


Innovations and Markets

IN CARBON EMISSIONS MANAGEMENT

October 2019



Prepared by: AJW

On behalf of: ICAC

THIS REPORT WAS PREPARED BY AJW, INC. FOR THE INSTITUTE OF CLEAN AIR COMPANIES (ICAC)

About AJW

AJW is the leading government affairs and business consulting firm serving technology innovators. We analyze regulatory risks and opportunities for avenues to expand market demand for advanced technology solutions. We then work to affect the public policy process to support our clients' strategic business planning goals. AJW provides the early support needed for businesses to overcome market barriers and achieve widespread product application.

About ICAC

For nearly 60 years, the Institute of Clean Air Companies has been *the* trusted voice in the clean air technology industry. ICAC provides members with unique opportunities to sharpen market awareness and enhance business planning through valuable engagement with market influencers and policymakers.

Acknowledgements

AJW would like to thank the individuals who contributed to or reviewed this report. Their time and expertise provided invaluable direction and insight.

Authors

Project Lead

Christopher Hessler – Partner

Contributing Authors

Haley Armstrong – Associate

Carl Leighty – Associate

Reviewers

Armond Cohen – Clean Air Task Force
Noah Deich – Carbon 180
Jeff Erikson – Global Carbon Capture and Storage Institute
Greg Filippelli – Lhoist North America
Lars-Erik Gaertner – Linde
Geoff Holmes – Carbon Engineering
Stan Mack – Johnson Matthey
Dan Menitti – Mississippi Lime/Breen Energy Solutions
Nathan White – Umicore
Joe Wong – Advanced Emission Solutions
Alex Zapantis – Global Carbon Capture and Storage Institute

Additional Contributors

Clare Schulzki – Executive Director, ICAC
Jake Smerchansky – Communications Intern
Karunya Krishnan – Communications Manager
Michael Goo – Partner
Ted Michaels – Partner
Patrick Wallace – Policy Intern

Additionally, AJW would like to recognize the existing work that has been done by many organizations to advance carbon emissions management. Although we could not possibly capture the entire body of work being conducted in the carbon emissions management field, we would like to highlight some of the leading organizations whose work we relied on to write this report. This report was made possible by the information found in reports and other publications produced by the following groups:

Bipartisan Policy Center
Carbon 180
Carbon Capture Coalition
Clean Air Task Force
Global Carbon Capture and Storage Institute
Energy Futures Initiative
Energy Transitions Commission
Information Technology and Innovation Foundation
Innovation for Cool Earth Forum
Intergovernmental Panel on Climate Change
International Energy Agency
The National Academies of Sciences
The Rhodium Group
Third Way
University of Michigan's Global CO_2 Initiative
U.S. Department of Energy
U.S. Environmental Protection Agency
World Resources Institute

Glossary of Terms

Term	Definition
ADM	Archer Daniels Midland Company
BPC	Bipartisan Policy Center
BECCS	Bioenergy with Carbon Capture and Storage
CAA	Clean Air Act
CAPEX	Capital Expenditure
CATF	Clean Air Task Force
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CEM	Carbon Emissions Management
CH_4	Methane
CMM	Coal Mine Methane
CMOP	Coalbed Methane Outreach Program
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq or CO_2-eq	Carbon dioxide equivalent
ComSos	Commercial-Scale Solid Oxide Fuel Cell
CPP	Clean Power Plan of 2014
CRCGGT	Cooperative Research Centre for Greenhouse Gas Technologies
DAC	Direct Air Capture
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
ETC	Energy Transitions Commission
EtO	Ethylene Oxide
FOAK	First of a Kind
GDP	Gross Domestic Product
GHG	Greenhouse Gas

Term	Definition
Gt CO_2	Gigaton (billion tons) of carbon dioxide released into the atmosphere
HAPS	Hazardous Air Pollutants
Hg	Mercury
ICAC	Institute of Clean Air Companies
IEA	International Energy Agency
IEEFA	Institute for Energy Economics and Financial Analysis
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
ITIF	Information Technology and Innovation Foundation
LCFS	Low Carbon Fuel Standard
MATS	Mercury and Air Toxics Standard
MW	Megawatt
NAS	National Academy of Sciences
NET	Negative-Emission-Technology
NETL	U.S. National Energy Technology Laboratory
NOAK	Nth of a Kind
NOx	Nitrogen Oxide
NRCAN	Natural Resources Canada
OPEX	Operating Expenditures
Pb	Lead
$PM_{2.5}$	Particulate Matter 2.5
PM_{10}	Particulate Matter 10
ppm	Parts per million
PTC	Production Tax Credit
RCO	Regenerative Catalytic Oxidizer
RD&D	Research, Development and Demonstration
RFS	Renewable Fuel Standard
RIA	Regulatory Impact Analysis
RIN	Renewable Identification Number assigned to a batch of biofuel to track its production, use, and trading in accordance with EPA's Renewable Fuel Standard
RTO	Regenerative Thermal Oxidizer
SBC Energy Institute	Schlumberger Business Consulting Energy Institute
SOFC	Solid Oxide Fuel Cell

GLOSSARY

Term	Definition
SOx	Sulphur Oxides
SO_2	Sulfur Dioxide
TRL	Technology Readiness Level
VAM	Ventilation Air Methane
VOC	Volatile Organic Chemicals
WMM	Waste Mine Methane
WRI	World Resources Institute

About This Report

This report was developed with two distinct audiences in mind: 1) emission control manufacturers, and 2) climate stakeholders and policymakers seeking to accelerate the pace of innovation and deployment of carbon emissions management (CEM) technologies.

Figure 1. *Petra Nova, located near Houston, TX, utilizes a post-combustion capture system and then transports the captured carbon via pipeline to an oil field for enhanced oil recovery. Source: NRG.*

For the emission control sector:

This report provides an overview of the growing body of information about CEM contributions to global decarbonization. Though nascent, policy support for CEM is expanding and is likely to continue as technologies improve their effectiveness. This report highlights the diversity of CEM technology opportunities and challenges. We hope this is a useful initial resource for companies starting to explore CEM opportunities that best relate to their own competencies and strategies.

CEM represents a potentially large commercial opportunity. The rate of commercial success will be determined by how actively the sector collectively engages in technology innovation and demonstrations with support by climate policies.

CEM is rapidly emerging and could become the largest commercial opportunity the emissions management industry has ever seen.

For climate stakeholders and policymakers:

This report sheds light on the barriers limiting private sector resource investment in CEM. It also offers actionable ideas for expanding investment in CEM technologies and commercial pathways that can deliver meaningful decarbonization benefits. Many calls have been made for greater private sector engagement in marshalling the financial, technical, and commercial resources necessary to bring CEM technologies to market. However, CEM policy proposals are often either overly general (e.g. “more funding”) or extremely narrow (e.g. sequestration injection regulations). This report seeks to capture both general principles and specific policy approaches to further develop the discussion.

Definition of Carbon Emissions Management

Our definition of CEM encompasses all variants of carbon capture, utilization, and sequestration (CCUS), including negative-emission technologies (NETs). Capture technologies can address CO_2, methane, and all other greenhouse gas (GHG) emissions. “Management” in CEM encompasses the full range of post-capture opportunities, including manufacturing products that would sequester GHGs on a short-term or long-term basis.

About the Compendium

This report includes a comprehensive database of carbon emission management activities worldwide. Much of this report is based on our interactions with technology developers and project managers in development of this compendium.

DISCOVER THE GROWING OPPORTUNITY

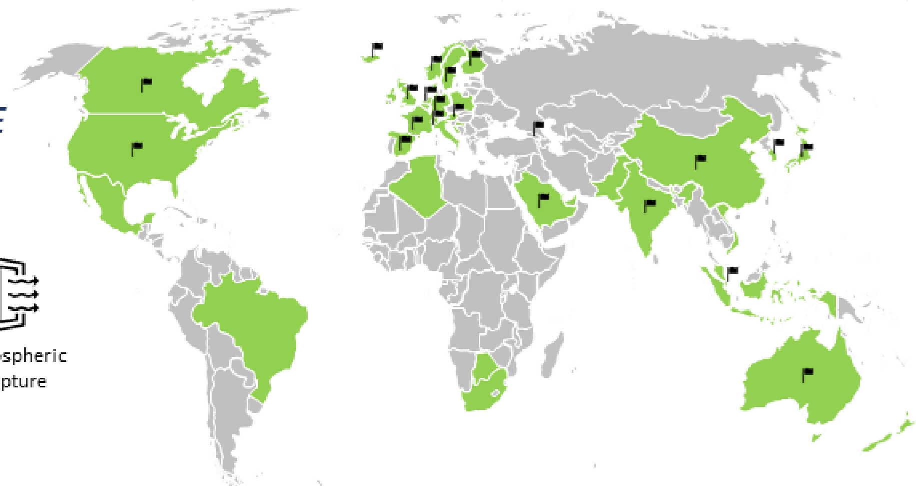
$800 BILLION *POTENTIAL MARKET*	**450+** PROJECTS *in 40 countries* *& 42 U.S. States*	**300+** TECHNOLOGIES *from 23 countries* *& 36 U.S. States*

GLOBAL CO_2 CAPTURE

Industrial Capture

Atmospheric Capture

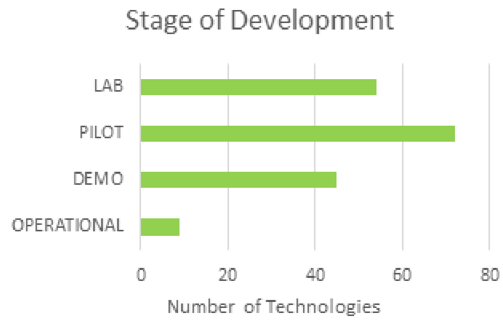
Fugitive Emissions



CO_2 UTILIZATION PROJECTS

- *35%* Building materials
- *25%* Geologic storage
- *20%* Enhanced oil recovery
- *10%* Syngas/biofuels
- *7%* Commodity chemicals
- *3%* Food & beverage

DEVELOPMENT DIVERSITY



BROAD SUPPORT

$7.4 BILLION
U.S. GOVERNMENT
FUNDING IN LAST DECADE

200+ *INNOVATION COLLABORATORS*

Government, Academia, Investors, Coal, Oil & Gas, Manufacturers

INSIDE THE CEM COMPENDIUM

- ✓ How the Technologies Work
- ✓ Stage of Development
- ✓ Contact Info (phone + email)
- ✓ Strategic Partnerships
- ✓ Associated Projects

Available Now for Purchase

www.icac.com/CEMInnovations

A Brief History of ICAC

An Industry with the Proven Expertise

Since the 1960s, the Institute of Clean Air Companies (ICAC) has been the trusted technical voice of the emissions control and measurement industry. Its members are innovators who are providing cost-effective solutions for implementing the Clean Air Act (CAA) of 1970 and the subsequent U.S. air pollution control and measurement regulations.

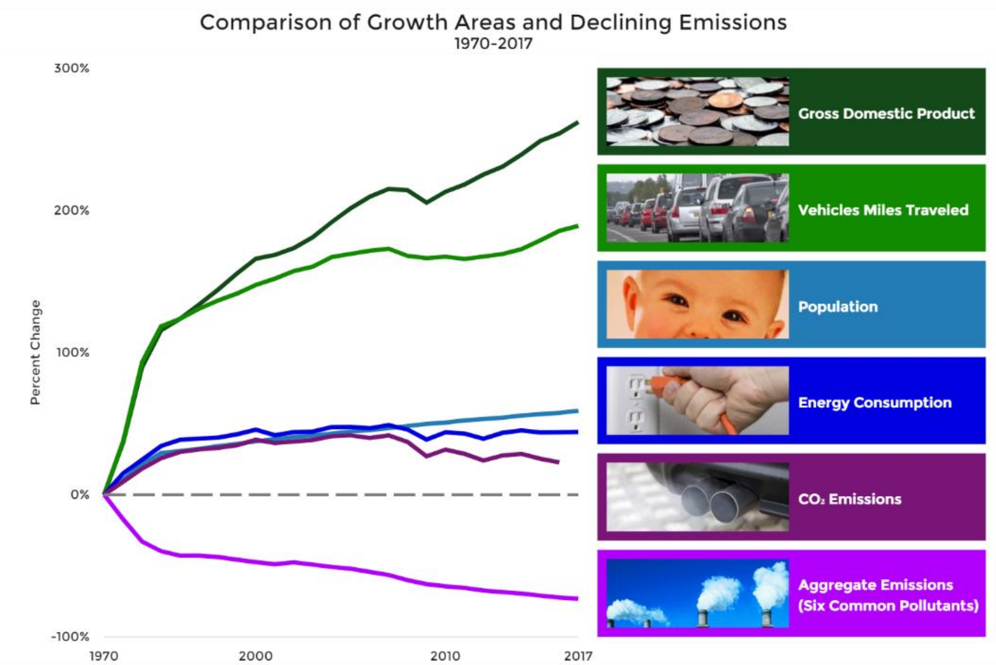


Figure 2. *The combined emissions of the six common pollutants (PM, SO_2, NO_x, VOCs, CO and Pb) dropped by 73 percent from 1970-2016, while the U.S. GDP grew by 262 percent and the population increased by 59 percent. Source: U.S. EPA.*

The enactment of these regulations made clear the need for new and more cost-effective air pollution control and measurement technologies. ICAC members responded with innovative solutions, providing their customers (power generation and industrial facilities) with effective and affordable compliance strategies. Since the 1970s, these technologies have enabled the reduction of criteria pollutants (PM, PM, SO_2, NO_x, VOCs, CO and Pb) by 73 percent, while the U.S. economy grew by 262 percent, as shown in ***Figure 2***.[1] This has also been the case for the hundreds of hazardous air pollutants (HAPs) and air toxics also contained within the CAA.

This industry now has an opportunity to apply its expertise to a new and critical challenge: Carbon Emissions Management.

[1] Comparison of Growth Areas and Declining Emissions. Taken from *Our Nation's Air* by U.S. Environmental Protection Agency. (2017).

Strategic Product Development from Lab-Scale to Commercialization

1990s	Early 2000s	Today	Ongoing Development
• Multiple-pollutant control laboratory & pilot-scale studies • Major issues with mercury measurement at low levels	• Introduction of halogen-treated activated carbons • Measurement improvements & options expanded	• Identification of critical aspects of carbon that drive performance in mercury capture • Measurements still challenging and high-maintenance	• Solutions tailored for specific circumstances to achieve optimal compliance solutions

Figure 3. *A timeline of the strategic mercury control and measurement technology development steps from the 1990s to present. Source: ICAC.*

Emission Control and Measurement Successes

Despite initial concerns about the viability of new technologies and potential costs, ICAC members consistently develop efficient control and measurement systems that revolutionize the industry.

One example of the success of the industry is their response to CAA requirements to abate mercury emissions. ICAC members made significant investments to develop control technologies that capture mercury from flue gas and enable their customers to meet the federal Mercury and Air Toxics Standard (MATS). ***Figure 3*** outlines the timeline and respective steps taken that led to the successful commercialization of the mercury control technologies developed by ICAC members.[2]

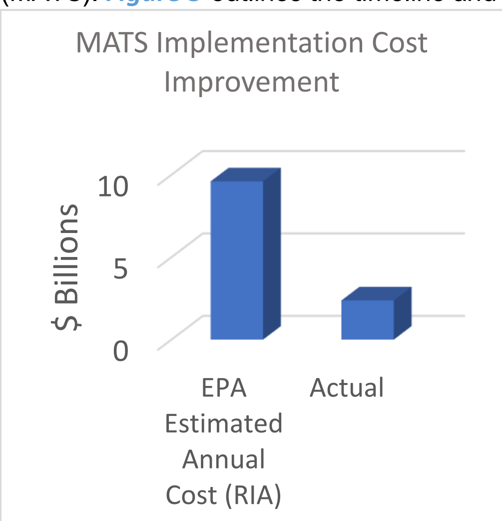


Figure 4. *The actual implementation cost of MATS was less than one quarter of EPA's original estimate in its 2011 Regulatory Impact Analysis (RIA). Source: Declaration of James Staudt. White Stallion vs. U.S. EPA.*

Initial doubts regarding prospects for mercury control proved unfounded as ICAC members' technologies achieved greater than 90 percent emission reductions at a fraction of EPA's initial cost estimates (see ***Figure 4***). According to the most recent estimates, the "true cost of the [MATS]" totaled approximately $2 billion per year – less than one quarter of EPA's original estimate of $9 billion per year.[3]

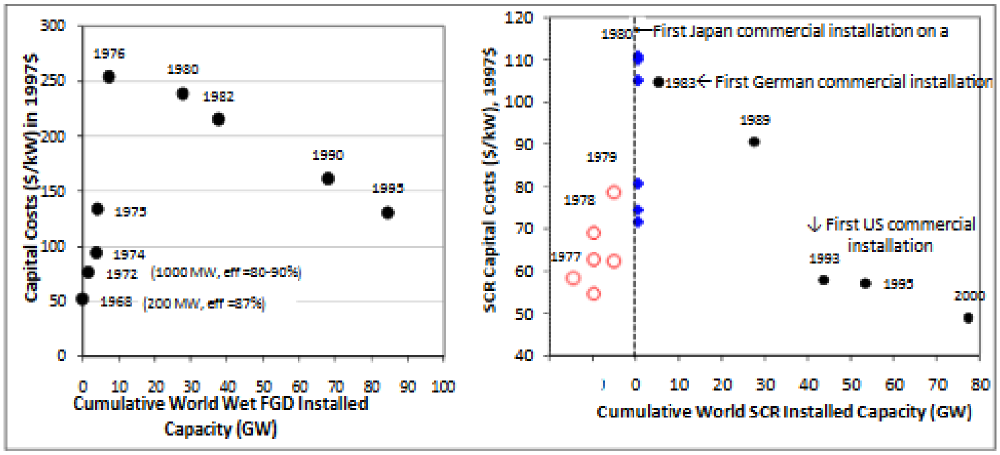
Similarly, **Figure 5** shows the steady decrease in cost for post-combustion SO_2 and NO_x control technologies for coal-fired power plants from the 1960s to 2000, by which point nearly all existing facilities had installed control technology.[4] These technologies delivered dramatic reductions in total emissions from coal generation – even as coal use continued to grow.

[2] Figure 3. MATS timeline. Adapted from *Issue Brief for United States Environmental Protection Agency* by the Institute for Clean Air Companies. (2017).

[3] Declaration of James Staudt. White Stallion vs. U.S. EPA. Dec. 10, 2013.

[4] Figure 5. Capital cost trends for post-combustion capture of SO2 and NOx at new coal fired power plants. Adapted from Use of experience curves to estimate the future cost of power plants with CO2 capture by Rubin, E. et al. (2007). Copyright 2007 by Elsevier Ltd.

Capital Cost Trends for Post-Combustion Capture of SO_2 (left) and NOx (right) at a New Coal-Fired Power Plant



Notes: On the left, capital cost trend for a wet limestone FGD system at a standardized new power plant (500 MW, 3.5% sulfur coal, 90% SO_2 removal, except where noted); on the right, capital cost trend for a SCR system at a new plant (500 MW, medium sulfur coal, 80% NO_x removal). Solid diamond symbols are studies based on low-sulfur coal plants. Open circles are studies prior to SCR use on coal-fired power plants.

Figure 5. *The demand for SO_2 and NO_x control technologies rose in response to the Clean Air Act of 1970, and the cost per kWh fell – even as demand for coal increased. Source: Rubin, E. et al.*

Meeting the Next Challenge

The air pollution control, measurement and monitoring industry has a history of working with both customers and policymakers to develop and implement emission control solutions that are achievable and clean the air. Through its members' unrivaled experience in addressing air pollution control, measurement and monitoring challenges, ICAC provides unbiased technical guidance. Sound technical knowledge is critical to developing and implementing emission control regulations successfully. Today, we face a new emission challenge on an international scale. Economic progress is raising living standards in countries worldwide, but with dangerous consequences tied to growing GHG emissions. In addition to deploying non-fossil energy resources (i.e. renewables), these nations need to make greater use of innovative CEM technologies and strategies. As CEM technologies develop over time, climate stakeholders will benefit from reliable sources of information regarding the readiness of these technologies. ICAC and its members can provide the unbiased assessments of technology readiness as the sector works to shepherd technologies from promising laboratory concepts to successful deployment and large-scale operation.

Table of Contents

ABOUT THIS REPORT IV

ABOUT THE COMPENDIUM V

A BRIEF HISTORY OF ICAC VI

EXECUTIVE SUMMARY XI

1 THE MARKET AND ENVIRONMENTAL OPPORTUNITY FOR CEM 1

Overview 1

1.1 A New Global Technology Leadership Opportunity 2

1.2 ICAC Members Have Global Expertise in Challenges Facing CEM 5

1.3 It is Time for the Emission Control Sector to Engage 7

1.4 Moving Past the Clean Power Plan 8

2 CEM TECHNOLOGY ASSESSMENT 14

Overview 14

2.1 The Current Status of CEM Technologies 16

2.2 Industrial Capture 16

2.3 Carbon Removal/Atmospheric Capture 30

2.4 Fugitive Emissions 37

2.5 Fate of Captured Carbon 44

3 DESIGNING POLICY TO ATTRACT CEM INVESTMENT 54

Overview 54

3.1 CEM Policy Support Is Accelerating 56

3.2 Designing Policies to Attract More Private Sector Investment 58

3.3 Principles to Ensure Better Policy Outcomes 62

3.4 Proposals for Innovative Policy Approaches 74

TABLE OF CONTENTS

APPENDIX A 80

The Vital Importance of CEM Technologies 80

APPENDIX B 88

Other Greenhouse Gases and Control Technologies 88

REFERENCES 90

Executive Summary

KEY TAKEAWAYS

With better collaboration between industry, government, and climate stakeholders, carbon emissions management technologies can:

- Accelerate and complement existing decarbonization efforts;
- Reduce the costs (further increasing the speed) of addressing climate change; and
- Become a global business opportunity.

For ICAC Members

Chapter 1: The Market and Environmental Opportunity for CEM

- CEM could soon be a multi-billion dollar technology market.
- CEM technologies will depend on materials and components that lie in the core competencies of the emission control sector.
- ICAC can unlock greater policy support for CEM development by producing white papers explaining technology development needs and barriers for specific applications.

Chapter 2: CEM Technology Assessment

- Early CEM market demand is likely to focus on capture from concentrated industrial CO_2 streams to serve enhanced oil recovery operations.
- Demand for CO_2 utilization as a chemical resource may develop slowly but represents a long-term opportunity that could exceed $800 billion in the next few decades.
- CEM technologies are at various stages of development that require technical and commercial expertise to bring these innovations to market. Many of these technologies also require existing air pollution control equipment as part of their processes.

Chapter 3: Designing Policy to Attract CEM Investment

- ICAC members should continue to share their expertise with policymakers and stakeholders regarding the effectiveness of policies designed to support CEM technology development and deployment.

For Policymakers

Chapter 1: The Market and Environmental Opportunity for CEM

- Support for CEM would build on a long, successful history of global economic leadership in emission management technologies that make North American industries and companies more competitive in global markets.
- Emission control companies will limit investments in CEM technology development absent policy support.

KEY TAKEAWAYS

For Policymakers (continued)

Chapter 2: CEM Technology Assessment

- CEM encompasses a diverse array of materials, components, and systems at varying stages of technology readiness. These technology innovations need long-term government support in order to overcome technological and market barriers.

Chapter 3: Designing Policy to Attract CEM Investment

- Policy innovation leads to technology innovation. If policy makers pay close attention to the way participating investors evolve through the technology development process, they can develop approaches that produce larger private sector investments while also reducing the risk of using tax dollars on "failed" projects.

For Climate Stakeholders

Chapter 1: The Market and Environmental Opportunity for CEM

- Optimism regarding CEM development is warranted, however, climate stakeholders are encouraged to understand and recognize the realistic development timeframes and challenges for CEM commercialization.

Chapter 2: CEM Technology Assessment

- While some CEM technologies have been used at commercial scale for decades, many promising technologies are not yet mature.

Chapter 3: Designing Policy to Attract CEM Investment

- Climate stakeholders can support efforts to refine policy approaches to provide effective, achievable, and durable policies that are not prone to political winds.

Will the emission control sector, climate stakeholders, and policymakers collaborate to meet this challenge and maximize the potential of CEM to contribute to decarbonization?

First and foremost, our aim in this report is to awaken a sleeping giant. Carbon emissions management (CEM) is a 21st century growth industry and perhaps the largest commercial opportunity the emission management technologies industry has ever seen. CEM technologies have already proven their commercial viability and revenue potential in certain markets, such as enhanced oil recovery for the oil and gas sector. Yet, only a select few in the emissions management industry are actively engaged in technology development efforts. Every level of organization in that sector – from applied science researchers to strategic executive leadership – should understand that it is now time to re-engage in this field. As with every emission control challenge before, policymakers are unlikely to take bold steps to encourage the use of technologies until there is a reasonable degree of confidence that such technologies will be dependable and readily available. Only the emission control sector can provide the unbiased technical expertise and knowledge of the challenges of commercialization that policymakers need in order to support the market.

Working together, industry, government, and climate stakeholders can:

- Accelerate and complement existing decarbonization efforts;
- Reduce the costs (further increasing the speed) of addressing climate change; and
- Generate national and international business opportunities.

Identifying Roles for Policymakers and the Private Sector

With this report, we hope to inform policymakers and climate stakeholders about the approaches that can attract more vigorous private sector investments in developing and demonstrating CEM technologies and commercial pathways. Absent clear policy signals supporting the technology development process, CEM will advance more slowly. Attracting the breadth of private resources needed to commercialize viable CEM technologies involves more than relying on a shopworn list of tax credits and other technology-specific incentives. Rather, the government should adopt a broad suite of integrated, technology-neutral policies that reward demonstrable progress toward decarbonization.

For carbon capture to deliver on its full potential, significant private resources will first need to be invested in the development and demonstration of new technologies. Constraints placed on how and when CEM's decarbonizing benefits can be deployed will lead to smaller and more fragmented investments towards commercializing CEM technologies.

Promoting all forms of CEM that can contribute to decarbonization is the best way to enable CEM's highest and best uses to become feasible and affordable within a meaningful timeframe. Previously, stakeholder emphasis on renewable generation as the primary – or total – solution for decarbonization limited interest in CEM and made it difficult for many companies to justify investments in this space. While we see clear signs that is changing, better policy approaches would help bring the emission control sector fully off the sidelines.

The emission control sector has significant financial, technical, and commercial resources to apply to CEM innovation challenges. For decades, emission control technologies have provided cost-effective solutions to mitigate the environmental harms of combustion.

Addressing climate change poses vast new emission management challenges and new technology opportunities. Will the emission control sector, climate stakeholders, and policymakers collaborate to meet this challenge and maximize the potential of CEM to contribute to decarbonization?

It's Time for ICAC Members to Rise to the Challenge

Several key factors are contributing to the emergence of an opportunity that not all ICAC members appear to be watching closely. That should change.

Demand for Core Competencies of ICAC Members

With the adoption of appropriate government policies, a multi-billion dollar market opportunity has the potential to rapidly emerge for exhaust gas management materials, components, and systems focused on capturing GHGs directly from power generation, manufacturing, mining, and the atmosphere. Meeting that market demand falls squarely within the core competencies of the companies that invented and deployed emission control technologies to reduce pollution from combustion sources for the past half century.

Addressing environmental challenges often relies on replacing polluting technologies with non-polluting alternatives, in conjunction with deploying technologies that both limit further releases of pollutants and clean up past pollution. In the climate context, renewable power is increasingly replacing reliance on fossil power. CEM technologies can be deployed to capture GHG emissions from ongoing fossil combustion and to capture (cleanup) CO_2 already in the atmosphere from previous combustion.

Policy Is Driving Demand

Emission control companies might recall with frustration that some of their earlier investments in carbon capture technology research, development and demonstration (RD&D) were foiled by policy. Climate change policies that almost exclusively focused on the deployment of renewable power generation have stymied investment in CEM for nearly a decade. Times are changing and attitudes are too. Policymakers and climate stakeholders are increasingly persuaded that the most rapid and cost-effective path to addressing climate change depends on achieving substantial emission reductions through CEM technologies.

There is no better evidence of this than recent policies adopted by the federal government and California that create a market value for captured carbon ranging from $35-200 per ton.[5, 6] Given the potentially significant revenue stream stemming from these policies, multiple investments in capture projects have been announced since these policies were adopted, and many more are in development. What's more, the demand for stronger policy to support CEM is growing among climate stakeholders seeking more urgent efforts on decarbonization.

Historically Large Market Opportunity

A 2016 McKinsey & Company estimate of demand for utilization of captured carbon is $800 billion by 2030 (see *Chapter 1,* **Figure 6** for more details). If abatement costs rise to average $100/ton and CEM contributes 20-40 billion tons of annual GHG reduction, the abatement market alone could eventually achieve annual revenues of $2-4 trillion per year.

While renewable power generation is booming, the growth in global demand for energy and materials like steel, cement, and chemicals is growing even more rapidly.[7] As a result, the rate of GHG emissions also continues to rise annually. The only practical way to address ongoing demand for low-cost fossil energy is the application of emission control technologies. Despite ongoing political battles regarding how to address climate change, there is steadily increasing support for technology innovations that will enable decarbonization.

As with all past emission control markets, technologies first developed, commercialized, and deployed in North America are likely to help meet global demand. Aggressive pursuit of CEM innovations can facilitate achieving the objectives of climate stakeholders (more rapid decarbonization), government (supporting economic growth and environmental protection simultaneously), and industry (maximizing growth and profit while limiting costs). That alignment of interests bodes well for the future market opportunity of CEM.

Climate Stakeholders Need to Engage the Emission Control Sector

It is easy to be enthused by the clear signs that some CEM technologies can begin moving quickly to commercial deployment. But climate stakeholders would benefit from better information about the scope of potential CEM technologies, and the barriers that need to be overcome to enable faster development and deployment for this key category of decarbonization technologies.

---

[5] Provisions for Fuels Produced Using Carbon Capture and Sequestration, 17 C.F.R. § 95490 2018.

[6] Bipartisan Budget Act of 2018, H.R. 1892, 115th Congress. (2018).

[7] Hoffman, N., Twining J. (2009). *Profiting from the low-carbon economy*. New York, New York: McKinsey & Company.

ICAC Members Can Share Technology and Commercial Expertise

For decades, ICAC members have provided unbiased technology and commercial readiness insights to policymakers, customers, and other stakeholders regarding emission control innovations. ICAC has provided accurate information regarding the capabilities and costs of emission management technologies. The diversity of viable CEM technologies and commercial applications presents far more challenges in understanding which technologies are ready for deployment, and what is required for commercial success.

To realize the potential of CEM, many early stage technologies need further development and those closer to commercial readiness need improved efficiencies, durability, and lower overall costs. Optimism needs to be measured with clear-eyed awareness of the challenges ahead. ICAC can support all stakeholders in understanding the critical balance between optimism and realism that will be necessary to bring CEM technologies to scale.

Collaborate to Overcome Barriers

To achieve the potential diverse range of opportunities with carbon capture technologies, numerous barriers will need to be overcome. The emission control sector has worked with all stakeholders to achieve massive reductions in air pollutants like NO_X, SO_2, and mercury without undermining the economic growth potential for the nation or for regulated entities.[8] Maximizing the speed of deployment for CEM will require an even greater level of collaboration than past emission control debates because the mix of emission sources and viable technology solutions is far more diverse and, therefore, complex. Transparent and ongoing collaboration is needed to maximize private sector efforts to accelerate innovation and deployment.

Given most CEM technologies will continue to be a net-cost, innovation alone will not drive market adoption. Innovators must mature their technologies to maximize efficiency and minimize capital and operating costs, while government policies must provide financial incentives or mandates to deploy these technologies on a commercial scale.

Maximize the Pace of Innovation Deployment

The potential for setbacks and disappointment in CEM deployment are easy to imagine. Forcing technologies before they are ready, adopting policies that favor some technologies over other viable options, on-again/off-again tax credits and incentives all hamper the development and deployment of innovation. Those that seek the most rapid possible deployment of decarbonization technologies should be eager to work with private sector innovators to develop approaches that increase the pace of innovation and adoption for CEM technologies.

Better Policy Design Is Essential to CEM Success

Although CEM technologies are, and will remain for the foreseeable future, a net-cost for energy providers, individual companies and project developers can earn revenue from the application of the technologies. However, even with promising options to use captured carbon in a variety of products and services, revenues from those activities are unlikely to offset the costs of capture. Unlocking the vast potential of private sector investment and expertise depends on well-crafted public policies. Unfortunately, policy innovation has not kept pace with technology innovation. Too often, the menu of available policies for promoting technology innovation is too narrow and inconsistent to attract sustained investment or private sector interest. Those seeking better outcomes should promote more effective public policies.

Attracting Crucial Private Sector Resources

Government incentives are critical to advancing CEM and other decarbonization technologies. Incentives are best used to leverage significantly more investment from the private sector than the public dollars

[8] U.S. Environmental Protection Agency. (2018). *Air Quality – National Summary*. Washington, D.C.: U.S. EPA.

committed to the incentive. Similarly, private sector commercial project expertise vastly outstrips government expertise in capturing market opportunities and mitigating market risk. Government policies need to leverage that expertise by better designing policies to be stable and technology neutral.

Reducing Investment Risks for Both Business and Government

Policies can be developed that reduce the risk exposure for both business and the government. By better allocating and addressing the inevitable risks of technology development and demonstration, it is possible to reduce the risk of spending public dollars on failed projects while simultaneously sending more dependable and stable investment signals to the private sector. Policies should offer clear and dependable rewards for achieving quantifiable goals. They should also focus on rewarding technology outcomes rather than the upfront costs of project development. *Section 3* of this report dives into detail regarding approaches that would invite greater investment in developing and deploying CEM and other decarbonization technologies.

Better Policy Will Produce Better Outcomes

Improvements in policy will enable more decarbonization technologies to reach the market and accelerate the speed at which they can be deployed. Technology-neutral policies can expand the diversity of CEM options available, and therefore expand the emission sources where CEM can be used. Technology neutrality can also lead to breakthroughs in materials (e.g. catalysts, membranes) that may have applicability in numerous capture strategies. Encouraging technology diversity will also unleash continuous market competition to develop more cost-effective solutions, driving down the costs of decarbonization. The net result of an expanding suite of increasingly cost effective CEM technologies will be faster decarbonization. Speed is an essential element in addressing the climate challenge. A ton of emission reduction achieved today does more to slow the atmospheric buildup of GHGs than a ton of emission reduction achieved a decade from now.

1 The Market and Environmental Opportunity for CEM

KEY TAKEAWAYS

ICAC Members

- CEM could soon be a multi-billion dollar technology market.
- CEM technologies will depend on materials and components that lie in the core competencies of the emission control sector.
- ICAC can unlock greater policy support for CEM development by producing white papers explaining technology development needs and barriers for specific applications.

Policymakers

- Support for CEM would build on a long, successful history of global economic leadership in emission management technologies that make North American industries and companies more competitive in global markets.
- Emission control companies will limit investments in CEM technology development absent policy support.

Climate Stakeholders

- Optimism regarding CEM development is warranted, however, climate stakeholders are encouraged to understand and recognize the realistic development timeframes and challenges for CEM commercialization.

Overview

There is a global environmental challenge to reverse the buildup of GHGs in the atmosphere, regardless of whether they come from man-made or naturally occurring sources. For more detailed information on specifics about temperature increases and decarbonization targets see *Appendix A* at the end of this report.

Some have argued that a simple switch to renewable energy would reverse the buildup of GHGs. However, while increases in renewables have made some impact, GHGs are still building up in the atmosphere as developing economies, such as China and India, continue to grow. In addition, some industrial sectors, such as cement and steel, which are vital materials with demand curves tightly tied to economic growth, are examples of industries that currently have no viable alternatives for fossil fuels in their production process. Similarly, energy intensive and difficult to manage emissions in transportation

Given current technological limitations, it is not currently possible to switch entirely from fossil fuels to renewable energy and meet the demands of a growing global economy.

sectors, such as the aviation and maritime industries, have few economically attractive options to decarbonize and little prospect for improvement. Given current technological limitations, it is not currently possible to switch entirely from fossil fuels to renewable energy and meet the demands of a growing global economy. Even as efficiency gains and other process improvements reduce the carbon intensity of production, these sectors remain large and growing emitters of CO_2. CEM technologies will have a critical role in helping meet the global GHG challenge.

As a result, CEM technologies provide unique combinations of both environmental and economic opportunities. On the environmental side, CEM can contribute to an accelerated and less expensive path to lower levels of CO_2 in the atmosphere. On the economic side, CEM presents a CO_2 utilization market opportunity that could exceed $800 billion and enable the United States to establish global economic leadership built on technology innovation and financial expertise.

The National Academy of Sciences released a report in October 2018 on *Negative Emissions Technologies and Reliable Sequestration*. The report points to using a "broad portfolio of technologies" for the "least expensive and least disruptive solution" to decarbonization. The report concluded that the U.S. government should invest in the advancement of CEM technologies, citing "intellectual property and economic benefits" that will accrue to the nations that develop the best technologies. The basis for their conclusion included the following:

> *States, local governments, corporations and countries around the world are making substantial investments to reduce their net carbon emissions and plan to increase these investments. This means that advances [in technologies] will benefit the U.S. economy if the intellectual property is held by U.S. companies.*[1]

For now, this is a largely untapped opportunity. Current commercial activity related to the "capture of carbon waste gases is limited with 45 large-scale carbon dioxide capture projects operating with a total capacity of 80 million tons per annum, globally."[2]

1.1 A New Global Technology Leadership Opportunity

The U.S. has long held a global leadership role developing and exporting emission control technologies. U.S. companies designed, produced, installed, and maintained the technologies that eliminate an aggregate of 73 percent of the SO_2, NO_x, mercury, and other harmful emissions generated by industrial combustion – and greater than 90 percent reductions were achieved for other pollutants.[3] CEM represents a logical extension of that expertise to meet the challenges of decarbonization and to seize the global technology leadership opportunity offered by a new market.

In the early 1970s, the use of catalysts had been demonstrated to reduce harmful exhaust pollutants from cars and industrial combustion. However, efficiency and durability issues first needed to be addressed before developing affordable, effective, and durable exhaust gas management technologies. We are in a similar state of CEM development. Basic scientific demonstrations have proved various techniques for carbon capture and utilization are viable, but nearly all need further refinement.[4]

For example, improvements in the efficiency of chemical separation of CO_2 would enable smaller capture system components, lower material and operating costs, and overall improvements in durability and cost effectiveness. The Information Technology and Innovation Foundation (ITIF) notes: "All of the technologies previously described would benefit from more fundamental breakthroughs in catalysts or materials discovery and require better control and understanding of structures and functions at atomic – and even subatomic – scales."[5]

Chemical separation with engineered membrane technology has been used in industrial settings for decades. If membrane separation is to be available for industrial scale CO_2 separation, improvements are needed to increase membrane durability during long exposures to complex exhaust gas environments. Vacuum pumps used to move gases over the membranes need to be more efficient to reduce size and energy demands. Achieving these improvements will deliver needed reduction in CAPEX and OPEX of membrane capture systems.

Similarly, amine-based chemical separation systems need refinements in the chemistry that can enable optimization of gas flows. Greater efficiency in CO_2 separation using amines will reduce processing equipment sizes as well as limit the amount of amine losses requiring the addition of make-up amine volumes. Achieving these improvements could enable meaningful improvements in commercial viability of amine capture systems.

Developers are already working to achieve these and many other improvements in chemicals, materials, and systems to reduce the cost of CEM (see *Chapter 2* for more information on this). As in past emission management challenges, balance must be found between technology optimism and realistic understanding of the barriers impeding full commercialization.

The U.S. emission control sector repeatedly invented, commercialized, and deployed technologies that originally had been decried as not possible or too expensive. These companies are the global technology leaders that have time and again moved scientific concepts through technology innovation and ultimately into full-scale production and commercial deployment. CEM poses the next frontier in the battle to ensure continued progress on enabling economic expansion to co-exist with environmental protection.

1.1.1 CEM Is a Large Environmental Opportunity

Carbon capture technologies have the potential to address current and future CO_2 combustion emissions. All capture and reduction strategies, including direct air capture, pre/post-combustion emission capture strategies, oxy-fuel combustion, and fuel cells, can contribute to decarbonization. As the National Academy of Sciences notes, "Removing CO_2 from the atmosphere and storing it has the same impact on the atmosphere and climate as simultaneously preventing an equal amount of CO_2 from being emitted."[6]

The World Resources Institute summarizes a 2017 United Nations report on needed decarbonization measures by observing:

> *The world faces a dwindling "carbon budget," which is the amount of CO_2 emissions that humanity can emit in the future while still having a likely chance of limiting global temperature rise to a given target… Current mitigation efforts are insufficient.*[7]

It is against this background that most have come to focus on what CEM technologies might add to decarbonization efforts. Estimates vary, but all reflect a significant environmental role for CEM:

- Modeling suggests the need to achieve 2 $GtCO_2$/year of carbon capture and storage in 2030 and that 7-17 $GtCO_2$/year will be needed between 2050 and 2100 in order to limit global temperature increases to 2°C.[8]
- Carbon capture will enable 5-8 $GtCO_2$/year emission reductions from harder-to-abate sectors including cement, steel, and plastics production.[9]
- 94 $GtCO_2$ are expected to be delivered by CEM before 2050, which "amounts to 12 percent of the cumulative emissions reduction task" from the energy sector.[10]
- An additional 29 $GtCO_2$ in reductions is needed from CEM applied to industry – equivalent to "20 percent of the cumulative emission reductions anticipated from this sector through 2050."[11]
- Annual emissions reductions of about 9.2 $GtCO_2$ – or 27 percent of total emissions – are possible from essential economic activities in hard-to-decarbonize sectors (e.g. aviation, long-distance transportation and shipping, structural materials including steel and cement, and highly-reliable electricity).[12]

- For critical "load-following" electricity supplies alone, 4000 $MtCO_2$ in 2014, or 12 percent of global fossil fuel and industry emissions are needed.[13]

Not only are climate stakeholders open to significant decarbonization from CEM, pragmatic experts are incorporating it into their projections and plans for slowing and reversing the buildup of GHGs in the atmosphere.

