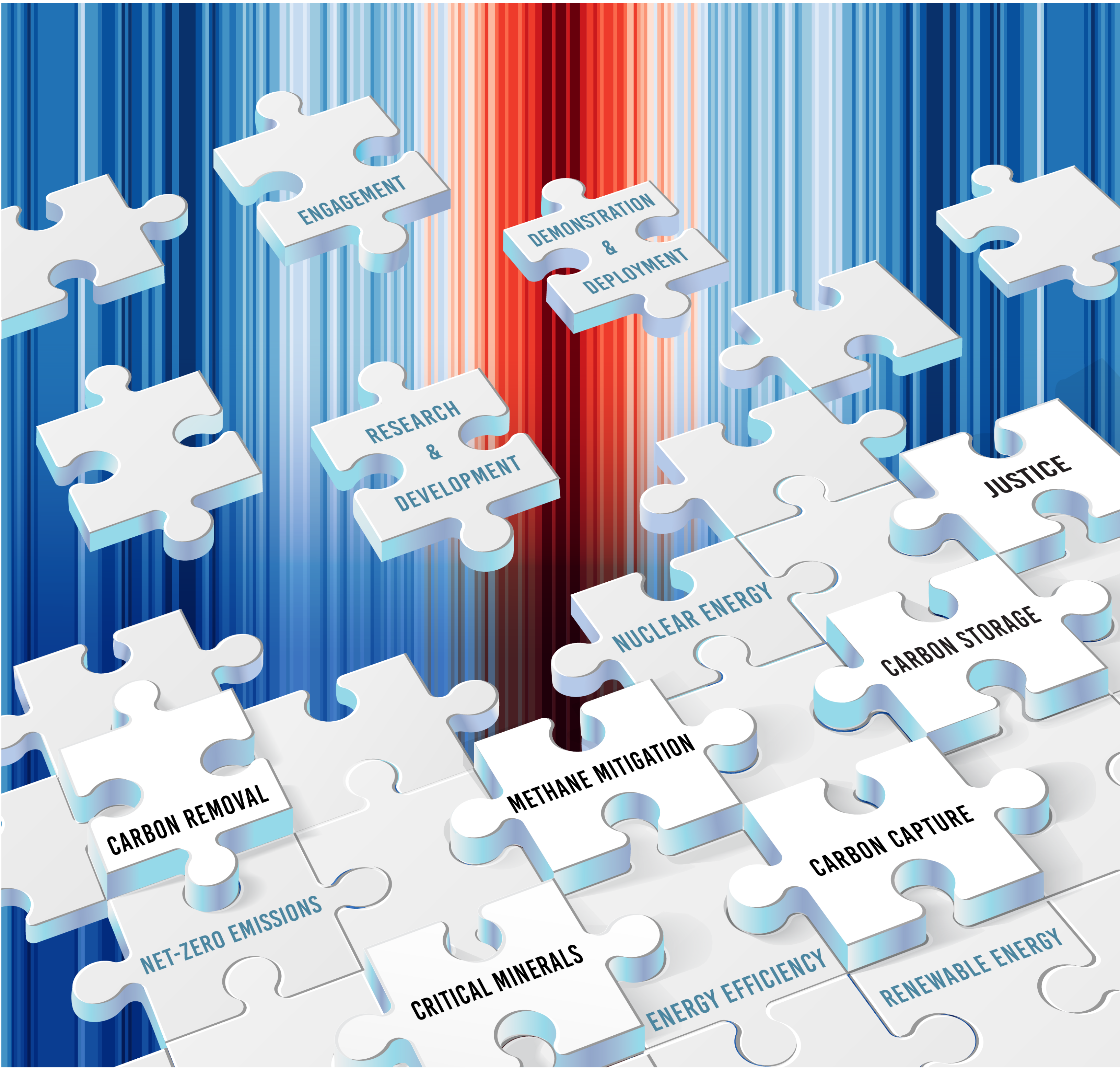
STRATEGIC VISION

The Role of Fossil Energy and Carbon Management in Achieving Net-Zero Greenhouse Gas Emissions



U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

The cover photo of the Office of Fossil Energy and Carbon Management's (FECM) Strategic Vision portrays a puzzle in progress. FECM priorities are represented as puzzle pieces of a larger portfolio of approaches that will be collectively required to achieve net-zero greenhouse gas emissions by mid-century. The striped backdrop illustrates observed warming global temperature trends with a stylized reversal evoking the long-term potential to slow, then possibly reverse warming as we reach zero, and eventually negative emissions.

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STRATEGIC VISION SUMMARY

With Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, President Biden set a goal to "lead a clean energy revolution that achieves a carbon pollution-free power sector by 2035 and puts the United States on an irreversible path to a net-zero economy by 2050" (Federal Register, 2021).

The U.S. energy portfolio and U.S. economy depend heavily on fossil fuels and other sources of GHG emissions today, spanning sectors like power generation, industry, heat and transportation fuels. Advancing clean energy, carbon capture with durable storage in both the power and industrial sectors and CDR are imperative for achieving net-zero GHG goals. FECM envisions enabling the demonstration and ultimately deployment of technologies for carbon management and mitigating challenges of fossil fuel use in a just and sustainable way, with the goal of achieving net-zero GHG emissions by mid-century. FECM prioritizes the following three strategic directions and related priorities to achieve these goals:

Advancing Justice, Labor and Engagement

Justice: FECM is committed to incorporating justice principles throughout our work. FECM prioritizes the meaningful participation of communities, with special focus on disadvantaged communities; a just distribution of benefits; and emphasis on remediating legacy harms while also mitigating new impacts. These principles will be at the center of funding decisions, including implementation of Justice40, and partnership development.

Labor: FECM aims to accelerate the growth and preservation of good-paying jobs in the production of responsible clean energy and climate change solutions. FECM will implement, support and expand robust labor engagement in disadvantaged communities, empowering them to implement place-based solutions that address their unique resources and needs. This work will be done both through newly built programs like the Interagency Working Group on Coal and Power Plant communities, as well as through stakeholder engagement and a focus on workforce development.

International and Domestic Partnerships: FECM will foster and leverage connections with international and domestic partners, collaborate within DOE and the broader government and encourage public-private partnerships to assist in meeting the Biden Administration's climate goals.

Advancing Carbon Management Approaches toward Deep Decarbonization

Point-Source Carbon Capture (PSC): FECM will invest in RDD&D to reduce the cost, increase the efficacy and advance the deployment of commercial-scale PSC technologies in the power and industrial sectors, coupled to permanent storage.

Carbon Dioxide (CO_2) Conversion: FECM will accelerate capabilities for large-scale conversion of CO_2 into products that advance net-zero and justice goals, facilitated by markets for CO_2 as a feedstock. FECM will help accelerate the path to a net-zero refinery, advance mineral carbonation approaches and expand the availability of synthetic fuels.

Carbon Dioxide Removal (CDR): FECM will invest in a diverse set of CDR approaches to support DOE's Carbon Negative Shot of just, sustainable and scalable CDR at costs below $100/net metric ton of CO_2-equivalent (CO_2e). This full suite of CDR approaches will help address emissions from extremely hard-to-decarbonize sectors and eventually address legacy emissions. Near-term focus areas include advancing DAC coupled to durable storage and creating a framework for developing the full portfolio of CDR methods.

