add a little bit to that as well?

Mr. JENVEY. Definitely. The United States, as I said in my testimony, is a global leader in CCUS, so indeed there's a marketplace internationally there for that leadership, both in technology and capability, that's being built here. There are consortium collaborations internationally on this already. The Clean Energy Ministerial has now started to include CCUS within its work and provide protocols and methodologies to include CCUS within, of course, some of those international agreements to reduce greenhouse gas emissions. So it's good to see those.

Mr. BABIN. Yes, sir. Thank you.

I see my time has expired. It's amazing how fast 5 minutes goes by. But thank you, and I yield back.

Chairwoman FLETCHER. Thank you, Dr. Babin.

We are pleased to invite some of our Houston colleagues who are able to join us this morning. I'm very pleased to be able to recognize Mr. Crenshaw, who is joining our Committee this morning, for 5 minutes.

Mr. CRENSHAW. Thank you, Chairwoman Fletcher; thank you, Ranking Member Randy Weber, for having me. This is a huge interest of mine, and I appreciate this Committee, by the way, for allowing my bill, the *Leading Act*, which repurposes grant money from DOE for carbon capture in the natural gas sector, for adding that to legislation in this Committee.

This is a really important subject because the question is not whether about supporting environmentalism or supporting cleaner air. The question is about how we do it and what the best way to do that is, and playing to our strengths as Americans.

And that strength is innovation. That strength is technology. We could do something like implement a Green New Deal and ban fossil fuels, and we would take care of 15 percent of emissions worldwide, OK? We would also destroy our economy, and we'd have a negligible effect on the environment.

There are other ideas out there from leading Presidential candidates to, say, ban fracking. That would be an interesting shock to the economy and really put any of these ideas right out of business.

It would also be interesting because, Dr. Krishnamoorti, as you mentioned in your testimony, there's been a 20 percent reduction in emissions per capita largely because of natural gas. There was another study by DOE that showed if we replaced China's and India's coal-burning oilers with natural gas, they would reduce their emissions by 40 percent. You add carbon capture to that mix, you're talking 90 percent reductions.

So focusing on what works is so unbelievably important, and I want to get to that and what barriers are in the way, what government needs to do to help this and actually get us to an eventual net zero emissions.

Dr. Krishnamoorti, you briefly touched on this, and I saw a little bit more of it in your written testimony, about reclassifying CO_2 as a commodity as opposed to a waste, and that's interesting. Is there a regulatory barrier there?

Dr. KRISHNAMOORTI. Yes. It is considered a waste item today. It is considered not a commodity that can be economically advantaged for a broad group of people, and therefore cannot access common carrier pipelines. That is perhaps the biggest challenge today to moving CO_2 around.

Mr. CRENSHAW. Is that an EPA (Environmental Protection Agency) regulation?

Mr. WEBER. [Inaudible.]

Dr. KRISHNAMOORTI. I'm not sure. I can get back to you on that.

Mr. CRENSHAW. Mr. Kennedy, I'd like to go to you on everything you all have done. I want to ask where you're at now financially. I mean, we have to get companies like yours in a place where you want to do it, where the financial incentives work and it's viable. Are you at that place now?

Mr. KENNEDY. I think as we've said before, the economics on these projects are very, very challenging. So we eagerly await the 45Q guidance that we're awaiting from the IRS, and we continue to think that the technology providers need to drive cost out of the project to make things more attractive to new investors.

Mr. CRENSHAW. So without the 45Q credits, you don't think your project would be viable?

Mr. KENNEDY. I think new projects are very, very difficult. We're a little bit unique in the fact that we are vertically integrated. We have an ownership interest in the oil field. I think going forward you're going to see utility companies or power plant owners want to do a fence-line sale of $CO_2$2.

Mr. CRENSHAW. Could you briefly talk about the new source review regulations? Is there a reason you guys didn't retrofit. You decided to build an entirely new facility. Is that because of regulations like the new source review?

Mr. KENNEDY. It did not play into ours. We were challenged by the Department of Energy to demonstrate we could do this without having an impact on energy prices. So as opposed to being parasitic to the host coal unit and taking power and steam from that unit, we opted to build the cleaner burning gas co-gen facility. So that resulted in not only getting our power and steam, we have excess power off that facility that we sell into the grid. So we've actually added power supply.

Mr. CRENSHAW. And as far as scaling up these technologies, we've been talking about that constantly. We agree on a 45Q tax credit, for instance. We agree on grant money from DOE for pilot programs. Again, that's basically what my legislation is. What else? What other barriers are there?

As we go to Mr. Dewing as well, or anybody really can answer this, what other barriers are there that we need to get rid of, and what do you need help with? Where is that light touch of assistance that we need?

Mr. DEWING. I think the continued support, the DOE support, the grants to get projects going, the 45Q helps. For EOR, we can sell the CO_2, so that helps. If no one needs the CO_2, then we don't get that money.

But the key thing to me is where do you put it. We need the ability to put the CO_2 somewhere, so we need the pipelines, we need the connections, we need the storage locations. So if you can have the infrastructure for CO_2, I think that would be a seed for lots of smaller projects, because then they can see where that CO_2 can go.

Mr. CRENSHAW. OK.

Dr. Krishnamoorti, I want to go back to you. I mentioned before that there's talk of actually banning fracking right now. Could you just comment on what the consequences of something like that would be, if it happened tomorrow?

Dr. KRISHNAMOORTI. If it happened tomorrow, the growth in the Permian that we anticipated going from 3.5 million barrels a day to 7.5 million barrels a day would stop, and that's the kind of thing that has not only given us energy independence but has enabled us to be a net exporter of crude.

Mr. CRENSHAW. What's the environmental impact, though?

Dr. KRISHNAMOORTI. It can be done well. Fracking can be done well, and we've seen that being demonstrated many, many times.

Mr. CRENSHAW. Let me be more specific. What would the environmental impact be on emissions if we just stopped using natural gas all of a sudden?

Dr. KRISHNAMOORTI. We've got to find the energy somewhere. We need a lot of energy. We would probably go back and re-start coal-fired power plants. We might start to look at expanding some of our nuclear power resources.

Mr. CRENSHAW. Would there be most likely an increase in emissions or a decrease?

Dr. KRISHNAMOORTI. Increase.

Mr. CRENSHAW. Absolutely, an increase. That would be a problem, because I don't think we all want that.

I'm not sure what my time is, but I'll keep talking as long as I can.

Chairwoman FLETCHER. It's 10 minutes.

Mr. CRENSHAW. Thank you, Chairman, very much for indulging me. Thank you all for being here.

Chairwoman FLETCHER. Thank you very much, Mr. Crenshaw.

As we've all noted, 5 minutes goes very quickly, so we will probably do another round of questions.

But I'm very pleased to introduce another one of our Houston colleagues who has joined us today, and I'm proud and pleased to recognize Mr. Green for 5 minutes.

Mr. GREEN. Thank you very much, Madam Chair. And I'll thank my colleagues as well for allowing me to be an interloper today. I'm not of this Committee of jurisdiction, but I do believe that as a member of the Houston community and a Member from Texas it is appropriate that I be here. So, thank you very much.

Houston is known as the energy capital of the world. My intelligence indicates that approximately a third of all of the jobs are somehow connected to Houston. This is important, but I'd like to talk about it from another perspective.

Houston also has the largest medical center in the world, and this medical center is larger than the average city in the United States of America. We have a space port. We are consumers of energy as well, and I think that we have to look at it also from how our institutions will be impacted if we're not efficacious with our carbon management.

My question would go to you, and I trust that I will enunciate it properly, Dr. Krishnamoorti. My question to you, sir, is on the importance of carbon management solutions in terms of preserving existing jobs. Houston employs a lot of people. The port is here. We have two international airports. Houston could be a greatly different city if we don't get this right and manage the carbon capture properly.

So I yield to you for your sage advice.

Dr. KRISHNAMOORTI. Thank you so much, Congressman Green.

Mr. GREEN. Thank you.

Dr. KRISHNAMOORTI. It's a pleasure to have you here at the University of Houston.

We talked about the issue of affordable, reliable energy that drives the planet. But at the same time we have to address climate change risk, and there is no better industry that can deal with the carbon issue at scale than the energy industry, and it must be done in partnership with that industry in order for us to do it at the right scale and also do it where there's an economic advantage.

We have focused a lot on two aspects: Carbon capture and sequestration, both of which are costs, substantial costs. How do we find value in this business; that's the part we're focused on. How do we find utilization for CO_2? How do we make it an economically viable product?

It's in partnership with the industry. It's in partnership with the National Labs, working with places like NETL to find ways to make it a creative solution rather than just be a cost burden on society. That's the only way it can be done, and there's no better industry than the energy industry to do it.

Mr. GREEN. I want to thank you for your sage advice.

Madam Chair, as I explained earlier to you and I'll explain to everyone, I really am in the middle of doing something else someplace else, and I have to get back to what I've been engaged in. But I think this is an important hearing, and I'm honored that you would allow me to be a part of it today. I thank you and my colleagues for allowing such.

My belief is that there is not a problem that Houston can't solve. We have been innovators. We are the folk who decided that a ship channel ought to be inland, so we built the ship channel. Houston gets it done.

I thank you for this opportunity, Madam Chair, because you are getting it done.

I yield back the balance of my time.

Chairwoman FLETCHER. Thank you, Mr. Green. We appreciate you being here.

I really appreciate so many of our Houston Members working together on this issue, and there seems to be a consensus among the group that we have a lot more questions. I think we've seen that from everyone. So thank you so much for joining us, Mr. Green.

For those who are able to remain, we'll do a second round of questions, and I'll continue to recognize everyone for 5 minutes as we go.