1.1.2 CEM Is a Large Commercial Opportunity

The earliest commercial CEM opportunities likely will involve capture activities with limited or no initial technology risks and limited opportunities for revenue generation from selling the captured CO_2 for commercial use. Highly concentrated streams of CO_2 from ethanol fermentation or steam methane reformation could be initial targets for CEM deployment in commercial markets, although each has challenges and constraints that will need to be overcome. The recent adoption of a federal tax incentive and the carbon market in California will provide revenue to offset some of the costs of these activities and could attract significant interest in project development.

In their article on net-zero emissions energy systems, Steven J. Davis, et al, identify the costs of CEM technology as the immediate barrier for adoption of "combinations of known technologies" and make the point that "innovation and deployment can be expected to reduce costs and create new options."[14] Producing the cost reducing innovations needed for CEM adoption can unlock renewed demand for products and services from the emission controls sector.

Ambitions abound for utilizing large quantities of CO_2 utilization for oil extraction opportunities and as a feedstock for commercial production activities ranging from steel to fuels. Government policies like the 45Q tax credit create a revenue stream for utilizing captured CO_2. A 2016 McKinsey & Company report for CO_2 Sciences, Inc. (now The Global CO_2 Initiative) "identified 25 commercial products that could be made using CO_2, with a possible annual market of $800 billion to $1.1 trillion by 2030 and the potential to remove 10 percent of global CO_2 emissions."[15] ***Figure* 6** from The Global CO_2 Initiative provides a snapshot of the potential annual revenue from CO_2 utilization for the largest markets, showing estimates both with and without strategic actions implemented to incentivize these markets.

While many of these opportunities are dependent on refinements in early stage technologies, commercial demand for CO_2 could generate revenue streams that compound the benefits of economic support delivered through government policies.

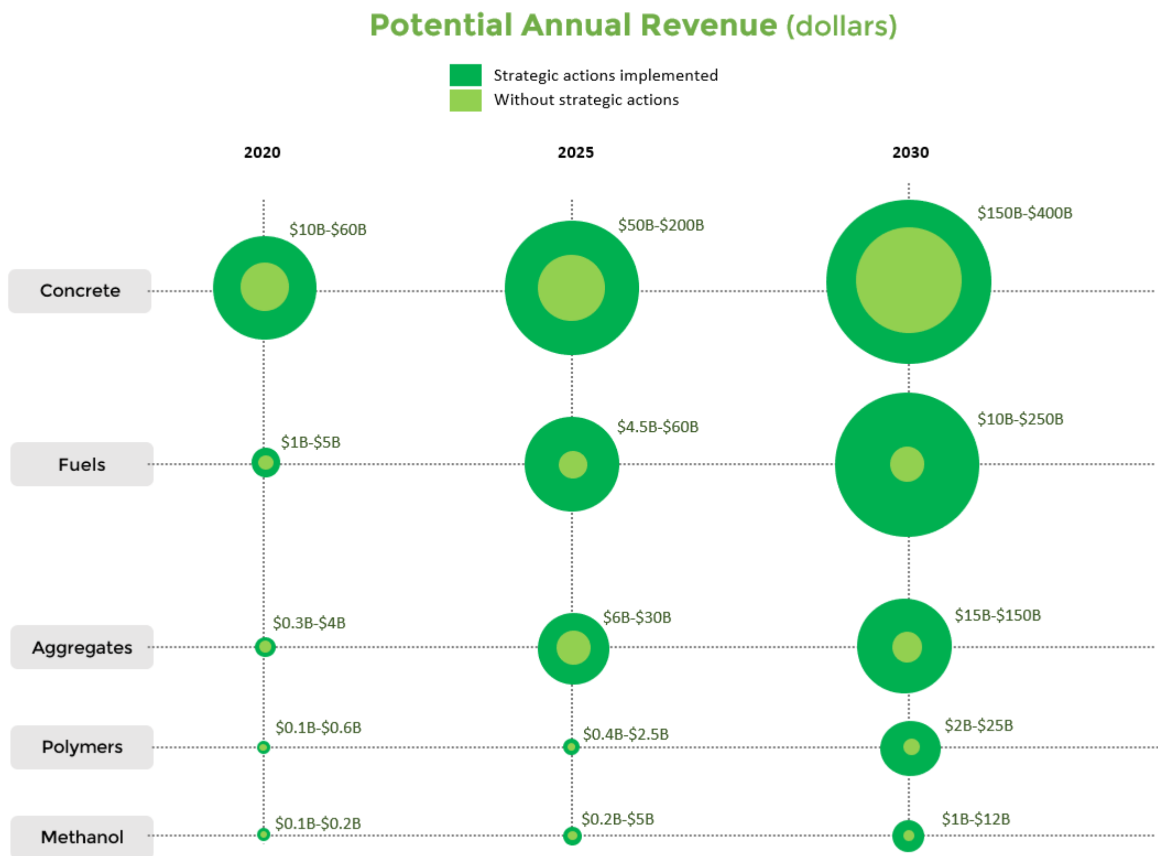


Figure 6. *A snapshot of the potential annual revenue increase from CO_2 utilization for the largest markets through 2020, showing estimates both with and without strategic actions implemented to incentivize these markets.*[16] *Source: The Global CO_2 Initiative.*

While there is a growing enthusiasm for those innovation and deployment activities, the commercial opportunity for the emissions control sector will be defined only with time and experience. We encourage ICAC members to undertake due diligence activities looking at this emerging commercial opportunity through the lenses of their own core competencies and strategic objectives.

1.2 ICAC Members Have Global Expertise in Challenges Facing CEM

It is wise to recall the patience and determination that was required in prior emissions and effluent challenges.

Given the success of efforts – now largely complete – to invent, install, and operate emission controls on power generation and industrial facilities throughout North America, it may be tempting to minimize the degree to which those efforts were initially seen as daunting. Many claimed that such efforts would prove technologically impossible and cripplingly expensive. Of course, emissions of nitrogen oxides, sulfur oxides, mercury, and various other hazardous and toxic emissions and effluents have since been successfully – and cost-effectively – controlled.

The effort to develop and commercialize CEM technologies should be discussed in full awareness of the history of prior environmental challenges overcome by large combustion and industrial production facilities. Recognizing the technological and commercial challenges that lie ahead, it is wise to recall the patience and determination that was required in prior emissions and effluent challenges.

Many in the industry that accomplished these prior feats of invention and engineering are members of ICAC. These companies have varying degrees of engagement in the CEM technology development efforts – some leading and some lagging. But ICAC members collectively have world-class expertise in the materials and components needed to capture and convert CO_2. They have successfully designed and retrofitted the largest emissions sources in the world while simultaneously achieving cost reductions in control technology. It is precisely this expertise in basic and applied science, engineering, design, and construction that is needed to advance and commercialize CEM technologies.

Materials that could be in demand to enable new CEM technologies include:

- Aerosols
- Alloys
- Catalysts
- Ceramics
- Membranes
- Polymers
- Reactants
- Resins
- Solvents
- Sorbents
- Xerogels

Components likely to be growing in demand include:

- Absorbers
- Air Contractors
- Calciners
- Compressors
- Electrolyzers
- Monitors
- Reactor Vessels
- Sensors

As policy solidifies the rewards for successful technologies, the demand will grow for a variety of **new systems**, including:

- Catalyst systems
- Gas capture
- Gas cleanup
- Gas management
- Oxygen injection
- Sorbent technology
- System controls

1.2.1 The Technology Challenge: Develop New Gas Management Technologies

Numerous innovations and refinements that are within ICAC members' areas of expertise are needed to support CEM development.

New and Better Materials Are Needed

The physics and chemistry of CEM technologies will demand purpose-built materials. In some cases, existing materials are available and can be made serviceable with relatively minor re-imagining of how they can be employed. In other cases, significant innovation is required to produce materials that will provide the efficiencies needed to withstand the rigors of industrial-scale gas capture and processing.

Catalysts are widely used in emission control technologies for criteria pollutants and "are also key elements of carbon utilization processes that could turn industrial CO_2 waste into high-value products such as fuels and plastic."[17]

Absent better catalysts, a wide range of decarbonizing CEM technologies could struggle to commercialize, including carbon capture, energy (battery and chemical) storage, ammonia production, fuel cells, and more.

New and Better Components Are Needed

Those materials, once available, will be incorporated into components of new CEM technologies. Again, in some cases, off-the-shelf technologies are suitable for the designs of CEM systems with few or no modifications. In other instances, the components have yet to be designed or reengineered to support efficient large-scale CEM systems.

Integrated Gas Management Systems Are Needed

Carbon capture demands an unprecedented scale and diversity of gas management systems to capture, process, convert and utilize the vast volumes of CO_2 and other GHGs emitted by modern technologies. Though CEM technologies are more than theoretically possible, most still require significant improvements to become commercially viable on a scale necessary to be impactful.

The next great challenge (and business opportunity) for the emission control manufacturing industry lies in developing innovative systems that satisfy scale, durability, and efficiency requirements.

1.2.2 The Commercial Challenge: Making Technology Work for Real-World Customers/Conditions

In addition to their technology development expertise, ICAC members have a long track record of ensuring that new gas handling technologies work at scale and in commercial settings.

Customer Expertise

To add new exhaust gas management (e.g. GHG capture) to an existing industrial facility is a significant undertaking. Facilities are designed, optimized, and operated under conditions that could be fundamentally transformed by the addition of new gas management equipment. Ensuring that new systems can be incorporated into existing industrial processes and sites requires significant planning and coordination. Failure to anticipate and prevent integration problems may result in challenges that slow or stop the progress toward deploying pollution control equipment. ICAC members have worked with all manner of power generation and industrial facilities to ensure emission control equipment installations provided minimal disruption and least possible costs for their customers.

Production Expertise

The need for innovation and investment will extend beyond the challenge of designing and demonstrating new technologies. To deploy CEM technologies on an environmentally meaningful scale, new production capacity will need to be developed for a variety of systems and components. The manufacturing lag between order and delivery for certain gas capture components already stands at twelve months. Assuming commercial demand expands for CEM systems, any delays in critical component manufacturing would ripple throughout the commercial and governmental spheres engaged in addressing climate change. ICAC members have the expertise needed to address and mitigate supply chain challenges.

A diverse range of **products** could conceivably create demand and value for captured GHGs, including:

- Carbon composites
- Carbon fiber
- Carbonates
- Cement
- Fuels
- Graphene
- Plastics
- Polymers
- Steel
- Synthetic hydrocarbons

Expertise Managing Captured Materials

A central component of the economics of CEM will depend on the extent to which captured materials can become valued feedstocks for other products or processes, creating revenue streams that offset some costs associated with capture.

1.3 It is Time for the Emission Control Sector to Engage

ICAC members' expertise could catalyze work already undertaken by leaders in the CEM innovation field. Those that ignore this opportunity may find themselves outside of a large and growing market opportunity as technology development progresses from the lab to the market. ICAC members can leverage a diverse body of work ready to be taken up by commercial technology developers. As ITIF points out, "research to date has been confined mostly to academic studies and modeling, with limited public support – either domestically or internationally – to develop the technologies that climate models say are needed to achieve deep decarbonization."[18] Greater public support is needed for RD&D efforts. Greater engagement and investment from the emission control sector is vital as well.

ICAC members are among the best positioned and most experienced to help speed the development and deployment of CEM technologies. These companies have expertise moving new technologies from scientific breakthroughs into viable gas capture and management systems. ICAC members and their suppliers, colleagues, and competitors have expertise in innovating, commercializing, manufacturing, engineering, and installing materials, components, and systems for industrial-scale gas management, monitoring, measurement, and capture.

While some in this sector are engaged in efforts to develop CEM technologies, these tend to be limited efforts. For the most part, the scientific, engineering and design, production, and capital resources of the industry are not pursuing CEM opportunities. Nor are they participants in many of the policy dialogues regarding the prospects for, and the barriers facing, CEM development and deployment. That reality should be deeply concerning for those anticipating large-scale deployment of CEM.

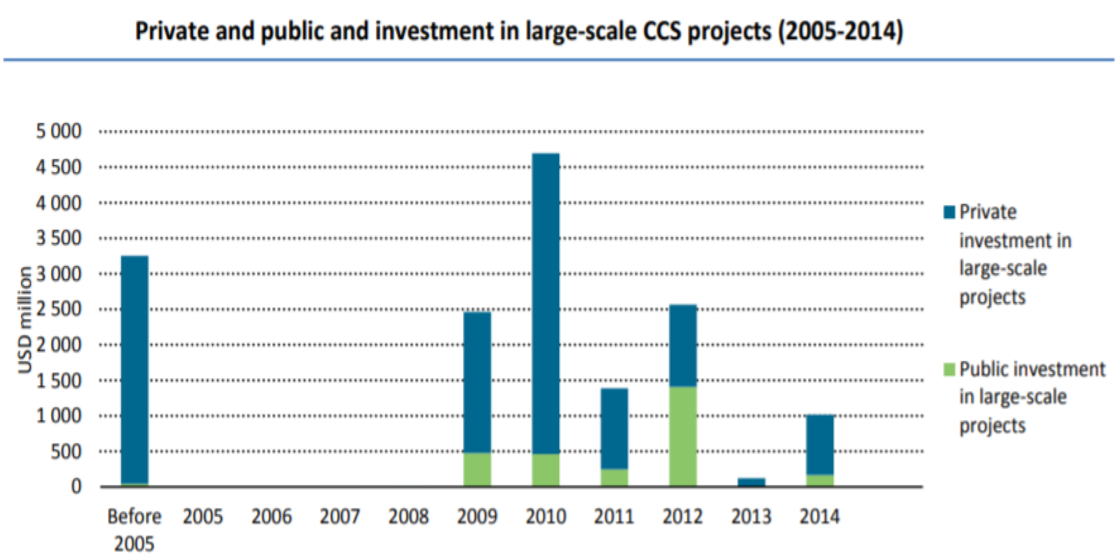
More broadly, stakeholders in the climate debate should read the limited engagement of this industry to date as a warning signal that governmental policies have yet to animate the scale of private sector response necessary to achieve the CEM contributions to GHG reductions envisioned by the IPCC and other organizations when assessing needed technologies.

1.4 Moving Past the Clean Power Plan

One contributing factor for the indifference of many in the emission control sector toward the commercial opportunities of CEM stems from disappointment in the 2014 proposal of the Clean Power Plan (CPP).[19] Prior to that time, significant resources were being committed by ICAC members and others to explore gas capture, handling, and processing systems in anticipation of GHG emission reduction regulations.

As indicated in ***Figure 7***, the CPP's emphasis on replacing coal with gas or renewable resources, such as wind and solar, left little opportunity for GHG capture initiatives to reduce GHG emissions by utilities.[20] As a result, investment in RD&D for CEM was curtailed or eliminated by many ICAC members, although some efforts persisted. Many emission control manufacturers radically reduced or eliminated RD&D budgets focused on developing GHG capture systems.

Few observers at the time expressed concern about the exclusion of capture technologies from the program. But views regarding the role of CEM in tackling the climate challenge have evolved considerably. Because of renewed interest in the potential of CEM, RD&D efforts are gradually being revived.



Source: BNEF (2016), Clean Energy Investment Trends.

Figure 7. *The private sector invests significantly in CEM technologies in the years leading up to the CPP, however, industry investments and RD&D efforts are left stranded when the CPP is released in 2014 with an emphasis on renewables rather than a diverse set of decarbonization solutions. Source: BNEF.*

Patent Filings Highlight Increasing Commercial Potential

Increasingly, patents are being sought to protect the intellectual property (IP) being developed around CEM technologies, materials, and concepts. This is reminiscent of the development – and protection – of IP related to past emission control technologies. It is a clear indication of commercial interest in applying chemistry and physics concepts to this new challenge. While an uptick in research and new inventions does not guarantee commercial technologies will follow, it is a necessary precursor. ***Figure 8*** tracks the growing number of patents related to carbon capture technologies, showing that the U.S. accounts for approximately one-quarter of global patents.[21] Again, this points to the country's opportunity for technology leadership and exports.

Number of Patents Pertaining to Carbon Capture in the U.S. (left) and Globally (right)

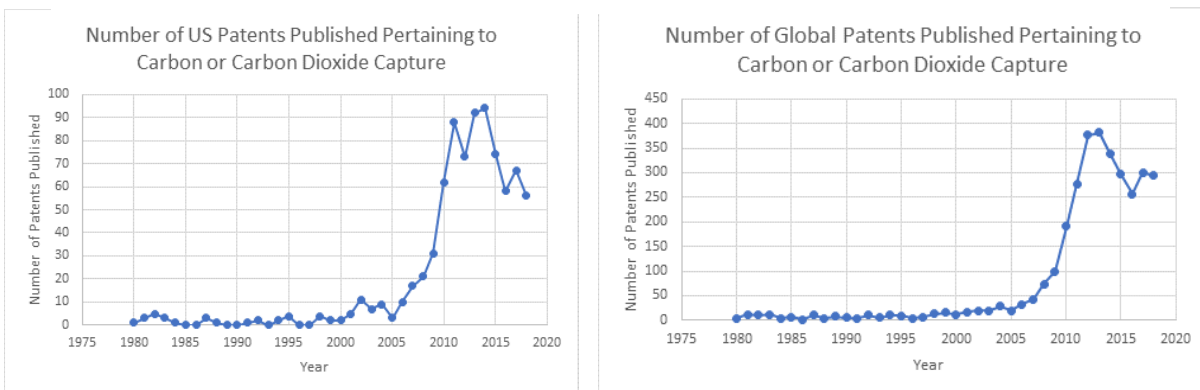


Figure 8. *The growing number of patents for CEM technologies reflects a growing interest in commercial applications and represents a potential leadership role for the U.S. given the country's share of patents to-date. Source: Espacenet.*

Although there has been an increase in research and patented technologies related to CEM, more work is needed. The ETC report points out: "Current innovation systems are poorly connected, with little coordination between public and private RD&D and a lack of international forums to carry an innovation agenda focused on harder-to-abate sectors."[22]

Active participation in the growing national and international CEM dialogue by ICAC members could enable climate stakeholders to better engage in efforts to design and promote actions that support CEM innovation and market development.

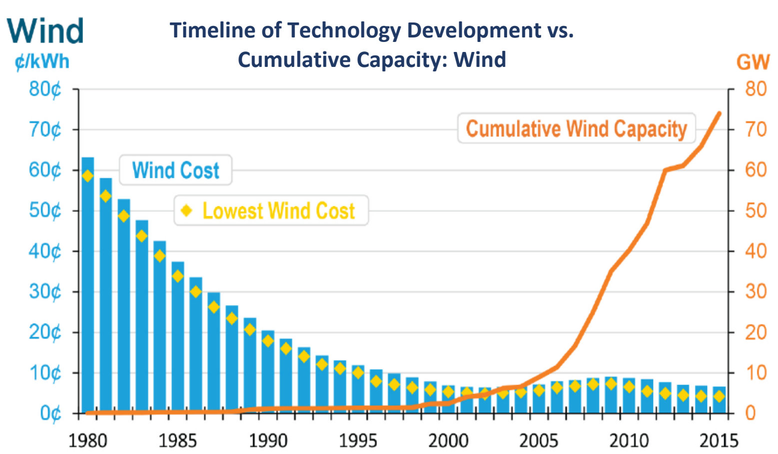


Figure 9. *As the cost of wind energy decreases from 1980-2000 - and eventually levels out - the capacity and market for wind energy rapidly increases. Source: U.S. Department of Energy.*

1.4.1 How Soon will CEM Scale Up?

Demand for new technologies reaches critical mass when the maturity of the technology is matched by production costs below marginal market prices. The energy sector is replete with examples of technologies that, after years or even decades of development, suddenly burst onto the market. For example, wind turbines were under

The key challenge with carbon capture and use is not a fundamental technological one, but rather a question of how to achieve sufficiently large-scale deployment to drive economies of scale and learning curve effects.[25]

development for decades. While demand for wind power is currently booming, wind turbines' marketplace prominence is a relatively recent development.[23] ***Figure 9*** documents the rapid rise of wind power capacity in concert with falling costs.[24]

Numerous factors contribute to the regular commercial use of any new technology. Only when all relevant factors are in place – technology readiness, integration challenges, established and reasonably predictable profit opportunities – will a technology truly achieve commercialization. A fully mature technology will be disparaged as "too expensive" until either its costs fall below the market marginal price or demand drives the marginal price above the costs of the new technology.

These factors will help determine the rate of CEM commercialization.

Commercialization Overview

Historically, costs of emission management technologies tend to fall radically with clear commercial opportunities. CEM costs now are high, and many, if not most, of the systems and components needed to enable commercial deployment of CEM remain pre-commercial. Climate stakeholders should be optimistic that the current state of technology demonstration validates their expectations that CEM technologies could soon play an important role in a portfolio of decarbonization solutions under the proper policy and market conditions.

In fact, one could compare the current state of CEM technologies to prior emission management technologies, including mercury, SO_x and NO_x, and others. In each case, policy interest first supported these technologies before the technologies had sufficiently matured for commercial deployment. In each case, focused innovation, development, and deployment activities led to an array of viable technologies and falling costs.

The air pollution control and measurement industry has a proven record of driving down costs of compliance through collaboration and technology innovation. Take, for instance, coal-fired mercury emission control technologies. Research into these technologies began in the 1990s with laboratory and pilot-scale studies. In the next decade, these technologies achieved tremendous improvements, and new options for mercury control became commercially available. Today, mercury-control technologies are found on coal-plants across the U.S. and are beginning to be adopted by global energy systems.

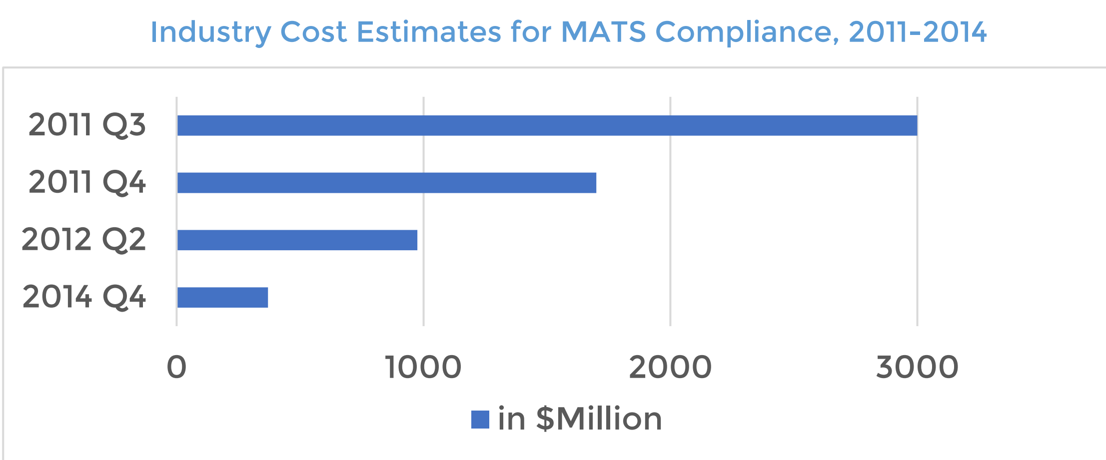


Figure 10. *Compliance costs for MATS drop from $3 billion in 2011 to less than $500 million in 2014 as a result of industry collaboration and advancements in technology innovation. Source: The Institute of Clean Air Companies.*

Early-stage technologies are typically associated with high costs. Estimates of current costs and the potential for future cost reduction can be highly uncertain because of a lack of RD&D and deployment and installation experience.

As shown in ***Figure 10***, the power sector's 2011 estimate for the costs of compliance with federal Mercury and Air Toxics Standards (MATS) was approximately $3 billion. Three years later, compliance costs fell beneath $500 million, as technology innovations and industry collaboration brought cost-effective products to market for their power plant customers.[26]

Optimism Might Be Warranted – But Realism is Necessary

Overpromising and underdelivering in the CEM space needs to be avoided. False expectations only undermine the opportunity to develop CEM technologies. Climate stakeholders need well-grounded technology assessments from sources with both expertise and independence and ICAC has a long history of providing exactly that.

We recognize that this report is a high-level overview and not a technology assessment. We encourage ICAC members, in collaboration with other technology experts and climate stakeholders, to consider how they might develop useful assessments for CEM technologies with the same rigor and credibility that they applied to other air emission technologies.

CCUS technology deployments face a host of unresolved impediments that are unlikely to be mitigated by market demand for CO_2 alone in any near- to intermediate-term scenario.

In the absence of ICAC participation, other organizations have attempted to fill the void, but few have the combination of technical qualifications and history of independent analysis that ICAC can claim. Unsurprisingly, some reports either lack insight into the challenges for new technologies, ignore the potential to overcome such challenges, or are limited by the technical or commercial expertise of the reports' authors. While there are strengths and value in many of these reports, there also is a role for ICAC members to add their expertise to the discussion.

In November 2018, the Institute for Energy Economics and Financial Analysis (IEEFA) issued a report titled "Holy Grail of Carbon Capture Continues to Elude Coal Industry." The report observes that "15 years after CCS development work began in earnest, there remains only one operational coal-fired carbon capture project in the U.S.: NRG's experimental Petra Nova project south of Houston."[27]

This report discusses some of the commercialization difficulties that have limited the pace of CEM innovation and deployment.

There has been relatively limited investment in large-scale CCS projects to date in part due to the absence of targeted policies. The exception to this has been investment in projects which can secure an income stream from the sale of CO_2 for EOR in established markets in North America.

However, nothing in the "Holy Grail" suggests that technological and commercial success with CEM is beyond our grasp. The authors present information in a manner that might encourage some readers to be pessimistic about the prospects for CEM as the title conveys a slightly mocking tone regarding the pursuit of waste-gas capture. While the document accurately describes the status and challenges of various CCS efforts, it fails to discuss any of the opportunities for technology improvements.

There are lessons to be learned from the projects discussed in the "Holy Grail," yet none of these are discussed in the IEEFA paper. For example, some technologies were rushed to commercial use without employing an appropriate and disciplined scale-up process. Few process engineers would encourage technology scale-up steps larger than ten times the largest previous operational size. Despite this, the performance of several key components in these projects was not adequately demonstrated at smaller scales prior to commercial-scale construction.

Using a disciplined scale-up process enables developers to identify operational, design, and engineering problems early on. That enables modifications to be developed and implemented more quickly and at lower costs. Avoiding such mistakes will be critical for future development efforts in the CEM sector.

ICAC could contribute to the commercial and policy dialogues by providing accurate and unbiased assessments of CEM technologies and identifying key remaining technology and performance barriers along with cost estimates.

CEM is Unlikely to Pay for Itself Anytime Soon

No natural market demand exists for CEM. As WRI notes:

> *Carbon removal technologies are likely to rely on regulatory mandates or carbon pricing mechanisms to be deployed at large scale on a sustained basis. Carbon removal technologies provide a public good. To the extent that they also provide valuable private goods (e.g. energy or products), the goods are not cost-competitive with goods produced by other means without explicit or implicit carbon pricing.*[28]

For now, CEM will remain a net-cost and GHG capture will remain an added cost. Industrial and power exhaust gas streams for decades have been managed and processed to remove harmful pollutants in the interest of protecting human health and the environment. It has always been an added cost of production, although much of these costs were typically a fraction of the early estimates. It is promising that there are clear prospects for productive commercial utilization of captured GHGs beyond enhanced oil recovery (EOR). Current U.S. commercial demand for CO_2 for non-EOR uses could be fully satisfied by the captured emissions of a single coal-fired power plant.[29]

Revenue streams from utilization opportunities will not be a motivating factor for near-term investment in capture technologies absent additional economic drivers. Yet, making CEM commercially viable depends on further innovation that will occur only with the commitment of significant investments and time.

Policy Will Be Needed

Absent policies that address the net-cost of CEM technologies, private resources have little incentive to explore them. Organizations with a stake in CEM technologies point to the need for policies that will lead to substantial deployment:

- The IEA says “major breakthroughs and cost reductions will likely only be achieved through actual deployment at scale.”[30]
- The Energy Transitions Commission notes: “Since most decarbonization routes will entail a net-cost, market forces alone will not drive progress; and strong policies – combining regulations and support – must create incentives for rapid decarbonization.”[31]
- The WRI argues: “Ultimately, all carbon removal technologies will depend on sustained public support, including funding.”[32]
- The National Coal Council calls on the Department of Energy to “reinvigorate its RD&D program on advanced (‘next generation’) CO_2-EOR technologies.”[33]

None of this should surprise observers of the past half-century of emission control development and deployment. Emission control technologies have always been developed and deployed as a partnership between the public sector and private sector technology innovators, needing both to develop and demonstrate applications that can be reasonably integrated with the operations of the regulated entities.[34] Technologies must be developed by the private sector to the point of maximum efficiency and maturation in order to bring down costs as much as possible. At the same time, stable government policies, such as grants, regulations, or tax credits, are necessary to bridge the gap between these technology costs and the market value of captured CO_2.

With respect to CEM development, private sector expertise and resources vastly outstrip those of the public sector. The pace of CEM development will depend on public policies that attract and reward private sector engagement in developing, demonstrating, and deploying CEM technologies.

So, how will investment in carbon capture technology development become sufficiently attractive to private sector actors?

In the near term, there is only one practical answer: government policy. In *Chapter 3*, we delve into options for successful policies that will help bring CEM technologies to a useful scale. The private sector will need to see the prospect of profits in pursuing the challenge of refining carbon capture concepts, systems, and materials into commercially viable systems on an enormous scale.

Unless governmental policy establishes a clear, dependable market demand for GHG reductions, the private sector will continue to regard CEM as an added cost with limited or no revenue advantages.

Support for CEM is on the Rise

Governments are beginning to take the action needed to drive investments in innovation, but it is still tentative, with the exception of China. At a Global CCS Institute forum held in Shanghai in May 2018, China's Department of Climate Change Deputy Director General for the Ministry of Ecology and Environment, Mr. Sun Zhen, said that carbon capture, utilization and storage technologies will be vital in reducing CO_2 emissions. There are currently 24 large-scale CEM projects at various stages of development in China. In the West, RD&D capital will flow only if policies create the right incentives.[35]

New policies are adopted only when there is sufficient demand for government to act. Organizations were formed to support policies that can accelerate CEM development and institutions have ramped up their engagement with researchers, industry, labor and government to promote a market for wide-spread research, development, and deployment CEM technologies.

Please refer to the *Acknowledgements* page at the beginning of this report for a list of some of the organizations engaged in this space. Our list is by no means exhaustive, as there are many organizations playing a critical role in this effort, each providing important information and impactful work. The intent of this paper is to build on the existing network of CEM activities by providing a unified industry voice with strong technical knowledge and experience.

2 CEM Technology Assessment

KEY TAKEAWAYS

ICAC Members

- Early CEM market demand is likely to focus on capture from concentrated industrial CO_2 streams to serve enhanced oil recovery operations.
- Demand for CO_2 utilization as a chemical resource may develop slowly but represents a long-term opportunity that could exceed $800 billion in the next few decades.
- CEM technologies are at various stages of development that require technical and commercial expertise to bring these innovations to market. Many of these technologies also require existing air pollution control equipment as part of their processes.

Policymakers

- CEM encompasses a diverse array of materials, components, and systems at varying stages of technology readiness. These technology innovations need long-term government support in order to overcome technological and market barriers.

Climate Stakeholders

- While some CEM technologies have been used at commercial scale for decades, many promising technologies are not yet mature.

Overview

A limited number of carbon capture projects have existed on commercial scales for decades around the world, primarily to enable enhanced oil recovery. Many of these commercial applications to date represent only a small fraction of the diverse CEM strategies currently being explored.

We assess the state of technology development and identify key commercial issues that will likely dictate the potential pace of commercialization and deployment for CEM technologies. While our assessment is limited by access to confidential business information, we are confident in the general accuracy of this assessment, which is based on our own extensive research, including primary discussions with technology and project developers.

This chapter is largely an overview of information in our technology compendium, which is available for purchase (http://icac.com/CEMInnovations). The compendium identifies more than 300 unique technologies under development and over 450 projects currently underway to refine, demonstrate, or employ those technologies. We believe this is the most comprehensive database of global CEM activity. In this rapidly advancing field, we expect this assessment to continue to develop.

History/Timeline

For nearly half a century, the private and public sectors have been developing technologies that handle carbon dioxide and other GHG emissions. Since the early 1970s, CO_2 has been used in a practice called enhanced oil recovery (EOR), recovering CO_2 emissions from natural gas processing facilities, injecting highly pressurized supercritical liquid CO_2 to re-pressurize otherwise uneconomic oil fields to produce more crude. In 1982, the Enid Fertilizer processing facility became the first industrial facility to capture its CO_2 emissions for the purpose of EOR. In 1996, the world's first geologic storage project began at the Sleipner CO_2 Storage facility off the shores of Norway, permanently sequestering CO_2 underground in a deep saline reservoir. In 2009, Chaparral and Conestoga Energy Partners' Arkalon Bioethanol plant came online as the first ethanol facility in Texas to capture CO_2 emissions.

In 2012, Air Products Port Arthur Steam Methane Reformer project became the first hydrogen production facility to capture CO_2 emissions. In 2014, the Saskpower Boundary Dam project in Canada became the first coal-fired power plant retrofit with carbon capture technology, selling CO_2 for EOR in Saskatchewan. In 2016, Phase 1 of the Abu Dhabi CCS project became the first operational carbon capture project on an iron and steel plant, once again producing CO_2 for EOR. In 2017, Petra Nova was completed on time and on budget, capturing 90 percent of CO_2 emissions from the W.A. Parish coal power plant in Texas. Also, in 2017, the ADM Illinois Industrial Carbon Capture and Storage Project became the world's first operating bioenergy with carbon capture and storage (BECCS) facility, capturing CO_2 from the ADM Decatur Ethanol facility and storing it in deep underground saline formations.

Technology Readiness Levels

Originally designed by NASA in the 1980s, Technology Readiness Levels (TRLs) have become an accepted metric for describing technological development progress. Depicted in ***Figure 11***, the scale begins at the concept stage with TRL 1 and continues to TRL 10 representing a commercial scale demonstration. Typically, multiple iterations at full-scale are needed to refine technologies and processes to a point where they can support commercial operations. That point is sometimes overlooked in a world where an app designed on a home computer can appear on millions of smartphones seemingly overnight.

Phase	Applied Research			Development			System Demonstration			Commercial Demonstration				Deployment
Technology Readiness Level (TRL)	1	2	3	4	5	6	7	8	9	10	X	X	X	N^th^ of a kind (NOAK)
Scale	Pre-technology			Bench		Pilot	Demonstration			Commercial				
Stage Gate	Concept			Feasibility		Engineering & Design				Finance & Market				

Figure 11. *Technology Readiness Levels provide standardized metrics to assess technologies from the research phase through deployment. Source: AJW, Inc.*

The TRL is a useful but imperfect tool for assessing complex systems. Various components of the technology may be at different stages of development, but most systems are only as good – or as ready – as their weakest component. The TRL system provides an accurate representation of status, scale, and stage along the innovation process, but fails to accurately assess remaining technology development barriers or attribute failures appropriately.

Technology Development Challenges

Innovation is inherently difficult and presents risks. Below, we focus on two primary components of risk: technology and commercialization. Even a well demonstrated technology may fail to find market demand if the technology remains uneconomic, or undesirable for other reasons. For those interested in understanding the commercialization challenges facing decarbonization technologies, it is useful to focus on the reality that success depends on both technology performance and commercial viability.

Technology risk refers to the potential for a technology to fail to perform reliably under anticipated operating conditions. Technology risk is most often addressed by a disciplined scale-up process. The new technology is built at increasingly larger scales and operated under conditions that increasingly resemble commercial operating conditions. Only when the full-scale system is proven to be replicable and reliable under an appropriate range of operating conditions is technology risk resolved.

Commercial risk refers to the potential for projects using a specific technology to yield a reasonable return on investment. Commercial success need not be immediate, but operators need to see results that will inspire confidence that they are on a path that will yield revenues that will exceed costs within a reasonable timeframe. Success can be undermined in a variety of ways. Offtake demand for a product may bring reducing revenues to an unsustainable level. Shortages of critical materials could impact productivity and drive up operating costs. Competition could alter demand for the technology, adversely impacting productivity as well as profitably. Investors need to constantly assess commercial risks. The more commercial uncertainties a project faces, the more difficult it will be to attract investment.

2.1 The Current Status of CEM Technologies

We divide technologies into two primary segments: one to describe capture techniques and the other to assess the utilization of the captured CO_2.

Capture includes:

1. *Industrial Capture* - Carbon captured or removed from any part of a process (e.g. post-combustion pre-combustion, oxy-fuel combustion, chemical looping combustion, fuel cells, and BECCS) in any power-generating, industrial, or other commercial facilities
2. *Atmospheric Capture* - Carbon removed directly from the atmosphere
3. *Fugitive Emissions Capture* - GHG emissions stemming from unexpected/uncontrolled operations (e.g. mine-mouth capture, methane pipeline leaks)

Carbon utilization includes:

1. *Permanent Sequestration* - Any utilization resulting in the permanent sequestration of carbon underground (e.g. geologic storage, EOR)
2. *Long-term Storage* - Any product made from captured carbon that does not release CO_2 or other GHGs when used but that may release GHGs when disposed or reprocessed, (e.g. cement, steel, polymers, carbon fibers)
3. *Short-term Storage* - Any product (made from captured carbon) the use of which releases CO_2 or other GHGs (e.g. synthetic hydrocarbon fuels, industrial chemicals, food and beverage applications)

2.2 Industrial Capture

Industrial capture is the containment of CO_2 from any commercial production facility, including power generation, industrial manufacturing, or other sources, through either pre-combustion, post-combustion or a hybrid of the two. The captured CO_2 can then be utilized for new products or for storage. ***Figure 12*** depicts these processes.[36]

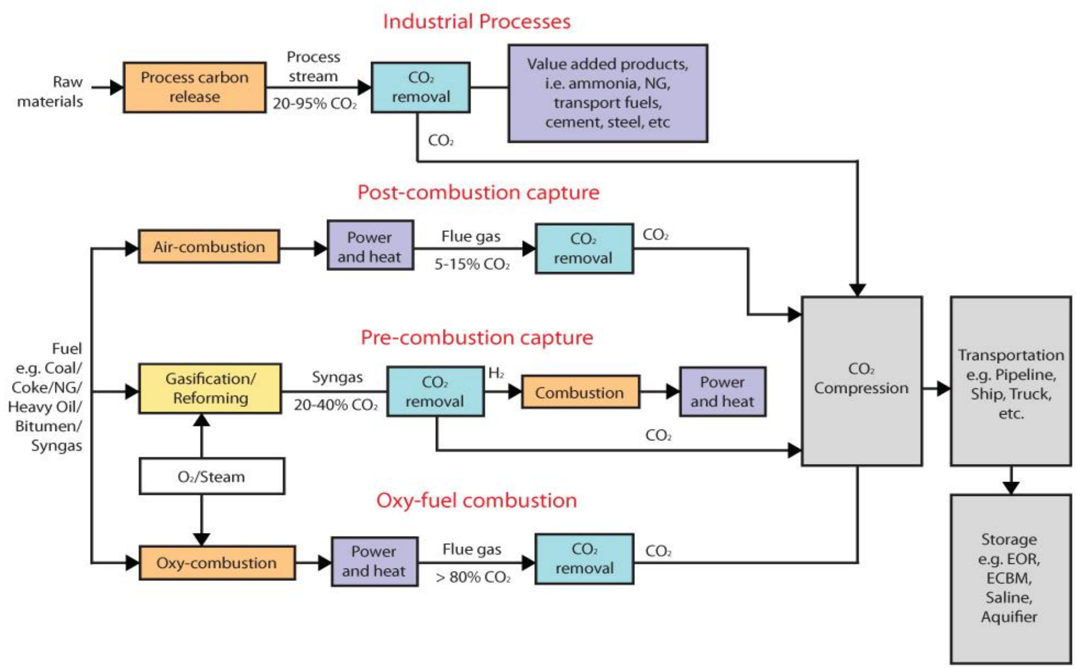


Figure 12. *Industrial capture processes from any commercial production facility can eventually be used for new products or for storage. Source: Natural Resources Canada.*

The Industrial Capture category can be broken out into six distinct technology types:

Post-combustion: Separation and capture of CO_2 from flue gases after a fuel has been burned.

Pre-combustion: Removal of CO_2 from fossil fuels before combustion is complete.

Oxyfuel combustion: Utilization of nearly pure oxygen rather than atmospheric air for combustion, resulting in a more concentrated and easier-to-separate CO_2 exhaust gas stream.