Reliable Carbon Storage and Transport: FECM will establish the foundation for a successful carbon transport and storage industry, supporting the transition from carbon production to storage, by making advancements in storage technologies and transport mechanisms, providing technical assistance in Class VI well permitting and supporting large-scale transport and storage facilities and regional hubs.

Advancing Technologies that Lead to Sustainable Energy Resources

Hydrogen with Carbon Management: FECM will invest in RDD&D for hydrogen production coupled with CCS using sustainably sourced carbon-based feedstocks (e.g., biomass, fossil fuels and plastics, including wastes). FECM will invest in the advancement and utility-scale demonstration of hydrogen supply and utilization technologies like hydrogen storage, reversible solid oxide fuel cells (SOFCs) and 100 percent hydrogen fired turbines, supporting DOE's Hydrogen Shot target.

Domestic CM Production: FECM will help grow an environmentally and economically sustainable, secure, diverse and resilient domestic CM and carbon ore resource recovery industry, especially coupled to remediation of legacy wastes. FECM will support demonstrations for extraction and remediation to processing and refining for building a strong CM supply chain while creating good-paying jobs.

Methane Mitigation: FECM will invest in minimizing the environmental impacts associated with the extraction of fossil energy sources produced in the United States, including coal, oil and natural gas, with a specific focus on methane mitigation. FECM plans to advance cost-effective technology to efficiently identify, quantify and predict methane leaks across sectors more efficiently, and improve accessibility and reliability of methane emissions data.

As we continue to invest in technologies that lead to achieving the Administration's net-zero GHG emissions goals, we will be thoughtful and strategic toward prioritizing approaches that minimize environmental and climate impacts from the extraction of fossil fuels and carbon-based feedstocks to their end use for meeting our energy needs.

A MESSAGE FROM THE FECM LEADERSHIP TEAM

The Office of Fossil Energy and Carbon Management's (FECM) core mission is to address the climate crisis. Addressing climate change is more urgent than ever, and we must do all we can to limit harm to people, communities, the planet and the economy. In partnership with other offices in the U.S. Department of Energy (DOE), FECM supports this mission through investments in research, development, demonstration and deployment (RDD&D) of technologies and solutions to ensure clean and affordable energy, a healthy climate, policy development and stakeholder engagement—specifically focused on minimizing the environmental impacts of fossil fuels and helping the nation achieve net-zero greenhouse gas (GHG) emissions through activities like expanding the reach of carbon capture and storage (CCS) technologies, advancing carbon dioxide removal (CDR) technologies, reducing methane emissions from the fossil fuel supply chain, advancing a clean hydrogen economy and developing domestic sources of the critical minerals (CMs) that will be required in a clean energy economy.

FECM's priority is reaching the Biden Administration's goals of a fully decarbonized power sector by 2035 and net-zero U.S. GHG emissions by 2050 (facilitated by an interim goal of achieving 50-52 percent reductions by 2030 below 2005 levels). This Strategic Vision will enable DOE to make strategic carbon management decisions and ensure the use of fossil fuels is put into proper context with climate change and is designed for a future that achieves and maintains net-zero GHG emissions.

This document outlines a vision with energy and environmental justice at the core of FECM's work, as the office strives to build energy infrastructure in a just and sustainable way. FECM must constantly reexamine the meaning of success in order to build creative approaches that enable the Office to advance the country toward a net-zero future. DOE supports projects with large, long-lived assets. In some cases, designing investments for the highest possible value and impact may mean that the metrics and choices seem counterintuitive from the perspective of 2022. It is imperative to remember these investment strategies are designed to be maximally successful in 2050 and beyond, not over the next budget cycle. ***Specifically, searching for and finding ways this work can enable and reinforce broader decarbonization, without creating path dependencies that lock into patterns of the past, is one mission and a major charge of FECM.***

For FECM, the orientation of investments means focusing on the path to net-zero GHG emissions and also constantly evaluating how these efforts integrate with the systems that will exist in the future. Consider what 2050 will look like after the successful decarbonization transition in the United States, catalyzed by the efforts of FECM, other DOE offices, other agencies and civil society:

> *Electricity is generated from sources that produce effectively no air emissions, like GHGs, and supports total electrification for applicable systems. Homes and other buildings are highly efficient, providing climate resilience and allowing for more flexible demand while accommodating a mature, decarbonized energy system. CDR is deployed at a scale necessary to account for residual and legacy GHG emissions, especially for those difficult-to-abate sectors like agriculture. FECM's research on CDR, industrial CCS and 100 percent hydrogen-fired turbines has resulted in the maturation and widespread industrial deployment of these technologies. Other research on methane mitigation from fossil systems, carbon-based hydrogen production, power sector CCS and remediation-linked recovery of CMs used for clean energy infrastructure enabled a highly successful decarbonization transition. This research paved the way for new focus areas like residual GHG management from non-fossil activities, water management, critical mineral recovery from non-fossil wastes and much more.*

> *Access to clean electricity to run flexible direct air capture (DAC) plants for CDR has allowed for CDR to be used on a global scale. Clear policy support for clean products such as cement, concrete and steel has helped drive lower costs, more sustainable materials and new opportunities to achieve negative emissions. Fossil fuels are replaced by low-cost zero-carbon alternatives, enabling a phase-down and just transition toward a point where a transition of skills and geology— formerly devoted to fossil fuel extraction—is now devoted to geothermal and carbon storage technologies, potentially including biomass with carbon removal and storage (BiCRS).*

These future goals are highly relevant to the decisions FECM makes in the near term, particularly as FECM commits to long-term, capital-intensive infrastructure. FECM's role, in part, is to ensure these technologies are not only compatible with but optimized for a long-term future.

Because infrastructure like pipelines and industrial facilities can last for multiple generations spanning a century or more, system planning on a multi-generational time scale is a crucial consideration for FECM. For instance, DAC facilities sited for access to natural gas supplies with low methane emissions might make sense in 2022. From the vantage of 2050, however, siting facilities with excellent access to geothermal heat, transmission lines and variable power might be more prescient. Developing hydrogen systems with carbon management that easily transition to electrolytic hydrogen, similarly, requires anticipating the future: placing new hydrogen pipelines in places optimized for hydrogen production (e.g., with plenty of water and storage capacity) rather than natural gas supplies, could be highly beneficial in the future. Designing capture-based CDR and CCS systems that can provide demand flexibility to support reliable power system operations would also be an example of recognizing that future needs differ from present needs. Across everything FECM does, designing systems resilient to anticipated climate change—including heat, flooding, drought, more intense storms and other outcomes—is also at the core of this vision supporting the future.

A standout decarbonization challenge between now and 2050 is that neither the historical carbon-based system nor the future net-zero system will be fully deployed, which means that systems will need to integrate and adapt in ways that might be temporary. Although FECM's vision plans toward accommodating a zero-carbon future rather than the existing system, FECM has a significant role in ensuring that the current fossil fuel-based system downscales gracefully during the energy transition. Abrupt shifts in resource sustainability may create reliability challenges and have significant economic consequences. Retrofitting some existing natural gas-fired power plants with CCS can build knowledge about CCS systems through "learning by doing" that can then be applied to industrial facilities and further decarbonization. Similarly, building up supplies of carbon-neutral hydrogen can encourage facilities to use hydrogen, clearing the way for the long-term integration of clean hydrogen while acting as a disincentive to new investments in fossil fuel-dependent assets. Methane mitigation has an immediate impact due to methane's especially large short-term warming impacts, with a long-term pathway to unlocking technologies for other GHG management beyond the fossil sector. Work on carbon dioxide (CO_2) transport and storage is a facilitating effort that is likely to remain domestically and globally relevant indefinitely. Directing resources to efforts with near-term benefits, like increasing technological readiness, decreasing cost and facilitating international deployment, can be an important de-risking contribution by FECM to the overall net-zero goal.