Certainly, several of the things you've said have given us more questions, and, of course, my colleagues have also raised some questions that I also have. So I'm going to go ahead and start the second round for 5 minutes.

I really want to touch on two things. There's something very specific that you raised, Dr. Krishnamoorti, that I want to go back to. Several of us up here are also on the Committee on Transportation and Infrastructure, so your comments about the infrastructure for carbon dioxide were important and interesting. I think that what we've seen is that there are challenges with some of the sequestration sites. There's a need for transportation.

I was interested in your written testimony about the potential for dual-use LNG (liquified natural gas) and carbon dioxide ships as an alternative transportation method. So if you could just expand a little bit beyond pipelines or, A, what does the pipeline need; and, maybe B, what innovative other options do we have for transporting carbon dioxide from the source to the injectionsite without adding large amounts of carbon emissions in the process?

Dr. KRISHNAMOORTI. Thank you so much. So, we do ship LNG and LPG (liquefied petroleum gas) out from the Gulf of Mexico ports all over the world. There are countries like Korea, Japan, which import a lot of this and do combust those fluids. They do have incentives there for carbon capture, and they are ready to capture that carbon and trade it. So it's a small engineering feat that needs to be achieved, which is, can we use those ships to reverse-transport CO_2 back to the U.S.? And the second part of this is, would that CO_2, because CO_2 is a global challenge, be something that would receive the 45Q credit? Because, again, we have offshore—the Gulf of Mexico is a ripe target to sequester CO_2. We could do this with no additional substantial transportation costs. That breaks down one of the biggest barriers to doing this. We could do this from Europe, we could do this from Asia. Both of these places are receiving our LNG and LPG, and that would be a substantial effort to really transform the way we think about sourcing CO_2.

Chairwoman FLETCHER. Terrific. Thank you so much.

And then my next question, which will probably be my last, I'm going to start with Mr. Jenvey and kind of work this way. But I'm interested more generally—as I mentioned in my first round of questions here, we sit up here as Members of Congress wanting to know what we can do to further the goals that we are talking about here today.

So, Mr. Jenvey, in particular, you talked a lot about what we need to do to maintain our leadership position in the United States around the world on this technology and these issues. Do you know whether some of the things that we have already worked on—for example, the *Fossil Energy Research and Development Act*—take the right steps to maintain that goal? And what other things, or maybe what are the priority things that you and everyone on the panel would recommend to us to do to make sure that we're continuing to advance in this area and remain the world leader?

Mr. JENVEY. Thank you. So, definitely continue to do what you're doing. The unwavering support that Congress has provided over the last couple of decades really has, of course, established this technology and capability the United States has. I would say this is really probably the time. It's a matter of timing, and now is the time to really now make sure that this happens and double down on some of those research, development, and demonstration support to help, indeed, the valley-of-death technologies that you've invested in already, to help them get to market.

There's a market evolving there, and particularly here in Houston, along the Gulf Coast. We have already the world's best CO_2 storage geology sitting underneath our feet. We have LNG plants, petrochemical facilities, other industrial facilities here, and really if we can get this done here as a cluster, it's a real shining light to the rest of the world as well.

So I'd encourage you to, from a national Federal perspective, double down on the R&D and really deliver the value that it has that the previous investment has got to, and also here locally in Houston work with the public-private partnerships that already exist and are interested in doing things to help them deliver something that will make sure that Houston remains the energy capital of the world.

Chairwoman FLETCHER. Thank you, Mr. Jenvey.

Mr. Dewing, do you want to weigh in on what the congressional priorities—what you think would be most helpful for us to focus on?

Mr. DEWING. We'd like to see the continued support of our projects. Port Arthur was successful because of funding. We need that initiative, that funding to get things moving and develop further. We're seeing it elsewhere in the world with governments in Holland and the U.K. sort of discussing ways and means of getting projects going. So I think you're already two or three steps ahead, and we'd like to continue that.

Chairwoman FLETCHER. Thank you.

Mr. Kennedy?

Mr. KENNEDY. Yes, I would agree also. We probably have not stressed enough the role that the DOE has played in our project. We're coming up on 10 years of a relationship with the DOE on the Petra Nova project, and they have done a major amount of not only helping us financially but just spreading the word of the project. They've been responsible for hundreds and hundreds of visitors internationally and domestically coming to the site and spreading the information on technology. So their ability to continue to build on what they've done and continue to do the R&D work that's needed to advance the technology would be very helpful.

Chairwoman FLETCHER. Thank you, Mr. Kennedy. That's a great segue over to Dr. Long.

Dr. LONG. OK. Thanks. I would suggest that we need to up our investment in the basic research side of things. There's been huge advances in how we make porous materials and membranes that can affect and impact and improve the way we do energy in the future. Right now there's not enough support for that science. Taking it, for example, and creating something like an energy hub for carbon capture, I don't know why we don't have this yet. We have one for solar fuels, we have one for batteries. But things like that, long-term support of new science, we've got to feed technologies into the pipeline for the future.

Chairwoman FLETCHER. Thank you, Dr. Long.

Dr. Krishnamoorti?

Dr. KRISHNAMOORTI. Thank you so much. And just to follow up, I would suggest that that hub needs to be carbon capture and utilization.

Mr. WEBER. And in Houston. Just saying.

Dr. KRISHNAMOORTI. And in Houston, absolutely.

[Laughter.]

Dr. KRISHNAMOORTI. We have already made that pitch.

The other one that I think we need to really be fostering is disruptive technologies. For instance, something that Nigel mentioned, modular distributed capture. Right now, 45Q does not advantage that type of capture in any shape or form. One hundred thousand tons a year is a lot of CO_2. We can find technologies that can be deployed at much smaller levels that need to be advantaged.

The second point is the utilization side of the business has not received as much interest from funding. That must be made a priority.

Chairwoman FLETCHER. Thank you, Dr. Krishnamoorti.

I have once again gone over my time, so I will now recognize Mr. Weber for 5 minutes.

Mr. WEBER. Thank you.

Dr. Krishnamoorti, in your conversation with Dr. Babin you said that gasification would never receive the light of day. Was that coal gasification process?

Dr. KRISHNAMOORTI. Yes, coal gasification.

Mr. WEBER. OK, thank you. I just wanted to clarify that.

Mr. Dewing, in your conversation with Dr. Babin you talked about gasification, working with China, for example. In my research I ran across an article from *Science Direct* about China from 2014 where they talked about the amine-based post-combustion capture, that it was a problem for China, these coal-fired power plants. That's 5 years old. Has that changed?

Mr. DEWING. I don't know. I'm not sure whether that has changed, but we're looking at converting, doing pre-combustion capture.

Mr. WEBER. This is post-combustion.

Mr. DEWING. Air Products' view is to convert the coal, the hydrocarbon upstream, make hydrogen, which can be burned and used in any way. It can be distributed. To capture the CO_2 there.

Mr. WEBER. OK. I wanted to clarify that.

A question for all the panel. Mr. Jenvey, we'll start over here so you don't feel left out.

As I said earlier, we need to bring everybody along to this: Industry, government, fossil fuel industry, clean energy, everybody, our environmental industry friends. How do we do that?

Mr. JENVEY. That's a very good question, how do we do that. So, I've always believed that just sticking with the value that this has to our industry and to society is the clearest way to really establish——

Mr. WEBER. When you say value, do you mean the monetary value? Clean air, better environment, less climate change, if you will, all the while maintaining a focus on energy and the monetary part of that.

Mr. JENVEY. Yes, sir.

Mr. WEBER. OK.

Mr. Dewing, do you agree with that?

Mr. DEWING. I think so, yes.

Mr. WEBER. I'll make it real easy on you all. Mr. Kennedy?

Mr. KENNEDY. I do as well.

Mr. WEBER. OK. None of them will dare say no.

[Laughter.]

Mr. WEBER. Dr. Long?

Dr. LONG. [Inaudible.]

Dr. KRISHNAMOORTI. Likewise.

Mr. WEBER. Very good. As long as it's in Houston. You left that part out.

[Laughter.]

Dr. KRISHNAMOORTI. It's got to be in Houston because this is the only place where you can solve it.

Mr. WEBER. Absolutely.

So, let me keep going. Direct carbon capture from air, and I'll start with you, Mr. Kennedy. Number one, how do we do that? Are we able to do that? Very quickly; I only have about 2-1/2 minutes left. And is that competition for what you all are doing?

Mr. KENNEDY. So, probably my colleagues on the panel here are much more versed in that technology than I am. I have been really focused on Petra Nova technology. But I think from a capital perspective, I think it's more capital intensive for the CO_2 benefits you get, so definitely a need to continue to evaluate that technology and look for ways to try to drive the cost down.

Mr. WEBER. Right.

Dr. Krishnamoorti, I think you talked about the air—we call them small modular reactors in the nuclear industry. That's great, but how do you get that infrastructure to now transport? Like I said, when life gives you CO_2, make it energy. How do you do that with SMRs, or whatever you want to call them?

Dr. KRISHNAMOORTI. Deployment of direct air capture is actually the easiest thing because they're small, they're modular, and they use atmospheric air. So you're not trying to go off a petrochemical plant or a refinery.

Mr. WEBER. Right. So you put them over in a truck, you say this truck is going down the highway, whether it's carrying propane or whether it's carrying CO_2, oxygen, gasoline, whatever it is, and you can take them to a centralized distribution point?

Dr. KRISHNAMOORTI. The way we think about it, we go to a producing oil field or a producing wind farm and set up a direct air capture there. So you capture the CO_2 and then you pump it into the ground right there.

Mr. WEBER. OK. At a wind field?