Chemical looping combustion: Utilization of oxygen for the combustion process, achieved through a metal or metal oxide reaction. The reaction between the fuel and the metal creates a concentrated CO_2 flue gas stream, while the metal is returned to its original state. The process continuously repeats.

Fuel cells: Fuel cell technology for carbon capture combines the plant's flue gas with the fuel cells to generate power, which in turn creates a concentrated CO_2 waste stream that can be recycled in the system for combustion use or can be separated and captured for external utilization. The CO_2 capture is a side reaction of the fuel cell's power generation.

Bioenergy with Carbon Capture and Storage (BECCS): The process by which biomass (plants, trees, and crops) are grown, naturally sequestering CO_2, and used as feedstocks for fuel production or combusted for power or heat production with an industrial carbon capture system to capture CO_2 emissions from the industrial fermentation or combustion process.

Broadly speaking, industrial capture technologies are the most developed among the suite of CEM technologies. Some post-combustion amine-based solvents have been used for EOR since the 1970s.

Several industrial capture technologies are operating at or near commercial scale and are ready for widespread deployment, given favorable commercial conditions. Many more technologies are in development at earlier TRLs as researchers work to drive down costs and increase efficiency or seek capital necessary for demonstration projects.

The diversity of viable technologies increases the prospects for industrial capture technologies to be deployable with the support of well-targeted policy incentives. For example, capture of CO_2 streams from biofuel fermentation and steam methane reforming (SMR) face no technology barriers – only cost and commercial barriers. The Energy Transitions Commission estimates SMR alone could contribute 2-3 $GtCO_2$ of emissions reduction by 2030.[37] Further research could lead to improvements in the materials and component technologies in these applications and likely would increase the viability of carbon capture from various hard to decarbonize sectors.

In all cases, equipment that increases complexity and costs while potentially reducing profitability will face resistance from facility owners and operators and their political representatives. That is especially likely for petrochemical, steel, and cement production – globalized industries with notoriously tight and competitive profit margins.

Hyperbole regarding the viability of CEM technologies is abundant in statements made by both supporters and skeptics. Given the diverse set of opportunities and obstacles facing this suite of carbon capture technology applications, more nuance is warranted in discussing its prospects.

Notably, some large-scale capture projects garnered attention for achieving operational success. However, some were simply scaled-up without appropriate incremental demonstrations, encountering commercial barriers and instilling limited optimism for further projects. Even some of the successfully demonstrated technologies are regarded as undesirable for reasons independent of technical capability. For example, projects that capture CO_2 from fermentation streams of ethanol plants are often opposed by those critical of biofuels.

As with all CEM technologies, sustained development and deployment activities will only be possible with a combination of supportive policies designed to establish a clear market demand for emerging technologies and assistance in reducing the private sector costs and risks associated with refining and demonstrating the technologies.

2.2.1 Post-Combustion Capture

Post-combustion capture, presented in ***Figure 13***, involves the separation of CO_2 from flue gases after a fuel has been burned.[38]

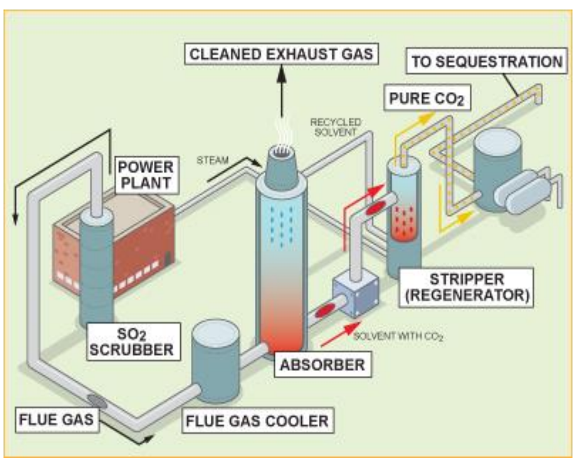


Figure 13. *Post-combustion capture systems separate CO_2 from flue gases after a fuel has been burned. Source: Clean Air Task Force.*

Post-combustion capture technologies include:

- Abiotic electrolyzers
- Amine solvents
- Amine-free solvents
- Catalysts
- Chilled ammonia processes
- Cryogenic separation
- Liquid absorption
- Membrane filtration
- Mixed salt solution
- Porous solids
- Swing adsorption cycle

At this stage of development, post-combustion capture is primarily applicable to sources burning pulverized coal or natural gas, where the fuel is burned with air in a boiler to produce steam that drives a turbine generator designed to generate electricity.[39]

Current Status of Post-Combustion Capture

Post-combustion capture is the most commercially ready technology within the industrial capture category. Many of these technologies have operated at commercial scale for decades; however, there are novel technologies in development at the pilot and bench scale. Additionally, further research should decrease costs and increase the efficiency of existing commercial processes.

Innovation Highlight: Gaston Power Plant/Wilsonville Project

Industrial Capture: Post-Combustion Capture

PROJECT OVERVIEW:

- **Location:** Alabama, USA
- **Project Duration:** 2011-2016
- Located at the Gaston Power Plant (operated by Southern Co.) at the site of the National Carbon Capture Center
- Pilot plant capacity: 1.5 MWe

TECHNOLOGY: Linde-BASF OASE™ Blue Novel Amine-Based Technology

- Advanced amine-based post-combustion CO_2 capture

CO_2 UTILIZATION:

- Enhanced Oil Recovery (EOR), urea production, small food-grade products

PROJECT PARTNERS:

- U.S. Department of Energy-NETL, BASF, Linde, NCCC, Southern Company and EPRI

FUNDING: Approximately $22.7 million total

- **U.S. Department of Energy:** $16.2 million
- **Private Sector Cost-Share:** $6.5 million

Wilsonville, AL Pilot Plant

CONTACT
BASF: Todd Spengeman
Todd.Spengeman@basf.com;
346-252-4181
Linde: Lars-Erik Gaertner
Lars-Erik.gaertner@linde.com
www.basf.com www.linde.com

Amine-based solvent systems are the most commercially available technology in this category. Since the 1970s this technology has been used to remove CO_2, H_2S and acid gases from gas treatment facilities and create supplies of CO_2 available for EOR.

Emerging post-combustion technologies include non-aqueous solvents, solid sorbents, and membrane technologies.[40] These technologies are currently at the demonstration stage or earlier. They could provide significant advantages, including a reduced need for steam and/or chemical inputs in the capture process.

The most advanced and commercially available of these processes are amine-based solvents, used by companies such as Alstom-Dow, Fluor, Linde, BASF (shown in the *Innovation Highlight* above), and Mitsubishi Heavy Industries (MHI). MHI's amine-based capture technology has been used at the Petra Nova plant in Houston, TX, where the captured CO_2 is transported to oil fields for EOR.

Commercial Advantages

Some post-combustion capture technologies are already in commercial use. These technologies can be fitted onto new or existing plants, offering flexibility and an increased number of opportunities for applications.

There already exists a robust and growing body of materials research, identifying technical barriers to be overcome. While there is potential value in ongoing scientific discoveries and improved technical understanding, industry know-how of post-combustion capture processes outstrips most other capture alternatives.

Table 1

Advantages and Challenges of Post-Combustion Capture	
Advantages	**Challenges**
• Applicable for both existing and new plants. • Well established and commercially available. • High-concentration CO_2 waste streams require less energy for separation. • Industrial waste streams management done for other pollutants.	• Adds operating costs and complexity to facility operations. • Can require large amounts of steam (solvents) or energy. • Physical and engineering limitations for some existing facilities.

Post-combustion capture technologies offer an economic opportunity through utilization in some cases (e.g. EOR). Opportunities for high volumes of carbon capture exist at post-combustion capture facilities, which are generally placed near existing fossil infrastructure, granting easy access to transportation and utilization destinations.

Commercial Challenges

For post-combustion capture technologies to gain widespread commercial success, innovators must address the high energy demands (i.e. parasitic load) required to operate them. The high energy demands are caused by the difficulty of separating the CO_2 from a complex waste stream that contains a number of gases other than CO_2.

Discussion

While post-combustion capture technologies are among the closest to commercial readiness overall, they require significant cost offsets to make up for the parasitic energy load and other costs related to installing and operating them. Further research into improving the efficiency of these technologies can be beneficial but likely will materialize only in response to clear market demand.

Post-combustion capture technologies to-date represent some of the lowest cost capture solutions world-wide. As a result, any sustained policy support for deployment of carbon emissions management technologies would likely drive demand for post-combustion capture, leading potentially to rapid wide-scale deployment.

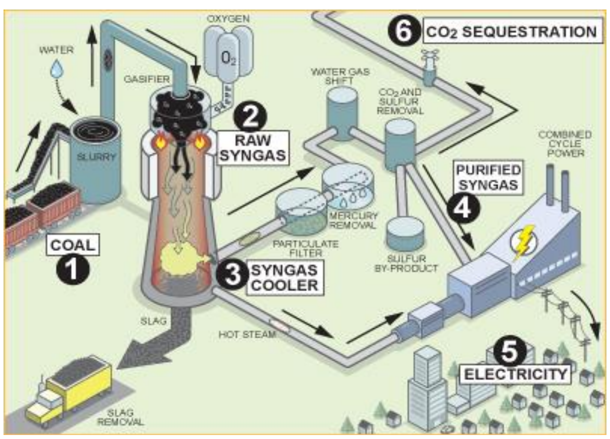


Figure 14. *Pre-Combustion capture removes the CO_2 from fossil fuels before the combustion is complete.*[56] *Source: Clean Air Task Force.*

2.2.2 Pre-Combustion Capture

As shown in ***Figure 14***, pre-combustion capture entails the removal of CO_2 from fossil fuels before combustion is complete.[41] Pre-combustion capture technologies currently in development for power generation use one of two methods: Integrated Gasification Combined Cycle (IGCC) and membrane-based chemical separation.

IGCC plants convert fuel into a syngas - a gaseous mixture of hydrogen, carbon monoxide and CO_2 - through gasification or reforming. According to the Clean Air Task Force, plants can reduce their carbon dioxide emissions by about 90 percent using this method.[42]

Current Status of Pre-Combustion Capture

A more nascent branch of CEM technologies, many pre-combustion technologies are not as developmentally advanced as post-combustion technologies; however, several ongoing demonstrations point toward progress.

Gasification techniques are used at refineries and chemical plants around the world, but no large-scale power generation facilities are currently using pre-combustion capture.

New RD&D efforts include advanced solvents, solid sorbents and membrane systems for the separation of hydrogen and CO_2. There is additional research into novel technologies that use a hybrid of these techniques and others that involve membranes or solid adsorption, which are maturing from the lab to pilot scale.[43]

Linde and OSAKI CoolGen are two notable innovators in pre-combustion capture with IGCC projects with industry partners in Europe and Japan, respectively. Membrane-based technologies are much earlier in their development at the lab and pilot stages.

Commercial Advantages

Pre-combustion capture technologies provide an undiluted waste stream with pure CO_2, which results in a less energy intensive separation process compared to post-combustion capture systems. With lower parasitic loads, pre-combustion capture technologies could provide comparative energy and cost savings for operators. These technologies also provide an overall increase in efficiency for plants.

The option to sell the hydrogen produced during separation stage provides an additional economic incentive. Hydrogen can be used for fuel for electricity, transportation, and heating homes with near-zero emissions.

Commercial Challenges

Based on current technology designs, pre-combustion capture applications for power generation appear to be economically viable only for future greenfield plants. Retrofits are likely to require disqualifying levels of re-design and construction.

Two significant challenges face pre-combustion capture technology for power generation applications (i.e. IGCC): 1) the market shift from coal to natural gas as a feedstock, particularly in the U.S., and 2) overcoming its history over the last decade of scaling-up too quickly.

Table 2

Advantages and Challenges of Pre-Combustion Capture

Advantages	Challenges
• CO_2 is not contaminated by combustion byproducts. • The hydrogen co-products have commercial value. • Lower-cost optimized processes can be designed. • Membrane processes minimize losses of economically valuable chemicals.	• High energy is needed to pump solvents. • Liquid-gas sorbents are needed rather than solid reactants in gasification applications. • Membranes entail high capital costs. • Pre-combustion methods can only be applied to new facilities.

Currently, natural gas is less expensive than coal. Unless this changes, new investments into IGCC plants for power generation are unlikely. Gasification for non-power processes, such as producing hydrogen, syngas, and other chemicals, is more viable.

The challenges that Mississippi Power's Kemper plant faced often overshadow this technology's potential. The Kemper plant, owned by Southern Co.'s subsidiary Mississippi Power and jointly funded by U.S. DOE, was a pre-combustion IGCC project that was burdened by both of the challenges outlined above: the increasing cost of coal and scaling-up a technology too quickly. These challenges ultimately resulted in the project being shelved due to cost overruns and the inability of the plant to ever run at full capacity.[44]

The Kemper project left a negative impression on investors and utilities in the U.S., decreasing the likelihood that another such project would be funded. However, the project served to advance the technology development process, and new IGCC demonstrations are taking place at smaller scales in other countries.

Innovation Highlight: Air Products Port Arthur ICCS Project

Industrial Capture: Pre-Combustion Capture

PROJECT OVERVIEW:

- **Location:** Texas, USA
- **Project Duration:** 2009 – Ongoing
- One of three projects for DOE's Industrial Carbon Capture and Storage (ICCS) program
- Originally demonstrating a system to concentrate CO_2 from two steam methane reformer (SMR) hydrogen production plants; operating commercially since 2013
- Air Products has captured and stored over 3,640,000 metric tons of CO2 as of April 30, 2017 and is on pace to capture and store the 4,000,000th metric ton of CO_2 around the September 2017 timeframe.

TECHNOLOGY: Air Products CO_2 Separation

- Vacuum swing adsorption (VSA) system (retrofitted to plants)
- +97% CO2 purity; +90% CO_2 removed

CO_2 UTILIZATION:

- Enhanced Oil Recovery (EOR) via the Denbury pipeline to the West Hastings field for a monitoring, verification and accounting project

PROJECT PARTNERS:

- U.S. Department of Energy, Air Products, Denbury,

FUNDING: Approximately $400 million total

- **U.S. Department of Energy:** $284 million
- **Private Sector Cost-Share:** $116 million

Air Products Port Arthur, TX
Hydrogen Production Facility

CONTACT

AIR PRODUCTS

Simon Moore
mooresr@airproducts.com
610-481-7461

Discussion

While pre-combustion capture is commercially available for refineries and chemical plants, this technology still requires significant refinement and demonstration for power generation. It could offer a competitive cost for capture (NAS estimates range from $42-87 per ton of CO_2 captured).[45] With strategic deployment and thoughtful project management, these technologies could offer an effective solution where renewable generation is not viable and new power production facilities are in demand.

2.2.3 Oxy-Fuel Combustion

Oxy-fuel combustion, depicted in ***Figure 15***, uses nearly (95 percent) pure oxygen rather than atmospheric air for combustion, resulting in easier-to-separate exhaust gas.[46] This technology provides an alternative to post-combustion technologies, which require more invasive separation of CO_2 from the flue gas.

The oxygen enters the boiler with fuel, resulting in steam and flue gas. The steam generates energy, while the flue gas is recirculated into the boiler and the CO_2 is captured, compressed and ready for utilization.

This process results in 75 percent less exhaust gas, which is comprised of mostly water vapor (H_2O) and CO_2. This exhaust gas mixture is easy to separate and produces a high-purity CO_2 stream that is ready to transport or utilize through direct physical compression and cooling techniques, such as a low-temperature separation/distillation process.

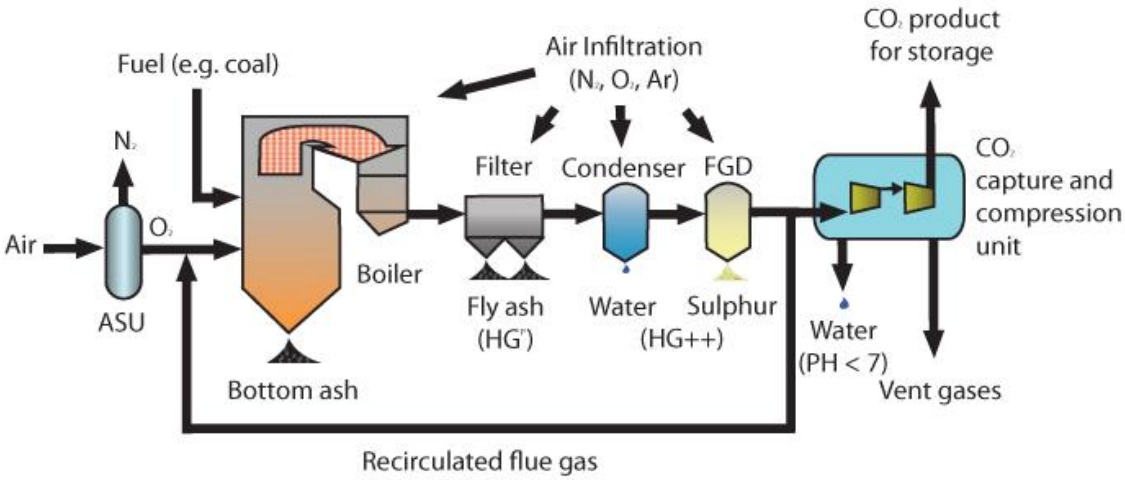


Figure 15. *The oxy-fuel combustion process uses nearly pure oxygen from an Air Separation Unit (ASU) rather than ambient air for combustion with the fuel. Source: Natural Resources Canada.*

Current Status of Oxy-Fuel Combustion

The welding and metal making industries have historically used oxy-fuel combustion, as the purer intake air allows for higher temperatures.[47] Most oxy-fuel combustion technologies for power generation are currently at the pilot or demonstration stages of development.

Oxy-fuel combustion has seen recent success in applications for cement production. The European Cement Research Academy (ECRA) announced in 2018 two demonstration plants that will use oxy-fuel combustion – one at a Heidelberg Cement in Italy and the other at a LaFarge Holcim plant in Austria.[48]

Additional research is ongoing into novel technologies for near-zero emission systems and integrated systems for hydrogen fuel production opportunities.

Traditional oxy-fuel combustion processes offered by companies such as Linde, Alstom-Dow and Amec Foster Wheeler continue to be refined to increase operational and capture efficiency at both new and existing facilities. In addition, alternative oxy-fuel combustion solutions in development aim to increase the efficiency of carbon capture.

For example, NET Power's Allam Cycle overcomes the challenge of providing expensive oxygen for combustion by recycling captured CO_2 to power the turbine within the system to generate electricity. By using the recycled CO_2 as part of the combustion process, the amount of oxygen required is decreased, thus reducing the cost of powering the air separation unit. Excess CO_2 that is not needed for the system itself is ready for utilization.[49] NET Power's process is currently being demonstrated at a 50 MW plant near Houston, TX.

Commercial Advantages

The key technological advantage for oxy-fuel combustion is the use of pure oxygen rather than atmospheric air for the intake air. This results in a highly concentrated waste stream comprised of mostly water and CO_2. Due to its purity, the CO_2 is immediately ready for transportation or utilization. As economic incentives are offered for the utilization of recycled CO_2, this ready-to-use CO_2 would provide an advantage over CO_2 that is not so pure.

Additional advantages of the pure intake air can be attributed to the lower amounts of nitrogen found in oxygen compared to atmospheric air, which is comprised of nearly 80 percent nitrogen. This leads to a decreased amount of fuel consumed in the combustion process and a reduction of other emissions in the flue gas as well (virtually eliminating NOx emissions), making for an integrated emissions control system for the plant operator. This also results in a much smaller combustor unit size required (one-fifth the size of one using atmospheric air).[50]

Oxy-fuel combustion technologies can be retrofitted onto existing plants or built at new facilities, which offers a wider range of possible applications. Its commercial utilization has been proven at glass facilities, but other industrial applications are at earlier stages of development.

Table 3

Advantages and Challenges of Oxy-Fuel Combustion	
Advantages	**Challenges**
• The process can work at new or existing facilities. • Concentrated exhaust stream of CO_2 reduces capture energy costs. • Opportunities integrate with other emissions control (e.g. NOx emissions management). • Combustion is more efficient, thereby increasing revenue and reducing capital costs. • The process is effective for hard to decarbonize industries, such as metal production.	• This energy intensive process can require increased fossil fuel consumption. • It adds cost and complexity to traditional power generation processes.

Commercial Challenges

Oxy-fuel combustion offers a variety of benefits for a plant, yet the need for pure oxygen for the intake air causes the process to require a significant amount of energy to produce the oxygen supply (approximately 15 percent of the plant's total output at times).[51] The additional energy demand has the potential to both increase operating net operating costs and create additional GHG emissions depending on the energy source used. These challenges may be mitigated through the use of chemical looping combustion technology (see *Table 4*).

Discussion

To offset incremental energy cost requirements, policy incentives are required to support oxy-fuel combustion projects.

In addition to its commercial applications in the glass industry, oxy-fuel combustion has seen recent success in the implementation of the technology through demonstrations in the cement industry, as noted above. Other industries have considerably less commercial experience. Some projects are now underway at the pilot and demonstration stage for applications outside of glass production. NAS places this technology at a TRL of 7.

2.2.4 Chemical Looping Combustion

Chemical looping combustion uses oxygen in a two-step combustion process to generate power or heat by using metal or metal oxide reaction – similar to the process of iron rusting. Chemical looping utilizes gaseous, solid or liquid fuels and can be applied to an IGCC plant. The reaction between the fuel and the metal creates a pure CO_2 flue gas stream, while the metal is returned to its original state. The process continuously repeats. See the process depicted in *Figure 16*.[52]

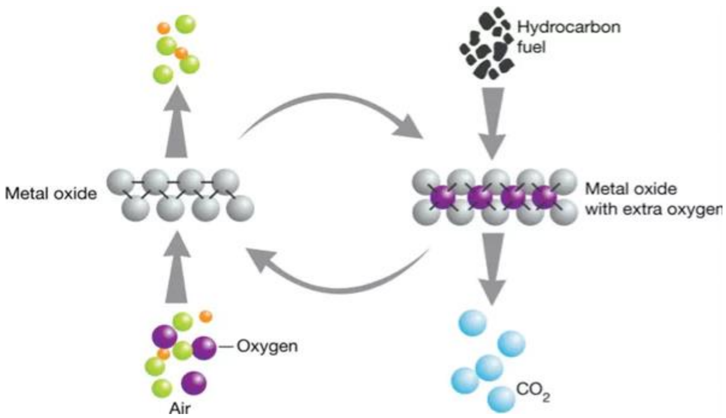


Figure 16. *Chemical looping combustion process entails a continuously repeating metal oxide reaction that generates oxygen for fuel combustion and produces a pure CO_2 flue gas stream. Source: CO_2 Costa Rica.*

Two distinct CO_2 separation processes exist in this space: chemical looping combustion (CLC) for pre-combustion capture and calcium looping combustion (CaL) for post-combustion capture.

Any fuel can be used for CLC, which is the "indirect combustion process in which fuel is combusted without direct contact with air. Transfer of oxygen between air and fuel takes place with the aid of a solid oxygen carrier (OC)." The CO_2 is then captured inherently from the condensing water vapor. Alternatively, CaL uses "the reversible chemical reaction between CaO and CO_2 in order to capture CO_2 from gaseous streams." CO_2 is captured as it is formed in the carbonator at 650°C. Heat from this process, which requires coal or natural gas combustion, generates steam for power.[53]

Current Status of Chemical Looping Technologies

Numerous pilot-scale projects have been completed using this technique since the early 2000s; many remain ongoing. While this technology is promising and has compelling advantages, such as low energy demand, it is still in development.

To date, the dozens of pilot tests in this space have been completed by universities and research labs, with a select number of large companies, such as Alstom-Dow, testing these technologies. Ohio State University (OSU) is one of the leading technology developers in this space, with application offerings for the power, hydrogen and syngas industries. The university is currently working with Babcock & Wilcox, DOE/NETL and other industry partners on a coal direct chemical looping pilot project (10 MW) using a technology that originated in the OSU lab.[54]

Other notable projects include an EU-sponsored project led by SINTEF in Norway, Chalmers University's (Sweden) 10 MW unit and Alstom-Dow's 3 MW unit. NETL supports ongoing bench and pilot scale projects for chemical looping technologies in addition to the OSU project described above.[55]

Table 4

Advantages and Challenges of Chemical Looping

Advantages	Challenges
• The energy demand is small. • Parasitic loads are typically low. • The resulting pure CO_2 stream enables easy separation.	• Process abrasion can wear down plant equipment. • It is more expensive than other capture processes due to deterioration of the plant's equipment.

Commercial Advantages

Chemical looping combustion uses oxygen rather than atmospheric air for the coal combustion process. The technology relies on a repeating metal reaction to generate oxygen and create the pure CO_2 stream. This self-sustaining looping process does not require significant amounts of energy as other capture technologies do, which represents cost savings for the operator.

Similar to other processes that utilize purer intake air, the CO_2 in the flue gas is more highly concentrated, enabling easy separation of the CO_2 from other exhaust gas components.

Commercial Challenges

Abrasive wear and tear on the plant's equipment will increase maintenance and operating costs. Innovators may be able to develop a less abrasive process or more resilient equipment.

Discussion

Chemical looping technologies offer an efficient alternative for electricity generation or the utilization of CO_2 for storage, fuels or commodities. The lower operating costs provide a promising option for the future of combustion of solid fuels (e.g. coal).

There are currently lab, pilot and demonstration-scale projects underway for power generation applications.

2.2.5 Fuel Cell Technology

Fuel cell technology for carbon capture combines the plant's flue gas with the fuel cells to generate power, which in turn creates a concentrated CO_2 waste stream that is relatively easy to separate and capture. From FuelCell Energy:

> *Similar to a battery, a fuel cell is comprised of many individual cells that are grouped together to form a fuel cell stack. When a hydrogen-rich fuel, such as clean natural gas or renewable biogas, enters the fuel cell stack, it reacts electrochemically with oxygen (i.e. ambient air) to produce electric current, heat and water. While a typical battery has a fixed supply of energy, fuel cells continuously generate electricity as long as fuel is supplied.*[56]

The electrochemically charged carbonate ions that are formed as a result of the CO_2 and oxygen filtering through the fuel cell react with the hydrogen to produce water, CO_2, and electrons. The CO_2 is then recycled into the system again for continued utilization. Fuel cell plants can utilize the exhaust gas from nearby sources, such as power, steel or cements plants, to contribute to the CO_2 needed for the continuous charging of the fuel cells.[57]

Depicted in **Figure *17***, fuel cell technology generates an increase in electricity compared to other capture technologies that require a portion of the host plant's energy output to capture the CO_2.[58] ExxonMobil's published fuel cell research suggests that a 500 MW power plant using a carbonate fuel cell may be able to generate an additional 120 MW of power.[59]

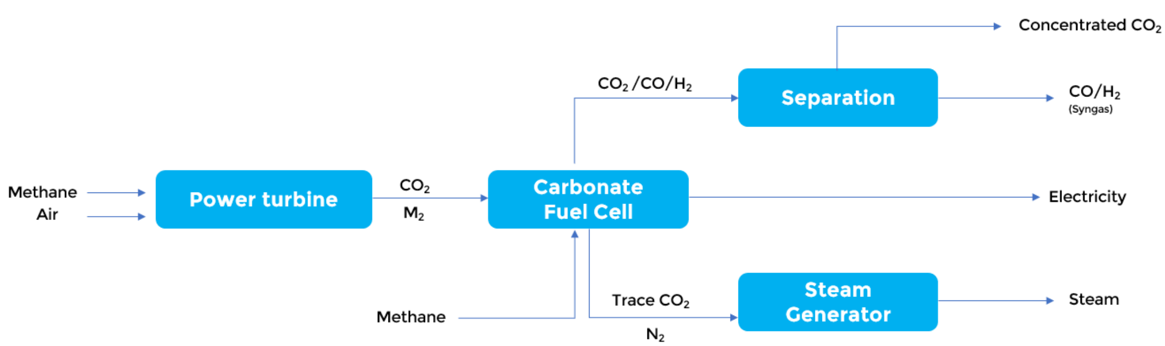


Figure 17. *Fuel cell technology utilizes CO_2 from a plant's flue gas, interacting with the fuel cell to generate electricity and create a concentrated CO_2 waste stream for easy separation and eventual utilization. Source: U.S. Energy Association.*

Current Status of Fuel Cell Technology

Fuel cell categories include solid oxide fuel cell, molten hydroxides fuel cell, molten carbonate fuel cell and molten tin anode solid oxide fuel cell.

A limited number of fuel cell technologies are commercially available for carbon capture; most are based on carbonate fuel cell technology. These commercial applications can be found at projects in California, Asia, and Europe. For example, FuelCell Energy's SureSource™ offers utility-scale and on-site power generation, carbon capture, and local hydrogen production for both transportation and industry.

Other types of fuel cell technologies and research into efficiency increases are in earlier stages of development. The European Union has sponsored a demonstration-scale project aimed at further development of solid oxide fuel cell (SOFC) technologies in client environments for low-emission heating and electricity. Known as Commercial-scale SOFC Systems, or ComSos, the project will test 25 different solutions. Additionally, the Georgia Institute of Technology and South Korea's Ulsan National Institute of Science and Technology are collaborating on a project that relies on a hybrid sodium-carbon dioxide (or hybrid Na-CO_2) fuel cell submerged in water that eliminates CO_2 that is injected into the water through an electrochemical reaction and uses the resulting hydrogen and water's current to produce electricity.[60]

Researchers are focused on increasing knowledge of the fundamental science behind fuel cell technology while operating lab and pilot scale projects to increase efficiency of the carbon capture step.

Table 5

Advantages and Challenges of Fuel Cell Technology	
Advantages	**Challenges**
• Modular technology can be located anywhere, at any scale. • Power generation during carbon capture adds economic value to the facility. • Highly efficient separation provides a pure CO_2 waste stream. • Facilities can use natural gas, coal or biomass. • The process has the potential to produce hydrogen. • The pure CO_2 is ready for utilization. • Because there is no fuel combustion, there are fewer overall emissions.	• Further research is needed to increase efficiency of carbon capture and reduce the costs with fuel cells. • Infrastructure challenges may impede the widespread hydrogen distribution necessary to enable fuel cell use. • Applications must compete with lower cost/lower risk commercial alternatives.

Commercial Advantages

Fuel cell technologies offer a variety of exciting commercial opportunities. The most intriguing benefit from fuel cell technology applications is that they increase a plant's energy output. Although the electricity is three to four times more expensive than conventional coal-fired power, the co-generated heat and electricity that resultddds in an 80 percent boost in electricity output from the plant begins to make an economic case for the fuel cell technology.[61]

This varies significantly from other CEM technologies, which require a portion of the plant's energy output for carbon capture. This economic value-add combined with any potential policies that provide financial incentives for carbon capture would make this suite of technologies significantly more attractive.

Additional commercial advantages include its modularity and ability to be located anywhere in the world, its pure CO_2 waste stream, and the potential to produce hydrogen to sell as a fuel. Further, since the fuel cell system uses the CO_2 itself to generate power, there is no need to find significant storage or utilization sites for the captured CO_2.

Commercial Challenges

Additional technology development is needed to optimize this technology for commercial applications. Even the most advanced of the demonstration projects continues to focus on gaining a better fundamental understanding of the opportunities that lie within fuel cell applications and increasing the efficiency of CO_2 capture.

National policies that incentivize the use of fuel cell technologies for increased energy production would expand their deployment.

Discussion

There is growing interest in fuel cell technologies to capture carbon and increase energy output.

The economic case for fuel cell technologies is rooted in their ability to produce more energy using less fuel than conventional plants. The potential economic advantages for hydrogen production, recycled CO_2 and other consumer products are attractive as well.

2.2.6 Bioenergy with Carbon Capture and Storage (BECCS)

Depicted in ***Figure 18,*** BECCS is the process by which biomass (plants, trees, and crops) are grown, naturally sequester CO_2, and then are subsequently burned for energy, processed into liquid fuels and/or heat production with a carbon capture system installed at the facility to capture CO_2 emissions from the combustion process.[62] BECCS uses stack capture technologies that could be applied to a fossil fuel source (pre- or post-combustion or oxy-fuel combustion). To achieve net-negative emissions, captured CO_2 can then be permanently sequestered in geologic formations, with or without being used for EOR.[63]

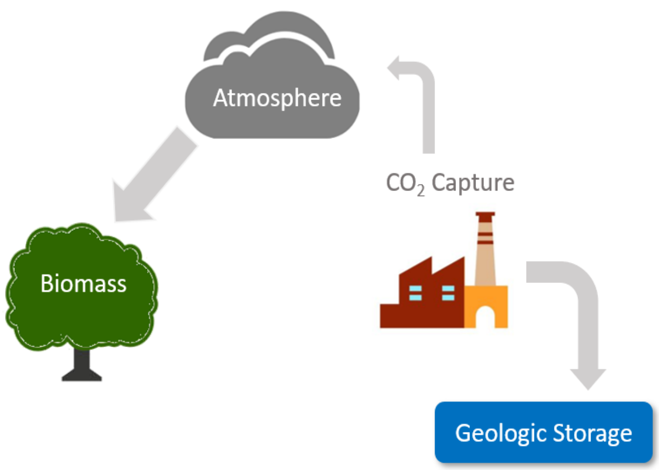


Figure 18. *Biomass captures CO_2 from the atmosphere. The biomass is then used as a fuel at an industrial plant and the CO_2 in the flue gas is captured. Source: Biorecro.*

BECCS needs to be discussed in terms of both industrial capture and atmospheric capture technologies. BECCS begins with biomass absorption of CO_2 from the atmosphere, but the capture of CO_2 from commercial fermentation (for liquid fuel production) or combustion (for heat and power) is an essential tool for maximizing the decarbonizing potential of this approach.

BECCS can be applied at power plants, pulp and paper mills, municipal solid waste treatment facilities, or ethanol and biogas facilities.

BECCS can be achieved with different feedstocks (lignocellulose, algae, sugar/starch and organic waste) through processes such as anaerobic digestion, torrefaction, hydropyrolysis, hydrothermal liquefaction, fermentation, gasification, pyrolysis, and aqueous phase reforming.

Current Status of BECCS Technologies

The National Academy of Science identifies BECCS as one of the CEM technologies most ready for large-scale deployment.[64]

Most BECCS projects in North America and Europe are at ethanol plants and municipal solid waste processing facilities.

Since many industrial capture technologies can be used for carbon capture during the processing/use of biomass feedstocks, the technology readiness level can vary broadly across applications. Capture of the near-pure CO_2 stream from fermentation is commercially available technology. Post-combustion capture technologies are the next most advanced in their development and offer the option of retrofitting to existing or newly built sources. It should be noted that post-combustion capture itself offers a range of technologies, so end-users must carefully select which design is most appropriate to use.

Alstom-Dow has implemented its amine-based solvent technology at the first large-scale application of BECCS at the Illinois Industrial Carbon Capture and Storage (ICCS) project located at ADM's bioethanol plant. Headquartered in Sweden, Biorecro is researching next-generation gasification techniques for ethanol plants.

Table 6

Advantages and Challenges of BECCS	
Advantages	**Challenges**
• Costs are low compared to other carbon removal technologies. • It yields nearly pure streams of CO_2, reducing the need for additional waste stream. management and providing a near commercial product. • The technology is well understood.	• The land-use footprint for biomass production can create challenges with respect to the location of geologic formations required for CO_2 storage. • Competition for land use could create political and economic challenges as well as feedstock price risks. • CO2 transportation and storage will depend on locations and pipeline availability. • BECCS costs approximately 50 percent more than carbon capture from a fossil-fuel facility.

Commercial Advantages

As a net-negative capture technology that can be applied to a variety of CO_2-emitting facilities, BECCS offers commercial advantages in addition to its near-term commercial readiness for large-scale deployment. Fermentation of biomass can produce highly concentrated streams of CO_2, allowing for cost-effective, large volume capture.

Economic opportunities through liquid fuel production could advance the deployment of BECCS applications. This option provides more incentives than storage or the production of other products using recycled CO_2.

Commercial Challenges

One of the most significant challenges for BECCS is the land-use footprint and limited viable locations for the application of the technology. If BECCS can be expanded without disrupting the food supply, then BECCS combined with reforestation could deliver net-negative CO_2emissions of up to 10 Gt/year, equivalent to just under 25 percent of global CO_2 annual emissions.[65] However, this would require further developments in agricultural productivity, without which that level of decarbonization would be difficult to achieve.[66]

Biomass-to-power plants today suffer from an inability to sustain a consistent biomass supply, price, and composition and from low power plant efficiency. These both present barriers to the deployment of carbon negative biomass-to-power with carbon capture.[67]

Further, transportation of captured CO_2 is limited by lack of access to pipeline infrastructure. Given trending low oil prices, the costs of capture, compression, and transport outweigh the revenue received for delivering CO_2 for injection, despite the high concentrations of CO_2 given off a bioenergy operation.[68]

Moreover, BECCS can cost as much as 50 percent more than capturing carbon from a fossil fuel source, such as coal or natural gas. Economic incentives from the production of liquid fuels or other policy incentives would be critical to its widespread deployment.

Discussion

BECCS is uniformly accepted by most climate researchers to be among the ripest candidates for immediate deployment of carbon capture technologies worldwide.

The technology is well understood, relatively low-cost, and can be readily applied by existing industries. There is little doubt this combination of factors will lead to rapid deployment of BECCS with sufficient policy incentives. Some projects, such as ADM's facility in Decatur, IL, are commercially operational and permanently sequestering CO_2 emissions deep underground in saline formations.

Widespread deployment of BECCS will raise the profile of complex environmental concerns related to land use. Worldwide, full-scale BECCS deployment could require 300-600 million hectares of land, an area roughly the size of Australia.[69] In addition, using BECCS for ethanol production could lead to greater crop deployment and the potential for habitat loss, nutrient depletion, and water quality concerns. Such factors would need to be addressed before widespread support for this decarbonization approach could be expected.

None of these concerns should prohibit deployment of BECCS technology, and many may be addressed through improved research and implementation of agricultural practices. Nonetheless, they must be addressed if BECCS is to become a key factor in carbon emissions management.

Innovation Highlight: Archer Daniels Midland (ADM) Illinois Industrial CCS Project

Industrial Capture: Bio-energy with CCS (BECCS)

PROJECT OVERVIEW:

- **Location:** Illinois, USA
- **Project Duration:** 2017-2022
- Located at ADM's corn-to-ethanol fermentation facility
- First large-scale application of BECCS in the world and 12th large-scale CCS facility in North America.
- Ongoing research into monitoring geologic storage impacts (i.e. seismic activity)

TECHNOLOGY: Alstom-Dow UCARSOL™ FGC-3000 Process

- Post-combustion advanced amine-based process

CO_2 UTILIZATION:

- CO_2 is transported 1.5 miles underground via pipeline for geologic storage in the Mt. Simon Sandstone
- Injects 1 million tons of CO_2 annually (3,000 MT/day)

PROJECT PARTNERS:

- U.S. Department of Energy/NETL, University of Illinois, Richland Community College, LBNL, Silixa, Schlumberger Carbon Services

FUNDING: Approximately $208 million total

- **U.S. Department of Energy:** $141.1 million in grants
- **Private Sector Cost-Share:** $66.5 million

ADM's Decatur Corn Processing Facility

CONTACT ALSTOM
Tim Brown
Timothy.S.Brown@power.Alstom.com
202-495-4968
https://www.alstom.com/

2.3 Carbon Removal/Atmospheric Capture

Carbon removal technologies are unique in their ability to remove legacy CO_2 emissions that have accumulated in the atmosphere. Similarly, carbon removal technologies present an opportunity for hard-to-decarbonize sectors to off-set their emissions. Technologies that enable removal of atmospheric CO_2 provide an important additional decarbonization tool. As with past pollution problems (e.g. soil contamination), it is sensible to apply a combination of reducing pollution (stop adding to the problem) and removing pollution (clean up past pollution). Direct Air Capture (DAC) and other atmospheric capture technologies offer the prospect of cleaning up GHG pollution. Most credible models (e.g. IPCC, IEA) have found that carbon removal technologies will be required to meet our global emissions goals, in addition to other emission reduction pathways, such as increased deployment of renewables. ***Figure 19*** compares the commercial viability for carbon removal solutions that address reducing and removing pollution.[70]

While most of these technologies are at the lab/bench scale, a few industry leaders are working through the pilot and demonstration phases. Recently, interest in these emerging technologies has grown as new projects and funding from strategic partners gain media attention.

Compared to technologies that capture carbon from a specific facility or plant, atmospheric capture technologies rely on a more dilute CO_2 resource (ambient air), which increases the cost and complexity of separating the CO_2.