FECM has a very important role to play, but the Office cannot accomplish this vision without strong partnerships and collaboration within DOE, other federal agencies, other governments, industry and non-governmental organizations and communities. Reaching these bold climate goals will take historic domestic and international efforts to re-establish global energy partnership coupled with environmental stewardship. FECM must seek international partners who share this vision of carbon management technologies that promote global climate, energy and environmental justice. The future described in this document can be accomplished through FECM's collaboration with other DOE programs to create innovative ideas, leveraging cross-departmental expertise and building up programmatic synergies. A focus on improving access to the best data and tools to improve FECM's analytic capabilities is critical to the success of this mission. Obtaining accurate cost and performance data to use in energy and climate models will help decision-makers understand the role FECM technologies can play in lowering costs and achieving deep GHG reductions. This analysis, coupled with robust life cycle analyses, will drive the best decision-making concerning FECM's programs and projects. Some critical elements to be considered include ecosystem benefits of some specific pathways such as reclamation (improved water), terrestrial sequestration (enhanced soil, wildlife habitat, recreation) and avoided negative land-use change (landfills).

Finally, FECM has an important role in shaping the design of policies and regulatory frameworks by sharing programmatic expertise and lessons learned with a broad range of stakeholders and the public.

EXECUTIVE SUMMARY

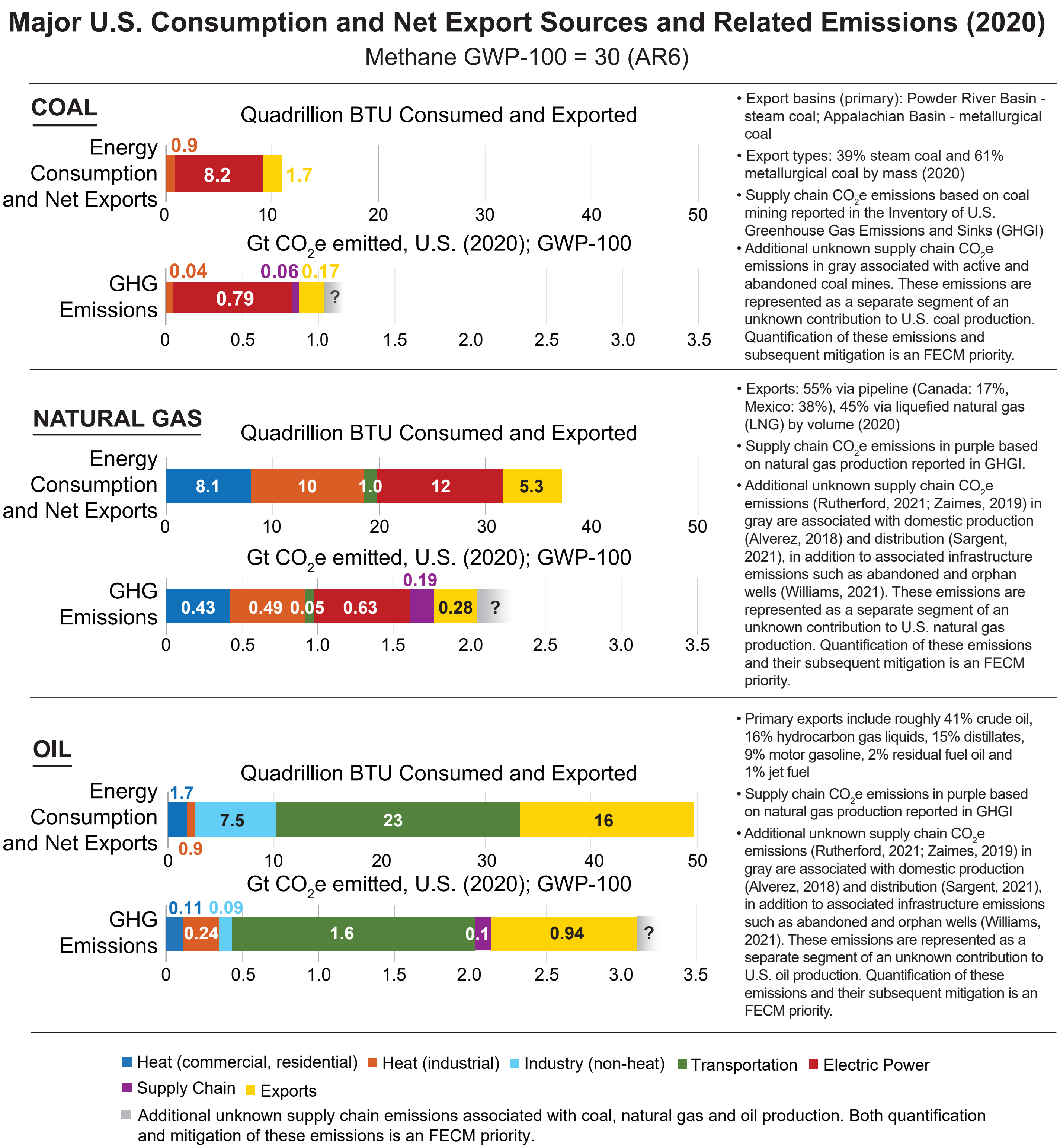
The Office of Fossil Energy and Carbon Management's (FECM) core mission is to address the climate crisis. Addressing climate change is more urgent than ever before. In 2020, global fossil CO_2 emissions were approximately 35 gigatonnes of CO_2 ($GtCO_2$), led by emissions from China (11 $GtCO_2$) and the United States (5 $GtCO_2$) (Ritchie & Roser, 2020) (Union of Concerned Scientists, 2018). Historical emissions, at 420 $GtCO_2$ for the United States and 240 $GtCO_2$ for China, tell a different story – as do emissions per capita (United States, 14 tonnes of CO_2/person in 2020; China, 7 tonnes of CO_2/person in 2020) (Global Carbon Budget, 2021). Emissions of all GHGs, including methane, are higher than ever before. Nations like the United States that have significant legacy and ongoing responsibility for emissions have a particular leadership obligation for addressing the climate crisis, which is expected to affect people who have often contributed very little to emissions but are highly vulnerable to climate change first and worst. For instance, 2020 per capita emissions for Kenya are approximately 0.3 tonnes of CO_2 per person, and 2018 droughts left more than a million people at the edge of famine. Haiti, where per capita emissions in 2020 were also roughly 0.3 tonnes of CO_2 per person, is among the most climate-vulnerable countries in Latin America, subject to hurricanes, storm surges and flooding made worse by climate change.

GHG emissions have risen dramatically over the past several decades, driven by fossil fuel use and adding to the existing GHG pool in the atmosphere. In accordance with the Paris Agreement and climate data, it is critical to take aggressive action today to limit global warming to well below 2ºC and preferably below 1.5ºC – a target that will likely require net-zero, then net-negative GHG emissions starting around mid-century (IPCC, 2021). Continued support for zero and low-carbon technologies that help the phase-out of fossil fuel use and deployment of CDR methods must be prioritized domestically and globally to meet our net-zero goals.