Dr. KRISHNAMOORTI. A wind farm, because you get cheap electricity.

Mr. WEBER. And you pump it into the ground at the wind farm?

Dr. KRISHNAMOORTI. Or you ship it to an oil field and you pump it down.

Mr. WEBER. There you go.

Dr. KRISHNAMOORTI. All in pretty close proximity in west Texas.

Mr. WEBER. Dr. Long? I've got 45 seconds.

Dr. LONG. Yes, it's absolutely true that it's a much more energy intensive process to remove the CO_2 at these very dilute concentrations from air. This is a fundamental science problem, how do we do that at maximum efficiency. We need to invest in research to do that. I think no matter what, it's an important issue.

Mr. WEBER. That's a good point.

Madam Chair, I yield back 15 seconds.

Chairwoman FLETCHER. Thank you, Mr. Weber.

I'll now recognize Mr. Cloud for 5 minutes.

Mr. CLOUD. Thank you. Again, this is a wonderful opportunity for us all to work on this issue. I appreciate the consensus and having a forward-looking approach to meeting these challenges, and realizing actually that the world's demand for energy growing is actually a good thing. That's people coming out of poverty. That's people finding mobility, being able to heat their homes for the first time and those kinds of things. So I've always thought that the answer to that is for America to meet the challenge, because we will always do it a lot more responsibly than many of the other countries across the pond, so to speak, who don't have our best interests in mind.

Going along a little bit with what Mr. Crenshaw was saying, I'd like to ask you, Mr. Krishnamoorti, if we were somehow to constrict the fossil fuel industry, we understand the economic impact it would have, the national security implications along with that. Could you also speak to—you said this a number of times, that it's the only industry really capable of addressing this issue. Now, if that industry was not to have the economic thriving that we currently see, what would that do to the research and technologies currently being developed to answer some of these challenges?

Dr. KRISHNAMOORTI. I think, as you would probably have noticed, most of the large deployments of carbon capture projects are being done by the oil and gas industry, whether it is Chevron, whether it is Oxy, whether it is Exxon Mobil. Clearly, they see that this can be created for them to be a part of the ecosystem.

I assert that this industry is critical because of the scale of the problem. Thirty-six gigatons globally is not going to go away when making plastics. You've got to make plastics. We probably use about 2 percent of that, and that would satisfy all the plastic needs of the world. If we're trying to make cement, we'll probably use about 5 percent. If I make methanol, if I make gasoline, I could use a substantial part of that 36 gigatons of CO_2. That's the reason why this industry knows how to make hydrocarbons. We know how to use natural gas. We know how to use other light hydrocarbons in order to make economically—still competitively, but economically you can make hydrocarbon fuel.

Mr. CLOUD. That's the most likely path forward is to continue to advance these technologies to market viability.

Dr. KRISHNAMOORTI. Absolutely.

Mr. CLOUD. Mr. Jenvey, you mentioned that there's 12 other projects going on around the world, 12 or 15 projects. I'm curious from the U.S. remaining the competitive leader, and also any national security implications. Could you give us the lay of the land of what's going on globally and how the U.S., can stay ahead of that? And if any of you have anything to add to what Mr. Jenvey says, please do.

Mr. JENVEY. Thank you. So, yes, those projects are in different regions, a number in China, the Middle East, and in Europe, of course. Australia has also had a number of projects and has a couple of projects coming through into those advanced stages of development, yet there definitely is a marketplace out there.

I would say historically there has been these waves of CCUS investigation and development. But a lot of the time, unfortunately, the projects in those other regions haven't actually materialized fruit to a final investment decision, as opposed to here in the United States. So where those projects are being developed globally, they then reach a final investment decision. They then don't have the policy, the supportive regulatory frameworks, or indeed the capability and the backbone of the oil and gas industry and the rest of the industrial infrastructure here in the United States. So they do, then, hit a certain limit in their ability to actually do these projects indeed at these large scales. But there are a number of other projects globally.

Mr. CLOUD. That's interesting.

Mr. DEWING. I can comment on some other projects. The Port of Rotterdam is looking at putting in CO_2 pipelines so that a number of companies can feed into that CO_2 line for sequestration. Norway is looking at two projects. The U.K. has three or four that are being proposed at the moment which are a consortium of companies, BP being a leading company there. So there's a lot of interest, a lot of projects going through, but whether they actually all come to something or not will be interesting to see. One of them in Norway is an interesting one, the Northern Lights. They're actually looking at shipping CO_2, so they've developed a ship design that can take CO_2 at minus 25° C and move it as a liquid around. So there's interest elsewhere now.

Mr. CLOUD. My time is up. Thank you, I appreciate it.

Chairwoman FLETCHER. Thank you, Mr. Cloud.

Dr. Babin?

Mr. BABIN. Yes, ma'am. Thank you so much.

Mr. Dewing, what sort of responses are you seeing from many of the large-scale energy companies to the implementation of these new CCUS technologies? What kind of responses?

Mr. DEWING. Very positive. I think we talk to large energy companies, they want to work in joint ventures, they're interested in the technology, especially the technology we've developed at Port Arthur. That's a great reference for us. It has new absorption technology we want to use again. So we are trying to work very closely with Shell, with BP, with Exxon Mobil, a number of companies.

Mr. BABIN. That's good news, very good news.

Along the lines of what my colleague, Mr. Crenshaw, was talking about, Dr. Krishnamoorti, what would be the result of banning all new offshore drilling, as well as the fracking, that several of the candidates running for president have promised to do? Where would that leave our Lone Star State of Texas?

Dr. KRISHNAMOORTI. I think the problem is actually global, because the issue has been we have ignored the offshore industry production for a while. It can be done safely, it can be done reliably, and safeguards can be put in place. There has been a huge change in the offshore industry. We can take people out of danger, doing it automated. There's regulatory issues that prevent us from doing automated work in the Gulf of Mexico. The North Sea, they're doing it today. We are falling behind in those technologies already.

If we ban that, we will lose a huge source of hydrocarbon energy that we will continue to need, not only in the U.S. but also globally.

Mr. BABIN. I hope our friends on the other side of the aisle can hear that, because we may as well pack up and go home here in the State of Texas. As you just pointed out, it would have a global negative effect. A lot of the folks that are now—someone mentioned a while ago—newly heating their homes. The new energy sources that we're having and that are being disseminated around the world would dry up. Thank you very much.

Also, Mr. Kennedy, in your prepared testimony you described how the carbon dioxide captured at your plant is, in turn, used for enhanced oil recovery, or EOR. We talked about it a little bit, but can you please explain for many of us exactly how the EOR process works? As briefly as possible. And then what are the benefits and limitations of this new technology?

Mr. KENNEDY. Yes, sure, and I can be very brief because I am not a reservoir engineer. Actually, the use of CO_2 for enhanced oil recovery has been around since the 1970s, for example. In the Permian Basin. What's unique about our process is the source of CO_2, not the use of the CO_2. So the CO_2 is basically delivered at injection pressure and injected into the reservoir. At West Ranch we use a strategy called wagging, which is water alternating gas. So they basically put water in, get pressure in the reservoir up, put in CO_2. CO_2 uniquely interacts with the locked or blocked molecules of oil, loosens those up, and allows us to push them through with water for recovery. When you get the production fluids back you basically separate the water, you reinject it, you separate the gas, recompressurize it, and reinject it, and then you have the oil available for market.

Mr. BABIN. Great. If we did not follow this technology up, CCUS, would we lose an enormous opportunity to be able to produce more energy using waste products? One day maybe it will be a commodity, but right now it's a waste product.

Mr. KENNEDY. That's correct. Several have mentioned here that there is a demand for CO_2. So to the extent that more CO_2 supplies could be provided, it will help that process.

Mr. BABIN. Right. It's certainly an advantage, that's for sure.

I will yield back, Madam Chair. Thank you.

Chairwoman FLETCHER. Thank you very much, Dr. Babin.

Mr. Crenshaw?

Mr. CRENSHAW. Thank you, Madam Chair.

Dr. Long, I want you to expand on the CCUS energy hub that you mentioned. What exactly does that look like, and would that solve some of the problems you said about fundamental science needing to be focused on more?

Dr. LONG. Yes. The tools that scientists are using today are completely different from the tools that were used when our current carbon capture technologies were discovered. We've made advances in how to build materials and control absorption within materials and diffusion through porous materials because of those tools, because of advanced computational techniques, and that's not being leveraged here for new carbon capture technologies, and it's also not being leveraged for utilization.

Mr. CRENSHAW. Does that need authorization from Congress?

Dr. LONG. I believe the energy hubs are approved through this Committee. Having these hubs—what these hubs mean is sustained long-term funding for scientists to think about how do we do this in the most energy-efficient and cost-effective manner, how do we create materials that will revolutionize the future ways in which we do CO_2 capture and perhaps convert it into all kinds of products. That funding for fundamental science to drive future technology, there should be a lot more of it in this area.

Mr. CRENSHAW. I understand.

Mr. Dewing, in your testimony you talk about the retrofitting of existing hydrogen facilities, and I want to go back to this New Source Review. Are you familiar with New Source Review?

Mr. DEWING. I'm afraid not.

Mr. CRENSHAW. OK, then I won't ask that question. We'll just move on.

I will say it's nice to be in a hearing where we have a lot of viable solutions, and we've discussed a few of them. We've talked about energy hubs and the authorization needed for that; interesting ideas like reclassifying CO_2 as a commodity. It's interesting because it really is. It's used in EOR. You can make plastics. We could possibly one day make a gasoline out of it. Maybe this gets back to something we should research as a fundamental science and energy hub. I also heard it can be used for agriculture, of course. I mean, you can talk about a greenhouse that needs multiple times the CO_2 that is present in normal air, algae farms, things like that. There really are algae farms truck in CO_2 every single day. There really is a market for that.