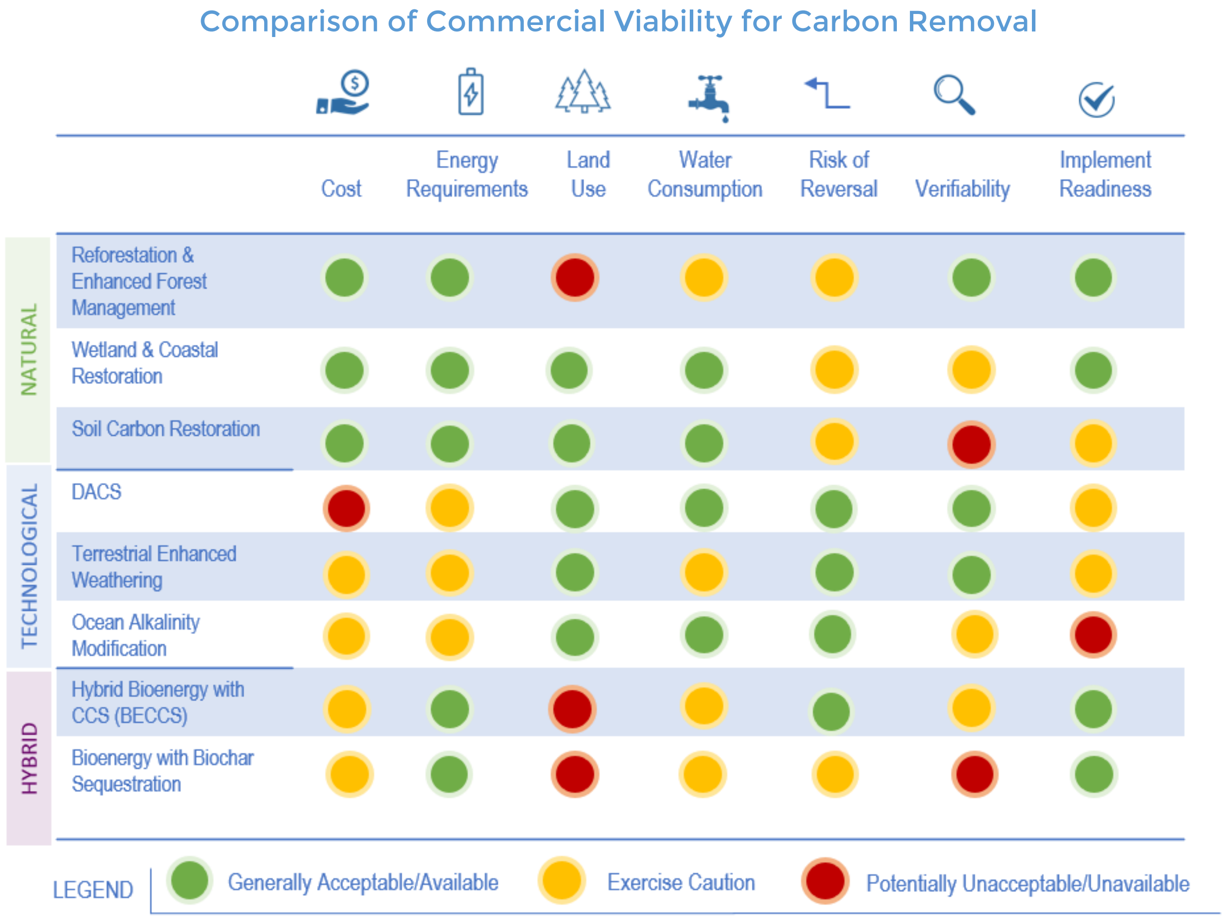


Figure 19. *An assessment of the options for removing legacy emissions directly from the atmosphere and their respective commercial viability. Source: Innovation for Cool Earth Forum.*

2.3.1 Direct Air Capture (DAC)

Direct Air Capture (DAC) technology captures CO_2 from ambient air in our atmosphere rather than from an emission point-source, such as those in power plants or industrial facilities. Unlike industrial capture, where carbon dioxide is concentrated and composes anywhere from four to 99 percent of a flue gas, ambient air contains CO_2 at roughly 400ppm, or just 0.04 percent CO_2.[71] DAC technologies must overcome high energy and water requirements needed to capture such dilute concentrations.

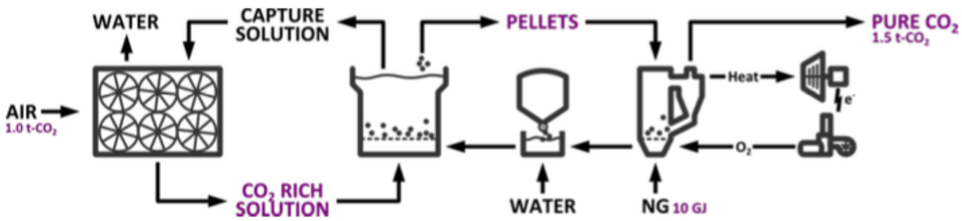


Figure 20. *In Carbon Engineering's DAC technological process, atmospheric air enters the chemically bound air contactor, CO_2 binds to a chemical agent, and then is separated from the chemical binding agent, leaving near-pure CO_2 ready for use. Source: Carbon Engineering.*

There are three primary direct air capture technologies: chemical, cryogenic, and membrane capture. Of these, liquid and solid chemical capture techniques are more well-developed.

Current DAC technologies accomplish CO_2 separation in two steps. First, atmospheric air is sent through an air contactor to interact with a chemical capture solution. Once CO_2 has been captured in a new compound, it is heated to separate the CO_2 from the chemical binding agent, resulting in a near pure stream of CO_2. **Figure *20*** shows Carbon Engineering's technological process.[72]

Because DAC's primary limitation is cost rather than location or scale, some regard DAC as the carbon removal technology with the highest potential to address legacy carbon emissions.[73]

Current Status of DAC Technologies

Many theoretically possible DAC technologies remain unexplored or are at the earliest RD&D stages. Some candidate technologies are currently scaling up to the pilot and demonstration stages with support from strategic investors and industry partners. Additional RD&D is necessary to drive down overall costs.

There are two primary chemical DAC technologies operating at a pilot or larger scale to date: one using a solid sorbent (Climeworks and Global Thermostat) and the other using an aqueous solution (Carbon Engineering). Historically, DAC cost estimates have ranged from \$100 to \$1000 per ton, but a recent analysis by The Rhodium Group showed that costs have dropped to a median of \$242 per ton[74] One techno-economic analysis by researchers at LUT University in Finland concluded DAC systems could be as low as \$60 euros/ton by 2030 and further reduced to \$32 euros/ton by 2050.[75]

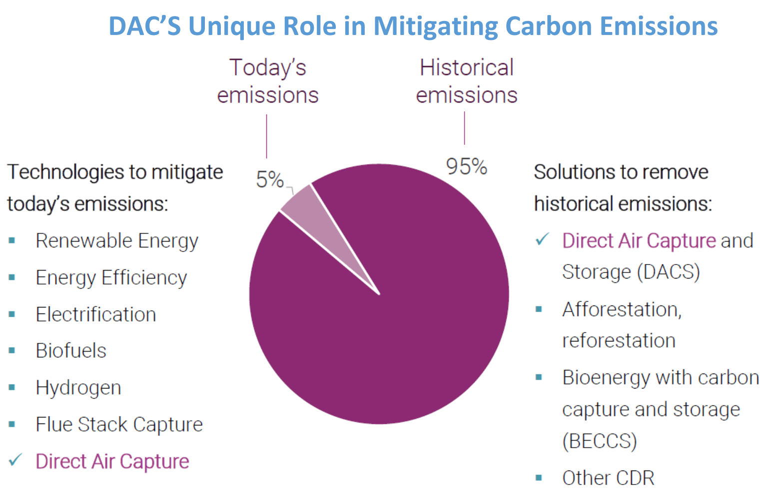


Figure 21. *Direct air capture is the most commercially viable technology that can tackle historical emissions, which make up 95 percent of CO_2 in our atmosphere.[87]* Source: Carbon Engineering.

Recent investment announcements suggest growing optimism within some organizations that costs at the lower end of that range may be achievable.

As documented in ***Figure 21***, the importance of DAC to remove the vast amounts of CO_2 in the atmosphere cannot be overstated.

Table 7

Advantages and Challenges of Direct Air Capture	
Advantages	**Challenges**
• DAC addresses legacy CO_2 emissions.	• Atmospheric CO_2 is much more dilute than industrial waste streams.
• DAC operate virtually anywhere.	• It is currently among the most expensive capture technologies.
• It operates compatibly with with renewable energy generation.	• It entails high energy costs relative to flue gas capture.
	• Commercial-scale demonstrations are needed to inspire public confidence and private investors.

Commercial Advantages

Even under the most rapid scenarios for reducing global GHG emissions, atmospheric concentrations are projected to continue to rise for a considerable period. DAC can address the legacy emissions in the atmosphere.

Because DAC systems would be using atmospheric air as their feedstock, they could be located virtually anywhere on the planet and are highly scalable. As a result, DAC projects can be located close to the location of CO_2 demand, thereby reducing infrastructure costs associated with transporting captured CO_2.

DAC facilities can be co-developed with new renewable power generation and serve as a long-term off-take customer. Such projects would create better economics for renewable deployment while creating greater decarbonization opportunities than a DAC or renewable project alone could achieve.

Presented in ***Figure 22***, the National Academy of Science recommends that federal funding for Direct Air Capture technology follow a 15-year plan that includes Basic & Applied Research, Development and Demonstration funding for ten years, with funding for Deployment allocated at Year 4 and continuing through Year 14.[76]

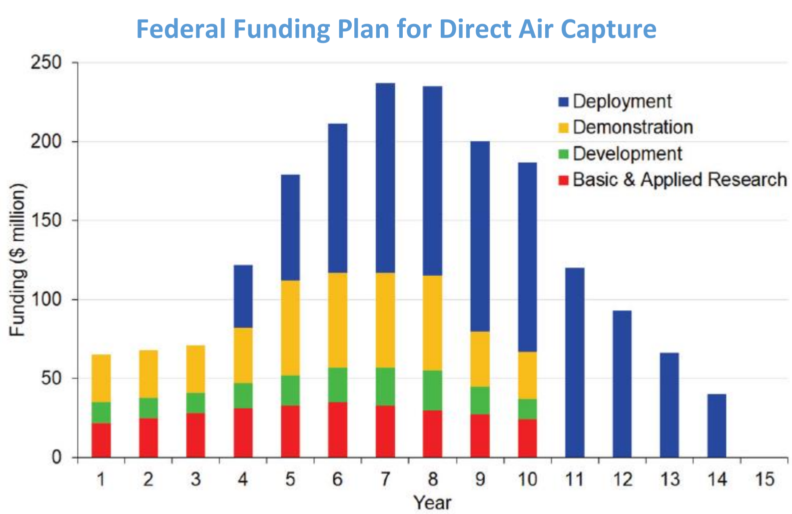


Figure 22. *The National Academy of Science recommends that federal funding for direct air capture technologies follow a 15-year strategic plan. Source: National Academy of Sciences.*

Commercial Disadvantages

Atmospheric gases contain a highly-dilute (0.04 percent) CO_2. Accordingly, large quantities of air must be processed to extract meaningful volumes of CO_2, incurring high energy costs and presenting other challenges.

The efficiency of air contactor and chemical processing systems is critical to constraining the costs and scale of equipment necessary to enable commercial DAC operation. Achieving appropriate efficiencies is the opportunity-defining commercial challenge for DAC.

Innovation Highlight: Carbon Engineering

Atmospheric Capture - Direct Air Capture

TECHNOLOGY: Direct Air Capture; AIR TO FUELS™

- Industrial-scale capture of CO_2 from ambient air using an aqueous chemical solution
- Ambient air goes through a closed, regenerative chemical loop, which extracts the CO_2 as a high-pressure, pipeline ready product for immediate utilization
- Captured CO_2 can be used to create synthetic fuels or for permanent sequestration
- Expected commercial costs of <$100/ton of captured CO_2

Artist Rendering of CE's Air Contactor

APPLICATIONS & INDUSTRIES SERVED:

- Transportation, power, industrial

PARTNERS:

- Bill Gates, Murray Edwards, BHP, Chevron Technology Ventures, Oxy Low Carbon Ventures, LLC, Bethel Lands Corporation Ltd, Carbon Order, Venture Capital Firms

NEXT STEPS:

- Construct commercial validation plant further validating capture technology, continuous operations capability, and demonstrating the Air to Fuels™ technology
- Build a first commercial scale DAC-EOR facility in partnership with Occidental Petroleum
- Eventual concept is to build individual facilities capturing up to 1 Mt CO_2/year or producing ~2,000 barrels of synthetic fuel per day

FUNDING:

- **U.S. Department of Energy:** $1.5 million
- **Private Sector Cost-Share:** $375,000
- **Private Sector Investment:** $68 million funding round closed March 21, 2019

CONTACT Carbon Engineering
Lori Guetre
t: 604.728.5674
e: lguetre@carbonengineering.com
w: https://carbonengineering.com/

Once demonstrated at scale, one rate-limiting factor facing DAC deployment will be the manufacturing capacity for key system components. Many components in DAC systems currently in development are commercially available; others are not. Wide-scale deployment of DAC would create a significant new market for these components. The pace of manufacturing capacity expansions would, therefore, dictate the potential rate of deployment for DAC systems.

Discussion

DAC technologies have been dismissed by many as impractical based on initial cost estimates of theoretical systems. Costs estimates are now decreasing, according to developers that have begun to design, engineer and test components and systems.

Sustaining these early deployment efforts will depend on policies that establish clear market value for CO_2 capture and offset some of the capital demands associated with development and scale-up of DAC technologies. DAC has received notable policy attention, such as California's September 2018 decision to make DAC systems eligible to generate revenue (up to $200 per ton) through its Low Carbon Fuels Standard.

An estimated 200 people worldwide are employed by DAC developers. Projects operating today are backed by revenue-generating agreements with the food and beverage and petroleum industries. Plans for the first large-scale DAC project, slated to capture 500 Kt CO_2/year, were recently announced by Carbon Engineering and Oxy Low Carbon Ventures, a subsidiary of Occidental Petroleum.[77]

2.3.2 Carbon Mineralization

Carbon mineralization, also known as "accelerated weathering," is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. CO_2 from the atmosphere forms a chemical bond with a reactive mineral. These include mantle peridotite, basaltic lava, and other reactive rocks, as shown in *Figure 23*.[78]

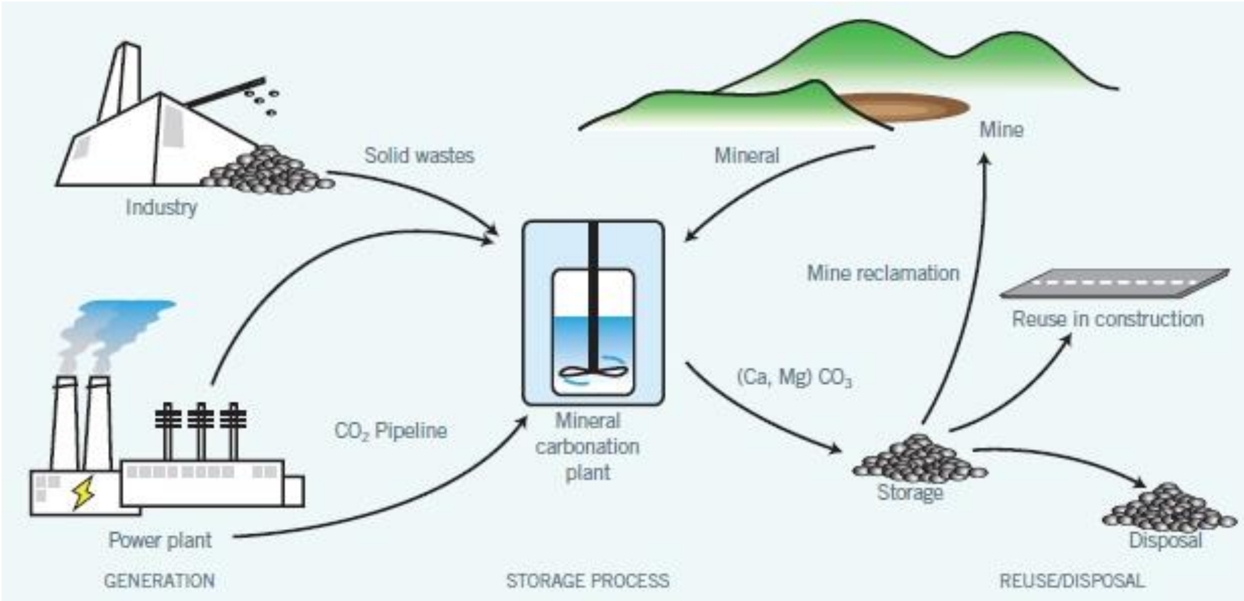


Figure 23. *Carbon Mineralization converts CO_2 into inorganic carbonates that can be reused for various purposes. Source: IPCC.*

This chemical bond can occur on the earth's surface, where CO_2 in ambient air is mineralized on exposed rock, and in the subsurface, where concentrated CO_2 streams are injected into ultramafic and basaltic rocks where it mineralizes in the pores of the rock.[79] The chemical bond results in the production of compounds such as magnesium carbonate and calcium carbonate.

Researchers are developing ways of speeding up the process of storing CO_2 in carbonate minerals in basaltic rocks in an industrial setting. In nature, the process would take several hundreds or even thousands of years, but researchers have been able to reduce that time to two years. The long-term storage of CO_2 in the carbonates has the potential to be used for building materials or mine reclamation with no risk of carbon leakage.

Current Status of Carbon Mineralization

Currently, accelerated carbon mineralization is in the research phase. This work should help technologists gain a deeper understanding of the science underlying the mineralization process.

Carbon mineralization has received media attention recently with technology advancements by an Icelandic company – CarbFix – that specializes in "the industrial process to capture CO_2 and other sour gases from emission sources and permanently store it as rock in the subsurface."[80] Their technology has progressed from pilot scale to industrial scale with its CarbFix2 project, which began in 2017. CarbFix2 has successfully captured CO_2 from the air and industrial facilities and transports the CO_2 1.5 km to a site for rapid mineralization.

Commercial Advantages

Carbon mineralization is in the earliest stages of research and development, but it offers exciting potential as a carbon removal technology.

This process uses naturally occurring materials to store CO_2. These materials could then be used commercially for construction and other purposes.

Table 8

Advantages and Challenges of Carbon Mineralization	
Advantages	**Challenges**
• High potential capacity for removing carbon. • Possible revenues from carbonate products. • Options for permanent storage.	• Limited understanding of carbon mineralization and permeability for in situ methods. • Dependence on the availability of silicate reserves.

Commercial Challenges

The primary economic driver for this technology would be the demand for recycled CO_2 products. There is currently a limited market for these products because they are more expensive and relatively unproven compared with traditional products.

Discussion

Although there remain significant gaps in scientific understanding, Carbon Mineralization offers an exciting option for carbon removal using naturally occurring materials.[81]

The market for producing building materials from CO_2 offers great potential for Carbon Mineralization, but there remains a lack of widespread acceptance of products made from these recycled sources. Products produced using CO_2 are not superior in quality to traditional materials, so the main benefit of using a carbonate product would be purely environmental and reputational.

2.3.4 Coastal Blue Carbon

As shown in ***Figure 24***, Coastal Blue Carbon refers to the "land use and management practices that increase the carbon stored in living plants or sediments in mangroves, tidal marshlands, seagrass beds, and other tidal or saltwater wetlands."[82, 83] Coastal restoration, adaptation, and management offer the potential to maintain and accelerate the rate of negative CO_2 emissions at a scale of 0.02-0.08 Gt/y CO_2.

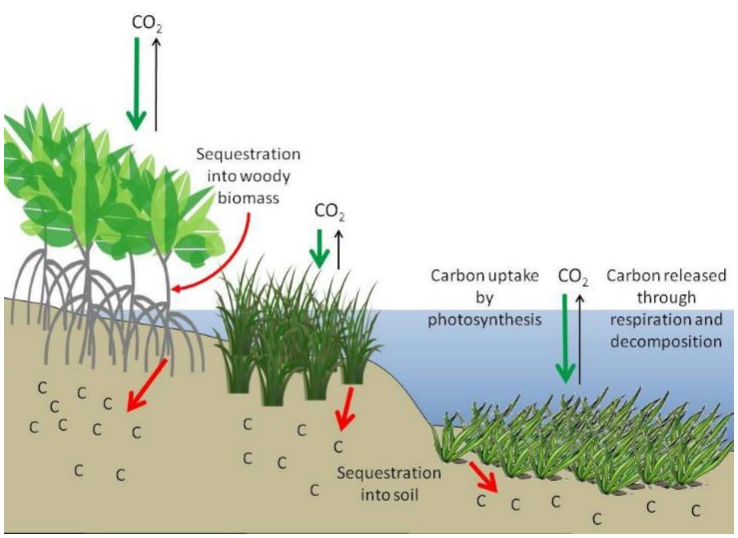


Figure 24. *The coastal blue carbon process makes use of biomass on the shoreline that absorb CO_2 from the atmosphere and naturally sequester the carbon in the soil and in plant growth. Source: Ecological Society of America.*

Current Status of Coastal Blue Carbon

Coastal blue carbon strategies are still at the concept or lab stages, as there remain scientific gaps in understanding of the technical challenges, coastal management requirements and the potential impact of rising sea levels.

However, the National Academy of Science identifies this technique as an approach with near-term readiness and low costs when coastal ecosystems are maintained, restored, created, or engineered with minimal hard infrastructure and for other purposes (e.g. coastal risk reduction, fisheries production).[84]

Federal, state and local governments around the world offer incentives for coastal blue carbon. Carbon markets for coastal blue carbon exist in China, Mexico, Australia, the European Union, South Africa, South Korea, and Kazakhstan. California and the Canadian provinces of Quebec and Ontario participate in a joint cap-and-trade auction, which sold 98,215,920 carbon credits as of 2018. In South Carolina, 5,500 acres have been registered with California's cap-and-trade program, bringing in $3.4 million for 450,000 metric tons of carbon credits.

The National Oceanic and Atmospheric Administration's (NOAA) National Estuarine Research Reserves and its partners are active in Coastal Blue Carbon as well. The agency works to make the conservation and restoration of wetlands profitable through blue carbon finance markets. Today, salt marsh restoration is eligible for international carbon markets. According to the NOAA's Office of Coastal Management: "acre for acre, coastal marshes, mangroves, and seagrass beds can absorb up to 50 times as much carbon as tropical rainforests and also store methane and nitrous oxide, two other greenhouse gases."[85]

Commercial Advantages

Unlike other carbon capture or removal technologies, coastal blue carbon relies on long-term maintenance of nature rather than the development of new technologies. This solution could be ready in the near-term at lower costs than technologies that require extensive energy use, substantial equipment inventories and costly facilities.

Commercial Challenges

Although technology costs would be minimal for the deployment of coastal blue carbon strategies, there would be significant costs associated with reclaiming coastal lands. There would also be potentially high costs associated with restoring these lands, depending on the state of the shoreline at each project site.

Another challenge would be public education and acceptance of repurposing land that is currently claimed for residential or commercial use.

Further demonstrations of the process and research into a number of areas (e.g. sea level rise, coastal management practices) would benefit the development of coastal blue carbon and justify its costs. For example, the development of mapping and remote sensing technologies and a database of potential project locations would help outline specific next steps for coastal blue carbon.

Discussion

If research into this technique proves successful, the National Academy of Science estimates that this form of carbon management can result in an annual flux of 0.037 Gt/y CO_2 by 2030 and 0.077 Gt/y CO_2 by 2060.

Ultimate success will depend on improved scientific understanding and public education.[86] Long-term success in removing CO_2 will depend on policies that maintain the coastal blue carbon site management.

2.4 Fugitive Emissions

Fugitive emissions of GHGs include methane leaks during production (extraction sites), transportation (pipeline leaks), or transfer and use (vehicle fueling), as well as chemical leaks of other GHGs during production, transportation or use. The sources of methane leaks are presented in ***Figure 25***.[87]

Fugitive emission technologies often focus on methane capture, which is 25 times more potent than CO_2 based on the IPCC Fourth Assessment Report estimate (IPCC 2007) and accounts for 20 percent of GHGs globally. Methane also has inherent commercial value as an energy resource; so, capture activities can be net-revenue positive.[88]

Current Status of Fugitive Emission Technologies

Fugitive emission technologies are available commercially, with an increasing demand for applications with the adoption of regulations to limit leaks, landfills and mine mouth emissions.

Research into new and improved technologies continues as the need to address fugitive emissions continues to grow. Innovators are also identifying ways to utilize the capture emissions for fuel or other products to create an economic incentive for the application of these technologies.

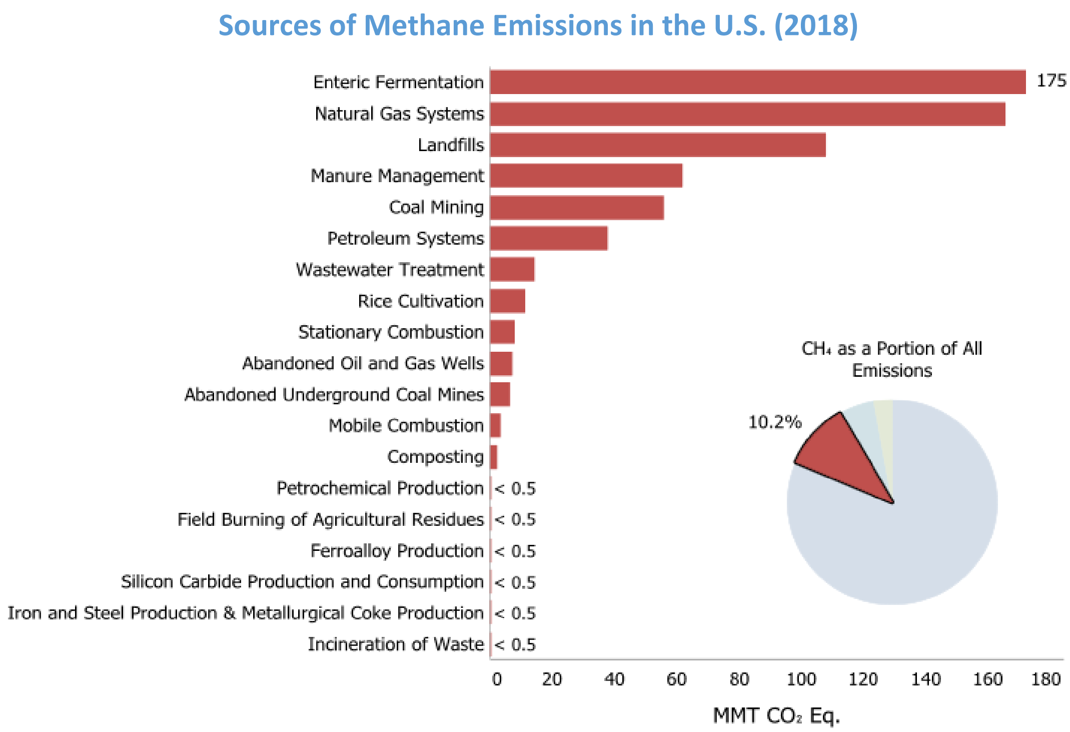


Figure 25. *Methane emissions in the U.S. originate from a wide range of sources – three of the top five (natural gas systems, landfills and coal mining) can be mitigated by fugitive emission control technologies. Source: U.S. EPA.*

Commercial Advantages

Overall, while further innovations are viable, these technologies have been developed and deployed commercially at locations globally. These proven technologies also benefit from the commercial utilization of the captured methane, which provides an economic incentive.

Table 9

Advantages and Challenges of Fugitive Emissions	
Advantages	**Challenges**
• Fully developed and commercially available technologies exist. • There is large global market potential. • It captures more potent GHG emissions. • Captured methane has commercial value.	• Current costs outweigh revenue prospects. • It is a smaller scale commercial opportunity than CO_2 capture. • It adds costs and complexity to existing systems and business models. • Monitoring challenges are substantial.

The market for these technologies is growing with the increased use of natural gas, the public attention to the potency of methane, and the technological developments now in place to capture methane from other sources, such as landfills. There are also policy drivers globally, particularly for mine mouth methane capture, that make these technologies more palatable than other capture technologies in certain instances.

Commercial Challenges

Compared to technologies that address CO_2 emissions, the market demand potential for capturing methane is much smaller and limited in its applications.

Although captured methane offers a potential economic incentive through its utilization, it currently does not offset the costs associated with applying fugitive emission technologies to a source. Further, these systems can interrupt the normal processes in place at a location, such as at a mine mouth.

Moreover, as shown in ***Figure 26***, global methane emissions are projected to rise significantly over the next two decades.[89]

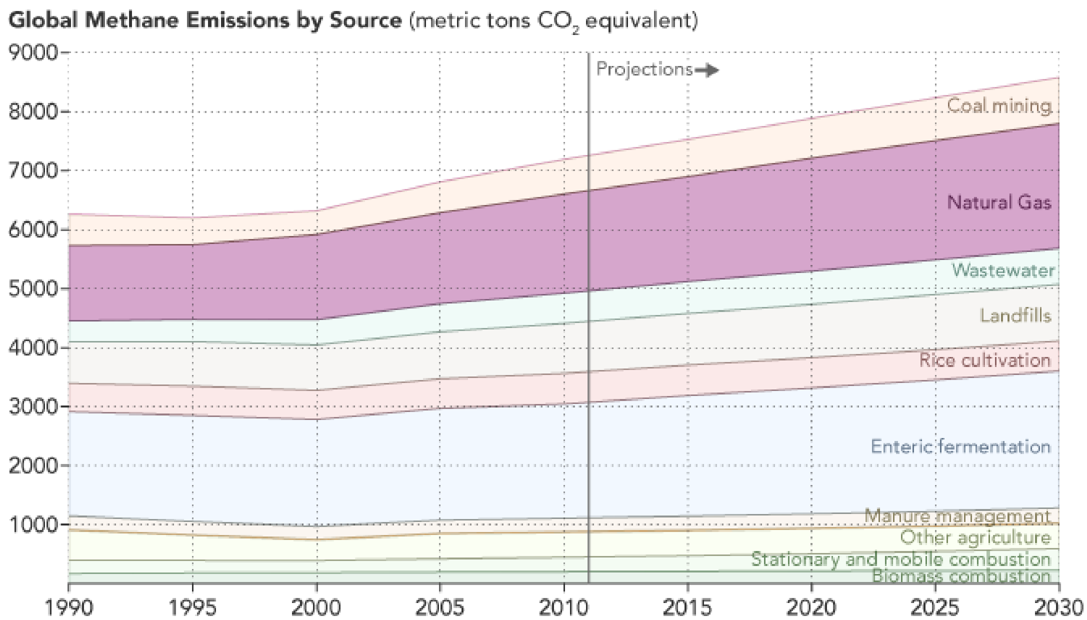


Figure 26. *Global methane emissions will continue to grow in nearly all emission sectors through 2030. Source: NASA.*

Discussion

Although fugitive emission capture technologies are commercially available, there is a lack of economic incentives to offset the costs of these technologies.

With the increased use of natural gas as a combustion source rather than coal, there has been recent media attention on natural gas pipeline leaks. The growth of the sector and the media attention has spurred both legislative and regulatory activity in various states and at the federal level for natural gas pipeline leak controls. While those activities could result in demand for technologies to address fugitive emissions, the future for such regulatory drivers remains unclear at this point. The investment into fugitive emissions capture technologies for pipelines will rely on ample monitoring and detection at pipelines, landfills and mine mouths.

2.4.1 Mine Mouth Methane Capture

Mine mouth methane capture systems extract methane from the exhaust air released from underground mines. The process is shown in ***Figure 27***.[90]

Although coal mine methane (CMM) is the most significant contributor to mine methane leakage (accounting for 9 percent of anthropogenic methane emissions in the U.S.), non-coal mines may also contain methane (i.e. sandstone, limestone, shales). These are referred to as waste mine methane (WMM).[91]

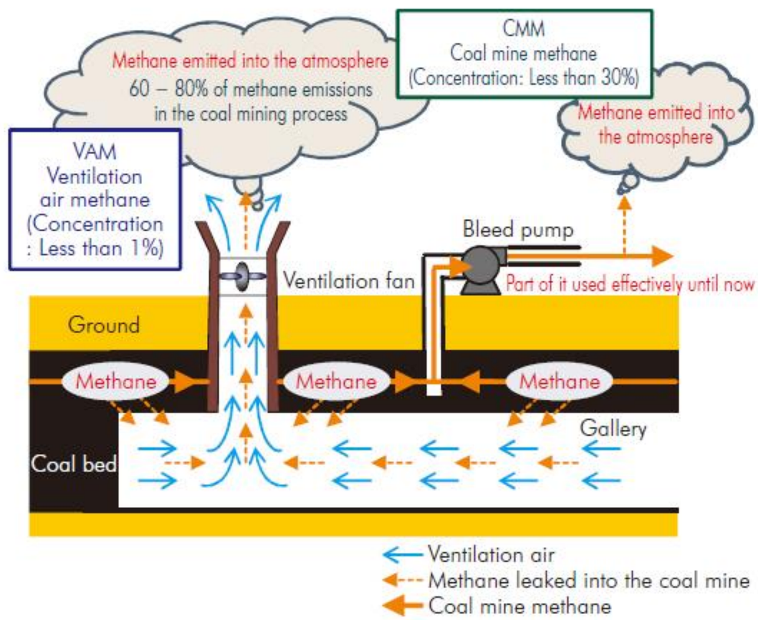


Figure 27. *Coal mines emit Ventilation Air Methane (VAM) and Coal Mine Methane (CMM) into the atmosphere. Source: Kawasaki Heavy Industries.*

The methane exiting coal mines is the largest source of methane in the atmosphere. CMM is created during the conversion of vegetation into coal and can be extremely hazardous to coal miners. The CMM can be ventilated out of the mines, captured by a CEM technology and utilized for energy, fuel or other applications. **Figure *28*** shows the sources of CMM in the U.S.[92]

A range of capture technology options exist for mine methane, including cryogenic technology, pressure swing adsorption, solvent absorption, multi-step membrane units, thermal oxidizers, and catalytic flow-reversal reactors. Emerging solutions in this space include VOC concentrators, various types of gas turbines, and hybrid technologies.[93]

Once captured, methane can be utilized for natural gas pipeline injection, power generation, coal drying, fuels, ammonia production or flaring.

Innovation Highlight: Mine Mouth Methane Capture

Fugitive Emissions Capture – Ventilation Air Methane Capture

PROJECT OVERVIEW:

- **Location:** Shanxi, China
- **Project Duration:** 2012 – Ongoing *(operational in May 2015)*
- World's largest ventilation air methane project/coal mine methane oxidation project
- Installation of 12 regenerative thermal oxidizers to dispose of ventilation air methane at the Gao He mine, owned by the Lu'An Coal Mining Group
- 100 million Nm^3 methane/yr to be utilized for power generation, reduces greenhouse gas emissions by 1.4 million tCO_2e/yr

TECHNOLOGY: Dürr Regenerative Thermal Oxidizer (RTO)

- Up to 1,020,000 Nm^3/h of ventilation air methane and 60,000 Nm^3/h of coal mine methane are thermally oxidized in the project using 12 of Dürr's Regenerative Thermal Oxidizer (RTO) technology.

CO2 UTILIZATION:

- Up to 300,000 Nm^3/h of hot exhaust gas is delivered to a boiler to generate water steam which is used for the generation of up to 30 MW of electricity by a turbine generator.

PROJECT PARTNERS:

- Dürr, Lu'An Coal Mining Group

Dürr mine mouth methane capture equipment in Shanxi, China

CONTACT

Nadine Schaser
Nadine.Schaser@durr.com
www.durr.com

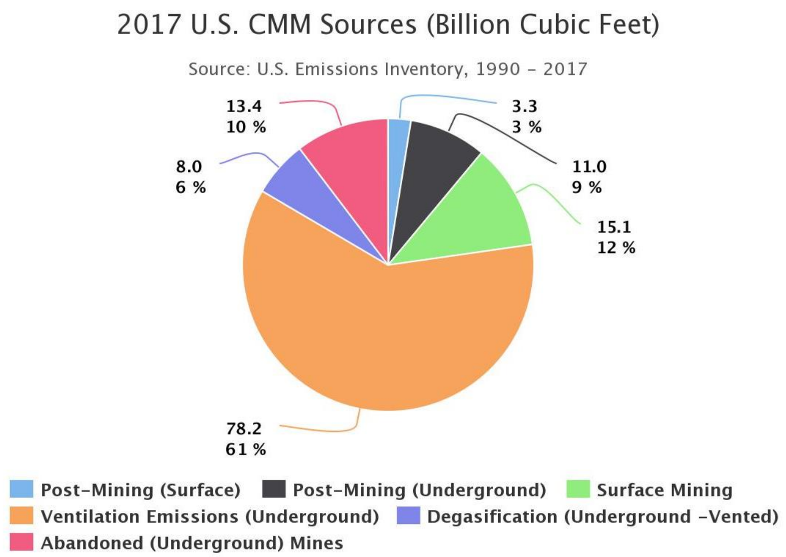


Figure 28. *CMM emissions arise from multiple sources. Source: U.S. EPA.*

Capturing methane from mines relies upon not only the capture technology, but also accurate monitoring of the mine's air quality. According to the U.S. Center for Disease Control (CDC), federal regulations require continuous monitoring of methane levels and must provide a warning when methane concentration levels reach or exceed 1 percent.[94]

Ventilation Air Methane (VAM) technologies capture low concentrations of methane and require the use of a regenerative thermal oxidizer (RTO) on an industrial scale. RTOs have been used to destroy volatile organic compounds (VOCs) since the 1990s, with the first commercial demonstration for VAM in 2007. VAM technologies include regenerative catalytic oxidizers (RCO), rotary kilns and lean-burn microturbines. However, these technologies are not widely available or developed at this time.

Current Status of Mine Mouth Capture

Mine mouth methane capture technologies are commercially available. Dürr Clean Technology Systems, Epcon Environmental and Anguil Environmental are among industry leaders for Regenerative Thermal Oxidizers (RTOs) in-use at coal mine mouths to capture and utilize methane. In 2015, Dürr installed the world's largest ventilation air methane/coal mine methane (VAM/CMM) oxidation and utilization project in China's Shanxi Province at the Gaohe coal mine. According to Dürr, the project enables 100 million Nm3 methane/yr to be utilized for power generation, reduces greenhouse gas emissions by 1.4 million tCO_2e/yr,"[95]

Johnson Matthey also manufactures the COMET™ catalyst, which is scalable, easy to operate and economically viable for the treatment of VAM.

Similarly, methane monitoring technologies are commercially available today, including coal bed methane monitoring from Thermo Fisher Scientific and Montrose Environmental' s Leak Detection and Repair (LDAR) services.

As of 2016, there were approximately 200 mine mouth methane capture projects worldwide that are capturing 5.5 billion cubic meters of gas each year - or the equivalent of 77 million metric tons of CO_2.[96] The largest share of these projects are found in China, Australia and the U.S.

U.S. EPA promotes the recovery and utilization of coal mine methane through the Coalbed Methane Outreach Program (CMOP), a voluntary effort that seeks to reduce methane emissions from coal mining activities and promote profitable recovery and utilization of coal mine methane.

Commercial Advantages

Mine mouth methane capture technologies can offer an economic advantage through their ability to be self-sustaining and produce energy and could play a valuable role reducing emissions worldwide. There has been an increase in demand for mine mouth methane capture technologies as a source of energy and as a result of a number of financial incentives that exist through policies (e.g. Kyoto Protocol's Clean Development Mechanism and Joint Implementation; California Cap-and-Trade program). The captured methane and generated energy can be utilized for power, fuel, coal drying, heat source, and other feedstocks.

Table 10

Advantages and Challenges of Mine Mouth	
Advantages	**Challenges**
• Self-sustaining power and energy sources. • Multiple utilization options (e.g., power, fuel, coal drying, heat source, feedstock) • Financial incentives to make methane capture profitable.	• Potential interference of mine operations. • Reduction of mine flexibility.

Commercial Challenges

Mine mouth methane capture technologies can interfere with normal mine operations and profitability and reduce the mine's flexibility or functionality due to new duct infrastructure.

Discussion

As with other CEM technologies, net cost associated with the technology limit demand and investment. Given the extent of CMM emissions in the U.S., the utilization opportunities for captured methane continue to grow. Additional technology advancements are likely as methane emission reduction becomes a priority for local, state and national governments. However, unless there are policies that support buying captured methane, end-users will opt for potentially cheaper energy or fuel sources.

2.4.2 Pipeline/Methane Leak Capture

As natural gas consumption continues to outpace coal in terms of utilization in the U.S. and other parts of the world, there is an expanding potential for fugitive methane emissions and an increasing need to mitigate methane leaks from the production and transportation of natural gas, as the U.S. map in ***Figure 29*** makes clear.[97]

Natural gas systems are the second largest anthropogenic source of methane emissions in the U.S., followed by landfills (see **Figure 25**). For natural gas systems, methane leaks can occur unintentionally (malfunctioning equipment) or intentionally when opening and closing valves. In addition to methane, natural gas releases hydrocarbons that have a negative impact on air quality.

Current Status of Pipeline Leak Technologies

Pipeline leakage has gained media attention in recent years with the advent of new monitoring technologies. Governments (local, state and federal) are taking action to limit methane emissions. In order to effectively regulate the emissions, further development and widespread deployment of technologies to detect methane emission leaks when they occur will be required.