Through Executive Order 14008, Tackling the Climate Crisis at Home and Abroad, President Biden set a goal to "lead a clean energy revolution that achieves a carbon pollution-free power sector by 2035 and puts the United States on an irreversible path to a net-zero economy by 2050" (Federal Register, 2021). Further, President Biden set an interim target for the United States to cut carbon emissions in half by 2030 compared to 2005 levels while addressing current and historical environmental injustice, including in communities negatively impacted by fossil fuel use and climate change. At the same time, the United States will "exercise its leadership [internationally] to promote a significant increase in global climate ambition" in meeting the overarching climate objectives of the Paris Agreement. President Biden also set a goal to "eliminate fossil fuel subsidies from the budget request for Fiscal Year 2022 and thereafter," financially aligning the federal budget toward low GHG emissions with a climate-resilient economy.

U.S. dependence on fossil fuels and other sources of GHG emissions spans sectors like power generation, industry, heat and transportation fuels. Figure 1 shows the breakdown of U.S. energy dependence on coal, oil and natural gas (quadrillion British thermal units (BTU)) alongside the breakdown of GHG emissions per sector (CO_2e), assuming a global warming potential over 100 years (GWP-100) of 100 for methane). In 2020, approximately 40 percent and 19 percent of the U.S. power generation was sourced from natural gas and coal, respectively (EIA, 2021a). In the same year, petroleum provided for approximately 90 percent of the transportation sector's energy consumption (EIA, 2021b). The largest share of the U.S.' CO_2 emissions footprint is associated with transportation. Industrial heat from natural gas also contributes significantly to emissions. When combined with industrial process emissions in some sectors (e.g., cement), these streams become more concentrated in CO_2, making emissions easier and less expensive to capture compared to more dilute sources. Natural gas, oil and coal supply chains also include emissions of methane, a powerful GHG that is the primary component of natural gas. Although the U.S. Environmental Protection Agency (EPA) has estimates of these methane emissions, as shown in Figure 1, official estimates are widely understood to be too low, in some cases substantially (Alvarez et al., 2018).

Figure 1 | Energy consumption and net exports (quadrillion BTU) and related GHG emissions ($GtCO_2e$, GWP-100), associated with coal, oil and natural gas.



At DOE, FECM envisions enabling the demonstration and ultimately deployment of technologies for carbon management and mitigating challenges of fossil fuel use in a just and sustainable way, with the goal of achieving net-zero GHG emissions by mid-century. In coordination with relevant offices across DOE and the U.S. government, FECM prioritizes the following three strategic directions and related priorities to achieve these goals:

Advancing Justice, Labor and Engagement

- Justice
- Labor
- International and Domestic Partnerships

Advancing Carbon Management Approaches toward Deep Decarbonization

- PSC
- CO_2 Conversion
- CDR
- Reliable Carbon Storage and Transport

Advancing Technologies that lead to Sustainable Energy Resources

- Hydrogen with Carbon Management
- Domestic CM Production
- Methane Mitigation

As we continue to invest in technologies that lead to achieving the Administration's net-zero GHG emissions goals, we will be thoughtful and strategic toward prioritizing approaches that minimize environmental and climate impacts from the extraction of fossil fuels and carbon-based feedstocks to their end use for meeting our energy needs.

Together, the seven research, development and demonstration (RD&D) pathways associated with advancing carbon management approaches toward deep decarbonization and advancing technologies that lead to sustainable energy resources show the core strengths of FECM, and the crucial role it plays in meeting the Administration's and the nation's goals. While each is distinct in its own way, these seven pathways must interact and integrate with each other in order to fulfill FECM's contribution to just and sustainable decarbonization.

To help achieve its climate goals, FECM envisions that the United States will advance the deployment of commercial-scale PSC technologies with long-duration carbon storage to the power and industrial sectors in the near term. Investing in RD&D on PSC will lead to "learning by doing" and ultimately cost reductions as these early investments help the deployment of lower-cost nth-of-a-kind projects at scale.

In conjunction with pathways like PSC and CDR, FECM envisions large-scale conversion of CO_2 into environmentally responsible and economically valuable products. Conversion technologies can play a catalyzing role in the CCS supply chain during the implementation of future decarbonization scenarios.

Regarding CDR, FECM will invest in advancing a diverse portfolio of CDR approaches that will aid in gigatonne-scale removal by 2050. These investments will support DOE's Carbon Negative Shot goal of $100/net metric tonne of CO_2e for diverse CDR approaches. FECM supports the robust analysis of life cycle impacts of various CDR approaches and a deep commitment to environmental justice throughout the research, development and deployment process. This approach will include rigorously evaluating CDR practices and technologies, ensuring robust community engagement and leveraging FECM's extensive leadership and expertise in carbon capture, durable carbon storage and rigorous carbon accounting analysis.

For the future of carbon storage and transport, FECM envisions establishing a successful industry by making key investments in RD&D, large-scale transport and storage facilities and regional hubs to support the rapid deployment of carbon storage. To achieve the goals for carbon transport and storage, FECM is focused on expanding storage infrastructure and planning for CO_2 transport that will enable the decarbonization of the U.S. economy.

The FECM hydrogen program is an integral part of the DOE-wide Hydrogen program (DOE, U.S. Department of Energy Hydrogen Program, 2021) which includes multiple offices covering diverse feedstocks (renewables, carbon-based feedstocks with CCS, nuclear) and multiple sectors (transportation, power generation, industrial), and is coordinated with DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE). The program is designed to support the Administration's targets of 50 to 52 percent GHG emissions reduction by 2030 below 2005 levels, a 100 percent carbon pollution-free electric grid by 2035 and net-zero GHG emissions by 2050. These reductions will be achieved through innovative, targeted RD&D efforts, close coordination within DOE and coordination with other government agencies, national labs, academia and industry. FECM is committed to close collaboration across offices in the development and deployment of effective, reliable, affordable and safe hydrogen technologies which support DOE's Hydrogen Energy Earthshot target of $1 per kilogram of clean hydrogen within one decade (i.e., 1-1-1). This was the first Energy Earthshot (DOE, Hydrogen Shot, 2021) launched by DOE and includes multiple pathways and energy resources including renewables, nuclear, fossil and waste resources with CCS. FECM activities such as thermal conversion RD&D (e.g., gasification, pyrolysis, reforming, etc.) can play a critical role in enabling a pathway to achieve the 1-1-1 goal, particularly in the near term before market penetration of renewables.

FECM will also work to catalyze a U.S.-based environmentally and economically sustainable CMs and carbon ore resource recovery industry. This industry will support clean energy deployment, create domestic manufacturing jobs, generate resilient and secure domestic CM supply chains and build environmental and social justice stewardship through production- and reclamation-based research and development (R&D).

FECM is also focused on minimizing the environmental impacts associated with extracting fossil energy sources consumed in the United States, including coal, oil and natural gas. Specifically, the mitigation of methane emissions will be the central focus of RD&D efforts in this focus area, from resource production, processing, transportation, utilization and storage, thereby mitigating methane emissions from fossil energy supply chains over the next decade. This focus area also includes addressing other environmental impacts from fossil fuel extraction, such as air quality, water contamination and induced seismicity.

Figure 2 shows the pathways from the various fossil fuels, coal, oil and natural gas emissions and their extraction and use today. Additionally, Strategic Vision areas that FECM is focusing on are highlighted in blue, while areas where FECM is working closely with DOE's EERE are highlighted in yellow. Finally, yellow and red hashes represent varying levels of technological readiness (TRLs) for a given approach, from the R&D stage to more advanced pilot and demonstration-stage opportunities.