It sounds like we need 45Q flexibility, additional flexibility in that, to provide for the incentives to actually capture CO_2 and then utilize it. CO_2 infrastructure, pipelines. We need to stop vilifying pipelines in this country; that would be great. It would be great if the northeast wasn't relying on shipping from Russia to get their natural gas and heating in their homes. DOE grants have proven to be a fundamental part, it sounds like, in incentivizing and getting this technology off the ground.

Let me be clear, Mr. Kennedy. You guys are at a point where you can operate in a stand-alone way; is that correct? Or do you still need those grants and still need those tax incentives? I mean, where are you?

Mr. KENNEDY. Yes, economics continue to be challenging. Like I mentioned, we're a little bit uniquely structured given the way we are with the oil field and stuff. But the focus on this next generation is hopefully driving cost down. But I think any new project, regardless of first generation, second generation, is going to need 45Q to support that.

Mr. CRENSHAW. Right.

Mr. KENNEDY. And government grants as well as additional R&D.

Mr. CRENSHAW. Yes, and that's great to hear, and these aren't enormous costs on the economy. We can get you started, we can maintain some kind of incentive structure, and as the technology improves, there's a real market for CO_2 where eventually you can stand on your own. When we're talking about solutions—and again, I want to get back to this main truth, which is that America is the innovation capital of the world, and ignoring that or destroying that capability by destroying the fossil fuel industry is actually bad for the environment. It seems counter-intuitive, but it's really not, and we've proven why today, because the rest of the world, and especially countries that emit far more carbon dioxide than we do, are relying on America to be the innovation engine of the future. We can't ignore that, and we have to be doing exactly what we've been talking about today to incentivize that and really keep this miracle going where we can actually have our cake and eat it too. I mean, that's a pretty great thing. We can continue economic development, we can continue being the greatest and richest country in the world, helping other countries continue to develop, but also clean up the environment, and I think that's a really cool thing.

So I just want to say thank you again for having me at this wonderful Subcommittee hearing.

Chairwoman FLETCHER. Thank you so much, Mr. Crenshaw.

And thank you all for being here today and for your testimony.

Before we bring the hearing to a close, I want to mention just a few things and go back to what I said at the beginning when we started the hearing this morning. I think we've seen today that in this Congress, this Committee has a strong track record of working together in a bipartisan way to solve problems and to support science, and that is critically important.

I think there is much consensus among my colleagues here today about the challenges and opportunities before us and, as always, the collaboration and cooperation amongst the witnesses, amongst the research institutions, industry, and our government agencies. What we've seen today and what we've heard about I think is very encouraging and is certainly a critical part of our path forward, and it's consistently what we see on our Science Committee.

So I thank you for your work, I thank you for your work together, and I thank you for your time here this morning.

The record of the hearing will remain open for 2 weeks, and that means that Members can add additional statements or submit additional questions, so we may have additional things coming to you.

Certainly, we had a lot of great questions here today and really appreciate your great answers, your time, and your commitment on this issue.

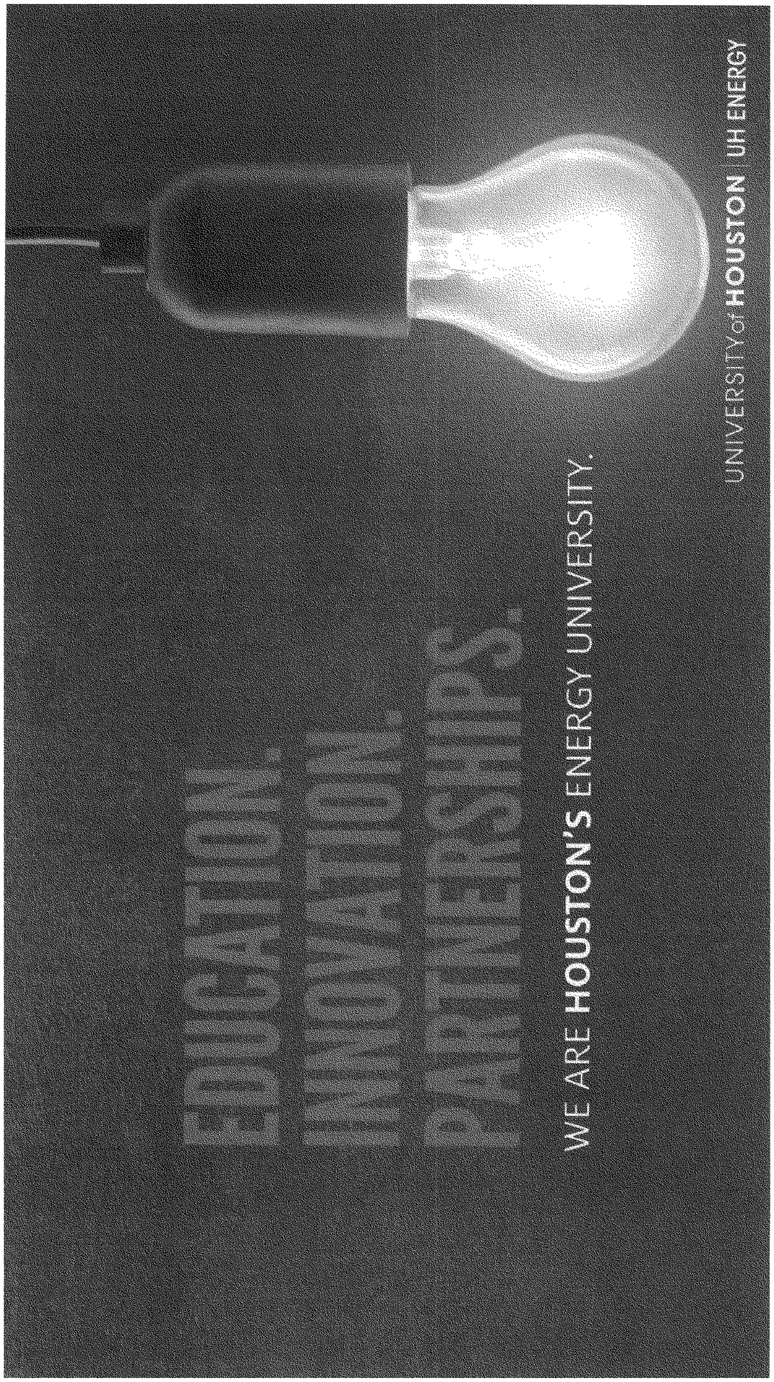
So, with that, the witnesses are excused and the hearing is now adjourned.

[Whereupon, at 12:13 p.m., the Subcommittee was adjourned.]

Appendix

Additional Material for the Record

PRESENTATION SUBMITTED BY DR. RAMANAN KRISHNAMOORTI

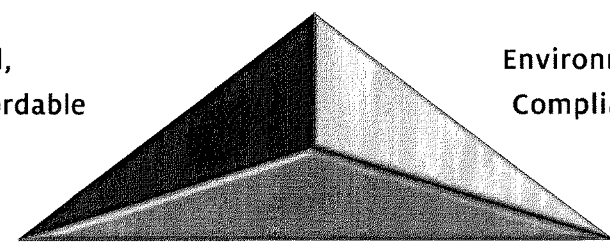


CENTER FOR CARBON MANAGEMENT IN ENERGY - CCME

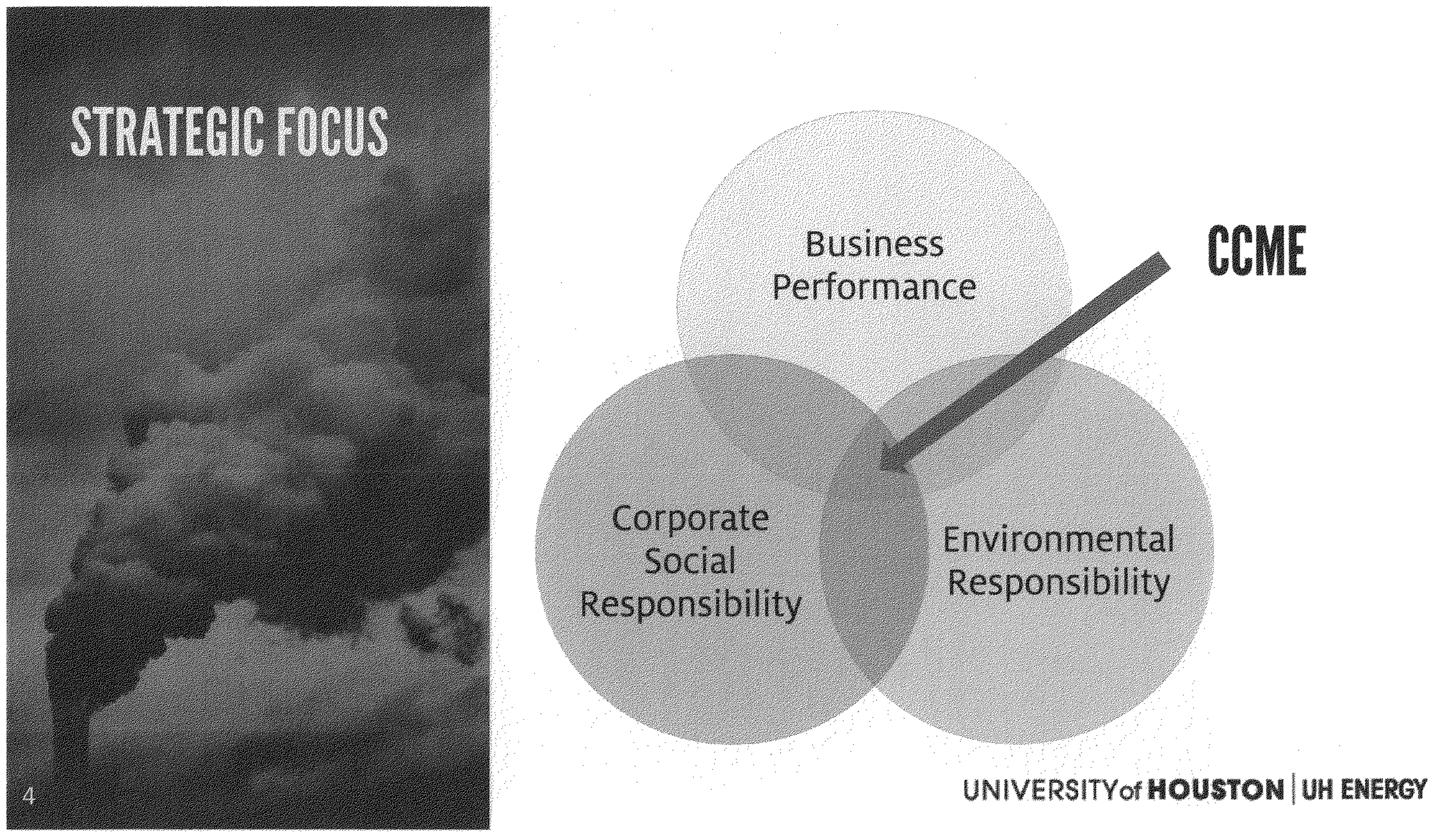
MISSION: Establish a globally recognized Center for Carbon Management in Energy to identify the key challenges and solutions necessary to lead the lower carbon future for the energy industry and societal marketplace.