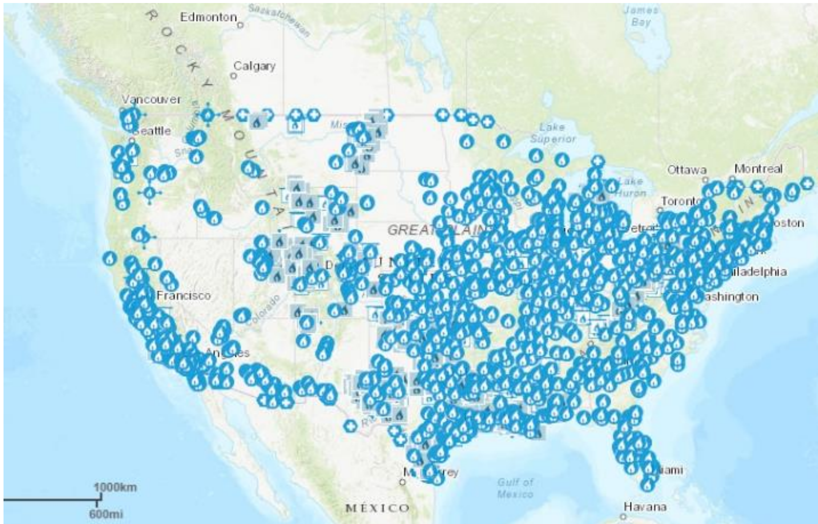


Figure 29. *The U.S. is home to a significant (and growing) natural gas system that will require leak monitoring and capture technologies as policies and public opinion point to methane leak controls. Source: U.S. Energy Information Administration.*

Quantification and monitoring technologies exist that allow utilities to monitor pipeline flow rates, which will indicate if a leak has occurred. Natural gas pipeline operators are implementing these techniques, yet nationwide implementation across all sectors has not yet taken place.

EPA has a number of programs that provide information on recommended technologies to use to reduce methane emissions including the Natural Gas STAR Program, the Coalbed Methane Outreach Program, the AgSTAR Program, and the Landfill Methane Outreach Program.[98]

Solutions to pipeline leaks include a technique called a "stopple," which isolates a section of a pipeline without losing service to an entire system. Pipeline operators can use the following methods to address leaks: temporary compression, separator dump valves, relief valves, in-line compression, portable flares, Yale closures, and reroutes.

Table 11

Advantages and Challenges of Pipeline Leak Technologies

Advantages	Challenges
• Potentially enormous market with the expansive natural gas infrastructure. • New, advanced monitoring capabilities and capture technologies. • Technologies commercialized and ready for widespread deployment.	• Methane leaks from natural gas infrastructure that is largely unregulated. • Monitoring and leak detection technology improvements needed.

Commercial Advantages

The technologies and processes to capture methane from pipelines is ready for widespread commercial deployment. Given the tremendous size of the natural gas infrastructure in the U.S., let alone the rest of the world, and the growing reliance on gas for power and industrial demands, the market for addressing methane leaks from the transportation of natural gas will continue to grow.

The market for these technologies will expand through an increase in public education about methane leaks and decision makers' priorities shift to implement local, state and federal regulations.

Commercial Challenges

Widespread use of pipeline capture technologies will not occur unless national policies to mitigate methane leaks from natural gas infrastructure are implemented and coinciding monitoring systems are put in place. Until then, these systems are almost too large for operators to address all leaks at their own expense unless given incentives or regulations.

Discussion

Given the recent media attention and regulatory actions around controlling methane leaks from natural gas infrastructure, there is likely to be a commercial opportunity for these technologies in the near-term.

However, reliable and timely monitoring of the leaks will be crucial for the smart and strategic deployment of these technologies.

2.5 Fate of Captured Carbon

Capturing carbon is only half the battle. After carbon has been captured, it must be used in a manner that will prevent it from being reemitted into the atmosphere through permanent sequestration, long-term storage or short-term storage. Our term "Carbon Utilization" is intended to cover all uses and applications of captured CO_2. We break these utilization activities into three broad categories:

- *Permanent Sequestration:* Any utilization resulting in the permanent sequestration of carbon underground (e.g. geologic storage, EOR)
- *Long-term Storage:* Any product made from captured carbon that, when used, does not release CO_2 or other GHGs but may release GHGs when disposed or reprocessed (e.g. cement, steel, polymers, carbon fibers)
- *Short-term Recycling*: Any product made from captured carbon that, when used, releases CO_2 or other GHGs (e.g. synthetic hydrocarbon fuels, industrial chemicals, food and beverage applications)

Technologies that enable the use of captured carbon vary in their stages of development. Some have been commercially ready for decades; others are emerging technologies at the lab, pilot or demonstration stages. Other than EOR, many of these technologies are relatively early in their development. Today, the U.S. consumes roughly 80 million tons of CO_2 annually, most of which is used for EOR. Non-EOR demand for CO_2, which comes largely from the food and beverage industries, account for less than the CO_2 emitted by an average-sized coal power plant annually.

Carbon is an essential building block for a diverse set of commercially used chemicals and materials. The Innovation for Cool Earth Forum (ICEF) CO_2 Utilization Roadmap Report (2017) discusses a wide range of potential new uses for captured CO_2 ranging from construction materials, such as steel and cement, to consumer products. The report notes:

> *These products all have different price points, market volumes and performance requirements. They are also used in different ways, have different lifetimes and are disposed of differently, making evaluation of their emissions impact complicated. Many of these applications will have specific geographic regions of early production or adoption based on local conditions and resources.*[99]

2.5.1 Permanent Sequestration

Illustrated in **Figure *30***, permanent sequestration includes any process that permanently captures carbon in geological formations beneath the surface of the earth.[100] The CO_2 can be captured in saline aquifers. Depending on the composition of surrounding rock formations, the CO_2 will either be chemically incorporated into the rock or simply contained in underground reservoirs.

Geologic storage in oil and gas reservoirs has been demonstrated for decades, while saline storage is a less well demonstrated technique to date, though fundamentally the processes are similar.

Permanent sequestration maximizes the environmental value achievable for carbon emissions management. Options for utilizing captured carbon in the production of commercial products may not be cost-competitive or provide a large enough market given the amount of CO_2 that needs to be captured. In addition, permanent sequestration may be preferable to parties interested in mitigating effects on the climate, as long-term storage and short-term recycling will result in less-favorable life-cycle reductions of GHGs in the atmosphere.

Geologic Storage

Captured CO_2 is compressed into a supercritical fluid state (similar in density to water) and then injected to subsurface wells. Ideal geologic formations are found in sedimentary basins, filled with ample porous openings that allow for spreading of compressed CO_2, layered beneath an extensive layer of impermeable top rock to prevent release of CO_2.

Industry has nearly 50 years of experience with CO_2 storage from EOR applications, and nearly 20 years of commercial experience with geologic storage in saline aquifers. The technology needed for underground injection of CO_2 is fully demonstrated and commercially available. Underground reservoirs have varying ability to permanently sequester injected CO_2. Characterization techniques to identify the storage potential of formations are well established. There is sufficient underground storage capacity in the U.S. to sequester over 500 hundred years of anthropogenic GHG emissions.[101]

Largely deemed ready and waiting for large-scale deployment of carbon removal technologies, geologic storage can benefit from sustained research and mapping of subsurface formations. Such research is "critical to improve decarbonization of fossil fuel power plants, and also critical for advancing direct air capture and BECCS."[102] With well understood processes, geologic storage deployment is handicapped solely by economic drivers. Stronger policy support could readily create economic and environmental incentives for greater use of permanent sequestration of CO_2.

The complete geologic storage process requires a number of existing ancillary technologies, beginning with CO_2 compressors, booster pumps, and surge tanks. Well-managed pipelines and monitoring technologies are necessary to transport CO_2 to the injection site. The technologies for CO_2 injection are used extensively in the oil and gas industry (e.g. lateral wells and advanced drilling). Optimization opportunities exist for large-scale deployment in concert with safe geologic storage, measurement, monitoring and verification technologies, notably seismic imaging and leak detection.

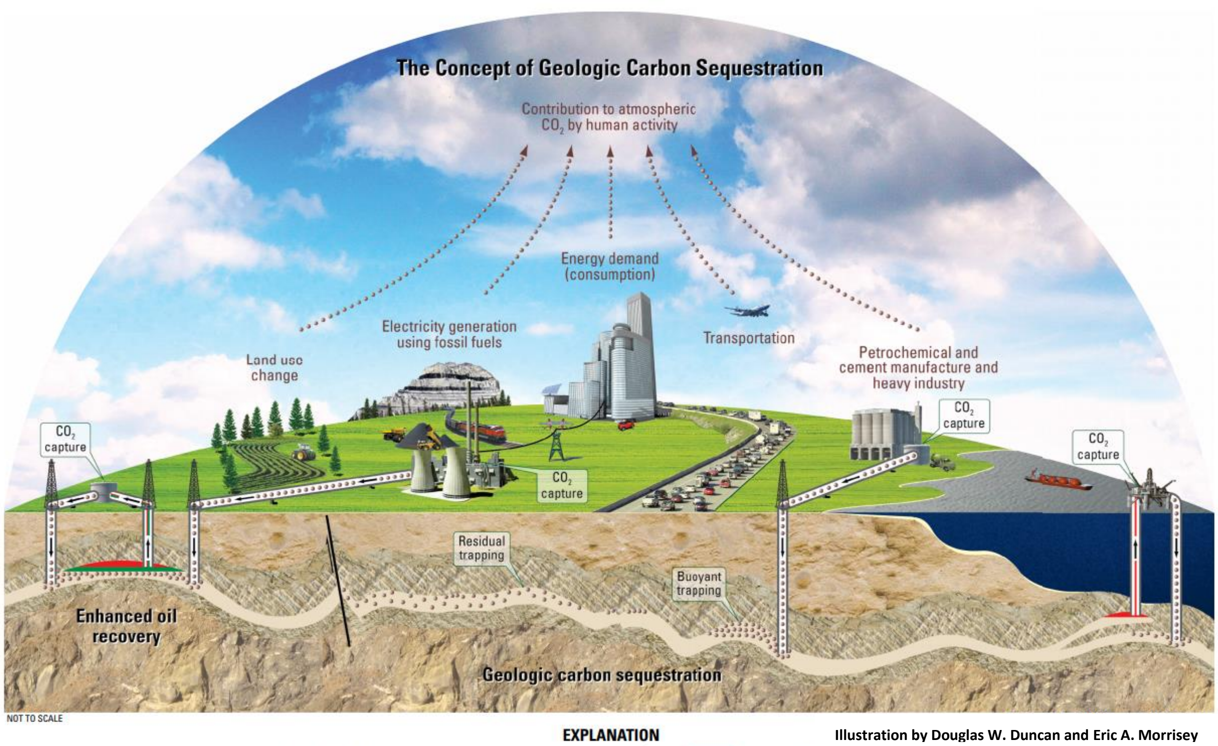


Figure 30. *CO_2 emissions and geologic sequestration - showing the full cycle of CO_2 emissions, from release to capture and various types of geologic storage. Source: U.S. Geological Survey.*

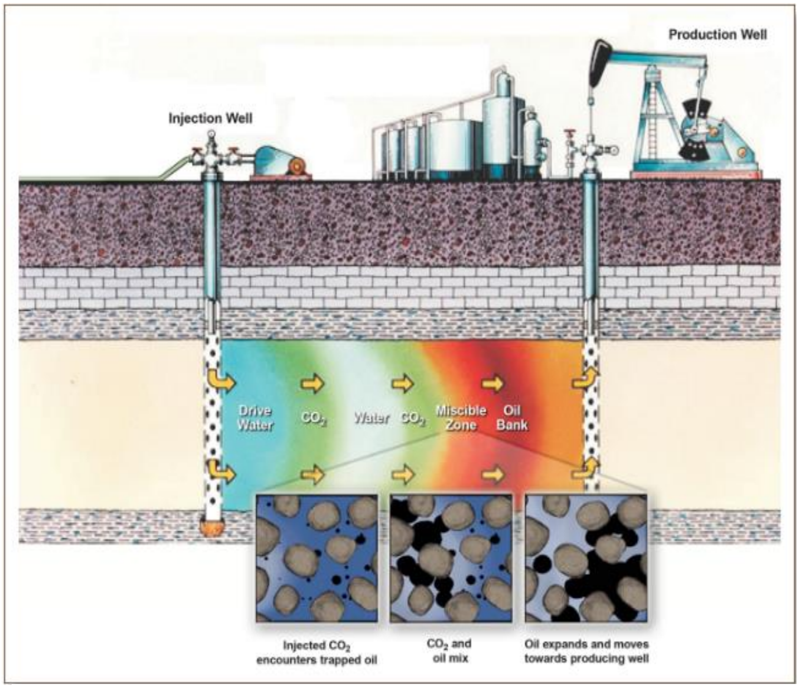


Figure 31. *CO_2 is injected into an oil field where it mixes with trapped oil, which expands and moves toward the well, allowing the field to yield additional oil. Source: U.S. Department of Energy.*

Enhanced Oil Recovery

In the context of carbon sequestration, enhanced oil recovery (EOR) is indistinguishable from other forms of geologic storage; however, it notably differs from other geologic methods in that EOR generates a revenue stream for its CO_2. It also creates additional emissions resulting from combustion of the produced oil. In all cases, the permanence of the sequestration depends primarily on the properties of the oil field and the use of appropriate injection techniques. ***Figure 31*** depicts the capture and use of CO_2 in the EOR process.[103]

Gas injection accounts for nearly 60 percent of EOR production in the United States. Gas injection is the process by which miscible fluids are injected into existing oil fields to interact with remaining crude oil, allowing 30-60 percent recovery of a reservoir's capacity, compared to only 20-40 percent when using primary (natural drivers) or secondary recovery (artificial natural drivers).[104] CO_2 is the most commonly used fluid due to its ability to reduce oil viscosity and because it is less expensive than miscible alternatives.

A commercial EOR operation will procure captured CO_2, transport it via pipeline to an oilfield, and then use gas injection to create revenue-generating crude oil while sequestering captured CO_2 deep underground. In the U.S. today, 80 Mt CO_2 per year is consumed; about five-eighths of that amount is used for EOR. Most EOR activity resides in, but is not limited to, the Permian Basin.[105]

EOR has provided an economic case for carbon capture since the 1970s, allowing oil and gas companies to extract significantly more resources from oil and gas fields. Currently, CO_2-EOR demand is expected to triple by 2050 in the Permian Basin alone. With slightly increased policy support, EOR projects could be adopted widely as a revenue-generating pathway for sequestering carbon emissions.

The U.S. Department of Energy has funded CO_2 injection in a deep saline reservoir since 2017 at the Illinois Industrial Carbon Capture and Storage (ICCS) Project, led by ADM. In Norway, Equinor (formerly Statoil) manages the Sleipner project, which has been capturing CO_2 and injecting it into a saline aquifer in the North Sea since 1996. In 2016, MIT estimated that the injection costs for this project run $17 per ton of CO_2. Technology improvements continue at this project, notably in monitoring.

Other notable projects include Snohvit (Norway), Ordos (China), and the planned Gorgon Liquefied Natural Gas Project (Australia) that will use Shell's Cansolv technology for CO_2 capture and is on track to be the largest CCS project in the world. Other planned geologic storage projects include KEPCO's 500 MW pre-combustion capture facility in South Korea, which is projected to capture 1.2 million tons of CO_2 per year.

Table 12

Advantages and Challenges of Enhanced Oil Recovery	
Advantages	**Challenges**
• Fully demonstrated technologies exist. • CO_2 is permanently stored deep underground. • Well-permanence standards minimize the risks of leakage. • Existing policies (e.g. 45Q tax credit) provide financial incentives for capture and sequestration. • Sequestering CO_2 during petroleum extraction can reduce net petroleum GHG emissions by 30% or more per barrel.	• Capture and injection costs tend to exceed the value of the extracted fuels. • Unsettled issues related to leak detection requirements and securing mineral rights necessary for injecting CO_2 for underground sequestration. • Targeted governmental policies and incentives can offset net costs. • Conflicts among Federal, state, and local laws need to be resolved. • Opposed by some climate stakeholders who prefer eliminating petroleum use.

Commercial Advantages

The abundance of CO_2 worldwide makes EOR a practical technology in the U.S. and elsewhere. It is equally important that the underground injection of CO_2 is well-managed with respect to safety and environmental risks. As a result, policy incentives can have immediate and positive impacts on the deployment of CO_2 capture technologies for underground storage. The U.S. recently expanded the Section 45Q tax credit for sequestration has been at least partially responsible for the announcement of several new investments for capture and sequestration projects.

Storing captured CO_2 underground permanently removes the CO_2 from the atmosphere, unlike other technologies that may “leak” some of the CO_2 into the atmosphere. With respect to the impact of policy objectives focused on the ultimate disposition of captured CO_2, EOR and other permanent storage techniques have an economic advantage over less-permanent options.

Innovation Highlight: NRG Petra Nova

CO_2 Utilization: Enhanced Oil Recovery (EOR)

PROJECT OVERVIEW:

- Location: Texas, USA
- Project Duration: 2014 – ongoing *(operational on Dec. 29, 2016)*
- Captures 5,200 short tons of CO2 per day from 240 MW coal exhaust slipstream at the W.A. Parish Unit 8
- 90% reduction in CO2 emissions; 1,300% increase in oil production

TECHNOLOGY: Mitsubishi Heavy Industries KM-CDR™ Process

- Post-combustion, amine-based solvent for CO2 absorption and desorption

CO2 UTILIZATION:

- Enhanced Oil Recovery (EOR) at West Ranch oil field (owned by Hilcorp Energy)

PROJECT PARTNERS:

- U.S. Department of Energy, NRG Energy, JX Nippon, Hillcorp Energy

FUNDING: Approximately $1 billion total

- **U.S. Department of Energy:** $190 million grant (Clean Coal Initiative)
- **Japanese Government Loans:** $250 million loan
- **JX Nippon:** $300 million in equity
- **NRG:** $300 million in equity

Petra Nova Plant, WA Parish Unit 8

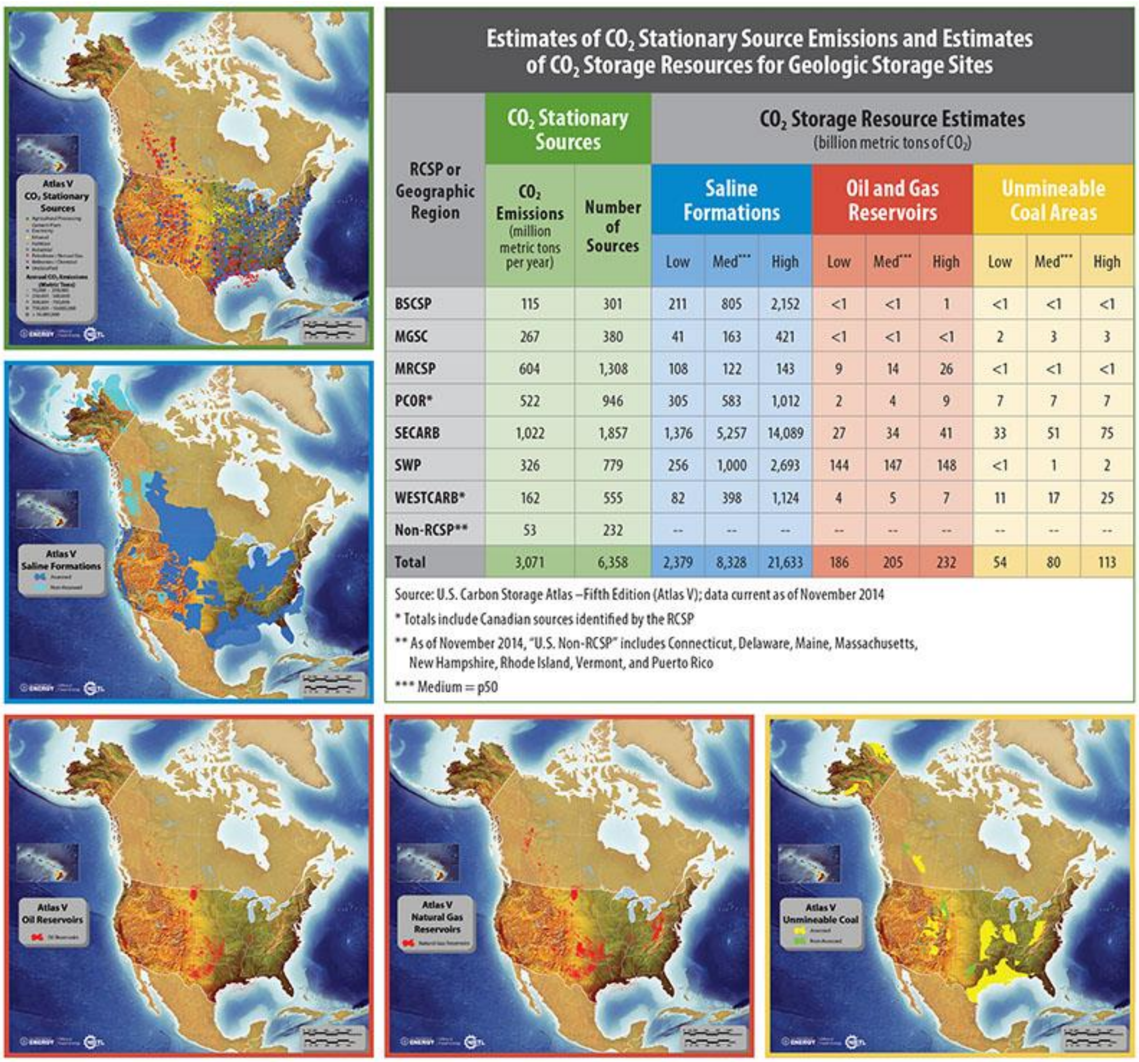
CONTACT
MITSUBISHI HEAVY INDUSTRIES
Osamu Usui
Osamu_Usui@mhia.com
www.mhi.com

Commercial Challenges

Permanent sequestration faces market barriers that could slow its deployment, even for projects with favorable economics under existing policies. Regulatory requirements continue to evolve regarding injection site monitoring for leaks. Issues centering on liability and mineral rights also need to be resolved. Additionally, in many cases, conflicts between federal and state or local laws and regulations also need to be addressed. Absent supportive policies, the cost of capture and injection could become uneconomic.

Discussion

Because of its permanence, CO_2 sequestration is potentially the best option from a climate perspective. Ample and reliable geologic storage capacity exists. To encourage greater use, governmental bodies at all levels need to create policies (e.g. tax credits) that serve to offset technological and organization costs. Before widespread deployment occurs, geological assessments and measurement protocols will need to be standardized. In sum, EOR benefits from significant experience and commercial readiness. There is no new technology needed, although the capture technologies continue to improve their costs and efficiency. The principal barriers are related to commercial availability and costs. As shown in ***Figure 32***, there are nearly 6,400 stationary CO_2 sources in the U.S.[106]



Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites

RCSP or Geographic Region	CO_2 Stationary Sources		CO_2 Storage Resource Estimates (billion metric tons of CO_2)								
	CO_2 Emissions (million metric tons per year)	Number of Sources	Saline Formations			Oil and Gas Reservoirs			Unmineable Coal Areas		
			Low	Med***	High	Low	Med***	High	Low	Med***	High
BSCSP	115	301	211	805	2,152	<1	<1	1	<1	<1	<1
MGSC	267	380	41	163	421	<1	<1	<1	2	3	3
MRCSP	604	1,308	108	122	143	9	14	26	<1	<1	<1
PCOR*	522	946	305	583	1,012	2	4	9	7	7	7
SECARB	1,022	1,857	1,376	5,257	14,089	27	34	41	33	51	75
SWP	326	779	256	1,000	2,693	144	147	148	<1	1	2
WESTCARB*	162	555	82	398	1,124	4	5	7	11	17	25
Non-RCSP**	53	232	--	--	--	--	--	--	--	--	--
Total	3,071	6,358	2,379	8,328	21,633	186	205	232	54	80	113

Source: U.S. Carbon Storage Atlas – Fifth Edition (Atlas V); data current as of November 2014
* Totals include Canadian sources identified by the RCSP
** As of November 2014, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico
*** Medium = p50

Figure 32. *There are nearly 6,400 stationary CO_2 sources in the U.S.- outlined here by region with data on the subsequent geologic storage options (saline formations, oil and gas reservoirs). Source: NETL.*

2.5.2 Long-Term Storage

Captured carbon can become a feedstock for construction materials (e.g. cement, concrete, bricks, plastics, or metals), polymers, and carbon fiber. Re-purposed carbon products also have the tantalizing prospect of providing consumers with environmentally friendly options in selecting their materials.

For long-term storage products, reliable CO_2 transportation is necessary to move captured CO_2 from its source to the new production facility. Pipelines and tank trucks are typical means.

Cement, concrete, and bricks, which use CO_2 as feedstock, do not require changes to their production systems. Injecting CO_2 requires pressure and temperature sensors and valves to ensure correct doses. For polymers and polyols, a catalyst is required to convert the CO_2.

Current Status of Long-Term Storage

Though there are commercial operations for long-term carbon storage products, they tend to be more costly than traditionally manufactured products. Development work is ongoing for a wide range of carbon storing commercial materials.

The compendium lists more than 40 unique technologies that seek to demonstrate the production of construction materials and consumer products using captured carbon. Current projects focus on concrete, plastics (polyols, polymers) and synthetic metals (magnesium carbonate, carbon fibers).

Using carbon as a feedstock or as a method for curing concrete or cement currently offers the nearest-term opportunity (with some technologies already commercially available) for a large market segment that will continue to grow.

Technologies that use carbon for the creation of plastics and synthetic metals are at an earlier stage of development. Other types of synthetic materials that are in the early stages of development are carbon nanotubes and graphene.

The most widespread deployment of long-term storage is within the cement industry. For example, CarbonCure's technology system for cement, concrete and ready-mix is now in use at more than 100 plants worldwide. CarbonCure and their partners have produced more than two million cubic yards of concrete to date. Projects in the plastics industry are at the pilot stage.

Table 13

Advantages and Challenges of Long-Term Storage

Advantages	Challenges
• Captured carbon can generate revenue. • Demand for environmentally friendly products continues to grow. • Carbon is an essential component used in the production of conventional materials (*e.g.*, steel, cement, etc.) as well as carbon fiber that are in wide commercial use. • The captured CO_2 is, as a practical matter, permanently stored.	• These products must compete against established goods that tend to be less costly. • New technologies and production methods are required. • Consumers of these products will need to perceive the value of selecting these products over conventional offerings.

Commercial Advantages

Using captured carbon to create or reinforce new products, long-term storage solutions offer a possible means to address hard-to-decarbonize sectors, such as the cement and steel industries—both of which continue to see rising global demand.

Recent policy developments related to building materials suggest a potential market opportunity for recycled CO_2 products. For example, New York City recently announced a limit on the construction of buildings made with large amounts of glass due to their carbon footprint. Corporate sustainability pledges could create some market demand outside of policy incentives, but it is unlikely to serve as a compelling market factor in the near term. Synthetic metals may be in the earliest stages of development, but they have a competitive advantage in certain markets. For example, carbon fiber production is a new technology, even without the use of recycled CO_2. The relative newness of this product may offer a window of opportunity for carbon utilization, as it would not be competing with long-standing suppliers, processes or markets.

Commercial Challenges

Market competition will continue to pose a significant barrier to carbon-storing products. New materials and products will need to compete against widely available supplies, often in markets with extremely tight profit margins. Under such conditions, being a profitable low-cost supplier is essential to success. To break into such markets, carbon-storing products will most likely need to provide exceptional materials, stimulate demand from environmentally conscious customers and benefit from governmental support that can reduce costs (e.g. tax breaks) and create opportunities (e.g. directed procurement of new materials for government projects).

Market demand for renewable products continues to rise driven by both corporate motivations and regulatory mandates. However, as with other CEM technologies, the costs must decrease, or incentives must be introduced, for sustainable growth in the sector.

The value of recycled CO_2 products varies greatly. Cement and concrete have relatively low margins. Certain synthetic metals can be more profitable but have less mature production technologies. These differences are part of a spectrum of market considerations facing project developers.

Synthetic metals, in particular, need significant funding to complete lab, pilot and demonstration stage RD&D before scaling up to commercialization.

Discussion

For all consumer products and building materials to be successful, policies must encourage competitive costs and innovators must educate customers about the reliability and quality of products developed with recycled carbon.

Innovation Highlight: CarbonCure CO_2 Mineralization in Concrete
CO_2 Utilization: Long-Term Storage

PROJECT OVERVIEW:

- **Location:** Nova Scotia, Canada (headquarters)
- 100+ applications/projects worldwide at concrete, read-mix and masonry plants since 2007
- 76.7 million pounds of CO_2 emissions recycled; 2.5 million cubic yards of concrete have been made in North America

TECHNOLOGY: CarbonCure Recycled Concrete

- Licensed, scalable technology that adds recycled CO_2 as a chemically converted mineral to fresh concrete
- Captured CO_2 is stored at cement plants in pressurized vessels to be refilled by gas supplier Technology can be retrofitted onto an existing plant in a single day

CO_2 SOURCE:

- Uses captured CO_2 from industrial emitters
- CarbonCure is a utilization technology that does not capture or sell the CO_2

PROJECT PARTNERS:

- Canadian government, Linde, Argos, SES, Southern Company, Thomas Concrete, Permacon, DIALOG, BURNCO, LS3P, Reed Jones Christoffersen, Walter P Moore, B&H

FUNDING:

- NRG COSIA Carbon XPRIZE Finalist
- Private investment

CarbonCure cement truck and system

CONTACT CARBON CURE

Ted Jones
https://www.carboncure.com/

2.5.3 Short-Term Recycling

We use "short-term recycling" to refer to products made from captured carbon that will release CO_2 as a function of their use. If, for instance, captured CO_2 is used to produce fuel, combustion of that fuel will necessarily emit CO_2 into the atmosphere. Examples of short-term recycling pathways include synthetic hydrocarbons, chemicals used in biodegradable plastics, and food and beverage production.

Products that rely on short-term carbon recycling would have a superior carbon footprint relative to existing fossil-dependent alternatives. If hydrocarbons produced from captured CO_2 replaced a portion of fossil-fuel use, it would reduce the rate at which atmospheric concentrations of CO_2 increase. Rather than moving carbon from storage in buried fossil fuels into the atmosphere, carbon taken from the atmosphere, or captured before reaching the atmosphere, would provide a commercial energy resource before being returned to the atmosphere.

Producing commercial products from CO_2 would create demand for new production technologies, including catalysts, ceramics, membranes, and various gas management systems to convert CO_2 to valuable chemicals, synfuels, and other products.

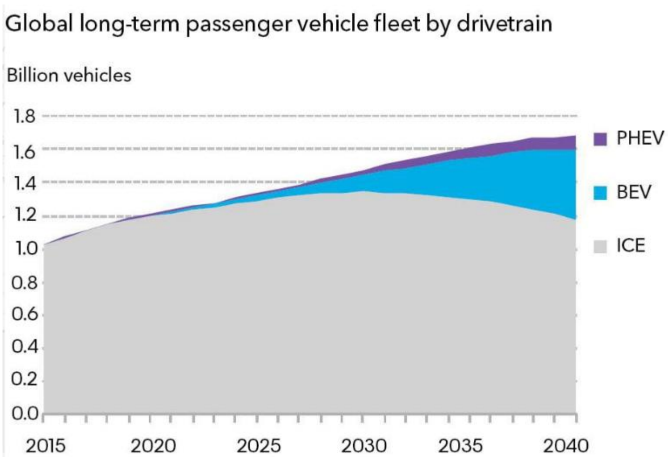


Figure 33. *Bloomberg's Electric Vehicle Outlook 2019 projects that, despite an increase electric vehicles entering the market, the long-term passenger vehicle fleet will continue to be dominated by ICE vehicles beyond 2040. Source: Bloomberg.*

Synthetic Hydrocarbons and other Commodity Chemicals

Captured carbon emissions and renewably produced hydrogen can create synthetic hydrocarbons and other commercially valuable chemicals. Conversion of captured CO_2 into chemicals can occur through various methods: thermocatalytic, electrochemical, biochemical, photochemical or hybrid approaches combining two or more of these methods. These chemicals could include a diverse set of compounds currently derived from petroleum and used as both feedstock and finished chemicals, including formic acid, ethylene, butanol, methanol, and many more. **Figure *33*** shows the continued global demand for internal combustion engine (ICE) vehicles.[107] ICE vehicles' carbon footprint can be improved through the use of syngas produced with short-term recycling technologies.

Examples include:

- LanzaTech's ethanol production
- CRI Catalyst's hydrocarbon production
- Hitachi Zosen Inova's renewable hydrogen and synthetic methane
- Carbon Engineering's "Air-to-Fuels" technology for DAC to syngas conversion
- Phytonix's emerging technologies to use CO_2 to produce industrial chemicals

Innovation Highlight: Alcohol to Jet (ATJ) Project

CO_2 Utilization: Short-term Recycling - Fuels

PROJECT OVERVIEW:

- **Locations:** Georgia, USA and London, UK (planned)
- **Project Dates:** 2011 – Present *(First flight on Oct. 4, 2018 with Virgin Atlantic)*
- World's first commercial flight using sustainable aviation fuel produced at LanzaTech's Freedom Pines biorefinery facility in Georgia, USA
- New production facility in the UK in planning

TECHNOLOGY: LanzaTech Carbon Recycling/Alcohol to Jet (ATJ) Technology

- Biological conversion of gaseous carbon waste from steel mills to ethanol and other chemicals through gas fermentation using a proprietary microbe
- Catalyst upgrades the ethanol to aviation fuel
- Blend of up to 50% renewable jet fuel with petroleum-based jet fuel

PROJECT PARTNERS:

- Pacific Northwest National Laboratory (PNNL)/U.S. Department of Energy Bioenergy Technologies Office (BETO), Virgin Atlantic, U.K. Government, Boeing, ArcelorMittal, Tata Steel UK, Greenergy, Air BP, SkyNRG

FUNDING:

- **US Department of Energy, BETO:** $4 million
- **UK Department for Transport:** £410,000
- **Private Sector:** Unknown

NEXT STEPS:

- LanzaTech has a variety of new projects, including a recent agreement signed with All Nippon Airways (ANA) to provide sustainable aviation fuel in Japan starting in 2021.

LanzaTech facility in Soperton, GA and Virgin Atlantic 747

CONTACT
Freya Burton
freya@lanzatech.com
https://www.lanzatech.com/

Food and Beverage Production

Carbon dioxide is widely used in the food and beverage industry, and high-purity captured CO_2 could be used in lieu of current CO_2 sources. Unlike commercial chemicals, food applications would not, for the most part, require additional technologies to enable the use of captured CO_2.

Climeworks and Coca-Cola, for example, have announced an agreement to use captured CO_2 in beverage production.[108] Demand for CO_2 in this sector will not lead to a significant market opportunity because the entire domestic demand for CO_2 in beverages could be satisfied by the emissions captured from a single mid-sized coal-fired powerplant.

Table 14

Advantages and Challenges of Short-Term Recycling	
Advantages	**Challenges**
• Markets exist for chemicals that could be synthesized from captured carbon instead of petroleum. • Demand for low carbon fuels is rising. • Processes requiring CO_2 will not need to change in the switch to captured carbon. • Short-term recycling would benefit hard-to-decarbonize sectors, such as aviation and maritime.	• Captured CO_2 is more expensive than conventional resources. • Technology barriers remain. • There are few policy incentives to use low carbon alternatives. • The processes tend to be energy intensive.

Commercial Advantages

Chemicals provide an opportunity to sell high-value products to a growing market without asking buyers to modify their systems or processes. Low-carbon feedstocks could be used in products ranging from fuels to footwear. By offering low-carbon substitute chemicals that are otherwise identical to currently used chemicals, low GHG alternatives would face few barriers other than cost. With the right set of policy incentives and sufficient improvements in technologies, using pure CO_2 for chemical production could provide a significant market opportunity.

California's Low Carbon Fuel Standard (LCFS) offers an insight regarding how a broader market could be established for low carbon chemical use. Currently, carbon is priced at $200 per ton in the LCFS. Since it is a technology-neutral program, incorporation of any chemical or production technique that reduces the carbon intensity of transportation energy sold in the state can create revenue up to $200 per ton of avoided CO_2 emission.[109]

Commercial Challenges

The primary challenges to utilization are the generally higher net-cost of chemicals produced from CO_2, and the relative immaturity of most production technologies. Broader economic incentives to substitute low carbon options could spur significant investment to address these barriers.

Using low carbon energy for the production of chemicals from captured CO_2 will be essential in most cases to preserve the carbon reduction benefit. Access and cost barriers related to low carbon energy could limit interest in developing some energy-intensive technologies in this field.

Discussion

Each year, organic chemical production results in approximately 2 Gt of CO_2 emissions through the direct or indirect use of fossil fuels. Capturing just a fragment of the CO_2 from these sources and creating new commodity chemicals from the recycled CO_2 would open doors to a wide range of end-use options for the chemicals, which creates an attractive opportunity for innovators.

Most serious forecasts show modest penetration of electric vehicles in the light duty fleet by 2050, with the transportation sector dominated by internal combustion engines for decades to come. In addition, forecasters doubt that electrification will ever be readily deployable to energy-intensive transportation sectors, such as heavy-duty trucks, aviation, or maritime industries.

Technologies represented in our short-term recycling section are often caught in a catch-22, where limited market projections limit investment in innovation, which in turn limits market penetration. However, groups such as Carbon180 project much more optimistic market opportunities. In a 2017 report, Carbon180 projected an annual total available market for carbon utilization technologies of up to $1.07 trillion per year in the U.S., and globally $5.91 trillion per year.[110]

As of today, little policy attention has been focused on the potential for the mass production of fuels, chemicals or the food and beverage industry to use recycled CO_2 as a feedstock. With incentives in place, these technologies may receive the funding necessary to bring them to wide-scale commercial use. Continued RD&D into more efficient production methods will be necessary to drive down costs to compete with existing technologies. Additionally, further research into minimizing energy-intensive requirements will be necessary. To that end, connecting chemical production with renewable energy sources will be important.

3 Designing Policy to Attract CEM Investment

KEY TAKEAWAYS FOR

ICAC Members

- ICAC members should continue to share their expertise with policymakers and stakeholders regarding the effectiveness of policies designed to support CEM technology development and deployment.

Policymakers

- Policy innovation leads to technology innovation. If policy makers pay close attention to the way participating investors evolve through the technology development process, they can develop approaches that produce larger private sector investments while also reducing the risk of using tax dollars on "failed" projects.

Climate Stakeholders

- Climate stakeholders can support efforts to refine policy approaches to provide effective, achievable, and durable policies that are not prone to political winds.

Overview

This chapter offers a perspective on policy for an industry that has half a century of experience inventing, manufacturing, deploying, and improving a wide range of interrelated emission control technologies.

Innovation Policies Should Attract and Reward Investment

For the decarbonization policy agenda to translate into meaningful results, new technologies and commercial strategies will need to be developed and compete successfully against well-established and highly efficient market incumbents. Only those that survive the difficult gauntlet from concept to commercial viability will have an impact on decarbonization. Policymakers need to recruit more private sector expertise to this complex effort. To do so will require policymakers to understand how to attract and reward those with the expertise and resources to invest in emission management solutions specifically, and decarbonization technologies generally. Figure *34* highlights the path that innovative technologies often take to achieve success in the marketplace.

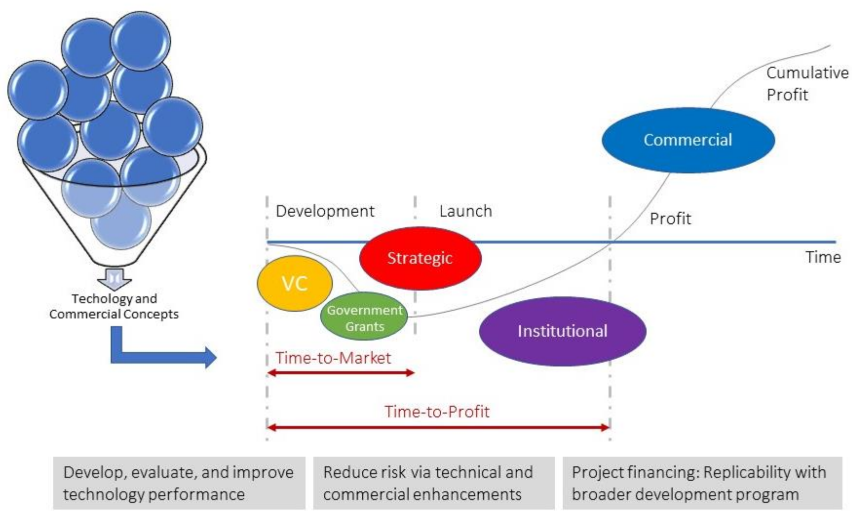


Figure 34. *Commercially successful technologies must endure a multi-stage, multi-investor development process that demands patience and strategic guidance. Source: AJW, Inc.*

At times, policy intended to support innovation can be crafted in ways that unintentionally limit the market's response. For example, policies that price an environmental attribute (e.g. tax credits for renewable power, or credit trading markets for decarbonization) often suffer value gyrations caused by government actions. Tax credits are subject to the politics of uncertain renewal/extension legislative battles. Regulators, legislators, and courts routinely intervene in the operation of emission-credit trading markets creating price fluctuations and instability.

These are difficult factors for business to plan around. Market participants are accustomed to price gyrations caused by changes in supply, demand, and other market conditions. Businesses develop the necessary expertise to manage market-driven fluctuations based on data and market expertise. Unlike supply and demand, there is no data that predicts government actions, only opinions. Unpredictability regarding key financial factors can sideline private sector capital that would be deployed if policy were more stable.

Innovation Is Needed in Policy – Not Just Technology

To develop CEM and other decarbonization technologies, the private sector will need to invest significant resources in opportunities that have reasonable chances for success. These technologies must be developed as quickly as possible with highest efficiencies while simultaneously reducing investment risks with appropriate government policy.