Even as significant efforts are made to advance all deep decarbonization approaches, climate models have made it clear that CDR at the gigatonne scale will also be required to achieve net-zero by mid-century. Figure 3 shows a breakdown of the various approaches, including biological, chemical, mineral and ocean systems. The bar graph in Figure 3 shows a breakdown of the U.S. sectors and associated emissions that are truly hard to abate today, such as agriculture, and aspects of the transportation sector that are difficult to electrify today, such as aviation, shipping and long-haul trucking. For some sectors, including power, cement and steel, avoidance and reduction approaches are not yet fully implemented but are ready for demonstration and deployment today. In these cases, using CDR to address these emissions is not appropriate.

To achieve maximum impact with CDR, it is critical to couple it to zero-carbon energy. Energy, water and land needs for CDR will likely compete with other uses, and careful examination of how these resources are stewarded and prioritized for use will be critical for effective and just pathways for deep decarbonization. The development of carbon management hubs centered around a common shared transportation and geological storage infrastructure, as demonstrated in Figure 4, represents a pathway that could accelerate the flow of CO_2 back into the Earth while maximizing efficient use of resources.

Careful carbon accounting is critical for understanding how activities affect emissions, and whether changes represent additions, mitigation, displacement or removals. Such accounting requires a full life cycle view that addresses GHG emissions associated with resource production, transport, use and other activities. Figure 5 illustrates some of the essential processes for carbon accounting associated with fossil fuels. The blue boxes in Figure 5 show pathways and technologies that are key priorities for FECM and are discussed in greater detail throughout the Strategic Vision.

Figure 2 | Pathways from various fossil fuels (coal, oil and natural gas), their end uses and the emissions associated with their extraction and use.

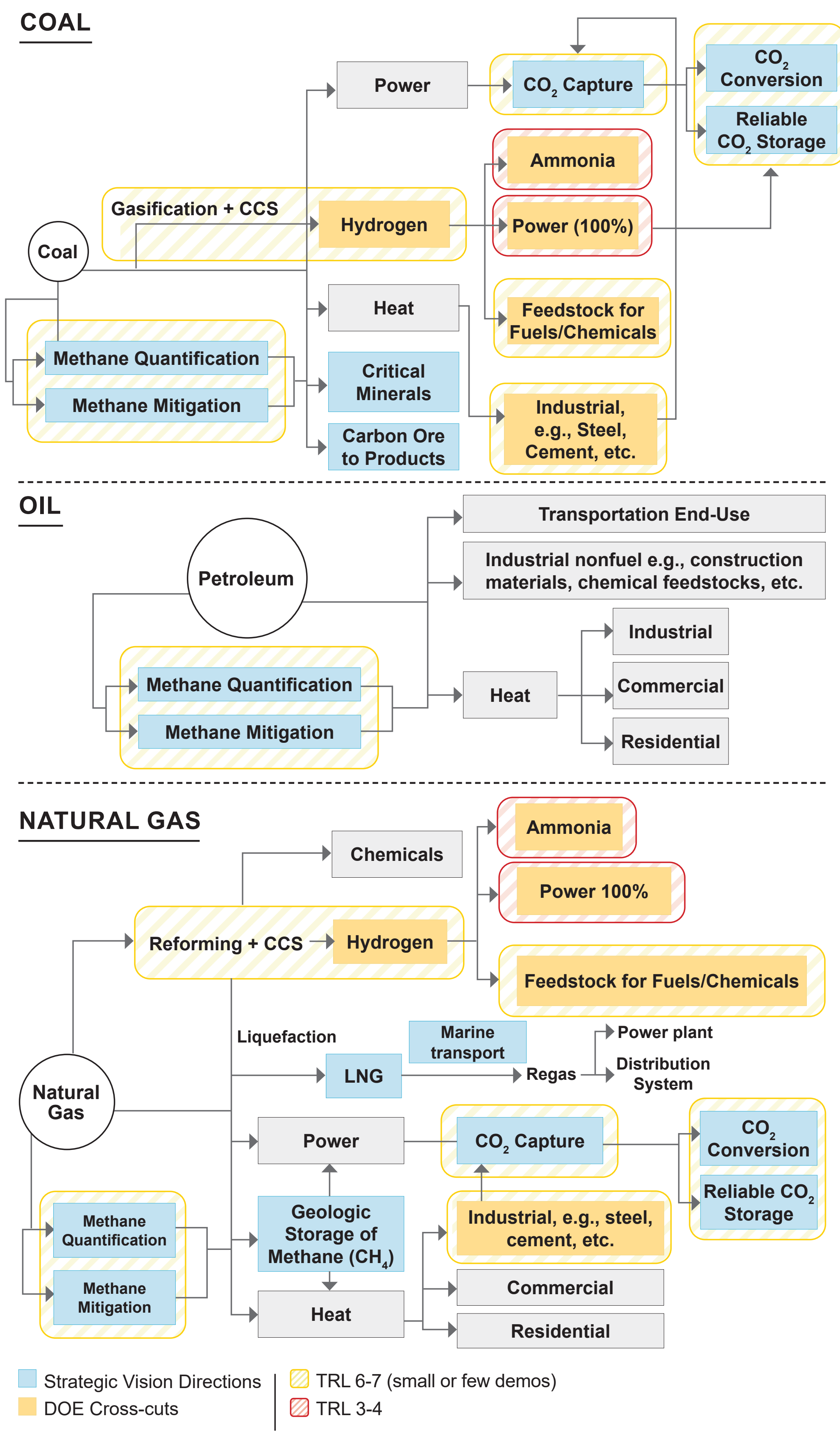


Figure 3 | Pathways associated with carbon dioxide removal alongside the sectors that are hard to decarbonize today.