The UH CCME will be strategically driven by the challenges in oil and gas production, petrochemicals, and electric power sectors (including renewable energy platforms), as well as the entire energy value chain to consumer end use, to advance innovative and transformative solutions for a sustainable energy future.

ENERGY SUSTAINABILITY is the Foundation



- Pursue all requirements in harmony – a balanced public view
- Global perspectives and Industry priorities - Developed and Developing worlds
- Embrace transformative approaches and policy to create the future
- New Energy ecosystems to transform science and technology development and investment in breakthrough materials, products, capabilities, and commerce


STRATEGIC FOCUS
4
Business Performance
Corporate Social Responsibility
Environmental Responsibility
CCME
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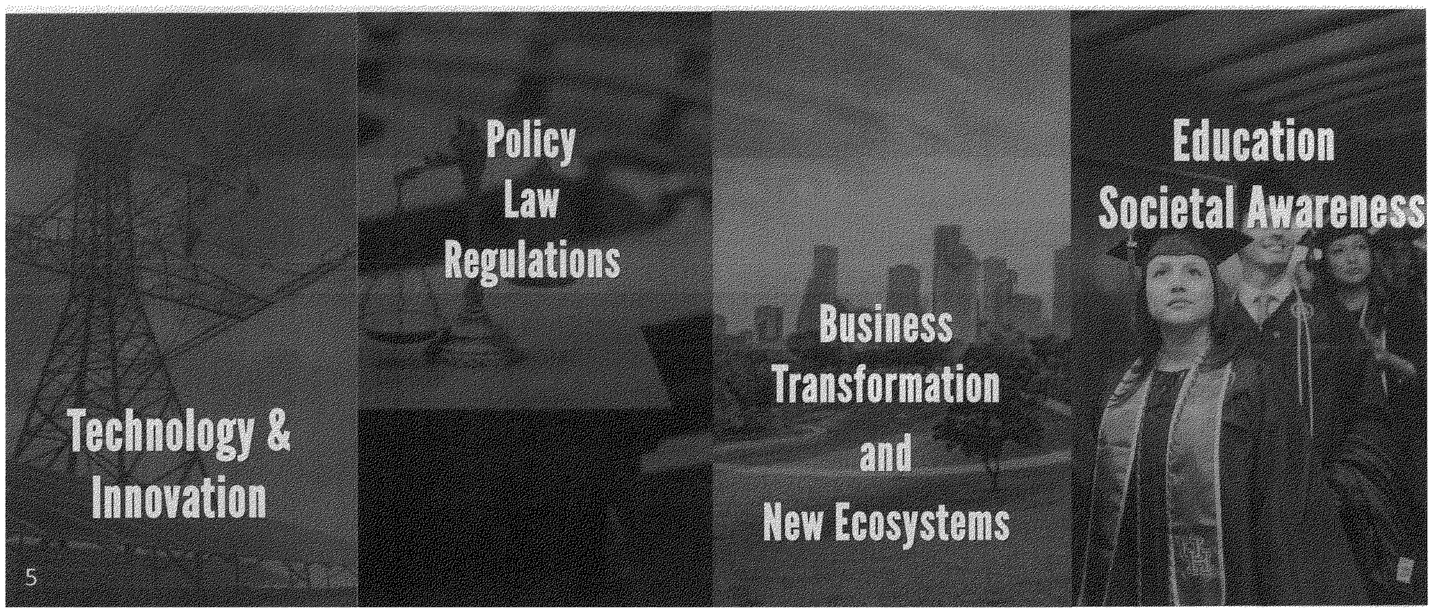
KEY STRENGTHS AND CAPABILITIES FOR CCME



Technology & Innovation

- Key Markets: Oil and Gas; Petrochemicals; Electric Power
- Systems Approach to Each Market and Value Chain

	Accretive Utilization	Emissions Reduction and Mitigation
CO_2	EOR and CCUS	CCUS and Integrated Processes
CH_4	Conversion	Monitoring and Mitigation
Hydrocarbons	Conversion	Process Intensification

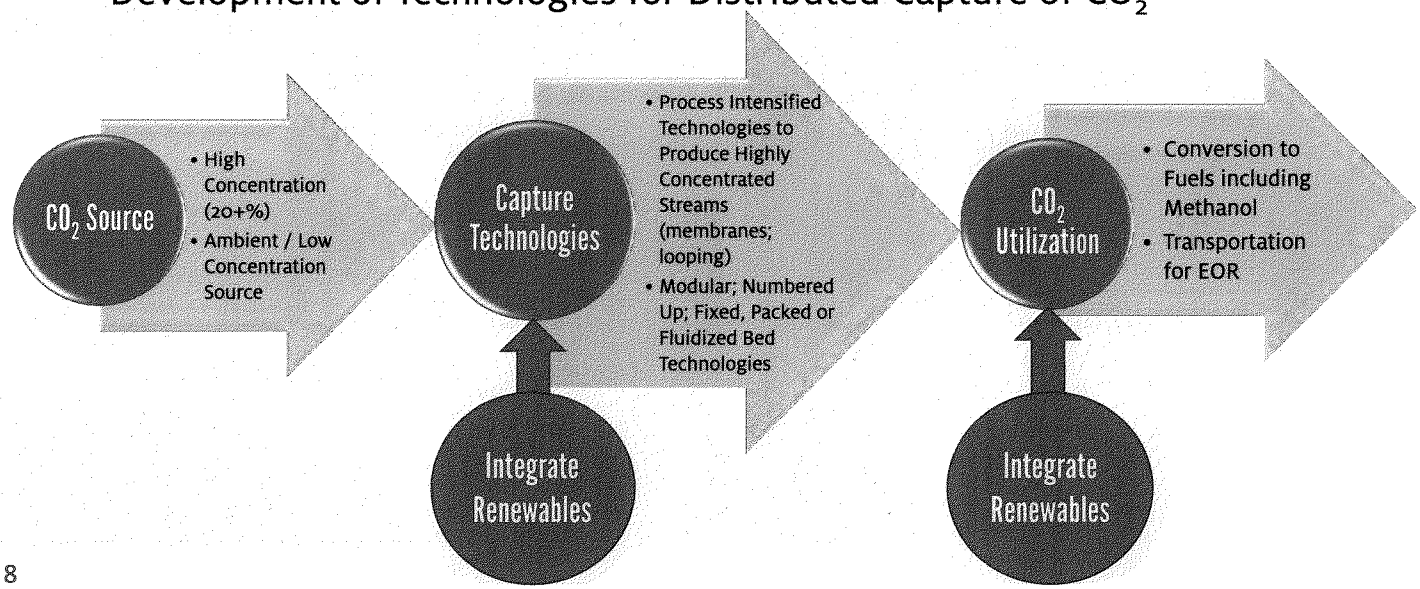
Technology & Innovation

	CO_2 Value Chain			Methane and Hydrocarbons	
	Capture	**Transportation**	**Utilization and Sequestration**	**Emissions: Monitoring and Mitigation**	**Conversion and Monetization**
Power Generation Hydrocarbon Exploration & Production Petrochemical Refining Chemicals and Fertilizers	<u>Novel Capture Technologies:</u> Adsorption; Selective Membranes; Modular & Distributed; Integration with Renewables <u>Re-engineering Processes:</u> Integration; Intensification	<u>Pipeline Technologies</u>: Materials, Corrosion & Leak Testing <u>Shipping of CO_2</u>: Technologies, Economics & Policies Compressors & Power Systems	<u>Conversion:</u> Fuels Chemicals Plastics <u>Enhanced Oil Recovery:</u> Conventional ROZ Unconventional Offshore Water Use & Recycle <u>Geological Sequestration:</u> Seismic, Acoustic, Modeling & Policy	<u>Monitoring:</u> (i) Remote Monitoring using Drones (ii) Distributed Acoustic Sensing <u>Mitigation:</u> (i) Pipeline Modeling (ii) Renewable Integration for Pneumatic Valves	Distributed Catalysis and Power Generation <u>Conversion:</u> Fuels (methanol) Chemicals Polymers & Materials <u>Monetization:</u> Gas Injection EOR