In turn, policy must be developed with an understanding that capital is always in demand. Business leaders are charged with finding only the *best* opportunities. So, the goal for policy must be attracting capital in a competitive market.

One largely unpredictable factor is political support. Enthusiasm for a new technology drives adoption of new policies to support development and deployment projects. Frustration follows when that technology either develops more slowly than hoped or when significant public funds are spent on a failing effort.

Innovative public policies should be designed to be more reliable, which will better attract and sustain both investor interest and political support. Reducing policy uncertainty is critical in government efforts to leverage private sector expertise which is best positioned to evaluate diverse technological and commercial risks and invest in promising opportunities. Unfortunately, few policies achieve these outcomes consistently. Too often, a limited set of technologies is favored over others, unintentionally raising barriers for compelling market alternatives.

In this chapter, we lay out some important principles for leveraging public resources to pursue decarbonization.

Using Policy to Promote CEM

The Information Technology & Innovation Foundation (ITIF) identified CEM as one of six needed decarbonization technology sets that are "underrepresented in the [federal] RD&D portfolio."[111]

One roadblock in securing CEM policy incentives is the skepticism among many in government regarding public expenditures to support commercial developments. Why can't decarbonization technologies, some might ask, mimic the commercialization success of other modern innovations, such as large-screen TVs and mobile phones?

Unlike TVs and phones, there is limited consumer demand for captured CO_2. Decarbonization addresses a societal need, rather than consumer demand. Even where decarbonizing products are available such as renewable and biomass-based energy resources, they must compete against fossil fuels that owe a substantial measure of their marketplace prominence today to decades of public support in the form of favorable tax treatment for exploration and infrastructure investments. To reduce the GHG concentrations that are inevitable byproducts of fossil-fuel combustion, government must now invest not only in renewable power generation, it must fund decarbonization technologies to mitigate the environmental, economic, and social damage created by fossil fuels.

3.1 CEM Policy Support Is Accelerating

There is increasing evidence of government interest in CEM. Policies that encourage CEM technologies have been enacted in ten countries: Norway, United Kingdom, USA, Canada, China, Japan, Netherlands, Denmark, Australia, and South Korea.

In February 2018, the United States signed into law amendments to the "Section 45Q" tax credit, placing a $35-50 per ton price on carbon.[112] To be eligible for this credit, an entity must capture carbon from any source, and ensure that it is stored or utilized. Its key features are summarized in ***Table 15.***

Table 15: Section 45Q Tax Credits

Category	45Q Credit Value and Eligibility Requirements
Enhanced Oil Recovery (EOR)	$35/ton for EOR or other utilization
Geologic Storage	$50/ton for geologic storage
Eligible Volume	All CO_x captured and stored for 12 years after beginning operation
Eligible Molecules	Applicable for all carbon oxides (important for industrial sector like Steel)
Eligible Facilities	More than 500,000 tons of emissions for electric generating facilities, more than 100,000 tons for industrial facilities (not including electric generating facilities), and more than 100,000 tons for DAC facilities
Eligible Projects	Any project beginning construction prior to January 1, 2024
Pilot projects	Pilot facilities capturing at least 25,000 tons CO_x per year
DAC Eligibility	Yes
Credit Recipient	Owner of capture equipment

Though Section 45Q credits are the main Federal incentive enacted for CEM projects, several additional incentives have recently been proposed in Congress. These are summarized in ***Table 16.***

Table 16. Additional CEM Incentives.

Additional Proposed CEM Specific Policies		
Bill Name	**Bill Description**	**Bill Number**
Utilizing Significant Emissions with Innovative Technologies Act (USE IT Act)	Authorizes $25 million prize program for DAC technologies. Authorizes $50 million for RD&D of CO_2 Utilization. Amends the FAST Act to include CCUS related infrastructure projects.	S.383; H.R.1166
Carbon Capture Modernization Act (48A)	Modifies the section 48A Advanced Coal Tax Credit by relaxing the efficiency requirements for new and retrofit projects if they include CCUS. Additionally, lowers the required CO_2 capture from 65 percent to 60 percent.	S.407; H.R.1796
Fossil Energy Research & Development Act	Amends EPAct of 2005 to provide objectives for fossil energy including: improving the conversion and use of CO2 from fossil fuels; lowering GHG emissions of fossil production; preventing and monitoring methane or other emission leaks from fossil production; reducing water use and minimizing environmental impacts from unconventional oil and gas production; and developing carbon use technologies.	H.R.3607
Financing Our Energy Future Act	Expands eligibility for master limited partnerships to include revenue from power plants that utilize CCUS.	S.1201
Carbon Capture Improvement Act	Authorizes the issuance of tax-exempt facility bonds (i.e. private activity bonds) for the financing of qualified carbon dioxide capture facilities.	S.1763; H.R.3861
Launching Energy Advancement and Development through Innovations for Natural Gas Act of 2019 (LEADING Act)	Amends EPAct of 2005 by establishing a program for the research, development, and demonstration of commercially viable technologies for the capture of CO_2 produced during the generation of natural gas-generated power.	S.1685; H.R.3828
Clean Industrial Technologies Act	Amends the Energy Independence and Security Act of 2007 to establish a program to incentivize innovation and to enhance the industrial competitiveness of the United States by developing technologies to reduce emissions of non-power industrial sectors.	S.2300; H.R.4320
FY20 Energy and Water Appropriations	Provides funding for the Department of Energy and other agencies for Energy and Water programs.	S.2470; H.R.2960

In addition to legislative efforts, the U.S. government has supported a robust carbon capture and storage program since 1997 through the Department of Energy. A summary of these efforts can be found in the box below.[113, 114]

U.S. Department of Energy's Investment in Carbon Capture and Sequestration

The U.S Department of Energy has supported three main aspects of integrated carbon capture systems since 1997. The three main steps are:

(1) separating CO2 from other gases and capturing it;

(2) purifying, compressing, and transporting the CO2 to the sequestration site; and

(3) injecting the CO2 into subsurface geological reservoirs.

In 1997, DOE allocated just over $1 million for carbon emissions management technologies, a number that has grown to $740 appropriated dollars in FY19. From 2012-2018, Congress has appropriated over $4 billion to the U.S. Department of Energy (DOE) for CCS-related activities, primarily within the Office of Fossil Energy (FE). Additionally, the American Recovery and Reinvestment Act allocated another $3.4 billion, resulting in over $7.4 billion in funding for carbon emissions management technologies from the U.S government in the last decade.

In addition to historically appropriated funding, proposed authorizing language for DOE, as outlined in Table 17, includes over $5.5 billion in funding through fiscal year 2024.

Table 17. *U.S. Climate Alliance Members committed to advancing the goals of the Paris Agreement.*

U.S. Climate Alliance Members (as of July 2019)	
California	New Jersey
Colorado	New Mexico
Connecticut	New York
Delaware	North Carolina
Hawaii	Oregon
Illinois	Pennsylvania
Maine	Puerto Rico
Maryland	Rhode Island
Massachusetts	Vermont
Michigan	Virginia
Minnesota	Washington
Montana	Wisconsin
Nevada	

State policies will also be influential in the pace of CEM development. In September 2018, California adopted a provision allowing CO_2 captured (using Direct Air Capture systems) and geologically sequestered to generate credits under its Low Carbon Fuels (LCFS) program. LCFS credits are currently trading around $200 per ton, and capture projects do not have to be in California to generate LCFS credits.[115]

States as diverse as California and North Carolina have announced plans to meet the goals in the Paris Agreement. As of July 2019, governors in 24 U.S. states and two territories have committed to the U.S. Climate Alliance, which has the aim of implementing policies to advance the goals of the Paris Agreement and accelerating new and existing policies to reduce carbon pollution and promote clean energy deployment at the state and federal level. See the list of member states in ***Table 17.*** These states may be open to establishing additional incentives to attract CEM development to their states.

3.2 Designing Policies to Attract More Private Sector Investment

Policy discussions tend to use the term "investor" as if it were a monolithic class of actors with a single, simple goal of getting a return on their investments. The roles, expertise, and objectives of investors vary widely and cover a diverse spectrum of organizations and activities. To craft and implement policies that will attract greater private sector engagement, it is beneficial to consider the complex ecosystem of innovation investment.

To meet investor demands regarding profit margins, the corporate managers in recent decades have deemphasized internal corporate RD&D. Early-stage technology companies have gained greater prominence but often lack the resources to advance their technologies to the market.

Resource constraints impact the pace of innovation in university labs and early stage companies as well as in multinational corporations. For decarbonization technologies to have a substantial impact requires investors, private as well as public. Here, briefly, are six types of investors:

A. Angel Investors

Typical Approach: This is the earliest stage of investor. Most often it is the smallest scale of investment and the least likely to be accompanied by relevant technology expertise. Angel investors tend to enter at the technology concept stage to help in the creation of small-scale proof-of-concept demonstrations. The angel investor may not have a long-term interest in the specific technology or market.

Typical Innovation Partners: Angel investors tend to offer funds to early-stage innovators for the purpose of helping a business develop a concept or application.

Policies That Attract Interest/Investment: Given the small scale of typical angel investments, policies tend not to have significant impact on commercial development.

B. Venture Investors

Typical Approach: Venture investors are experts in managing startup companies but tend to have limited exposure in commercial energy markets. Venture capital endeavors to build a capable team around a core technology and then exit their position with a significant return on their original investment. These investors tend to seek multiple opportunities to invest around a market concept. In the energy sector, many large corporations have “venture” investment units. While these are designed to explore the potential of innovative technologies, they operate more as strategic partners than true venture investors.

Typical Innovation Partners: Startup companies are the primary domain for venture capital investments. In the energy sector, small teams with scientific or engineering expertise work to mature an applied science concept into a commercially-viable technology. Innovators can benefit from venture capital to achieve early demonstrations and to attract investors with greater investment resources and a long-term interest in their target market.

Policies That Attract Interest/Investment: Since the venture model of investment is short-term in nature, it can respond well to specific short-term policy opportunities (e.g. cost-sharing development grants) and generalized long-term policy signals (e.g. carbon pricing via tax code, regulation, or emission trading markets). The early-stage company will benefit from pricing policies in the long-term, after the venture capital has exited its investment. Consequently, venture investors tend to be less cautious regarding long-term regulatory risks related to pricing policies than strategic or institutional investors.

C. Mission Investors

Typical Approach: These entities often support their portfolio companies with larger and longer-term investments than venture investors. They provide strategic business guidance and extensive networks to support technical, commercial, and financial development. This category of investor has the resources and commitment to support companies over a longer innovation journey than venture investors. As capital demands increase toward commercial scale demonstrations, mission Investors are likely to seek increasing participation from more conventional investors, including strategic and institutional investors.

Typical Innovation Partners: In the decarbonization sector, some well-funded organizations are pursuing a mission of nurturing the development of early-stage technology companies through multiple phases of development. The Gates Foundation investment in Carbon Engineering and other technology developers is one example.

Policies That Attract Interest/Investment: Mission investors will respond to the full suite of technology innovation policies because of their approach to partnering with innovators from concept through commercialization. Cost-sharing grants for RD&D can accelerate technologies and attract additional investments. Because the mission investor typically demands increasing participation from other investors as the technology matures and capital needs increase, the political stability of long-term incentive policies can be critical to mission investor decisions to sustain or abandon investments in a company or technology.

D. Strategic Investors

Typical Approach: Strategic investments typically come from large corporations that are manufacturers or suppliers. The strategic investor has deep expertise in the target market and is typically seeking to acquire technological innovations that will have a positive impact on their core business. Regarding environmental impact, strategic investors are looking to reduce their own GHG footprint and to supply customers with GHG reduction options. These investors are likely to have significant capital resources and relevant commercial expertise but tend to be risk adverse.

Typical Innovation Partners: Strategic investment typically centers on proven technologies and products. The closer to commercial viability, the more successful the partnership between investor and innovator is likely to be. The strategic investor tends to seek market advantage by expanding their technology expertise or acquiring rights to a new technology or product. But all strategic investors face constant pressure to demonstrate short-term profitability, which limits their appetite for investments with uncertain potential for return. It is not uncommon for technology development to stall when ownership rights are acquired by a strategic investor before the technology has proven its commercial viability. This can happen because the corporation has limited resources for internal innovation efforts and faces pressures from senior management to concentrate on projects more likely to generate near-term returns on investment.

Policies That Attract Interest/Investment: Sustaining the commitment of strategic investors demands the spectrum of policy support be available and dependable. Cost-sharing through RD&D grants increases their appetite to continue development. Pricing signals must be dependable to justify pursuit of long-term investment activities.

E. Institutional Investors

Typical Approach: This class includes the largest entities in global finance, as well as a dizzying array of smaller entities that play boutique roles in the finance landscape, such as "mezzanine" investments or stranded asset conversions. It is also the most difficult to summarize in the context of a technology innovation discussion. The institutional investor does not lack for capital and has a focused approach to investment that sharply defines the opportunities it is willing to consider.

Typical Innovation Partners: Attracting institutional investment can be crucial for innovators and often requires the technology to be well-developed. The closer to successful commercial-scale demonstration a project is, the greater its chances of attracting institutional investors.

Policies That Attract Interest/Investment: Institutional investors focus on commercial market opportunities. To the extent that technologies are not yet commercially-viable (because either they are still immature, or they represent net costs to customers – as is the case for nearly all CEM technologies) investor interest decreases. Policy support can contribute to mitigating a portion of those risks, thereby increasing private sector investment in the most promising technology opportunities.

F. Commercial Lenders

Typical Approach: Lenders play a critical role in the financial ecosystem but not as "investors." They need to be convinced that funds lent to the organization are highly likely to generate returns sufficient to repay all loans.

Typical Innovation Partners: None. Banks do not take technology risks. They lend rather than invest.

Policies That Attract Interest/Investment: Lenders are unlikely to provide financial support for innovations that have yet to demonstrate marketplace appeal. By contrast, an organization with an innovation that attracts commercial lenders is likely to attract investors of every type.

Figure 35 summarizes the roles played by organizations and investors in a technology's evolution and maturity.

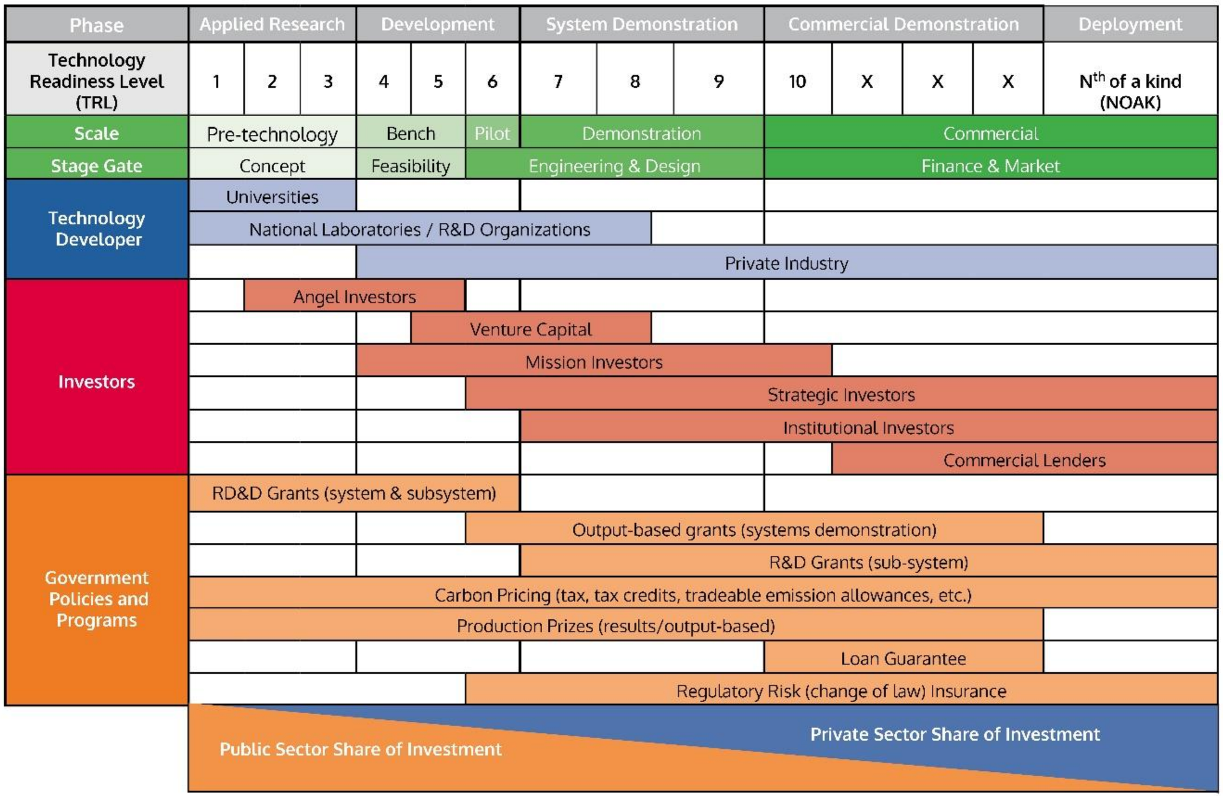


Figure 35. *The Theory of Everything. Private and public investment in innovative technologies must interact in the development and deployment process at the right time and in the right way in order to avoid project failures. Source: AJW, Inc.*

Politically-Stable Price Signals (Tax or Market Mechanism)

The most straight-forward market signal a policy can deliver is a predictable price. A price for carbon capture can be set through tax policy (e.g. 45Q) or a market policy (e.g. LCFS). The greatest risk of this type of policy is that subsequent government action will change the value or limit access to potential revenue streams (i.e. regulatory risk). When market participants regard such programs as politically stable, the prospect for investments improves along the spectrum of technology research, development, demonstration and deployment.

Price signals often fail to deliver hoped-for private sector investments, however. The two most common reasons are: 1) the market perceives a degree of regulatory uncertainty, and 2) the value of the price signal is insufficiently attractive. Correcting these breakdowns is politically challenging and requires innovative strategies. Yet, there are numerous examples of market programs delivering success that provide useful models.

Research, Development, and Demonstration Grants

Grants have long been a part of the innovation ecosystem. Grants focused on early-stage RD&D can leverage resources from private sector organizations ranging from universities to global corporations. This element of government engagement plays a larger role in technology development than may have been the case in the past when it was more common for corporations to invest heavily in applied science work to convert discoveries into applications. The evolution away from corporate RD&D spending and the greater importance of start-ups focused on specific innovations are important factors as governments contemplate their role in innovation.

Government grants focused on RD&D will fund research by universities and small technology-oriented firms. Even for commercialized technology, ongoing RD&D can support efforts to improve efficiencies and reduce costs. DOE has maintained an extensive RD&D program to support the fossil energy sector for exactly this purpose.

Absent government support through the entire commercialization process, including grant programs for commercial scale demonstrations, decarbonization technologies will continue to struggle and stall.

Demonstration project grants can mitigate the magnitude of private capital risk and enable projects to secure project financing. As the scale of the demonstration grows and the technology matures and gains market adherents, the government share of capital risk should decrease. Demonstration grants will entail large investments; they must be designed to protect government resources from excessive risks.

Loan Guarantees

Loan guarantees can be successful in catalyzing technology deployment in highly specific conditions. As solar generation costs fell, loan guarantees enabled project financing for the first utility-scale solar project. The success of these projects demonstrated that both the technical and commercial risks had been addressed, which enabled commercial lenders to step in to offer conventional debt financing for subsequent projects.

Loan guarantees should be thought of as the last step before commercial lending takes over.

3.3 Principles to Ensure Better Policy Outcomes

Given the scale of the climate challenge we are facing, we need the widest possible range of decarbonizing technologies to move from concept to commercial viability. Accomplishing this will require policies that incentivize use of products and services that reduce the combustion of fossil fuels and sequester increasingly greater portions of GHGs now in the atmosphere.

Government, universities, and early-stage investors can help technology innovators achieve a degree of early-stage maturity. Absent motivated private sector engagement in innovation and deployment, technology will inevitably fall short of its full potential.

What can be done to ensure CEM technologies overcome this well-documented innovation roadblock? Our policy prescription is what follows.

3.3.1 Research, Development and Deployment Are Each Essential

In its 2016 report, *20 Years of Carbon Capture and Storage,* the IEA points out that:

> *Research and development efforts will continue to be important in refining and improving CCS technologies, but major breakthroughs and cost reductions will likely only be achieved through actual development at scale.*[116]

It is an article of faith for many policy stakeholders that the “proper” role for government in supporting innovation begins with support for basic science and ends with support for applying scientific understanding in research and development projects. At times, the government has, of course, directly supported commercial demonstration activities but with wildly varying outcomes. Mixed results in government-sponsored technology demonstration projects have left doubts regarding whether and/or how the government can play a constructive role in the later stages of technology development.

We strongly agree with the diverse set of climate stakeholders that are encouraging the government to support CEM and other decarbonizing technologies through complete commercial demonstration. ITIF observes the "innovation agenda for deep decarbonization should embrace the entire innovation spectrum, from use-inspired basic science to technology development and demonstration to commercialization."[117]

Public investment in Research and Development (R&D) is an essential part of an effective innovation policy. But R&D alone is not enough. Effective clean energy innovation policy requires support across the entire innovation spectrum, from basic science and R&D through testing, demonstration, and smart deployment incentives. Public support is needed to bridge technologies across the "Valleys of Death" – the phases between R&D and prototyping the first generation of a technology, as well as the transition between the first demonstration at scale and commercialization.[118]

Why should public support be needed for CEM demonstration? There are two reasons:

1. CEM technologies are critical to achieving decarbonization targets.
2. They will entail costs that cannot be fully offset by commercial revenues.

CEM is unlikely to attract sufficient private sector investment to achieve commercialization without government support. Rather than support demonstration projects, the government, some might argue, could simply mandate the use of CEM technologies. That might work for the few technologies that have been fully demonstrated and are commercially ready. Most, however, are not.

Caution is also called for regarding the use of mandates. There is a rich history of regulations getting ahead of technology readiness. In most instances, the results are misspent resources and market uncertainty as regulators react to the inability of the market to produce compliant solutions.[119]

Some may take the view that CEM innovators will plow ahead because potential market opportunities are so great. That, too, is unlikely. Demonstrations of CEM technologies at scale will demand capital, technology, and commercial resources and expertise that are unlikely to be available to innovators until a dependable value is established for the capture and use of industrial carbon wastes. Until leading companies validate a business model based on CEM, few will take significant risks in pursuit of these opportunities. Public sector support to reduce the risk exposure of the early movers will expand the potential pool of market participants and CEM pathways explored.

Demonstration support is also needed so that technology development does not end with the construction of a first-of-its-kind facility. The first commercial scale demonstration of any production process is rarely the point at which commercial viability is confirmed. In most cases, multiple iterations are needed to establish standardized engineering and design approaches that maximize the efficiency of the operation and minimize the costs associated with subsequent iterations. Successful construction and operation of an industrial technology are notable achievements, but replication is the key to achieving cost reductions and economies of scale. Industrial technologies can be considered commercial only after performing successfully, and profitably, under commercial operating conditions. For certain CEM technologies, a multi-billion dollar capital expenditure may be necessary to achieve commercialization.

CEM is not unique among decarbonizing technologies in this regard. Similar challenges face the commercialization of carbon-neutral or carbon-negative technologies of all kinds. There are numerous ways policy could succeed in creating the necessary investment climate to drive CEM demonstration and scale-up. Some examples have already been adopted and implemented, but more will be needed.

3.3.2 Government Should Take the Right Risks – Not More Risk

Taxpayers and their elected representatives tend to dislike spending public funds on projects that fail to achieve their ends. If the government is going to support multibillion-dollar CEM demonstration activities, the most pressing question, before the first dime is spent, should be how best to protect against the risks of waste, fraud, abuse, and poor decision-making.

The good news is that the government can take a more expansive financial role in commercial demonstrations while still limiting its risk exposure. More importantly, by using policies that appropriately divide risks between the private and public sectors, government can make its technology innovation program more effective.

Assign Risks Correctly

Risk is an inescapable element of technology pioneering. One key in any new enterprise is to assign risk management to those best able to manage and mitigate those risks. When the private sector takes on a pioneering project, vendors ensure component performance within set specifications; engineering and construction firms guarantee process integration and construction timelines; financial experts manage capital flows. Supply and offtake contracts are structured to manage cost and revenue risks.

The government should not stand in place of private actors in addressing or managing such risks. It makes far more sense to structure incentives based on market actors successfully demonstrating that they have successfully managed those risks in projects that deliver vital public benefits, such as decarbonization. There are multiple virtues with this approach. The government relies on the private sector expertise to manage commercial and technical risks. Rewards can inspire wider and more diverse competition among companies racing to claim both the government rewards and a market leadership position.

Most importantly, by basing government support on demonstrated success, the government risk of funding failed projects is eliminated, and the investors' role of screening projects for viability is maximized. For this approach to succeed, the government's offer of a reward must be both financially compelling, and completely reliable.

Optimal Government Role in Demonstration Project Risk Mitigation

Government routinely identifies and defines outcomes that are in the public interest. In the case of climate change, the government should establish mechanisms that establish a clear market value for decarbonization. The more transparent, predictable, and dependable that value is, the more consistent the private sector response will be. The higher the value placed on delivering decarbonization, the larger the volume and diversity of resources that will be dedicated to capturing that market value.

In other words, the government can reduce risks for private sector technology innovation and demonstration efforts by establishing clear, dependable rewards for delivering the public benefit: decarbonization. This can and should be done with a portfolio of policies (discussed below) that:

- Establish long-term value for decarbonization, achieved by any technology or commercial process
- Support accelerated RD&D across the broadest possible set of decarbonization strategies, including CEM
- Provide guaranteed capital risk mitigation for demonstration projects that meet appropriate performance goals
- Reinforce private sector adherence to disciplined and stage-gated scale-up and demonstration processes

This approach will not immunize projects from failing to achieve start-up. It will, however, take an essential first step to reshaping how the government approaches such projects to protect its resources and maximize the potential for success. By investing in projects that succeed, the government will maintain the political support necessary to support technology demonstrations at a large scale.

The Government Needs to Reduce Regulatory Uncertainty

Uncertainty stifles investment and kills projects. When an opportunity exists for technology innovation to create a new business opportunity, the private sector will work to eliminate uncertainty. Cost uncertainties can be addressed in part through stringent contractual terms. Revenue uncertainties can be managed through well-defined pricing parameters. Technology uncertainty can be overcome through demonstrations and iterations that improve performance and reduce costs. Insurance can address unexpected events and residual risks. Reserve capital can be secured to anticipate and overcome setbacks.

Regulatory uncertainty refers to risks associated with changes in laws and regulations. The private sector may be able to influence them, but such risks cannot be completely eliminated. The government has the power to alter its programs and rules at any time. When it does, often some in the private sector are caught unprepared for the changes. When revenue derived from a government program (e.g. a tax credit) is an essential ingredient in the business case for a particular market, investments may be withheld in the face of uncertainties stemming from regulatory risk despite minimal exposure to technical or commercial risks for the project.

Addressing climate change hinges to some extent on decarbonization being priced into the market through regulations, tax credits, and market mechanisms to promote private sector demand for low-carbon solutions. Whenever decarbonization policies are implemented, it is vital they signal the market in ways limits the potential for regulatory risks that jeopardize investments.

One illustration of regulatory risk dampening a decarbonization market signal is price fluctuations the California Low Carbon Fuel Standard (LCFS) between 2013 and 2017. This program creates tradable credits that represent one ton of avoided CO_2 emissions from transportation sources. As ***Figure 36*** highlights, a variety of actions by different branches of government created significant swings in LCFS credit prices. While some might expect some degree of correlation between movements in fuel prices and fuel decarbonization*,* ***Figure 36*** clearly shows no correlation in price movements of LCFS credits and E10 (a blend of 90 percent gasoline and 10 percent ethanol) the dominant fuel in California's transportation market.[120]

On-again, off-again tax credits, changing eligibility requirements for renewable electricity programs, litigation and policy reversals on efficiency standards for vehicles, and many other examples exist. Nearly every field of decarbonization technology has been plagued by regulatory uncertainty. As a result, "smart money" tends to engage in short-term, low-risk decarbonization opportunities rather than pursuing technologies that could truly disrupt—and ultimately succeed—in the marketplace.

In *Section 4.4*, we suggest some approaches that would strengthen the confidence of investors in areas where the government hopes to attract significant technology innovation.

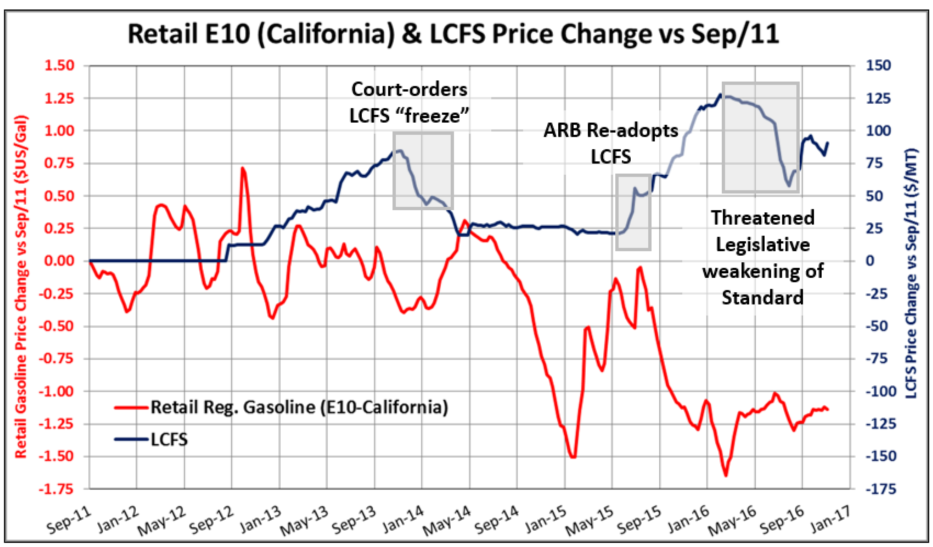


Figure 36. *Court orders, regulatory activities and political uncertainty led to wild fluctuations in the price of LCFS credits between 2011 and 2016, showing the impact of political fluctuations on the market.*[133] *Source: Adapted from Climate Solutions.*

3.3.3 Patience is a Virtue

The pace of technology innovation does not adhere to politically convenient timetables. While that should be obvious, the point sometimes seems overlooked in the effort to set easily communicated decarbonization targets. Program after program targeting new energy and environmental technologies attempt to dictate both the scale and the timing of new technology demonstrations. This typically leads to disappointing results. History illustrates this.

In September 2013, the U.S. Department of Energy issued a report on its efforts to accelerate the demonstration of advanced biorefinery technologies that would utilize its non-food biomass feedstocks to produce fuel and other commercial chemicals.[121] The report stated that the $600 million spent on integrated biorefineries failed to achieve the agency's "biorefinery development and production goals." A principle finding stated:

> *The Program awarded funding for commercial-scale projects even though the proposed technology had not been fully validated at pilot-scale or demonstration-scale facilities.*

The need to follow a disciplined approach to scaling up any new production technology is well understood by engineers in the energy and chemical sectors. Yet, too often government policies push emerging technologies to achieve scale-up targets long before they are ready.

Using public funds for construction of new technologies that have not followed a disciplined scale-up and demonstration process often results in funds for further work being terminated. By demonstrating what will not work at a large scale, such projects arm opponents of technology demonstration efforts with “evidence” that no technologies will work. In short, patience is necessary to allow technologies to mature through a careful development process.

3.3.4 Understanding Scale-up

In the development of new technologies that involve innovative engineering and design, the dangers of skipping incremental scale-up steps are numerous. To control costs, industrial technology developers tend to hold off scaling up until the design and engineering of the current scale have achieved prerequisite goals for performance and durability. These can often involve substantial iterations of the original design. Once satisfied with the performance of the technology, further scale-up is gradual with each new demonstration generally not more than 10 times larger than the previous scale. It costs considerably more to redesign, reengineer, and rebuild a portion of a process at larger scales. Identifying and solving problems at the smallest possible scale is the approach of most disciplined industrial technology innovators. It is also the best way to ensure capital resources are not wasted.

In a commercial context, skipping steps exposes the project or technology developer to a significant risk: investing large sums of capital in construction of a facility, only to discover process problems that could have been more quickly and inexpensively corrected at a smaller scale. Correcting such issues at a large scale is capital-intensive, wastes time and financial resources, and can jeopardize the prospects for further development.

Energy Technology Scale-Up Is Capital-Intensive

In our modern innovation economy, we are accustomed to the latest digital gadgets and applications rocketing rapidly to widespread use. Broadly speaking, digital technologies can be prototyped, rigorously tested, repeatedly refined, and achieve commercial viability, with far less capital risk than a single new energy technology. A single commercial-scale energy technology demonstration requires costly investments in RD&D to develop a commercial prototype. Improving the first prototype is no less necessary for energy technologies than for digital devices. The difference is the scale and the capital required to construct a full-scale demonstration. Policy tools must simultaneously support capital intensive demonstrations while limiting exposure to the risk of using public money on project failures.

Policy Should Support Technology Diversity

The urgency of the climate problem leads many climate stakeholders to call for programs that support the deployment of technologies that can make dramatic changes in decarbonization within a decade or two. Often, such urgency is paired with the notion that it is “too late” to bother with technologies that are “not ready” to be deployed at commercial scale. The problem with this thinking is that almost none of the portfolio of critically needed decarbonization technologies is, in fact, “ready.” There is substantial risk in promoting a too narrow set of technologies. The preferred technologies may very well stall for unexpected reasons. The outcast technologies, meanwhile, will have received little development support, but may in the long run prove to be more viable. Government policies should set targets for technologies to achieve rather than pre-selecting the technologies allowed to compete.

It took more than a century to invent and deploy the combustion technologies that led to the climate problems we now face. It will take time to invent and deploy the technologies needed to reverse the problem. Ignoring that hard reality and rushing to support technologies prematurely will make matters worse.

Impatience Contributes to Policy Fluctuations

One predictable consequence of policies that encourage innovators to rush to prove their technologies are ready is the construction of “white elephants” in the form of large-scale, non-functioning technology demonstrations. When this happens, the backlash undermines support for further investments. IEA points out that “CCS deployment has been hampered by fluctuating policy and financial support.”[122] In the lead-up to the 2009 climate negotiations in Copenhagen, more than $30 billion in public funding announcements were made to support CEM demonstration projects. However, projects encountered numerous, complex challenges and only $2.8 billion of the pledged funds were expended.

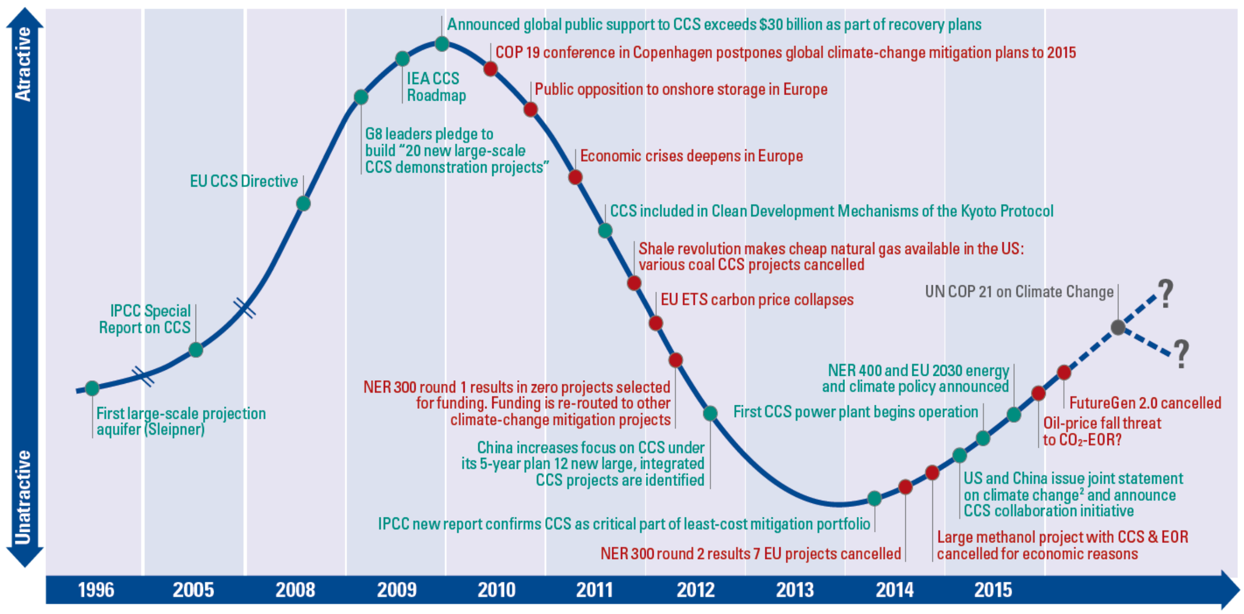


Figure 37. *CCS has received both support (green dots) and opposition (red dots) over a 20-year-period (1996-2016). Source: Adapted from SBC Energy Institute (2016), Low Carbon Energy Technologies Fact Book Update: Carbon Capture and Storage at a Crossroads.*

This problem is not unique to the U.S. In the U.K., where leaders have committed to reducing CO_2 emissions by mid-century, the public and private sector are still reeling from a 2015 decision in which the government cut £1 billion ($1.3 billion USD equivalent) of funding to build commercial-scale carbon capture demonstration plants in the country after accepting detailed proposals from Shell, Drax Group Plc and SSE Plc.[123] The government is now revisiting their investment in CEM technologies after studies have shown that the U.K. has vast geologic CO_2 storage capacity. However, after the government’s 2015 reversal, regaining support continues to be an uphill political battle. According to the U.K. Parliament’s Chair of the Business, Energy and Industrial Strategy Committee: “Clear policy signals will be crucial in creating a market in CCUS into the 2030s."[124] ***Figure 37*** shows the investment attractiveness for CEM technologies based on global political fluctuations.[125]

3.3.5 The Importance of Incremental Progress

Policymakers tend to set clear targets in compelling round numbers, such as 90 percent reduction by 2030. Technology rarely advances in such predictable metrics. Government programs must build in features that reward progress even if it falls short of the bold goals and timeframes propounded initially.

Gradual cost reductions in capture technologies will occur most rapidly with successful commercial deployment. Profits earned from early market successes can be plowed back into RD&D for improvements that will increase market demand. Policy should create systems that produce financial rewards proportional to the emission reductions achieved, such as in the 45Q tax credit and California LCFS that pay a market rate per ton of emissions avoided. In such cases, the private sector is likely to invest in the development of systems that enable larger quantities of emissions to be captured or repurposed at greater efficiencies and lower costs.

Part of incremental progress will necessarily be the use of cost-effective strategies to limit emissions from combustion rather than displacing combustion. This may seem to some to be a distraction from the more ideal solutions. However, if small profits can be achieved dependably with modest decarbonization successes, that will encourage bolder investments with more dramatic decarbonization potential to follow. In important ways, rewarding incremental progress will build momentum needed to reach global decarbonization targets.

3.3.6 The Rewards of Technology Neutrality

A comprehensive research agenda is needed to advance a wide range of carbon utilization technologies suitable for utilizing various carbon waste streams, incorporating enabling technologies and resources, and producing a variety of carbon-based products.

\- **International Energy Agency (IEA)**

Option generation is a key part of managing risks and investing in multiple clean energy buckets guards against the risk of any one technology failing to reach maturity or impact our energy system at a climate-relevant scale.

\- **U.S. Geologic Service (USGS)**

Embracing truly disruptive technologies would call for… a commitment to an overall program target rather than technology-specific allegiances within the various RD&D program offices.

\- ***Intergovernmental Panel on Climate Change (IPCC)***

Overall, a full portfolio of options has the greatest chance of success and lowest risk of failure.

\- ***-Innovation for Cool Earth Forum (ICEF)***

Given the uncertainty each [CEM technology pathway] faces, a broad portfolio of approaches and technologies could yield greater opportunities for achieving large-scale benchmarks for carbon removal than betting on just one or two.

\- **Intergovernmental Panel on Climate Change (IPCC)**

As the quotes above illustrate, many climate stakeholders encourage technology neutral approaches for decarbonization policies.

Yet, some climate stakeholders still promote technology-specific incentives (e.g. technology specific tax credits) rather than technology neutral programs (e.g. California's LCFS). To achieve the most rapid and cost-effective results, technology neutrality is essential.

Innovation is inevitably a winnowing process. Some technologies will succeed while others fail. When policy stakeholders rush to embrace a single technology pathway, regardless of how promising that technology may appear, it serves to increase the barriers for other technologies. Establishing a preselected list of technologies to support has limited the progress of decarbonization. Reducing costs and barriers for technologies based on political appeal rather than performance undermines investment in promising technologies that don't have political support. Government programs should not be used to undermine the introduction and development of viable decarbonization initiatives.

Some years ago, renewable energy and battery storage were deemed "winners" while CEM technologies were considered "losers" by default. Of late, select CEM pathways have come into favor among climate stakeholders while others are overlooked.

Some stakeholders, for example, promote exhaust gas capture for facilities that are difficult to decarbonize but oppose its use on steam methane reformers in refineries or gas turbine power generators, which may offer more economic opportunities to refine and commercialize capture technologies. Opposition to near-term capture opportunities could delay or prevent development of technologies that could otherwise address energy resources that would continue to consume carbon-emitting fuels for decades to come.