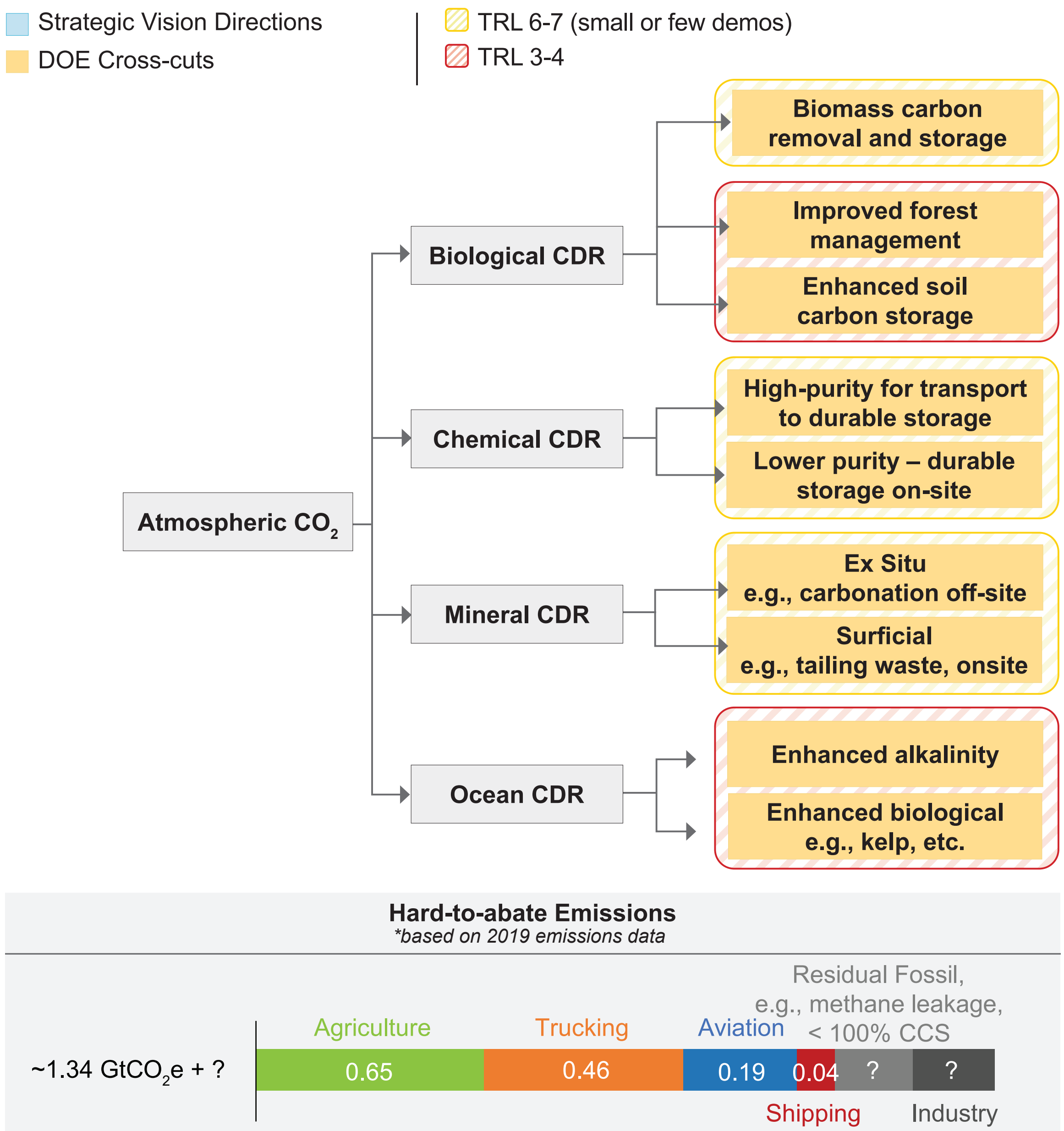
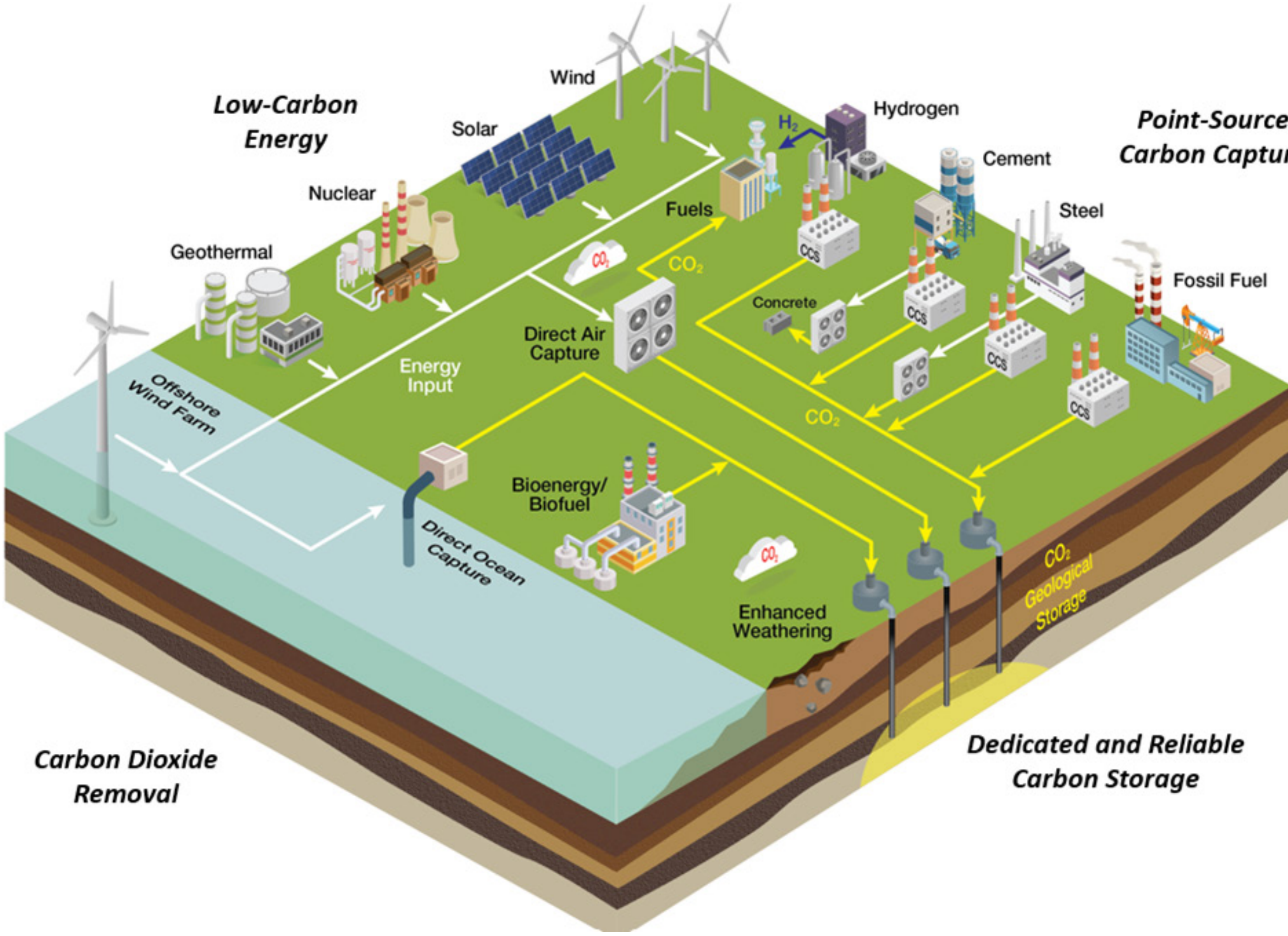