7

Technology & Innovation: Distributed Carbon Capture & Utilization

- Development of Technologies for Distributed Capture of CO_2



Technology & Innovation: Geologic Carbon Storage

Saline Aquifer Storage

- Primary storage*
  - Bulk CO_2 injection
  - Pressure limited
  - Infill wells to increase injection rate
- Secondary storage*
  - Displace water
  - Desalinate produced water
  - Reinject concentrate
  - Sell, discharge, or store fresh water

Other CO_2 Storage Options

- CO_2 EOR in tight oil and ROZ*
- CO_2 enhanced coalbed methane production
- Offshore EOR+ and saline aquifer storage*

* Various aspects of research and technology development supported by laboratory and modeling capabilities and skillsets existing at UH

CO_2 Enhanced Oil Recovery (EOR+)*

EOR+ Scenario	Description	Incremental recovery %OOIP	Net Utilization tCO_2/bbl	Net Carbon Ratio
Conventional	Miscible WAG flood with vertical injector and producer wells in a "five spot" or similar pattern. Operational practices seek to minimise CO2 use.	**6.5**	**0.3**	**0.7**
Advanced	Miscible flooding following current best practices optimised for oil recovery. May also involve some "second-generation" approaches that boost utilisation and recovery.	**13**	**0.6**	**1.5**
Maximum Storage	Miscible flooding where injection is designed and operated with the explicit goal of increasing storage. Could include approaches in which water is removed from reservoir to increase available pore volume.	**13**	**0.9**	**2.2**

Godec et al. 2011

Up to 139 $GtCO_2$ storage potential starting at $70/bbl oil price excluding capture cost

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Technology & Innovation: Enhanced Oil Recovery

UNIVERSITY of HOUSTON
ENERGY INDUSTRY PARTNERSHIPS

LOOKING TO RECOVER MORE OIL?
BUILD A PARTNERSHIP WITH THE UNIVERSITY OF HOUSTON

UH's Energy Industry Partnerships (EIP) team will:
- Partner with your asset team to optimize production and maximize value
- Develop integrated solutions by following a multidisciplinary team (MDT) approach
- Provide expertise for conventional and unconventional fields

Energy Industry Partnerships (EIP) team is leading the charge to help the University of Houston emerge as the leading energy university by bringing value to the energy industry using smart, innovative and integrated approaches to the recovery of oil and gas through research pertaining to CO2 – EOR conventional & unconventional Reservoirs, waterflood/IOR, and integrated reservoir management – conventional & unconventional Reservoirs.

CO2 & Gas EOR laboratory mechanistic studies, pilot design and field implementation

Unconventional field development

Reservoir management with a multidisciplinary approach

IOR – Waterflooding and infill drilling

Integrated reservoir characterization and simulation

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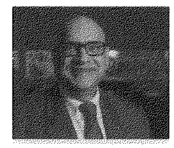
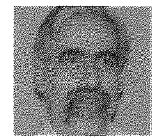
Technology & Innovation: EOR & CCUS Experience

CCUS Project Experiences:

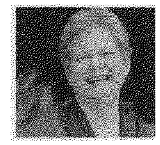
- Alaska
- Texas including Permian
- North Sea & Continental Europe



Ganesh Thakur
Professor, Petroleum Engineering



Dimitrios G. Hatzignatiou
Professor, Petroleum Engineering



Christine Ehlig-Economides
William C. Miller Endowed Chair Professor of Petroleum Engineering

C02 Storage

- Abundant oil fields and Post EOR
- Site Assessments & Phase I – VI of Site Development: Best Practices
- Post Injection Closure & Long Term Monitoring Development

Development of Technology Roadmap to meet "Broad Commercial Deployment of CCUS" as per NPC Study & Recommendations

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Technology & Innovation: Gas Injection

Foam Miscible Ethane Driven Oil Recovery in Low Permeability / Harsh Environments

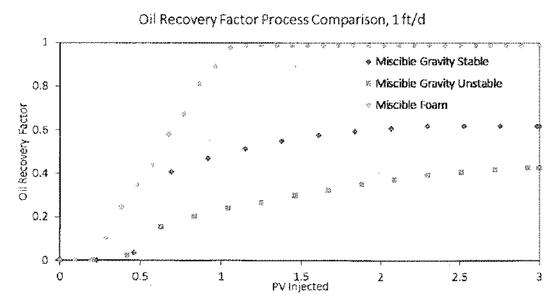
Key Takeaways from Lab Scale:

- Stable in Harsh Environments
- Gravity stable displacement delays gas breakthrough; higher recoveries
- Type I Low IFT miscible gas foams effective in a gravity unstable environment

Injectant	recovery @ 1 PV, %	recovery @ 3 PV, %
CO_2	80	95
100% ethane	82	97
100% methane	40	55
85% methane, 15% ethane	53	74
75% methane, 25% ethane	60	87
65% methane, 35% ethane	76	96

Next Steps:

- Displacement tests to characterize drive mechanisms
- Immiscible ethane foam process characterization
- Role of ethane vs. CO_2, N_2, and CH_4 in foam stability in porous media
- P_b depression in tight rock



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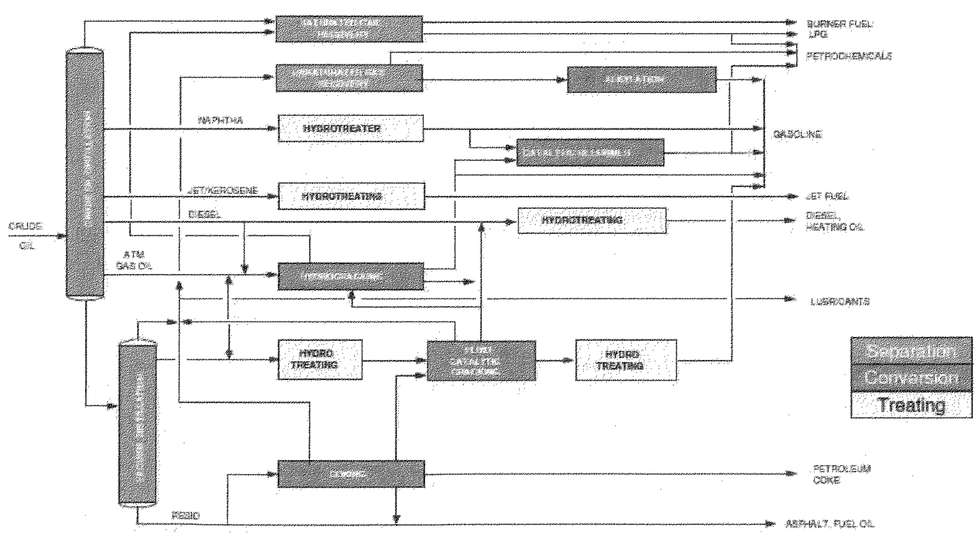
Optimization & Reconfiguring: Refineries



Opportunities:

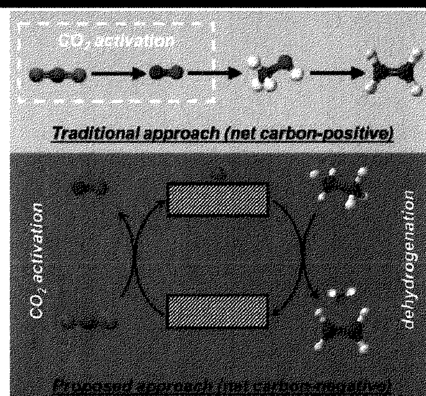
a. Energy Efficiency & Integration
b. Oxy-combustion for heat with CO_2 Capture
c. CO_2 to fuels
d. CO_2 to chemicals

Specific Cases:

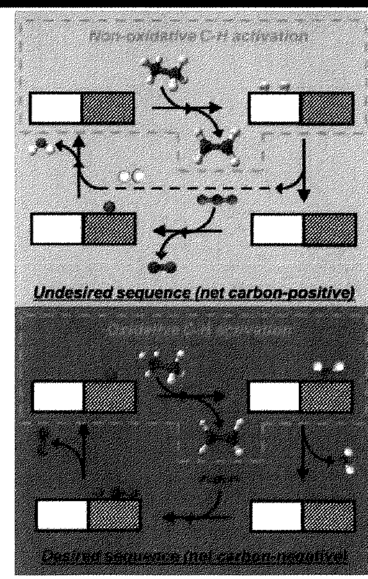
i. Furnaces and FCC Using O_2
ii. Electricity enabled air separation
iii. Electrochemical conversion of CO_2 to chemicals or fuels
iv. H_2 from renewables
v. Process Modeling
vi. Design & Simulations

Technology & Innovation: CO_2 a Soft Oxidant for Chemical Industry

CO_2 as a source of carbon <u>and</u> active oxygen



Can CO_2 be leveraged as a source of oxygen on catalyst surfaces to enable step-changes in process performance across the chemical industry?