Another justification often used for picking one technology over another is its supposed readiness. It is entirely reasonable to support technology demonstrations once projects and technologies are sufficiently demonstrated at smaller scales. However, the test should be performance and ability to achieve the outcome (i.e. capturing CO_2 volumes from any source). Choosing technology pathways first (e.g. post-combustion capture vs. direct air capture) limits options and signals the private sector to withhold investment from excluded technologies. Rather than increasing options and attracting more resources to decarbonization, the premature picking of winners and losers limits our options and resources.

History shows that it takes time for technologies to meet favorable market conditions but that deployment can accelerate once those conditions exist. While certain capture and utilization combinations look like promising commercial contenders now, it is too soon to know when, or if, they will become market-ready.

Incentive programs should maximize private sector capital and expertise spent developing decarbonizing solutions. Progress will be most rapid if technologies are measured by their contributions to GHG reduction and supported by policies that encourage markets to deploy any technologies that achieve proven performance and favorable economics.

By taking a broadly technology-neutral approach, policymakers will give the market time to develop and allow gradual commercial progress to build the private sector confidence needed to pursue more ambitious strategies for decarbonization.

3.3.7 Use Multiple Policies in Combination to Accelerate Innovation

In policy discussions related to innovative technology, one often encounters resistance to "double-dipping" or letting one technology or project benefit from more than one form of government support. It is not clear why this inclination is so strong, but we would urge climate stakeholders to focus on the private sector outcomes it seeks to motivate and use policies tailored to encourage those responses. Doing so, almost by definition, will encourage individual projects to make beneficial use of more than a single form of government support as a technology moves through the stages of development and commercialization.

Figure 37 lists some broad categories of policy organized in a manner that is meant to illuminate where each can – if well-crafted and politically-stable – increase private sector engagement on developing innovative technologies. It is also meant to communicate where overlapping policies can be mutually reinforcing while operating to address distinct commercialization and financing challenges.

The sections that follow address three principal policy mechanisms:

Carbon Price

A carbon price can be conveyed effectively with different policy tools, including tax policy, environmental credit markets, or emission reduction mandates. When a transparent and dependable carbon price is established, it will support technology development activities from the earliest stages of development through market demand for fully commercial solutions. The extent to which the market views such a price as politically stable, concerns regarding regulatory risk abate and more ambitious long-term development projects will be pursued. The extent to which the price can close the profitability gap between GHG-emitting and GHG-reducing market options, the greater the investment in, and uptake of, low carbon options.

A carbon price is not a panacea. Demonstrations of first-of-its-kind technologies at commercial scales will almost never be cost-competitive even if they operate flawlessly. Only after engineering and design are streamlined and standardized and components procured with economies of scale will the economics of such facilities begin to be realized. Early-stage research to support technology development will be made more compelling by a carbon price, but its scope will most likely be limited. Additional public support can address research and demonstration challenges and substantially augment the attractiveness to the private sector of applying resources to the technology exploration and development process.

Grants

It is worth separating grants into those focused on early stage R&D (for basic science and applied science efforts) and those focused on the demonstration of new systems at pilot and larger scales. Early-stage research grants should continue to be awarded to reputable researchers with well-defined projects in a range of explorations from basic materials science to small scale chemical and physical systems. Learning from such efforts will inform new concepts and approaches to CEM technologies. Such grants are small, and the expected results entail new learning.

Grants are also needed to enable the government to reduce the capital risk of large scale demonstrations of CEM systems and accelerate their timetables. Through such grants the government can apply a thoughtful approach to engineering and design scale-up conventions. Grantees should be required to demonstrate successful operation of the technology and components at an appropriate prior scale, under appropriate operating conditions to warrant confidence in proceeding to the next level of demonstration.

In addition, government efforts to support demonstrations would be far more effective if grants were offered under a rolling deadline that put the emphasis on technology readiness and the completeness of prior demonstrations. Grants applications that must be finalized and submitted on an arbitrary government deadline encourage applicants to exaggerate their readiness and limit the government's ability to hold all potential grantees to equivalent standards regarding prior development work. This can easily contribute to awarding grants to unprepared or unqualified projects. Even if the grant money is never spent, the lack of results undermines confidence in the technology and the grant program itself.

Even as demonstration grants are being used, it would be helpful and appropriate to award related additional R&D grants focused on components and materials with the potential to become valuable improvements when incorporated into the larger technology system being demonstrated.

Innovative Policy Approaches

In *Section 3.4*, we discuss innovative approaches to policy. Innovations in policy are necessary to support innovations in technology. For example, prizes for achieving certain standards of technology performance, such as tons per year of CO_2 captured, that are large enough to make new plants profitable to build and operate could animate substantial infusions of private sector resources. Such prizes would be even more compelling in cases where a carbon price is already in place and would support demand for additional deployment of the prize-winner's technology.

3.3.8 Rely on Market Actors to Identify Integration and Optimization Strategies

Policies should leave as much room as possible for the private sector to develop integrated commercial strategies that allow market actors to optimize how best to integrate new technologies into commerce. It is easy for those in the policy realm to underestimate the array of technical and commercial choices that face those seeking to commercialize new technologies. Each choice can, on its own, advance the project or set it on a doomed course. ***Figure 38*** presents multiple options for biomass input, chemical processing and the resulting captured carbon products. It highlights the complexity of the decisions that would impact the application of BECCS technologies to one or more demonstration projects.[126]

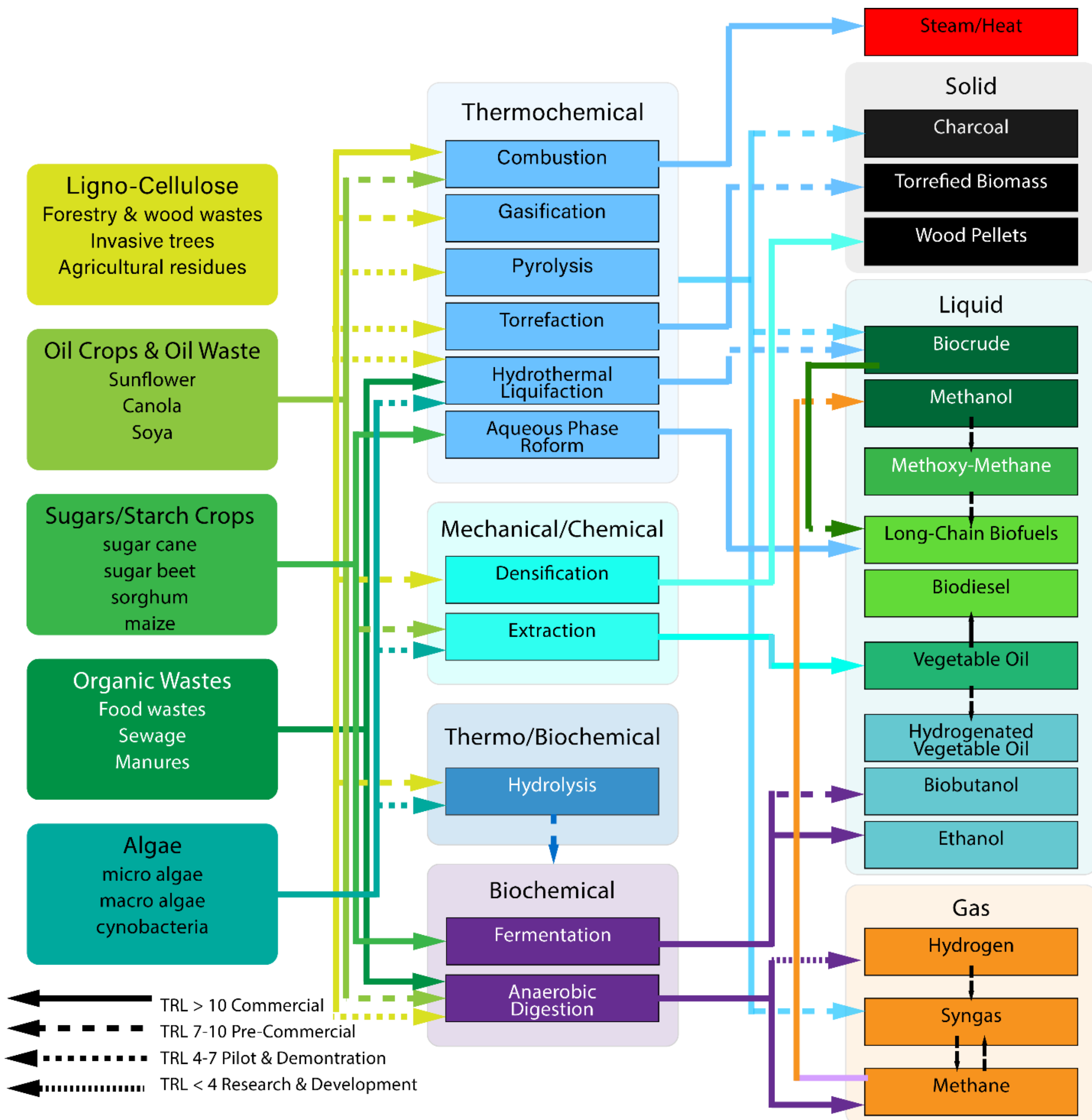


Figure 38. *There are a multitude of options for biomass input, chemical processing, and then resulting utilization of the captured carbon. This represents the series of pathway options that innovators and project managers must navigate for just one type of CEM technology – BECCS. Source: National Academies of Sciences.*

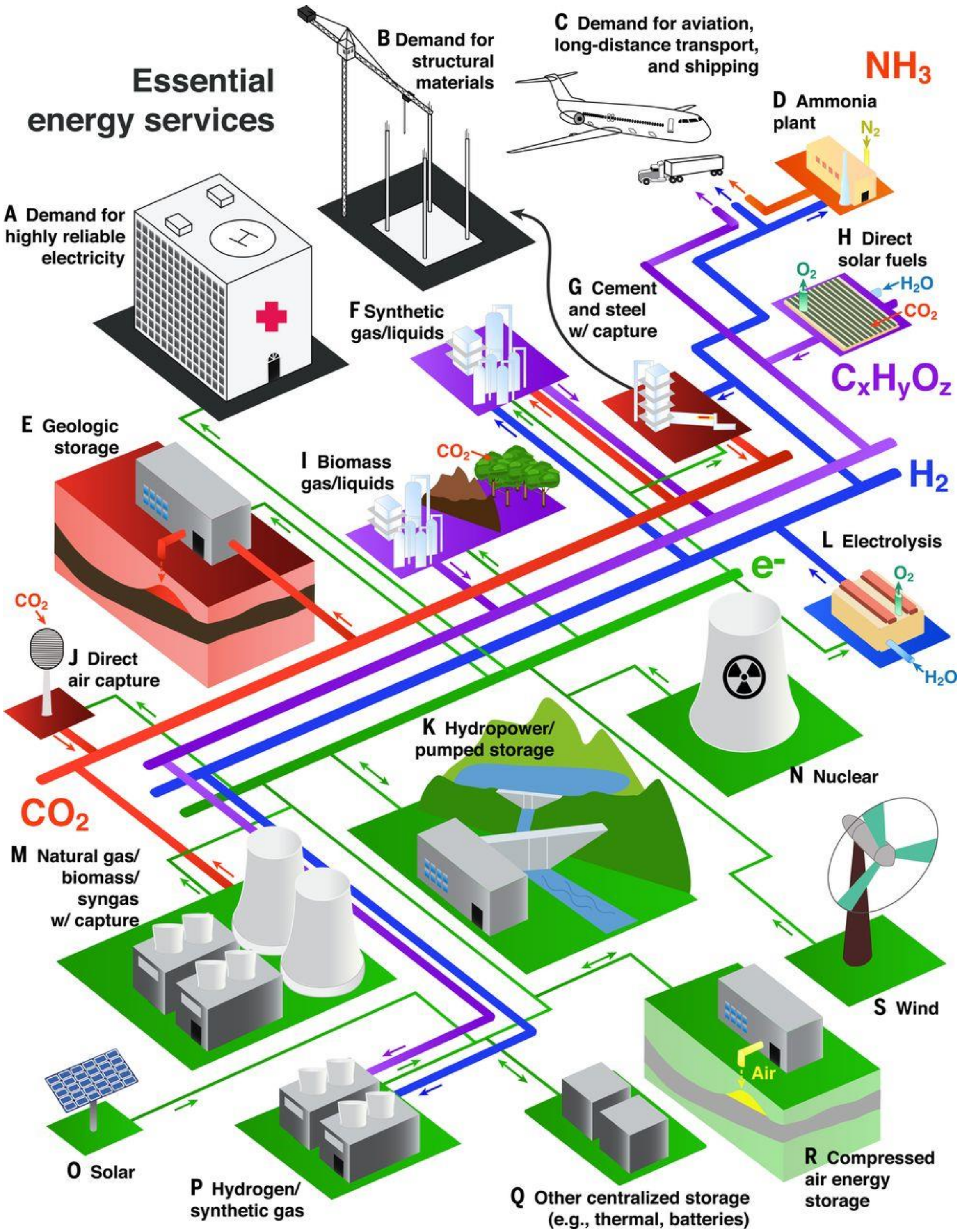


Figure 39. *Carbon utilization represents a vast, complex and evolving set of pathways that must be strategically examined when managing a CEM project. Source: American Association for the Advancement of Science.*

In addition to selecting the optimal combination of feedstock, conversion technology and commercial product outputs, the project managers would also need to select the carbon capture technology and the sequestration pathway. Those decisions will need to be made against a complex and evolving backdrop of a large and highly complex production landscape, depicted in ***Figure 39***.[127]

Market conditions, facility location, and technology readiness will present barriers that limit commercial and technology options for the new project. To the extent that policy imposes further restrictions, commercialization opportunities for new technologies will be additionally constrained.

For example, while there is a growing body of policy support for battery energy storage, there is growing interest in using surplus renewable energy to produce gas or liquids that could later be used for power generation for other purposes. These chemical energy storage options include ammonia, hydrogen, and synthetic hydrocarbons. Yet, energy storage in chemical forms is not incentivized by many policies. That inhibits the market from optimizing the use of renewable power in ways that could contribute meaningfully to decarbonization.

Those in the market have the greatest opportunity to identify and exploit market opportunities that maximize the optimization of decarbonizing resources. To the extent that policy establishes roadblocks that limit private sector options, it hampers commercialization. The government should maximize the speed of deployment of all potential pathways by simply creating clear economic rewards for measurable decarbonization and allowing the private sector to find the commercial and technology combinations that maximize their ability to secure and profit from those rewards.

3.4 Proposals for Innovative Policy Approaches

Innovation is needed in policy, not just technology. In the sections that follow, we highlight the importance of innovative policy to decarbonize the economy.

3.4.1 "Orteig Prizes" for Decarbonization

Why did Lindbergh cross the Atlantic? For the prize money! Prizes have often been discussed in the context of energy technology innovation. However, seldom do such prizes provide a scale or scope appropriate to inspire truly aggressive investments and problem-solving. It's worth looking at the Orteig prize as an early illustration of a successful technology innovation prize.

Charles Lindbergh's 1927 flight from Long Island to the outskirts of Paris is widely known. Less often discussed is just why the 25-year-old airmail pilot was able to accomplish the trip. In 1919, New York hotel owner Ray Orteig, seeking to increase business during the cold months when steamship traffic fell off, offered a prize of $25,000 to the team that completed the first non-stop trans-Atlantic flight. What followed was a furious effort by dozens of teams comprised of investors, engineers, aeronautics experts, and pilots, all striving to design and manufacture planes and components to meet this challenge.

About $10,600 was spent developing, building, and testing the Spirit of St. Louis. Upon wining Orteig's prize, the investors in Lindbergh's vision captured a tidy profit and significant additional business. Meanwhile, the $25,000 in prize money triggered innovation by individuals not involved with the airplane and the team that built it. The innovations from various teams' designs, coupled with Lindbergh's accomplishment, proved instrumental in the growth of American aviation.

Decarbonization technology today is a vehicle as tenuous as Lindbergh's plane. Many CEM technologies have passed beyond the conceptual demonstration stage but still need significant additional development to operate cost-effectively and commercially on a global scale.

The prize concept is being applied today through various public and private sector mechanisms. But to unlock a real race to commercialize decarbonization, it is useful to consider the elements that made the Orteig Prize a success:

- **Clear, Measurable, Commercially Relevant Goal:** Success was defined simply and clearly as a non-stop flight across the Atlantic. Once achieved, it was a short process to improve plane designs to accommodate the weight of cargo and passengers needed to unlock commercial opportunities.

- **Clear, Dependable Financial Reward:** The Orteig Prize sought to enrich the winner, not merely offset some of the costs of the effort necessary to meet the objective.
- **Technology Neutrality:** Teams were free to use any design and equipment they deemed useful to being first to fly to Europe.
- **Patience:** The original Orteig Prize had a five-year expiration date. Orteig was persuaded to extend that deadline when it became clear that the technology would not advance quickly enough to meet his hopes.

We believe a modern-day race could contribute substantially to the commercialization of CEM technologies. Our suggested design would involve the following for carbon capture projects:

- **Objective:** Capture a specified volume of CO_2 [e.g. 2 kilotons] in one 12-month period of operation.
- **Prize:** Offer tiered prizes to increase the private sector interest:
  - First Prize: $2 billon (approximately 3X current CAPEX estimates for a project this size)
  - Second Prize: $700 million (approximately 1X current CAPEX estimates)
  - Third Prize: $350 million (approximately 0.5X current CAPEX estimates)
- **Technology:** Provide a technology that captures CO_2 from any industrial process or directly from the air.
- **Time Limit:** None

This approach would be a highly effective use of $3.05 billion. The government would not spend any public funds until the performance targets were achieved. Meanwhile, the prize on offer would trigger the level of private investment needed for large-scale demonstrations of multiple capture technologies. Resources would pour into university laboratories and corporate innovation centers aimed at designing, refining, and demonstrating technologies that could achieve the goal. A wide array of technologies and commercial strategies would be employed, unlocking valuable learning applicable to a wide array of circumstances.

This type of policy would work to its greatest advantage if paired with a long-term price signal (e.g. a permanent tax credit or tradeable emission credit market program). The prize would greatly accelerate technology development largely through private sector investments. The price signal (of an appropriately attractive scale) would create an interest in long-term commercial opportunities that compel participation by the most sophisticated market actors.

The scale of a prize needed to drive the outcome we describe may strike some as impolitic. However, we believe it could be argued that this is a more politically-stable approach to driving innovation than many current policies. The prize approach eliminates the risk of spending tax dollars on unsuccessful projects and could leverage private sector investment that is a large multiple of the government funds that would be expended.

In our view, this would be a zero-risk government investment strategy that could be copied elsewhere.

3.4.2 Tax Credit Contracts

No policy mechanism is without some degree of risk. All tax credits carry regulatory risk for the investor. Even so-called "permanent" tax credits are only permanent until the government changes its mind and eliminates the incentive. The greater the uncertainty related to any given tax incentive, the more diluted its impact on the economy. Investors and lenders will charge premiums as risks rise. Higher costs will slow project development. Boom and bust wastes government and private sector resources and undermines the effort to accelerate innovation and adoption.

How tax credits are structured drives financial decisions regarding investment in new project deployment. Relying on annual or multi-annual reauthorizations provides little guarantee that credits will be available for future projects, needlessly adding to the already robust set of risks impeding investment. Examples of this phenomenon are easy to find, ranging from wind and solar power industries to electric vehicles and biodiesel fuels.

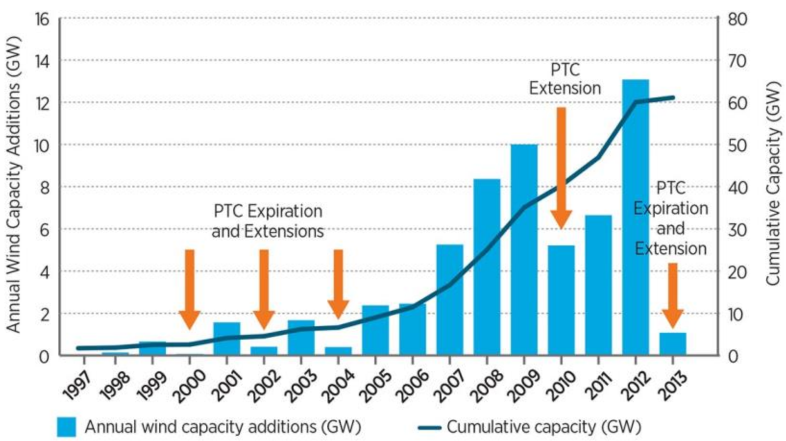


Figure 40. *Political Uncertainty surrounding the wind production tax credit shows strong positive correlation with lower annual wind capacity additions annually. Source: U.S. Department of Energy.*

Short-term tax credits create cyclical demand for investment. The history of the wind tax credit clearly demonstrates a boom-and-bust cycle tied to the expiration dates of a production tax credit (PTC) for wind turbine construction.[128] This is depicted in **Figure 40**.[129]

The wind PTC has been extended by Congress for a few years at a time in an almost-ritual cycle of two- or three-year incentives bracketed by political brinksmanship regarding the extension of the incentive. Each time the tax credit was extended, project investment soared. As the sunset of the incentive drew near and project completion by the relevant deadline became less likely, investment dried up and project development ground to a halt.

In addition to uncertainty of credit availability, tax credit caps (i.e. only applicable to the first 100,000 MW installed capacity) can scare investors as industry approaches the limit. Prior to the expansion of the 45Q tax credit in February of 2018, the 45Q tax credit only applied to the first 75 million tons of sequestered CO_2, driving away investments in new CEM projects whose investors had no guarantee credits would still be available after a multi-year construction commenced. Among other changes to the tax credit, the 2018 revamp instead allocates credits to any project which breaks ground before 2024.

One solution to these problems would be to assign tax credits to projects. Payment to projects would be guaranteed by contract and not liable to subsequent revision by government action. The certainty of a contract would enable projects to finalize financing more easily by eliminating the risk that a run-of-the-mill project delay would eliminate the project's eligibility for a given incentive, thus jeopardizing the project's financial viability.

This approach has a clear advantage for government accounting as well. It would enable far more predictable cost exposures compared with tax credits that may prompt greater or less utilization. The government could control the eligibility of projects by using the tax code to dictate the terms necessary to receive credits, which could include ceilings on total credits and time limits for eligibility. As political will dictates, funds could be added to increase the available contracting authority and increase the scope and number of projects.

The key design features of such an approach would necessarily include:

- Allow interested parties to sign contracts with the government and claim the tax credit as the project satisfies the terms established by the government (e.g. production targets, etc.)
- Make contracts available on a first-come, first-served basis until authorized limit on credits is fully contracted.
- Require private sector contract holders to make escrow payments to keep contracts in force, which means investors will seek, and maintain, contracts for only those projects and technologies that they judge to be viable.
- Cease escrow payments for failing projects and use the surrendered contract value for other projects.
- Allow successful projects to claim tax credits as established targets are met, up to the limit of the contract.

The benefits of this approach include:

- The contract would enable investors to count the tax credit as part of ROI and pro forma financial statements and calculations.
- Without increasing the cost exposure to the treasury, tax credits could be used to induce investment in development and deployment of more ambitious and innovative technologies.
- The government would pay only for the results achieved by contract holders and could reduce the risk of investing in assets that could subsequently become stranded or uneconomic with the loss of revenues from tax credits.
- With this approach, the government would increase its reliance on the private sector's expertise in risk management and project development rather than its own assessment of technologies and project teams.

3.4.3 Better Grant Systems for Demonstration Projects

Pay for Success – Not Promises

Too often in the past, government technology assistance has been the first money into a demonstration project. That means the government takes the largest risks of any investor – yet in most cases the government agency will have less expertise than private sector project participants to judge the technology and commercial risks facing a project. As the capital needs of projects escalate, government contributions should be increasingly conditioned on the achievement of appropriate performance metrics. While this approach is likely to add slightly to the overall financing costs of a project, it will shift the technology performance risk back to the private sector where there is greater expertise to assess the risks.

The government should offer dependable, and financially attractive, contracts to technology developers that guarantee government payment once the performance goal has been met. In such system, projects with an appropriate level of technology readiness will be able to attract capital. In cases where the technology is not demonstrably ready, investments should flow into more rigorous demonstration or R&D as needed.

Use Rolling Applications

Innovation does not take place on a schedule. It proceeds by fits and starts. Consequently, the notion of holding a grant competition with a fixed closing date often forces applicants to exaggerate their readiness in order to satisfy the government deadline. If the government approach places its emphasis on demonstrations of readiness, rather than calendar-based deadlines, it is likely to encourage investment in technology validation activities among those seeking government support for their next scale-up project. That means the private sector will be more engaged in refining and proving its approaches and the government will get better-prepared projects to consider supporting.

3.4.4 Regulatory Risk Insurance

A persistent risk exists that any price signal created by a government program (e.g. tax credit, emissions trading credit, etc.) can be devalued by a future government action. Given that project investors have limited ability to secure guarantees that the government will not modify a program in the future, the value of these government programs are more limited than some might expect. This is especially problematic for projects with high CAPEX demands and long pay-off horizons. Investors considering projects that will break even or return profits quickly after startup may have fewer concerns about the potential loss of revenues from a government price signal. The longer the payback for a project, the more investors are forced to confront the long-term prospects that any branch of government may intervene to modify the program in the future in ways that undermine the project's profitability.

The consequence of the uncertainty is a greatly diminished appetite for private investment in technologies and projects with long development or payback time horizons. There are multiple tools available for projects looking to mitigate potential market risks, including contracts, counter-party bonding requirements, and insurance. There are no analogous tools to guard against the risk to a project from the loss of revenue predicated on a government program.

The government should consider offering insurance or contracts directly to projects to make financing based on government incentives viable for a larger number of projects. This approach would have the government sign a contract with the project guaranteeing to make up any losses if the value of, for instance, a tradeable emission credit falls below an established floor price. The government has long offered such insurance for farmers to support the economic viability of food production despite the vagaries of global commodity prices and weather conditions. It could take a similar approach to the development of decarbonization technologies – especially for those intended to benefit from purpose-built decarbonization incentives.

3.4.5 Improving and Standardizing Life-Cycle Analysis

Understanding the GHG consequences of commercial technologies and practices is a complex and unsettled field. How to properly and consistently account for direct and indirect GHG emissions attributable to any activity often depends on data that is not available or is spotty at best.

Decarbonization based on programs that put a price on decarbonization need greater certainty regarding how GHG emission accounting practices will work. Uncertainty regarding what is included or excluded from the carbon accounting for a given technology or project will add to investor reticence and slow technology development, demonstration, and deployment.

The government and climate stakeholders can contribute significantly to greater market confidence for decarbonization investments of all types by increasing the standardization of carbon accounting.

Appendices and References

Appendix A

KEY TAKEAWAYS FOR

ICAC Members

- CEM technologies are increasingly being viewed as a critical element of the response to climate change by policymakers and stakeholders.
- Future market demand for CEM technologies is likely to rise as efficiencies improve, additional technologies are demonstrated, and public policy support increases.

Policymakers

- Meeting decarbonization targets without CEM technologies could more than double the cost.

Climate Stakeholders

- Limiting global average temperature increases to 2°C will take longer and may be impossible without CEM technologies.

The Vital Importance of CEM Technologies

CEM Is Essential as World Economies Grow

Climate change is a global environmental challenge. The pressing need to reverse the buildup of greenhouse gases in the atmosphere cannot be met without significant contributions from carbon emissions management technologies. In this appendix, we explain why CEM technologies are poised to make a significant contribution to the portfolio of decarbonizing strategies.

Global GHG emissions continue to increase despite growth in renewable energy use.

Overview

Despite progress toward decarbonization, the global economy remains overwhelmingly powered by fossil fuels. To date, decarbonization has kept pace with the annual increases in energy demand, but GHG emissions are rising as global economic expansion drives greater demand for energy, largely from fossil fuels. [130] The International Energy Administration (IEA) reports that global energy demand will be more than 25 percent higher than today's levels by 2040, and more than 40 percent higher than 2010 levels. IEA projects that coal-fired power generation will remain steady or even slightly increase by 2040, primarily driven by increased generation by India, China, and the Middle East.[131] According to modeling done by Carbon Brief, an additional 236 GW are under construction, with plans for a further 336 GW of generation; by contrast, only 227 GW have been retired, with another 186 GW slated to retire by 2030.[132] Given the dual needs of sustaining global economic growth and reducing GHG emissions, CEM can make important contributions to decarbonization by capturing and managing CO_2 and other GHG emissions. ***Figures 41.1*** and ***41.2*** chart the world energy-related emissions and consumption from fossil fuels.[133, 134]

Paris Agreement Set 450ppm/2°C Limit

When international climate negotiators met in Paris in 2016, 195 countries signed the Paris Agreement, pledging decreases in greenhouse gas emissions to limit atmospheric GHG concentrations to 450ppm CO_2-equivalent with a goal of preventing global temperature increases above 2°C. Scientists widely agree that temperature increases above 2ºC will lead to potentially irreversible changes in our climate. Rapidly increasing concentrations of greenhouse gases (GHG) in the atmosphere will lead to temperature increases above 2ºC.[135] In fact, scientists are increasingly focusing on a 1.5ºC threshold as the safest pathway for humanity.

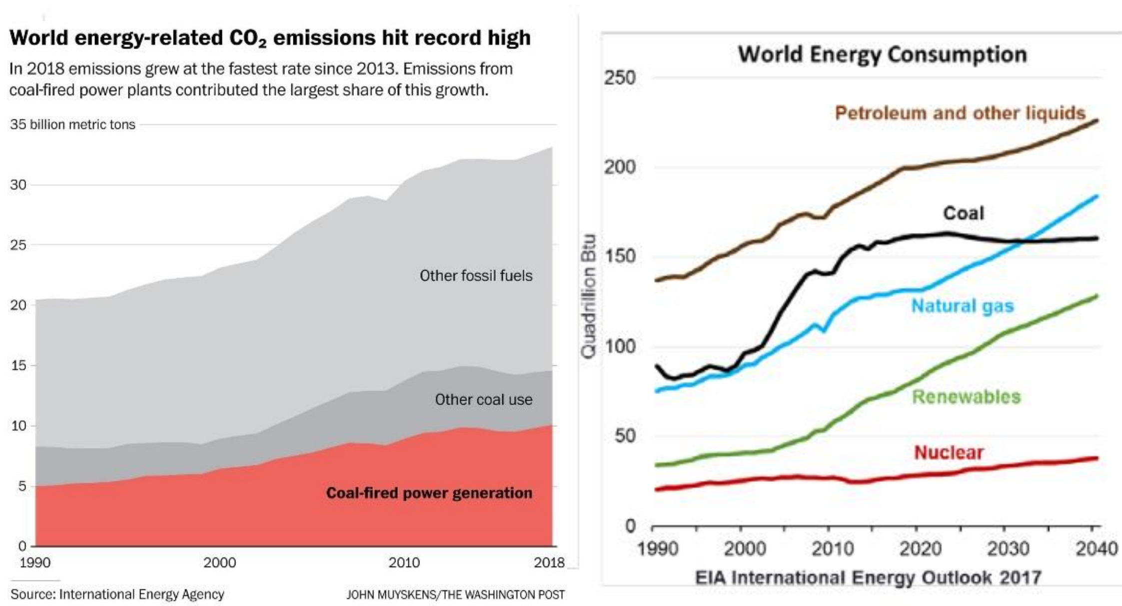


Figure 41.1/41.2. *Growing global energy demand results in increasing emissions from and consumption of fossil energy through 2040, despite a rise in renewables. Source: The Washington Post and U.S. Energy Information Administration.*

Figure *42* illustrates the modeling results that indicate limiting temperature increases to 2ºC above pre-industrial levels can only be accomplished by keeping atmospheric GHG concentrations below 450 ppm CO_2eq[136].

Support for CEM Evolved after the Paris Agreement

Focusing on the 2ºC target, climate researchers and stakeholders have turned to identifying the technologies needed to decarbonize the economy. Most economic activity consumes energy and most energy demand is currently served by fossil fuel combustion, which also releases enormous quantities of GHGs.

CO_2-eq Concentrations in 2100 (ppm CO_2-eq) [f] Category label (conc. range)	Subcategories	Relative position of the RCPs [d]	Change in CO_2-eq emissions compared to 2010 (in %) [c]		Likelihood of staying below a specific temperature level over the 21st century (relative to 1850–1900) [d, e]			
			2050	2100	1.5°C	2°C	3°C	4°C
<430	Only a limited number of individual model studies have explored levels below 430 ppm CO_2-eq [j]							
450 (430 to 480)	Total range [a, g]	RCP2.6	−72 to −41	−118 to −78	*More unlikely than likely*	*Likely*	*Likely*	*Likely*
500 (480 to 530)	No overshoot of 530 ppm CO_2-eq		−57 to −42	−107 to −73	*Unlikely*	*More likely than not*		
	Overshoot of 530 ppm CO_2-eq		−55 to −25	−114 to −90		*About as likely as not*		
550 (530 to 580)	No overshoot of 580 ppm CO_2-eq		−47 to −19	−81 to −59		*More unlikely than likely [i]*		
	Overshoot of 580 ppm CO_2-eq		−16 to 7	−183 to −86				
(580 to 650)	Total range	RCP4.5	−38 to 24	−134 to −50				
(650 to 720)	Total range		−11 to 17	−54 to −21		*Unlikely*	*More likely than not*	
(720 to 1000) [b]	Total range	RCP6.0	18 to 54	−7 to 72	*Unlikely [h]*		*More unlikely than likely*	
>1000 [b]	Total range	RCP8.5	52 to 95	74 to 178		*Unlikely [h]*	*Unlikely*	*More unlikely than likely*

Figure 42. *The projections above outline pathways to keep the earth's temperature below certain temperature increase thresholds. The key to staying below the critical 2°C is to have CO_2 concentrations of 450 CO_2-eq or less in 2100. Source: IPCC.*

For several decades, decarbonization focused mainly on energy resources that did not require combustion, such as increased energy efficiency, wind, solar, and nuclear power, as well as battery storage and hydrogen fuel cells. The common thinking was that if fossil combustion was the root cause of the problem, then displacing fossil energy was the solution. The potential for CEM to provide decarbonization went largely overlooked. Realistically, however, the dense energy provided by fossil fuels provides unmatched on-demand power and thoughtful analysts have concluded that fossil fuels will remain a key component of the energy mix for decades to come in both the electrical generation sector and in transportation.

As a result, in the years since the Paris Agreement, an increasing number of climate stakeholders now recognize and support the role of CEM technologies as a critical component of any serious decarbonization effort.

Furthermore, there is a growing interest in industrial combustion carbon capture, and for a wide range of other GHG capture, utilization, and sequestration strategies. CEM will serve a crucial role because of the following:

- Barriers limit the adoption of fossil-energy alternatives.
- Climate scientists have brought greater understanding of the urgency of the problem.
- Certain industrial sectors have little or no viable alternatives to fossil-fuel combustion.

To be clear, some climate stakeholders will continue to promote an "all-renewables" approach and will resist incentives that increase CEM's ability to contribute to decarbonization. The Energy Transitions Commission notes the persistence of this view in some quarters. "Several scenarios for achieving the Paris climate objectives assume that, by 2100, carbon capture and sequestration cold account for 18Gt per annum of emission reductions. There are concerns that these huge volume assumptions are used to justify continued large-scale fossil fuel production use."[137]

Diverse perspectives are commonplace in public policy debates. We believe the trend most worth watching is the growing enthusiasm for CEM among climate stakeholders rather than residual resistance to CEM's role.

Barriers Limiting Fossil Energy Replacements

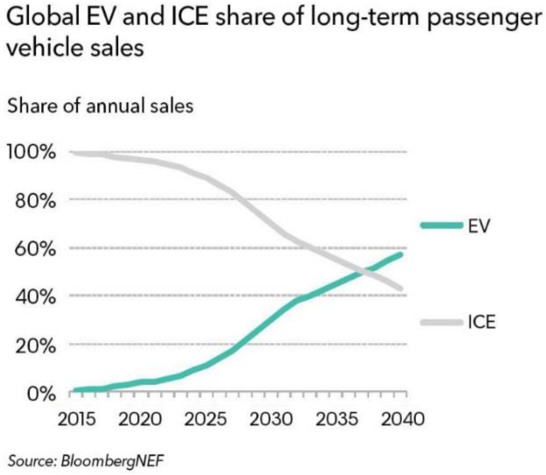


Figure 43. Bloomberg's Electric Vehicle Outlook 2019 projects that sales of EVs will not surpass sales of ICE vehicles until the late 2030s. Source: Bloomberg.

Renewable power generation is a booming business. Increasingly a least-cost option in the power market, but several factors constrain its ability to completely displace fossil combustion globally and domestically.[138]

The automobile sector is increasing low- and zero-GHG emission vehicle options, but sales are not projected to displace global demand for internal combustion engines in the next two decades (see **Figure 43**), even in those regions with the highest rates of electric vehicle adoption.[139]

The technical and economic challenges of managing decarbonization exclusively through renewable and storage solutions are increasingly clear. Progress toward decarbonization is accelerating, but all sectors face lengthy transition periods to net-zero GHG emissions. Progress overcoming political, technical, and commercial barriers is evident and should further accelerate adoption of fossil fuel alternatives.

The Urgency of the Problem is More Widely Understood

As physical evidence continues to validate scientific climate change predictions, the urgency for decarbonization increases. In many cases, prior projections underestimated the consequences of rising GHG concentrations. The scale and speed of decarbonization needed to keep global temperature increases beneath 2°C are driving stakeholders to embrace expanding options for technologies and

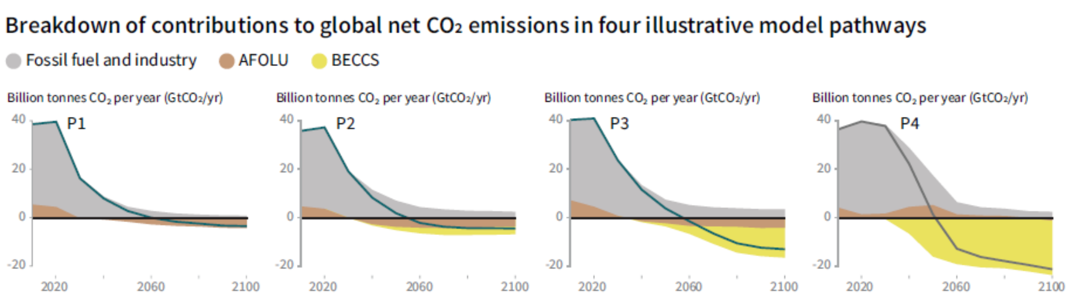


Figure 44. *IPCC's analysis on the effects of limiting warming to 1.5°C evaluates four scenarios in depth. All require significant emissions reductions of the fossil energy sector, with varying amounts of supplemental negative emission technologies including agriculture, forestry, and other land use (AFOLU) and bioenergy carbon capture and storage (BECCS). Source: International Institute for Applied Systems Analysis.*

commercial pathways that can achieve faster, more flexible, and less expensive decarbonization solutions. There is a growing realization that the portfolio of options for decarbonization must expand, as shown in **Figure 44**.[140]

GHG emission reductions achieved through fossil fuel alternatives are not keeping pace with global GHG emission increases related to economic expansion. Deployments of fossil energy replacement technologies are not occurring fast enough, leaving some industries with no viable pathways for eliminating fossil fuel combustion in the near term. As a result, climate researchers now routinely include CEM to model global GHG emission reduction scenarios – as shown in **Figure 45** from the IPCC.[141]

Policy developments around the globe reflect increased support for including CEM in the "portfolio" of decarbonizing technologies. More private sector resources are focusing on developing new materials and technologies to enable commercial deployment of CEM. While some of the largest emission control technology companies remain on the sidelines, we anticipate that will not remain the case for much longer.

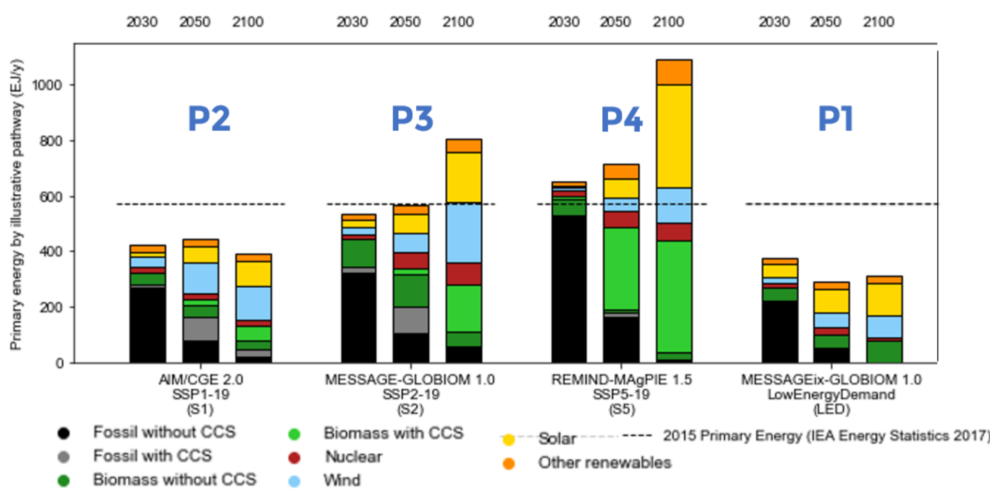


Figure 45. *Out of IPCC's four evaluated pathways to limit warming to 1.5°C, two assume reductions in energy consumption and two require increases in negative emissions technology. Source: Intergovernmental Panel on Climate Change.*

Certain Industrial Sectors Have Little or No Viable Alternatives to Fossil-Fuel Combustion

Some industrial sectors have little visibility on a low- or zero-GHG emission pathway. Cement and steel production – vital materials with demand curves tightly tied to economic growth – are two examples of industrial sectors that have no currently viable alternatives to using fossil fuels in the production process. **Figure 46** shows the growing global demand for cement through 2050, thus leading to the growing use of fossil fuels.[142] The cement industry expects a continued rise in demand through 2050, and other hard-to-decarbonize sectors (like steel) are facing similar projected increases in demand. These increasing demands are most prevalent in developing nations, such as India and China. However, even as efficiency gains and other process improvements reduce the carbon intensity of production, these sectors remain large and growing emitters of CO_2.