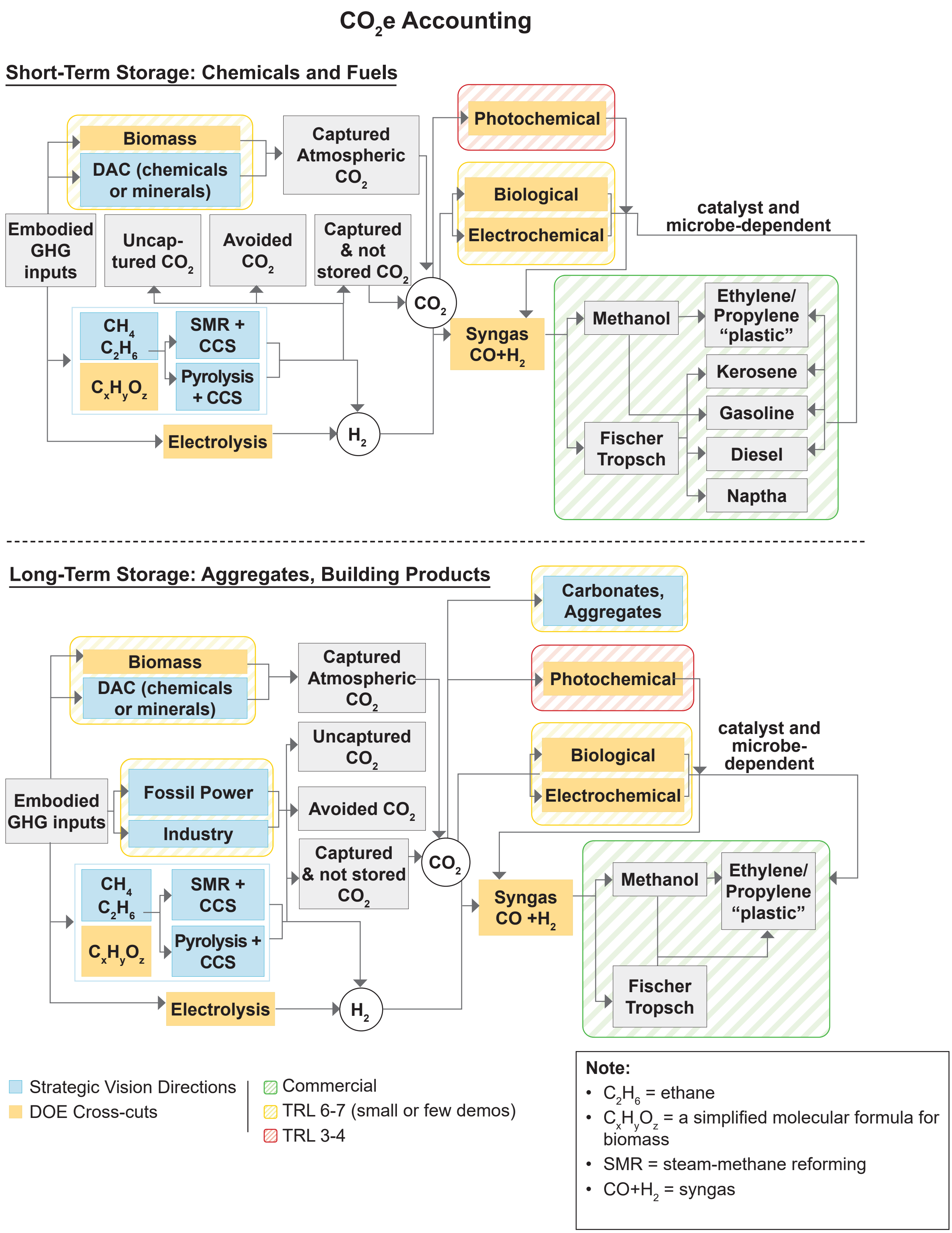
Figure 4 | Integrated carbon management hub that includes point-source capture and carbon dioxide removal all coupled to reversing the flow of carbon back into the earth.



FECM is committed to incorporating justice principles throughout our work. FECM prioritizes the meaningful participation of communities, with special focus on disadvantaged communities; a just distribution of benefits; and emphasis on remediating legacy harms while also mitigating new impacts. FECM will acknowledge and account for environmental and social impacts associated with past and ongoing fossil fuel use while considering project investments.

FECM will consider legacy, current and future impacts in its evaluation of projects to ensure that investments in carbon management prioritize the mitigation of environmental and climate impacts. Furthermore, FECM aims to accelerate the growth of good-paying jobs in the production of responsible clean energy and climate change solutions created through these strategic pathways, particularly in disadvantaged communities, with an emphasis on place-based solutions that address unique local resources and needs. At the same time, FECM will foster and leverage synergistic connections with international and domestic partners, collaborate within DOE and across government agencies and encourage public-private partnerships.

Figure 5 | Carbon accounting approaches for short-term storage (top) through the conversion of CO_2 with hydrogen to chemicals and fuels and for long-term storage (bottom) that involves the conversion of CO_2 with alkaline sources to produce carbonate products. FECM Strategic Vision Priorities are shaded in blue.



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ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial intelligence
AMO	Advanced Manufacturing Office
ARPA–E	Advanced Research Projects Agency–Energy
ATR	Autothermal reforming
BECCS	Bioenergy with carbon capture and storage
BETO	Bioenergy Technology Office
BiCRS	Biomass with carbon removal and storage
BTU	British thermal unit
C_2H_6	Ethane
$CaCO_3$	Limestone
CaO	Lime
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CarbonSTORE	Carbon Storage Technology & Operations Research
CC Program	Carbon Conversion Program
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CDR	Carbon dioxide removal
CEQ	Council on Environmental Quality
CMI	Critical Materials Institute
CMs	Critical minerals
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
$CO+H_2$	Syngas
Communities LEAP	Communities Local Energy Action Program
CORE-CM	Carbon Ore, Rare Earth and Critical Minerals
$C_xH_yO_z$	A simplified molecular formula for biomass
DAC	Direct air capture
DOC	The Department of Commerce
DOD	The U.S. Department of Defense
DOE	The U.S. Department of Energy
DOI	The U.S. Department of the Interior
DOS	The U.S. Department of State
DOT	The U.S. Department of Transportation
EDX	Energy Data Exchange
EERE	The Office of Energy Efficiency and Renewable Energy
EOR	Enhanced oil recovery
EPA	The U.S. Environmental Protection Agency
EPEAT	Electronic Product Environmental Assessment Tool
FDA	Food and Drug Administration
FECM	The Office of Fossil Energy and Carbon Management
FEED	Front-end engineering design
FGD	Flue gas desulfurization
GHG	Greenhouse gas
GHGI	The Inventory of U.S. Greenhouse Gas Emissions and Sinks
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Technologies
$GtCO_2$	Gigatonnes of carbon dioxide

GWP-100	Global warming potential over 100 years
H_2	Hydrogen
HFTO	Hydrogen and Fuel Cell Technologies Office
HBCU	Historically Black Colleges and Universities
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
kWe	Kilowatt equivalent
LCA	Life cycle assessment
LNG	Liquified natural gas
LPO	Loan Programs Office
MMT	Million metric tonnes
MRV	Measurement, reporting and verification
MSI	Minority-Serving Institutions
MSW	Municipal solid waste
MT	Metric tonnes
NASA	The National Space Agency
NE	The Office of Nuclear Energy
NETL	The National Energy Technology Laboratory
NGCC	Natural gas combined cycle
NOAA	The National Oceanic and Atmospheric Administration
NO_x	Nitrogen oxide
NRAP	National Risk Assessment Partnership
NSTC	The National Science and Technology Council
OE	The Office of Electricity
OSMRE	The Office of Surface Mining Reclamation and Enforcement
PSC	Point-source carbon capture
PV	Photovoltaic
R&D	Research and development
RCSP	Regional Carbon Sequestration Partnerships
RD&D	Research, development and demonstration
RDD&CA	Research, development, deployment and commercial application
RDD&D	Research, development, demonstration and deployment
REEs	Rare earth elements
RFS program	Renewable fuels standard program
R-SOFC	Reversible solid oxide fuel cells
SC	The Office of Science
SDS	Sustainable Development Scenario
SMART	Science-informed Machine Learning to Accelerate Real Time Decisions
SMART-CS	Science-informed Machine Learning to Accelerate Real Time Decisions for Carbon Storage
SMR	Steam-methane reforming
SOECs	Solid oxide electrolysis cells
SOFCs	Solid oxide fuel cells
So_x	Sulfur oxide
TEA	Techno-economic assessment
TRL	Technological readiness level
USDA	The U.S. Department of Agriculture
USDT	The U.S. Department of the Treasury
USGS	United States Geological Survey
WGS	Water gas shift

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CHAPTER 1 | CROSSCUTTING THEMES FOR THE FUTURE OF THE OFFICE OF FOSSIL ENERGY AND CARBON MANAGEMENT (FECM)

1.1 Justice

Vision Statement

Incorporate justice principles throughout the processes and outcomes of its work to ensure meaningful participation of disadvantaged communities (Federal Register, 2021b), just distribution of benefits, mitigation of impacts and remediation of legacy harms.