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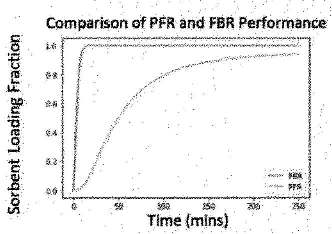
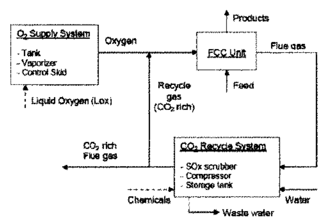
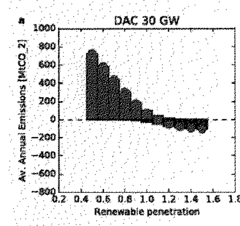
Technology & Innovation:
Carbon Capture & Utilization: Process Intensification

Goal: Develop process intensification and potentially modular routes for improved energy efficient carbon capture and utilization





Parameter	Reference	Study	Units
Capacity (BPD)	60,000	145,0000	BPD
Capacity Factor	-	0.6	
Cost Index	203	200	
CO_2 Produced	510	1,600	MTPY
CO_2 to Capture Plant (95%)	484.5	1,520	MTPY
CO_2 Capture Efficiency	90%	90%	
CO_2 Captured	436	1,370	MTPY
Capture Plant Capital Cost	174.4	291.75	$ MM
Capture Plant O&M Costs	18.2	30.5	$ MM/yr
Pipeline Capital Cost	-	167.3	$ MM
Pipeline O&M Costs	-	8.4	$ MM/yr
Storage Costs	2.94	4.92	$/tonne
Tax Rate	-	34%	
Depreciation Schedule	-	Straight Line	
CO_2 Avoided Cost	94	109	$/tonne



Key results:

- Evaluation of solid adsorbents for direct air capture of CO_2 including different reactor configurations. LCA's and techno economic evaluation along with process intensification underway.
- Developing modular intensified carbon capture systems paired with renewable power generation. Engineering analysis and field scale demonstration of various technologies ongoing
- Evaluation and optimization of processes and dual shipment model to integrate LNG and LCO_2 value chains.

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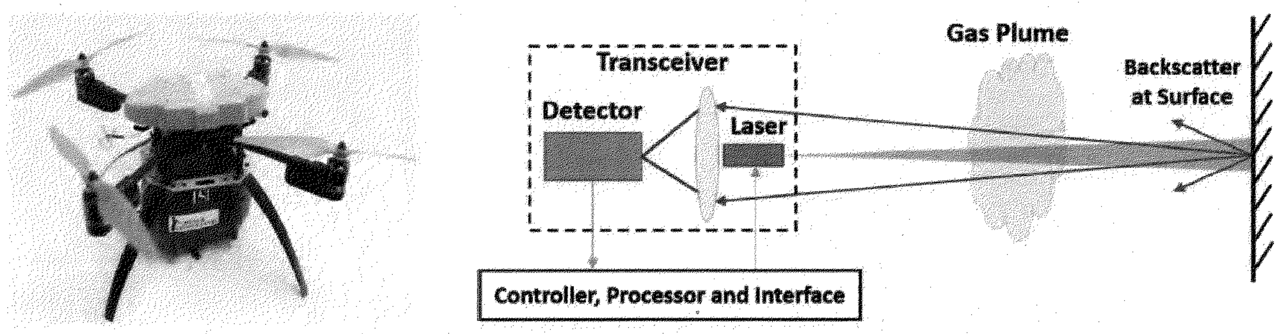
A UAV Drone System to Locate and Quantify Fugitive Methane Emissions

Dr. Robert Talbot, University of Houston

Dr. Mickey Frisch, Physical Sciences, Inc.

UNIVERSITY of HOUSTON
EARTH AND ATMOSPHERIC SCIENCES

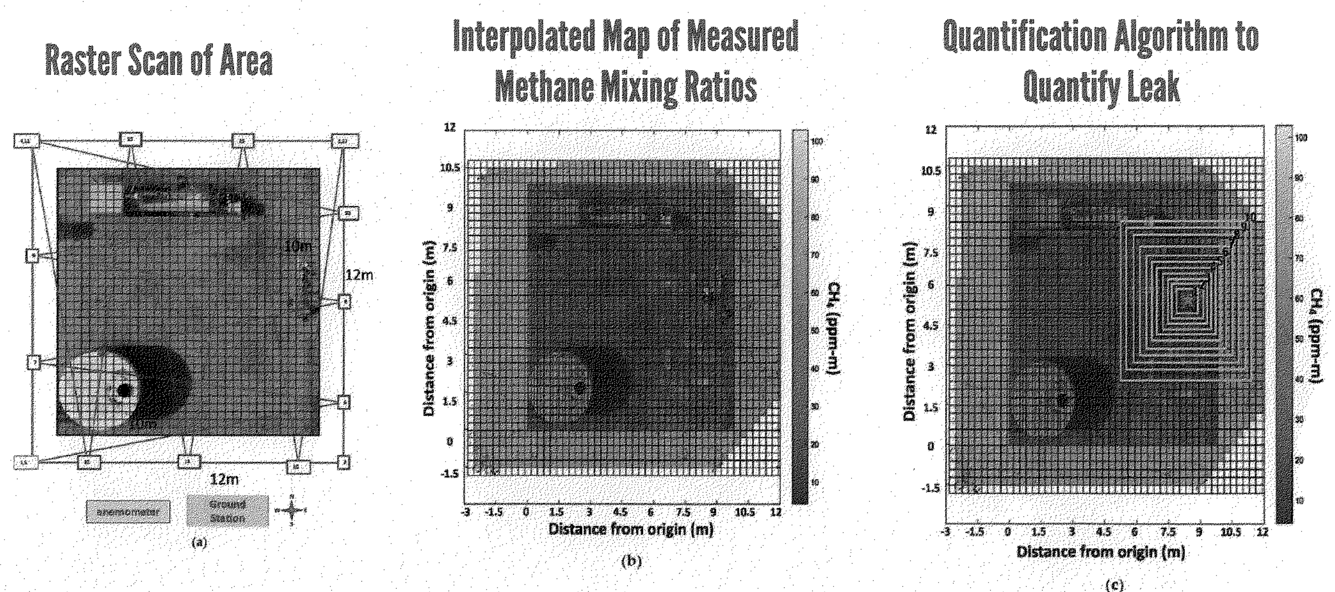
PSI Physical Sciences Inc.



(a) (b)

Figure 1. (**a**) The images of the RMLD-UAV; (**b**) diagram of the basic premise of RMLD operation.

Three-Step Process to Locate and Quantify Leaks



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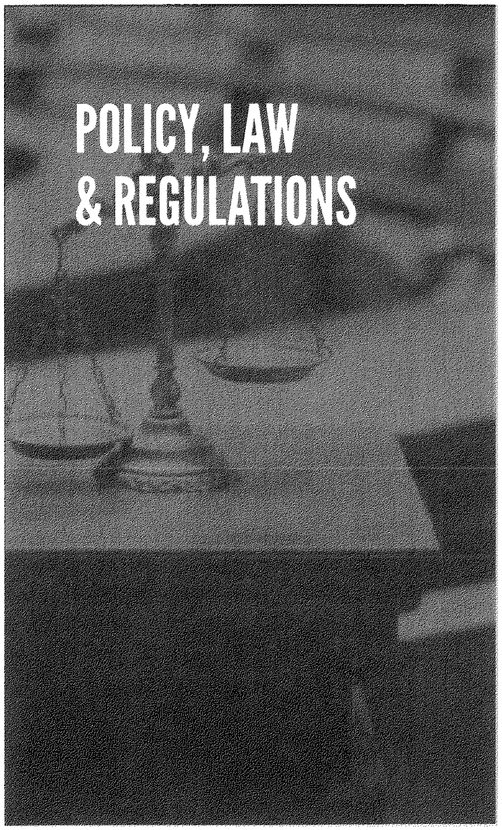
Technology & Innovation

- Data Sciences & Computational Analysis
- Artificial Intelligence
- Robotics – Linkage to Subsea Systems Institute
- Process and Materials Optimization via Computational Analysis



Regulatory & Public Policy:

Compliance and Assurance

Market Innovation

- Existing (example: 45Q Tax Credits)
- New: Low carbon products and services
- Incentivizing Negative Emissions Technologies
- Structure: Current and necessary frameworks

Expanded Policy & Research for Advocacy

- O&M
- Financial Investment
- Business Models
- Liability and Ownership
- Carbon Tax
- Cap and Trade
- International Trading and Investment
- International Clean Development Mechanisms

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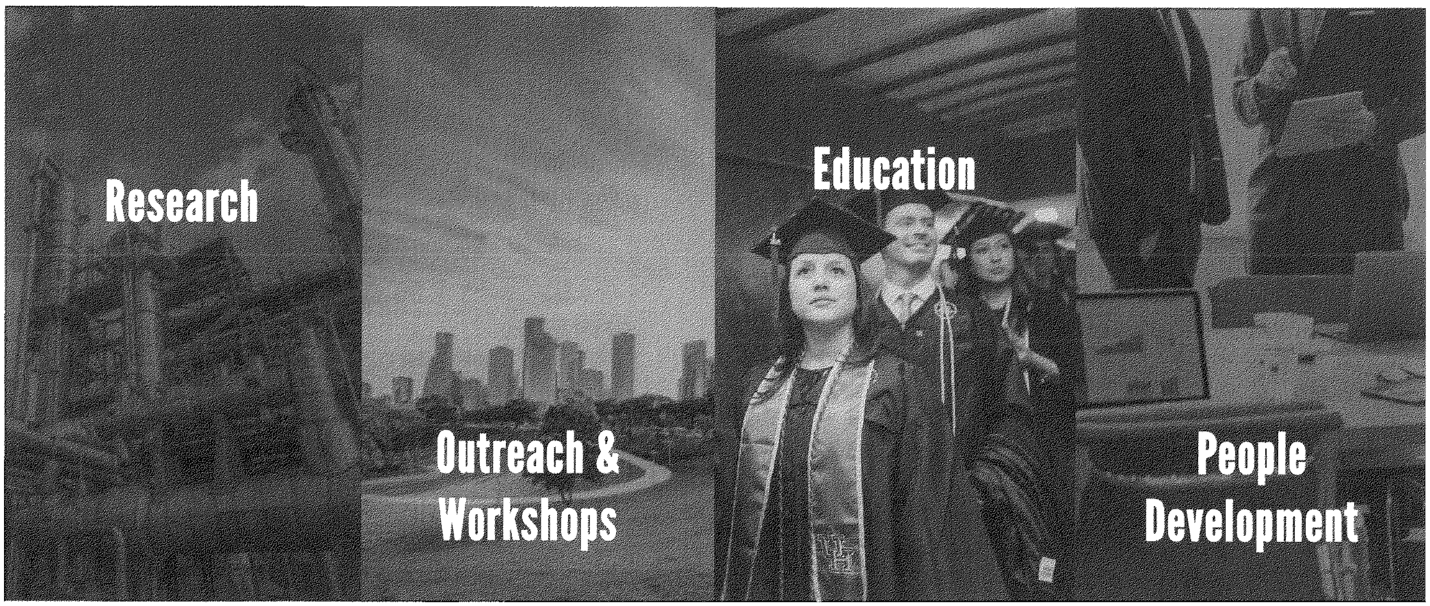
KEY CCME PROGRAMS