Various industries are expected to continue to depend on fossil fuels for decades. For these sectors, some form of industrial carbon waste management is the most likely path toward decarbonization. Leaving unaddressed the emissions from these sectors would undermine global GHG emission reduction efforts as economic growth continues to drive demand for steel, cement, chemicals, and products from other hard-to-decarbonize sectors.

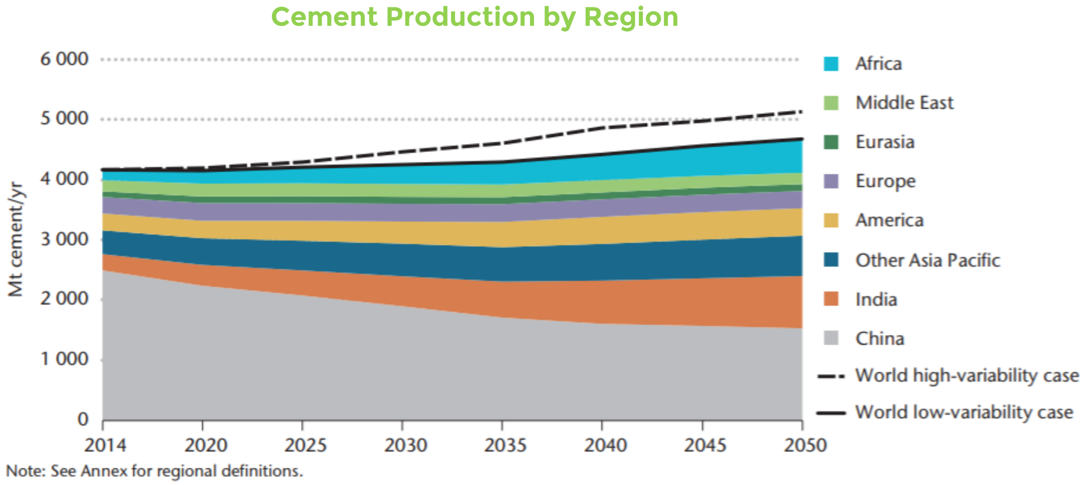


Figure 46. *Global demand for cement is projected to increase, representing a hard-to-decarbonize sector that will need CEM technologies. Source: U.S. Geologic Service.*

CEM Expands the Decarbonization Portfolio

The 2014 Intergovernmental Panel on Climate Change (IPCC) modeled scenarios needed to cap global temperature increases at 2°C.[143] All of the scenarios included significant contributions from CEM.

While many technologies, can reduce the rate at which GHG emissions occur, only CEM can meaningfully address the problem by pulling GHGs directly out of the atmosphere. Carbon captured from combustion sources in the power generation and industrial sectors can prevent dGHG emissions from reaching the atmosphere. Direct air capture (DAC) can remove previously released CO_2 from the atmosphere. Fugitive emission capture systems can prevent methane emissions from coal and gas extraction sites, as well as from gas processing and transportation infrastructure. Together, these capture mechanisms can significantly expand options for reducing atmospheric concentrations of CO_2.

Recognizing the importance of Carbon Capture and Storage (CCS – which we are treating as a sub-category of CEM), the International Energy Administration indicated the technology is crucial to address residual fossil use in power generation and industry.

Research into commercially viable CEM technologies covers an increasingly diverse exploration of capture, conversion, and utilization techniques. These range from current carbon capture and sequestration to highly experimental capture and utilization strategies. They include pre- and post-combustion carbon capture, direct air capture, and fugitive emission capture. They also include the potential use of captured waste material as feedstock to produce construction materials, fuels, and specialty chemicals. All of these applications will demand significant advances in enabling materials and components, as well as the design and manufacture of gas management systems on a scale never attempted. This will present new environmental challenges and business opportunities for the emission control sector.[144]

CEM Complements a Decarbonization Portfolio

CEM technologies will complement renewable and storage options and help to close the gaps between emission reductions achieved from fossil fuel displacement (via renewable energy, etc.) and the additional GHG reductions needed to achieve the goals of the Paris Agreement.

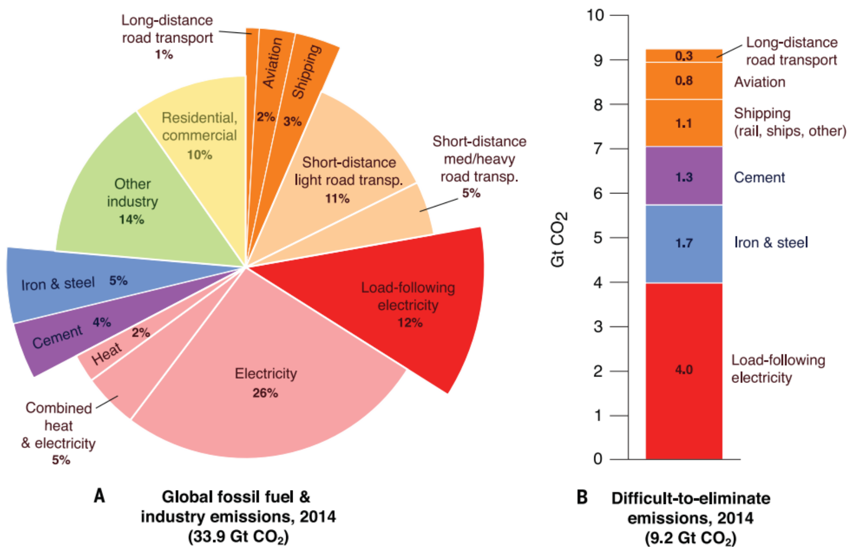


Figure 47. *Hard-to-decarbonize sectors' CO_2 emissions account for the largest percentage (approximately 28 percent) of total global fossil fuel and industry emissions.*

CEM technologies will expand the technology solutions and economic options available to multiple industries. Cement, steel and other sectors that are difficult to decarbonize will continue to produce GHG emissions absent the deployment of effective CEM technologies. Figure 47 highlights the fact that hard-to-decarbonize sectors account for the largest percentage of global fossil-fired emissions.[145] CEM can reduce emissions from sources that will continue to rely on fossil energy for decades, thus reducing emissions faster than would be possible from a strategy that relies solely on replacing fossil energy. CEM can also contribute to faster deployment of renewable power generation capacity by partnering with renewable power projects to supply energy needed for carbon capture and utilization. Renewable power projects often struggle to secure long-term offtake contracts lenders demand as routine project financing practices. CEM technologies all require power. The degree to which future CEM projects are powered by zero-carbon resources directly influences their overall decarbonization value. This creates an interesting commercial potential for the co-development of renewable power and CEM projects. Renewable power increases the decarbonizing benefit of CEM projects. Signing CEM projects as long-term customers will enable new renewable power projects to be more easily financed.

Without CCS, the transformation of the power sector will be at least $3.5 trillion more expensive.

CEM Addresses Hard-to-Decarbonize Sectors

CEM technologies will be particularly important in countries that cannot switch entirely from fossil fuels to renewables because their large population and demand for consumer goods will continue to expand, such as China and India. For example, 81 percent of India's electricity as of 2014 was generated by fossil fuels (mostly coal). In 2016, India added more than 72 GW of fossil-fired capacity to their electricity grid – one year ahead of projections.[146]

Even where government policies promote aggressive deployment of renewable power, certain sectors of the economy will be difficult to decarbonize. Fossil fuel combustion cannot be easily or economically eliminated from steel, cement, or chemical production processes. Aviation and other transportation sectors also lack viable alternatives to fossil fuel. Various carbon capture strategies, including DAC, can be used to mitigate or offset the emissions from these sectors.

CEM Reduces the Cost of Decarbonization

Cost is a central challenge facing the decarbonization effort. Fossil energy remains the least expensive means of powering economic development globally. Adopting lower GHG emitting strategies usually increases costs for businesses and consumers and unless government programs underwrite those added costs, low-carbon strategies will face market resistance. The higher the costs, the greater the market resistance and political resistance to programs designed to offset those costs.

One of the most important arguments in favor of CEM is that it dramatically reduces the costs associated with decarbonization. **Figure *48*** summarizes work done by the IPCC to test the cost implications of excluding certain technologies from the decarbonization portfolio.[147] This work found that achieving the 450 ppm CO_2eq target in the Paris Agreement without CEM would be the most expensive approach of all those tested. Excluding CEM increased costs of decarbonization by an average of 138 percent, and most models indicated the 450 ppm target could not be achieved at all without CEM. By contrast, models looking to achieve the 450 ppm target without renewable power were an average of 6 percent more expensive than those that included renewables in the technology portfolio.[148] Many other climate research efforts (including those by IEA) reached similar conclusions.

Mitigation cost increases in scenarios with limited availability of technologies

[% increase in total discounted mitigation costs (2015-2100) relative to default technology assumptions]

2100 Concentrations (ppm CO2 –eq)	No CCS	Nuclear Phase Out	No Solar/Wind	Limited Bioenergy
450	138% (29-297%)	7% (4-18%)	6% (2-29%)	64% (44-78%)

LEGEND* Less than 50% of models successful | 50-80% of models successful | 80-100% of models successful

*The range is determined by the central scenarios encompassing the 16th to 84th percentile range of the scenario set. Only scenarios with a time horizon until 2100 are included.

Figure 48. *The IPCC model shows that the cost to stay at 450 CO_2-eq would be 138 percent cheaper with CCS. Additionally, less than 50 percent of the models in the study found that the 450 CO_2-eq threshold would be attainable without CCS. Source: IPCC.*

CEM Does Not Present a Moral Hazard

Economists define a moral hazard as something that protects a market actor from exposure to the potential harms of an inherently risky behavior and serves to incentivize, rather than discourage, that behavior.

Some climate stakeholders have expressed concerns that investing in CEM could reduce the societal sense of urgency necessary to shift the global economy from fossil fuels to renewable resources. Others suggest that CEM may have a role to play but only after all opportunities to deploy renewable energy have been fully explored and deployed to the maximum extent possible.[149]

The National Academy of Sciences (NAS) disagrees: "Negative emission technologies [which includes CEM] are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of carbon dioxide only after anthropogenic emissions have been eliminated."[150]

Similarly, the World Resources Institute points to the ability of CEM technologies to play a "complementary role" alongside other decarbonization strategies.[151]

In sum, CEM technologies present no moral hazard. When used in combination with renewable energy resources, CEM provides decision-makers with tools for decarbonization that complement the goal of reducing GHG emissions and keeping global temperature increases below 2°C.

APPENDIX B

Other Greenhouse Gases and Control Technologies

Although carbon dioxide and methane account for the largest shares of the total U.S. GHGs (see *Figure 49*), there are additional GHGs that negatively impact the earth's atmosphere and are present in higher concentrations.[152]

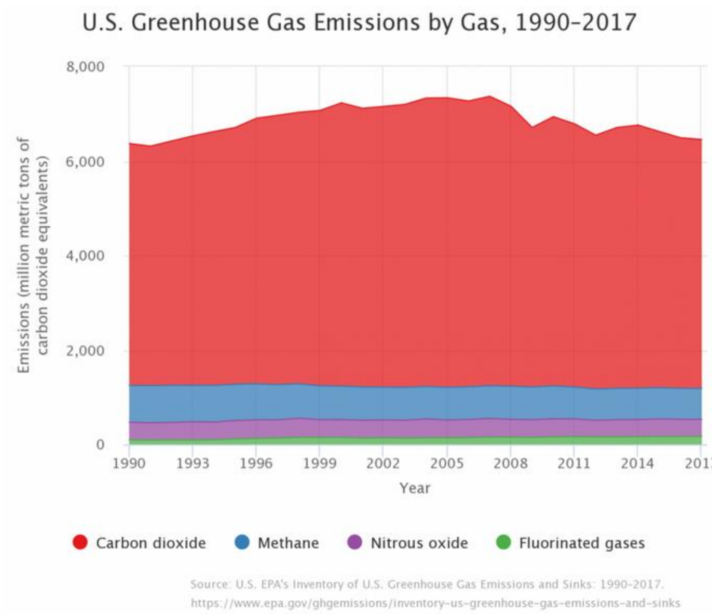


Figure 49. *Carbon dioxide is the most prevalent GHG, however, there are additional GHGs that negatively impact the earth's atmosphere that must be considered. Source: U.S. EPA.*

Nitrous oxide (N_2O) and fluorinated gases represent a growing emission control and measurement opportunity. These emissions are much more potent and have significantly greater global warming potentials (GWPs) compared to carbon dioxide and methane. Control technologies currently exist and continue to be developed with the intent to mitigate these GHGs and their impact.[153]

Below, we describe the background, current regulations and control technologies for Nitrous oxide (N_2O) and fluorinated gases.

Global Warming Potential (GWP) of Greenhouse Gases

Chemical	GWP (100 years)
Carbon Dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Fluorinated Gases	
HFCs	up to 14,800
PFCs	7,390-12,200
NF_3	17,200
SF_6	22,800

Source: U.S. EPA

Nitrous Oxide (N_2O)

Nitrous oxide is nearly 300 times more potent than carbon dioxide and accounts for nearly 6 percent of total greenhouse gas emissions in the U.S.

Human activities are increasing the amount of N_2O in the atmosphere. As of 2017, the largest contributing sector to N_2O emissions is agricultural soil management through nitrogen-based fertilizers (74 percent), while stationary combustion emissions accounts for 8 percent and industry/chemical production activities account for 6 percent. N_2O is also a naturally occurring emission from the nitrogen cycle associated with plants, animals and microorganisms. It can be destroyed naturally as well through bacteria absorption, UV radiation or chemical reactions.[154]

In the U.S., N_2O emissions have decreased by nearly 3 percent since 1990, however, overall global emissions have increased 20 percent over pre-industrial levels.[155]

N_2O Emission Regulations

Regulations exist in the European Union (EU) to set permit limits for N_2O emissions based on best available control technologies (BACT) in the EU Industrial Pollution Prevention and Control (IPPC)

Directive. Under the Kyoto Protocol's Clean Development Mechanism (CDM), countries can generate tradeable carbon credit and financial revenues through N_2O reduction projects.[156]

N_2O Control Technologies

N_2O can be controlled through the use of a catalyst. Catalysts have also been successfully reducing NO_x emissions for decades. This technology is commercially available today and is capable 99 percent N_2O reductions.[157]

BASF offers the NO_xCAT™ ZN_2O Destruction Catalyst that injects ammonia into the gas stream containing N_2O. Both NO_x and N_2O are reduced at temperatures as low as 300°C and up to 600°C. Operators can remove both chemicals through the combined use of other SCR technologies by introducing ammonia into the catalytic bed, consisting of an SCR catalyst and the NO_xCAT ZN_2O.[158]

Shell Catalysts and Technologies (CRI Catalysts) offers the C-NAT catalyst that can be used to reduce N_2O from industrial and chemical processes, such as nitric acid, Caprolactam, and adipic acid plants.

Other companies that offer solutions using catalysts include Clariant, Sud-Chemie, Uhde, and Yara.

Fluorinated Gases

Fluorinated gases are emitted from human-related activities through:

- Their use as substitutes for ozone-depleting substances (refrigerants, aerosol propellants, foam blowing agents, solvents and fire retardants), and
- Industrial processes (aluminum production, semiconductor manufacturing and electricity transmission).

Overall, they are the most potent greenhouse gas type. According to the EPA, the 'Global Warming Potential' of SF_6 is more than 22,000 times higher than CO_2.

Since 1990, fluorinated gas emissions have risen 70 percent in the U.S., largely through the increasing substitution (+240 percent) of hydrofluorocarbons (HFCs) for ozone-depleting substances.

Fluorinated Gas Regulations

The Kigali Amendment under the Montreal Protocol has put in place an international compulsory phase-out of chlorofluorocarbons (CFCs) and the United Nations has displayed support for a similar approach to phasing out HFCs.[159]

The EPA regulates fluorinated gases under the Significant New Alternatives Policy (SNAP) program and aims to reduce fluorinated gases further through the Fluorinated Gas Partnership Program. In this program, EPA coordinates with industry groups to cost-effectively reduce emissions through the development of technologies or the adoption of new practices.[160]

In the EU, the European Commission limits the number of fluorinated gases sold, used and emitted in an effort to cut emissions by two-thirds by 2030 compared to 2014 levels through the F-Gas Regulation and the Mobile Air Conditioning Directive.[161]

Fluorinated Gas Control Technologies

Various methods may be applied to destroy fluorinated gases, such as superheated steam, submerged combustion, ark plasma, solid alkali reaction, catalysts, municipal waste incineration, cement kilns/lime calcination furnaces, or electric furnaces.

Johnson Matthey offers LTC-20 for controlling halocarbons, including fluorocarbons. BASF offers the VOCat® 360 PFC catalyst, which can be used to destroy fluorinated and chlorinated VOC compounds.

Solvay Chemicals, a global supplier of SF_6, has introduced a re-use program to stop the release of the chemical into the atmosphere and regenerate it into a reusable state.

REFERENCES

[1] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 361). Washington, DC: The National Acadamies Press.

[2] National Academies of Sciences, Engineering, and Medicine. (2019). *Gaseous Carbon Waste Streams Utilization: Status and Research Needs* (pg 17). Washington, DC: The National Academies Press.

[3] The Institute of Clean Air Companies (ICAC) Domestic Conventional Pollutants Division and Emissions Measurement Division. (2017). *Issue Brief for United States Environmental Protection Agency*. Arlington, Virginia: The Institute of Clean Air Companies.

[4] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States.* Washington, DC: World Resources Institute.

[5] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio* (pg 44). Washington, DC: Information Technology & Innovation Foundation.

[6] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 15). Washington, DC: The National Acadamies Press.

[7] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States.* Washington, DC: World Resources Institute.

[8] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States.* Washington, DC: World Resources Institute.

[9] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 124). London, England: Energy Transitions Commission.

[10] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 10). Paris, France: International Energy Agency.

[11] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 11). Paris, France: International Energy Agency.

[12] Davis, S. J. (2018, June 29). Net-zero Emissions Energy Systems. *Science* (pgs 1-5), 9.

[13] Davis, S. J. (2018, June 29). Net-zero Emissions Energy Systems. *Science* (pgs 1-5), 9.

[14] Davis, S. J. (2018, June 29). Net-zero Emissions Energy Systems. *Science*, (pg 1), 9.

[15] 100 & Change. N.d. *CO_2 Sciences, Inc*. New York, New York: Foundation Center.

[16] Figure 6. Potential increase in market size due to implementation of strategic actions. Taken from *Global Roadmap for Implementing CO_2 Utilization* by CO_2Sciences/The Global CO_2 Initiative (2016).

[17] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio* (pg 45). Washington, DC: Information Technology & Innovation Foundation.

[18] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio* (pg 41). Washington, DC: Information Technology & Innovation Foundation.

[19] 40 CFR Part 60 [EPA–HQ–OAR–2013–0602; FRL–9930–65– OAR] RIN 2060–AR33 Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units AGENCY: Environmental Protection Agency (EPA). ACTION: Final rule.

[20] Figure 7. Private and public investment in large-scale CCS projects (2005-2014). Taken from: BNEF (2016) Clean energy and investment trends.

[21] Figure 8. Number of patents for carbon or carbon dioxide capture, U.S. and global. Espacenet. (2017). *Patent Search*. Retrieved from: https://worldwide.espacenet.com.

[22] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 28). London, England: Energy Transitions Commission.

[23] U.S. Department of Energy. (2016). *The Future Arrives for Five Clean Energy Technologies – 2016 Update*. Washington, D.C.: U.S. Department of Energy.

[24] Figure 9. Timeline of Technology Development vs. Cumulative Capacity: Wind. U.S. Department of Energy. Taken from *The Future Arrives for Five Clean Energy Technologies – 2016 Update* by U.S. Department of Energy. (2016).

[25] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 35). London, England: Energy Transitions Commission.

[26] The Institute of Clean Air Companies (ICAC) Domestic Conventional Pollutants Division and Emissions Measurement Division. (2017). *Issue Brief for United States Environmental Protection Agency*. Arlington, Virginia: The Institute of Clean Air Companies.

[27] Schlissel, D., Wamsted, D. (2018). *Holy Grail of Carbon Capture Continues to Elude Coal Industry* (pg 2). Cleveland, Ohio: Institute for Energy Economics and Financial Analysis.

[28] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States* (pg 5). Washington, DC: World Resources Institute.

[29] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States* (pg 7). Washington, DC: World Resources Institute.

[30] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 10). Paris, France: International Energy Agency.

[31] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 28). London, England: Energy Transitions Commission.

[32] Mulligan, J., Ellison, G., Levin, K., & McCormick, C. (2018). *Technological Carbon Removal in the United States* (pg 1). Washington, DC: World Resources Institute.

[33] National Coal Council. (2016). *CO_2 Building Blocks, Assessing CO_2 Utilization Options*. Washington, D.C.: National Coal Council.

[34] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 26). Paris, France: International Energy Agency.

[35] Global CCS Institute, 2018. CO2RE Database. https://CO2RE.co.

[36] Figure 12. CO_2 Capture Pathways. Taken from *Near-Zero Emissions Oxy-Fuel Combustion* by Natural Resources Canada. (2016).

[37] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 22). London, England: Energy Transitions Commission.

[38] Figure 13. Post-combustion capture process. Image from http://www.fossiltransition.org/pages/post_combustion_capture/110.php. Copyright 2019 by Clean Air Task Force.

[39] National Energy Technology Laboratory. *Carbon Capture Program.* Retrieved from https://www.netl.doe.gov/coal/carbon-capture

[40]U.S. Department of Energy. Accelerating Breakthrough Innovation in Carbon Capture, Utilization, and Storage. (2017). Washington, D.C. U.S. Department of Energy.

[41] Figure 14. Pre-combustion capture process. Image from http://www.fossiltransition.org/pages/pre_combustion_capture/110.php. Copyright 2019 by Clean Air Task Force.

[42] Clean Air Task Force. (2019). *Pre-Combustion Capture*. Retrieved from: http://www.fossiltransition.org/pages/pre_combustion_capture/110.php

[43] National Energy Technology Laboratory. *Pre-Combustion CO_2 Capture.* Retrieved from https://www.netl.doe.gov/coal/carbon-capture/pre-combustion

[44] Fehrenbacher, K. (2017). *Carbon Capture Suffers a Huge Setback as Kemper Plant Suspends Work.* Massachusetts: Greentech Media.

[45] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 148)*.* Washington, DC: The National Acadamies Press.

[46] Figure 15. Diagram for power generation with oxy-combustion capture. Image from Natural Resources Canada, (2016). Sourced from https://www.nrcan.gc.ca/energy/energy-sources-distribution/coal-and-co2-capture-storage/carbon-capture-storage/near-zero-emissions-oxy-fuel-combustion/4307

[47] Markewitz, Peter; Leitner, Walter; Linssen, Jochen; Zapp, Petra; Muller, Thomas; Schreiber, Andrea (2012-03-01). "Worldwide innovations in the development of carbon capture technologies and the utilization of CO2". *Energy & Environmental Science.* 6. 7281-7385. Retrieved 2019-09-07.

[48] European Cement Research Academy. Press release: *Cement industry launches an industrial-scale carbon capture project.* (29 January 2018). ECRA.

[49] NET Power. *Technology.* Retrieved from https://www.netpower.com/technology/#eor

[50] Natural Resources Canada. (2016). *Near-zero Emissions Oxy-fuel Combustion.* Retrieved from https://www.nrcan.gc.ca/energy/energy-sources-distribution/coal-and-co2-capture-storage/carbon-capture-storage/near-zero-emissions-oxy-fuel-combustion/4307

[51] L. Zheng. (2011). *1 - Overview of oxy-fuel combustion technology for carbon dioxide (CO2) capture, Oxy-Fuel Combustion for Power Generation and Carbon Dioxide (CO2) Capture*. In Woodhead Publishing Series in Energy. ISBN 9781845696719. Retrieved from: http://www.sciencedirect.com/science/article/pii/B9781845696719500016.

[52] Figure 16. *Chemical looping combustions process*. Adapted from CO2CRC. Copyright 2019 by CO2CRC.

[53] Lyngfelt, A. & Linderholm, C. (2016) *Chemical-Looping Combustion of Solid Fuels – status and recent progress*. Göteborg, Sweden: Elsevier Ltd.

[54] Velazquez-Vargas, L.; Sakadjian, B.; Flynn, T.; Bao, J. (2018). *10 Megawatts Electric Coal Direct Chemical Looping Large Pilot Plant – Pre-FEED Study.* Babcock & Wilcox.

[55] Lyngfelt, A., Linderholm C. (2016). *Chemical-Looping Combustion of Solid Fuels – status and recent progress*. Göteborg, Sweden: Elsevier Ltd.

[56] FuelCell Energy, Inc. (2018). *How a Fuel Cell Works*. Danbury, Connecticut: FuelCell Energy, Inc.

[57] Eisler, M. (29 May, 2018). *Fuel Cells Finally Find a Killer App: Carbon Capture.* IEEE Spectrum. https://spectrum.ieee.org/green-tech/fuel-cells/fuel-cells-finally-find-a-killer-app-carbon-capture. Retrieved 2019-07-09.

[58] Figure 17. Potential CO_2 Capture Using Carbonate Fuel Cells. Adapted from *Carbon Capture with Fuel Cell Power Plants* by United States Energy Association. (2017).

[59] ExxonMobil. (2018). *Advanced carbonate fuel cell technology in carbon capture and storage.* Irving, Texas: ExxonMobil.

[60] Nathan, S. (21 January, 2019). *Fuel cell-based system converts atmospheric CO2 into usable electric current.* The Engineer. https://www.theengineer.co.uk/fuel-cell-based-system-co2/.

[61] Eisler, M. *Fuel Cells Finally Find a Killer App: Carbon Capture.* (29 May, 2018) IEEE Spectrum. https://spectrum.ieee.org/green-tech/fuel-cells/fuel-cells-finally-find-a-killer-app-carbon-capture. Retrieved 2019-07-09.

[62] Figure 18. Bio-Energy with CCS (BECCS) carbon flow. Taken from *Scientific Background for BECCS* by Global CCS Institute. (2011), Biorecro AB. Copyright 2011 by Biorecro AB.

[63] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 4). Washington, DC: The National Acadamies Press.

[64] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 8). Washington, DC: The National Acadamies Press.

[65] International Energy Agency. (2019). *World Energy Outlook 2019*.

[66] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 10). Washington, DC: The National Acadamies Press.

[67] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 187). Washington, DC: The National Acadamies Press.

[68] State CO_2-EOR Deployment Work Group (2017). *Capturing and Utilizing CO_2 from Ethanol.*

[69] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 128). Washington, DC: The National Acadamies Press.

[70] Figure 19. Sandlow, D., Aines, R., Friedmann, J., McCormick, C., McCoy, S. (2018). *ICEF Roadmap 2018: Direct Air Capture of Carbon Dioxide* (pg. 10). Tokyo, Japan. Innovation for Cool Earth Forum.

[71] Lindsey, R. (2018). *Climate Change: Atmospheric Carbon Dioxide*. Silver Spring, Maryland: National Oceanic and Atmospheric Administration.

[72] Figure 20. Carbon Engineering's direct air capture process. Taken from *Direct Air Capture* by Carbon Engineering Ltd. Copyright 2019 by Carbon Engineering Ltd.

[73] Sandlow, D., Aines, R., Friedmann, J., McCormick, C., McCoy, S. (2018). *ICEF Roadmap 2018: Direct Air Capture of Carbon Dioxide* (pg. 15). Tokyo, Japan. Innovation for Cool Earth Forum.

[74] Larsen, J., et al. (2019). *Capturing Leadership: Policies for the U.S. to Advance Direct Air Capture Technology*. New York, New York: Rhodium Group LLC.

[75] Fasihi, M., Efimova, O., Breyer, C. (2019). *Techno-economic assessment of CO2 direct air capture plants*. LUT University, Lappeenranta, Finland. Retrieved from Elsevier Journal September 26, 2019.

[76] Figure 22. National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 169). Washington, DC: The National Acadamies Press.

[77] Carbon Engineering. (2019). *Written Testimony of Steve Oldham CEO, Carbon Engineering Before the Senate Environment and Public Works Committee*. Washington, D.C.: U.S. Senate Environment and Public Works Committee.

[78] Figure 23. Carbon mineralization process. Taken from IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[79] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 5). Washington, DC: The National Acadamies Press.

[80] CarbFix. N.d. *What is CarbFix?*. Retrieved from https://www.carbfix.com/what-carbfix

[81] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 13). Washington, DC: The National Acadamies Press.

[82] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 4). Washington, DC: The National Acadamies Press.

[83] Figure 24. CO_2 sequestration from coastal sources. Adapted from *Clarifying the role of coastal and marine systems in climate mitigation* by Howard, J., et al. (2017). Copyright 2019 by Ecological Society of America.

[84] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 62). Washington, DC: The National Acadamies Press.

[85] NOAA Office for Coastal Management. (2018). *Reserves Advance "Blue Carbon" Approach to Conserving Wetlands*. Charleston, South Carolina: National Oceanic and Atmospheric Administration.

[86] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 62). Washington, DC: The National Acadamies Press.

[87] Figure 25. 2017 Sources of CH_4 Emissions. Taken from *Inventory of U.S. Greenhouse Gas Emissions and Sinks* by U.S. Environmental Protection Agency. (2017).

[88] U.S. Environmental Protection Agency. (February, 2017). U.S. EPA. Retrieved from: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[89] Figure 26. Global methane emissions by source. Adapted from *Methane Matters* by Voiland, A., Stevens, Joshua. (2016). NASA Earth Observatory with data from U.S. Environmental Protection Agency.

[90] Figure 27. Ventilation Air Methane. Taken from *Lean Methane – Fueled Gas Turbine Generator Set* by Kawasaki. (2018), Kawasaki. Copyright 2018 by Kawasaki Heavy Industries, Ltd.

[91] U.S. Environmental Protection Agency. (2019). *Overview of Greenhouse Gases*. Retrieved from: https://www.epa.gov/ghgemissions/overview-greenhouse-gases#methane

[92] Figure 28. U.S. Environmental Protection Agency. (2017). *Coal Mine Methane Sources*. U.S. EPA. Retrieved from: https://www.epa.gov/cmop/coal-mine-methane-sources

[93] Özgen Karacan, C., Ruiz, F.A., Coté, M., Phipps, S. (2011). *Coal Mine Methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction*. Amsterdam, Netherlands: Elsevier B.V.

[94] The National Institute for Occupational Safety and Health. N.d. *Methane Detection and Monitoring*. Washington, D.C.: Center for Disease Control.

[95] Schaser, N. (2015). *World's Largest Ventilation Air Methane/Coal Mine Methane Oxidation Project Goes Live*. Bietigheim-Bissingen, Germany. Dürr Systems, Inc.

[96] U.S. Environmental Protection Agency Coalbed Methane Outreach Program. (February 2016). *International Coal Mine Methane (CMM) Database.* Washington, D.C.: U.S. Environmental Protection Agency.

[97] Figure 29. U.S. Energy Mapping System. Taken from *U.S. States State Profiles and Energy Estimates* by U.S. Energy Information Administration. N.d.

[98] U.S. Environmental Protection Agency. (April, 2019). *Recommended Technologies to Reduce Methane Emissions*. Washington, D.C.: U.S. EPA.

[99] Sandlow, D., Aines, R., Friedmann, J., McCormick, C., McCoy, S. (2017). *Carbon Dioxide Utilization (CO2U)*. New York, New York: Innovation for Cool Earth Forum.

[100] Figure 30. The Concept of Geologic Carbon Sequestration. Taken from *The Concept of Geologic Carbon Sequestration* by U.S. Geological Survey, Duncan, D., & Morrissey, E.

[101] American Geosciences Institute. (2019). *How much carbon dioxide can the United States store underground via geologic sequestration?*. Alexandria, Virginia: American Geosciences Institute.

[102] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 10). Washington, DC: The National Acadamies Press.

[103] Figure 31. U.S. Department of Energy, Office of Fossil Energy (2019). Image sourced from https://www.energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery

[104] Office of Fossil Energy. N.d. *Enhanced Oil Recovery*. Washington, D.C.: U.S. Department of Energy.

[105] Brinckerhoff, P. (2011). *Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide*. Melbourne, Australia: Global CCS Institute.

[106] Figure 32. Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites. Taken from *Carbon Storage Atlas* by National Energy Technology Laboratory. N.d.

[107] Figure 33. Global long-term passenger vehicle fleet by drivetrain. Adapted from *Electric Vehicle Outlook 2019* by McKerracher, C., Izadi-Najafabadi A., Soulopoulos, N., Doherty D., … (2019). Copyright 2019 by Bloomberg Finance L.P.

[108] Government, Europa. (2018). *Climeworks direct air capture to partner with Coca-Cola.* Congleton, United Kingdom: Pan European Networks Ltd.

[109] California Air Resources Board. (2016). *Weekly LCFS Credit Transfer Activity Reports*. Sacramento, California: State of California Environmental Protection Agency.

[110] Jacobson, R., Lucas, M (2017). *A Review of Global and U.S. Total Available Markets for Carbontech.* Carbon180. Oakland, California.

[111] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio.* Washington, DC: Information Technology & Innovation Foundation.

[112] Bipartisan Budget Act of 2018, H.R. 1892, 115th Congress. (2018).

[113] Congressional Research Service. (July 2018) *FY2019 Funding for CCS and Other DOE Fossil Energy R&D.* Washington, D.C. Congressional Research Service.

[114] U.S. Congress. (2018). *H.R.5895: Energy and Water, Legislative Branch, and Military Construction and Veterans Affairs Appropriations Act, 2019.* Washington, D.C.: U.S. House of Representatives.

[115] Provisions for Fuels Produced Using Carbon Capture and Sequestration, 17 C.F.R. § 95490 2018.

[116] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 10) Paris, France: International Energy Agency.

[117] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio* (pg 44). Washington, DC: Information Technology & Innovation Foundation.

[118] Cunliff, C. (2018). *An Innovation Agenda for Deep Decarbonization: Bridging Gaps in the Federeal Energy RD&D Portfolio* (pg 10). Washington, DC: Information Technology & Innovation Foundation.

[119] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 10) Paris, France: International Energy Agency.

[120] Figure 36. Retail E10 (California) & LCFS Price Change vs Sep/11. Adapted from *FAQ Clean Fuels Standard* by Climate Solutions.

[121] Office of Inspector General. (2013). *Follow-up Audit of the Department of Energy's Financial Assistance for Integrated Biorefinery Projects*. Washington, D.C.: U.S. Department of Energy.

[122] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage* (pg 10) Paris, France: International Energy Agency.

[123] Department for Business, Energy & Industrial Strategy. (2018). *The UK carbon capture usage and storage deployment pathway: an action plan*. London, United Kingdom: Government of the United Kingdom.

[124] Department for Business, Energy & Industrial Strategy. (2018). *The UK carbon capture usage and storage deployment pathway: an action plan*. London, United Kingdom: Government of the United Kingdom.

[125] Figure 37. Adapted from SBC Energy Institute (2016), *Low Carbon Energy and Technologies Fact Book Update: Carbon Capture and Storage at a Crossroads.*

[126] Figure 38. BECCS application pathways. Adapted from *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* by National Academies of Sciences, Engineering, and Medicine. (2019).

[127] Figure 39. Essential energy services. Adapted from *Net-zero emissions energy systems* by Davis, S. J. et al. (2018), Science 360. Copyright 2017 by The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science.

[128] Department of Energy. *Wind Vision Reports, Chapter 2, Pg. 20*. Retrieved from https://www.energy.gov/eere/wind/maps/wind-vision.

[129] Figure 40. U.S. Department of Energy. *Wind Vision: Chapter 2, A New Era for Wind Power in the United States* (pg.19).

[130] Climate Action Tracker. (2018). Addressing Global Warming. Retrieved from https://climateactiontracker.org/global/temperatures/.

[131] International Energy Agency. (2019). *World Energy Outlook*. Paris, France: International Energy Agency.

[132] Carbon Brief. (2019). *Mapped: The world's coal power plants*. London, United Kingdom: Carbon Brief Ltd.

[133] Figure 41.1. World energy-related CO_2 emissions hit record high. Taken from Mooney, C., Dennis, B. (2019). *In blow to climate, coal plants emitted more than ever in 2018*. Washington, D.C.: The Washington Post.

[134] Figure 41.2. World energy consumption by energy source. Adapted from *International Energy Outlook 2017* by U.S. Energy Information Administration. (2017).

[135] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 5 pp.

[136] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 22 pp

[137] Energy Transitions Commission. (2018). *Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century* (pg 26). London, England: Energy Transitions Commission.

[138] Figure 43. Global electric vehicle and internal combustion engine share of long-term passenger vehicle sales. Adapted from *Electric Vehicle Outlook 2019* by McKerracher, C., Izadi-Najafabadi A., Soulopoulos, N., Doherty D., … (2019). Copyright 2019 by Bloomberg Finance L.P.

[139] McKerracher, C., Izadi-Najafabadi A., Soulopoulos, N., Doherty D., … (2019) *Electric Vehicle Outlook 2019*. New York, New York: Bloomberg New Energy Finance.

[140] Figure 44. Adapted from International Institute for Applied Systems Analysis (IIASA) notebook *sr15_2.4.2.1_primary_energy_marker-scenarios*. (2018) Copyright 2018, IIASA, Energy Program.

[141] Figure 45. Intergovernmental Panel on Climate Change. (2018). *Global Warming of 1.5° C.* Switzerland: Intergovernmental Panel on Climate Change.

[142] Figure 46. Continued growth in hard-to-decarbonize sectors: cement. Taken from U.S. Geologic Service Cement Statistics and Information. Minerals Yearbook, Cement: 2014. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2014-cemen.pdf.

[143] Intergovernmental Panel on Climate Change. (2015). *Climate Change 2014, Synthesis Report.* Geneva, Switzerland: Intergovernmental Panel on Climate Change.

[144] International Energy Agency. (2016). *20 Years of Carbon Capture and Storage (*pg. 11*)*. Paris, France: International Energy Agency.

[145] Figure 47. Global fossil fuel & industry emissions. Adapted from *Net-zero emissions energy systems* by Davis, S. J. et al. (2018), Science 360. Copyright 2017 by The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science.

[146] U.S. Energy Information Administration. (2016). *Country Analysis Brief: India*. Washington, D.C.: U.S. EIA.

[147] Figure 48. Intergovernmental Panel on Climate Change. (2015). *Climate Change 2014, Synthesis Report.* Geneva, Switzerland: Intergovernmental Panel on Climate Change. Adapted from Table SPM.2 (pg. 25).

[148] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[149] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 4). Washington, DC: The National Acadamies Press.

[150] National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (pg 4). Washington, DC: The National Acadamies Press.

[151] Mulligan, J., Ellison, G., Levin, K. (2018). *Foundational Questions on Carbon Removal in the United States*. Washington, D.C.: World Resources Institute.

[152] Figure 49. U.S. Greenhouse Gas Emissions by Gas, 1990-2017. Taken from U.S. Environmental Protection Agency's Greenhouse Gas Emissions and Sinks.
https://cfpub.epa.gov/ghgdata/inventoryexplorer/#allsectors/allgas/gas/all.

[153] Global Warming Potential of Greenhouse Gases. Data retrieved from U.S. Environmental Protection Agency: Overview of Greenhouse Gases. https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

[154] U.S. Environmental Protection Agency. *Overview of Greenhouse Gases: Nitrous Oxide Emissions*. Washington, D.C. U.S. EPA.

[155] IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovern-mental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. (pg. 11). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

[156] U.S. Environmental Protection Agency Office of Air and Radiation. (2010). *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Nitric Acid Production Industry.* (pg. 10). Washington, D.C. U.S. EPA.

[157] The Institute of Clean Air Companies. (2009). NOx and N_2O Reduction in Nitric Acid Plants. (pg. 13). Arlington, VA. ICAC.

[158] BASF. NOxCAT™ ZN_2O N_2O Catalyst: For nitrous oxide emissions. Technology spec sheet.

[159] European Commission. *Fluorinated greenhouse gases: Policy.* Retrieved from https://ec.europa.eu/clima/policies/f-gas_en.

[160] U.S. Environmental Protection Agency. *Refrigerant Recovery and Recycling Equipment Certification.* Retrieved from https://www.epa.gov/section608/refrigerant-recovery-and-recycling-equipment-certification. U.S. EPA.

[161] European Commission. *Fluorinated greenhouse gases: Policy.* Retrieved from https://ec.europa.eu/clima/policies/f-gas_en.