Science, Technology, Innovation & Policy - 2

- Systems Focus:
  - Power Generation and Integrating Carbon Capture
  - Zero Emissions Refineries
  - Process Intensification for Chemicals and Fertilizer Production
  - Integrated Flaring Mitigation + Renewables + EOR

WHITE PAPER SUBMITTED BY DR. RAMANAN KRISHNAMOORTI

White Paper can be found at: https://pdfs.semanticscholar.org/970b/62daa17a329a98f03bcd33233199f42c5bcf.pdf?__ga=2.85876569.1336167076.1574703669-796248402.1574703669

REPORT SUBMITTED BY DR. RAMANAN KRISHNAMOORTI

Report can be found at: https://uh.edu/uh-energy/research/ccme/content/uh-energy-ccme-white-paper-series-03-2019-web.pdf

PRESENTATION SUBMITTED BY MR. NIGEL JENVEY

The Future of Advanced Carbon Capture Research and Development: An Air Products Perspective

Roger Dewing
Director of Technology for CCUS, Air Products

AIR PRODUCTS

Hydrogen as an enabler

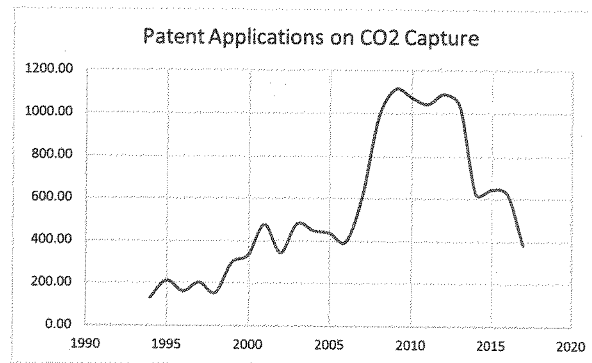
- Decarbonisation of hydrocarbons with CCS provides an energy source with zero or very reduced CO_2 emissions
- Produced hydrogen allows for decarbonised energy distribution and energy storage
  - Transportation
  - Heating and power
  - Energy intensive industry
- Integrated with green energy projects, it can provide carbon neutral energy storage and back-up
- Viable projects will only happen if you can answer two fundamental questions:

Where will the CO_2 go?
Who will pay?

AIR PRODUCTS

The Rise and fall ...and rise? ...of CO_2 capture

- Power companies drove interest in CO_2 capture from large coal power station 2005-2012
- 2008 recession eventually led to demise of most projects – the US being the exception due to existing enhanced oil recovery (EOR) demand for CO_2
- Renewed interest in US, EU, Canada, China
  - Multiple projects with a single storage solution
  - Energy clusters with hydrogen integration for distribution and storage



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US leadership in CCS Projects

- More operating projects than ROW combined
- 100s of miles of existing super critical CO_2 pipelines for EOR
- Long term EOR experience
- Federal 45Q – Tax credit provided for projects that capture and store CO_2.
  - Updated in 2018
    - \$35/MT for use in enhanced oil recovery (EOR)
    - \$50/MT for sequestration

Project	Location	Onstream	Sector
Century Plant	Texas, United States	Operating since 2010	Industry, Natural Gas Processing
Terrell Natural Gas Processing Plant (formerly Val Verde)	Texas, United States	Operating since 1972	Industry, Natural Gas Processing
Petra Nova Carbon Capture	Texas, United States	Operating since 2017	Power, Coal Power Generation
Air Products Steam Methane Reformer	Texas, United States	Operating since 2013	Industry, Hydrogen Production
Enid Fertilizer	Oklahoma, United States	Operating since 1982	Industry, Chemicals (ammonia)
Coffeyville Gasification Plant	Kansas, United States	Operating since 2013	Industry, Chemicals (ammonia)
Illinois Industrial Carbon Capture and Storage	Illinois, United States	Operating since 2017	Industry, Refining (biofuels)
Shute Creek Gas Processing Plant	Wyoming, United States	Operating since 1986	Industry, Natural Gas Processing
Lost Cabin Gas Plant	Wyoming, United States	Operating since 2013	Industry, Natural Gas Processing
Great Plains Synfuel Plant and Weyburn-Midale	North Dakota, United States & Saskatchewan, Canada	Operating since 2000	Industry, Refining (SNG)

CCS North America (ref International Energy Agency)

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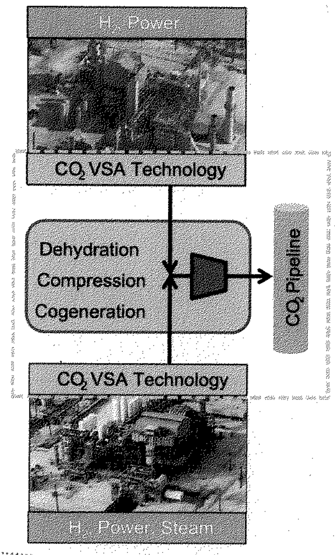
Project Overview: State-of-the-Art Carbon Capture from Two Port Arthur, TX SMRs

- American Recovery and Reinvestment Act Funding
- ~1 million tons of CO2 to be recovered and purified annually starting late 2012
- Valero providing land, rights-of-way, utilities
- Air Products supplying compressed and purified CO_2 to Denbury for injection into TX oilfields for enhanced oil recovery

Air Products' Port Arthur CO2 Project

Technology to recover anthropogenic CO_2 for EOR



- Retrofit of two Steam -Methane Reformers (SMR) located in the middle of a refinery
- Capture and purification of CO_2 from hydrogen plants for EOR
- Technology developed by Air Products
  - Vacuum Swing Adsorbers
- 90%+ capture of CO_2 from syngas
- ~2600 t/d (50 MMSCFD) of CO_2 to Denbury's Green Pipeline for West Hastings oilfield EOR
- 30 MWe cogeneration unit to generate power and make-up steam
- Full capacity achieved April 2013

Capturing 1 million tonnes/year of CO_2 since 2013

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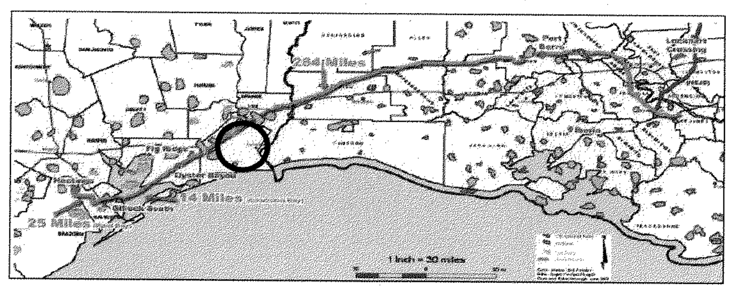
CO_2 Capture – Port Arthur Project Answers

- **Where will the CO_2 go?**
  - Port Arthur is 13 miles (21 km) from Denbury's existing "Green" 300+ Mile (~500 km) CO_2 Pipeline used for CO_2 EOR
- **Who will pay for the CO_2 capital and operating costs?**
  - US Government grant from the American Recovery & Reinvestment Act
  - Tax credits 45Q for CO_2 stored by EOR
  - Denbury pays for CO_2 to use in EOR applications



Map shows Denbury's Green CO_2 Pipeline.
Data source is Denbury, December 2011, CO_2 Flooding Conference

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Air Products' CCS focus

- Looking for viable CCS opportunities
- Further retrofits of existing hydrogen SMRs
- CO_2 Capture from Gasification
  - In preparation Air Products has purchased key Gasification technology of the leading suppliers
  - Gasification with CO_2 capture allows you to use high carbon content feed stocks to produce high value products with minimal carbon emissions
  - Air Products has developed a "Road Map" of technology applications for CO_2 capture on coal and refinery heavy residue feedstocks
- Development of in-house technology e.g. CO_2 VSA
- Decarbonization of natural gas
- Partnerships for storage options

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Summary

- Fossil fuels will be part of the global energy supply for a many years to come
  - CCS means we can continue whilst meeting CO_2 emission targets
- CCS allows the use of lower cost carbon rich "heavy" feedstocks with low atmospheric CO_2 emissions
- All the necessary technology to capture, purify and store CO_2 exists and is proven in long term operation
  - Technology available to commence projects immediately
  - R&D will improve efficiency and reduce cost
- A competitive alternative to other Green Energy projects
- Seed projects can be an enabler for further R&D, pilot plants, smaller scale investments

Where will the CO_2 go?
Who will pay?

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Thank You

tell me more

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