FECM is dedicated to implementing the principles of energy and environmental justice in the planning, processes and outcomes of its work in alignment with Executive Orders 14008 and 13985 (Federal Register, 2021a) (Federal Register, 2021b). This commitment requires that FECM meaningfully consults communities, especially historically excluded groups; ensures a just distribution of benefits; avoids inequitable distribution of harms; and prioritizes RDD&D investments that will mitigate the harm caused by legacy and ongoing fossil fuel use.

FECM primarily supports R&D activities and has historically focused on spurring research- and industry-led technological development while engaging primarily with technical stakeholders. However, the rapid societal transformation needed to achieve net-zero GHG emissions by 2050 requires that the office pivot towards the demonstration and deployment of technological solutions that meet the needs of specific communities (Federal Register, 2021b). Operating in a justice framework will help FECM be part of a future world that protects human health and the environment, empowers and benefits communities and workers, honors tribal sovereignty and provides accessible, affordable and reliable carbon-free services.

Achieving this vision requires that equity and justice be considered at every stage of FECM's work—from the envisioning of a project through its completion—and across all the program activities, including basic research, technology deployment, workforce development and technical assistance. This will require creativity and reimagination of processes and workflows, as well as new and transparent metrics to monitor progress towards energy and environmental justice (Federal Register, 2021b). FECM will work to integrate equity and justice across the following dimensions: distributive justice, procedural justice and restorative justice (Baker, 2021) (Heffron & McCauley, 2017).

1.1.1 Equitable Allocation of Benefits and Burdens (Distributive Justice)

The legacy of environmental racism has disproportionally concentrated the harms of the U.S. energy, transportation, and industrial systems on low-income communities, communities of color, and/or Indigenous communities, while simultaneously concentrating benefits in whiter, wealthier communities (Tessum, et al., 2019) (Tessum, et al., 2021) (ACEEE, 2016) (Sen, Bird, & Bottger, 2018) (Scheier & Kittner, 2022). FECM must work against this trend by ensuring benefits flow to disadvantaged communities first and that project impacts are mitigated.

Measuring progress towards distributive justice (Heffron & McCauley, 2017) requires a detailed assessment of the benefits and harms of FECM's programs and whether those impacts flow to marginalized communities. FECM should perform this accounting aligned with the Justice40 initiative (Federal Register, 2021b). Data collection and calculations (e.g., impacts disaggregated by census tract) should be performed in consultation with affected communities to accurately determine and communicate the impacts of these programs.

Pursuing an accurate assessment of FECM program impacts should not delay activities that clearly benefit disadvantaged communities: these must occur in parallel. For example, FECM must continue to invest in workforce development and training programs that target underserved groups (e.g., funding for Minority-Serving Institutions (MSI) and Historically Black Colleges and Universities (HBCU)) and adapt these programs to evolving place-based needs. Increased technical assistance should also be prioritized for communities with minimal technical resources resulting from systematic disinvestment.

1.1.2 Community Engagement (Procedural Justice)

Procedural justice (Heffron & McCauley, 2017) ensures disadvantaged communities have meaningful opportunities to provide input into FECM's processes and that communities are empowered to co-create the energy systems they are impacted by. Through its RDD&D activities, FECM has an opportunity to spur economic activities across the United States and support the creation of new and reimagined industries with long-lived infrastructure (Larsen, Herndon, & Hiltbrand, 2020) (LEP, 2021) (NASEM, 2021) (NPC, 2019) (Initial Report, 2021). Engagement with traditionally excluded communities across our RDD&D portfolio is essential to ensure fair access to economic opportunities and the responsibility of these industries.

Building relationships with, seeking input from and empowering disadvantaged communities will be a substantial shift for FECM as previous outreach has prioritized industry stakeholders. Looking forward, FECM will proactively engage with disadvantaged communities and those that have been harmed by the legacy and ongoing use of fossil fuels. Centering environmental justice for FECM also means engaging diverse communities in the creation of new technologies, including strengthening partnerships with MSIs and HBCUs for research activities, continuing training and educational programs for underserved communities and spurring innovation and entrepreneurship among minority-owned enterprises.

FECM recognizes that we must prove our commitment to justice, particularly due to this Office's historic and ongoing work with the fossil fuel industry. We must begin by listening to the needs, concerns and hopes of communities and incorporate their feedback into our processes in a transparent way. FECM must also work to provide tools, training and economic opportunities that will reduce barriers to FECM opportunities and enable communities to co-create their energy systems.

Community engagement must be proactive and sustained, ideally providing ample opportunities for input before decisions are made (Shalowitz, et al., 2009) (EPA, 2021). For example, when studying potential routes for CO_2 transport infrastructure, communities should be engaged early in the modeling process as opposed to after routes have been identified or chosen. Workforce development, educational and economic development activities should also be responsive and flexible to the needs of the community.

To guide and prioritize engagement with disadvantaged communities, FECM will create a strategic engagement plan. This engagement plan will include a renewed focus on both formal and informal tribal engagement. FECM will also facilitate direct industry engagement with communities to encourage industries to be transparent and accountable to local stakeholders and provide fair access to economic opportunities. Coordination and involvement of various partners—including at the local, state and regional levels—will be critical for effective and sustainable engagement.

1.1.3 Addressing Past and Ongoing Harms (Restorative Justice)

The use and extraction of fossil fuels have generated pollution streams that are causing the climate crisis and additional negative health impacts, especially for disadvantaged communities (Casey, Cushing, Depsky, & Morello-Frosch, 2021) (Perera, 2018). As a RDD&D-focused office, FECM has some limitations in actions that can be directly supported. However, whenever possible, FECM will pursue and prioritize RDD&D projects leading to benefits for harmed communities. Coordination across DOE and with other agencies, informed by meaningful community engagement, is key to this effort.

For example, FECM can enable the removal of legacy CO_2 emissions from the atmosphere and limit climate harm through the development of sustainable and just CDR. The incorporation of energy justice principles for CDR necessitates understanding the resources required for CDR, prioritizing deep decarbonization and supporting communities to pursue beneficial place-based approaches.

1.2 Workforce

Vision Statement

Work toward the accelerate the growth of good-paying jobs in the energy and climate solutions sectors in disadvantaged and distressed communities and shall empower such communities to implement place-based solutions that address their unique resources and needs.

Workers across sectors face threats from climate change. Workers in fossil fuel and other GHG-intensive industries face a changing landscape due to market dynamics, automation and other factors—resulting in job loss and reduced tax base (Initial Report, 2021). Meanwhile, jobs in the clean energy sector have continued to increase (DOE, 2021). These changes present real economic challenges for energy communities and individuals employed in the fossil fuel sector, but it also provides an extraordinary opportunity to lift up working people and communities as we build our net-zero future. Together, we must create new energy systems and climate change solutions that honor workers, ensure good quality jobs, support place-based solutions and prioritize investments in clean energy and disadvantaged communities.

FECM is investing in areas that have the potential to create a significant number of good quality jobs and substantial tax revenue over the coming decades, including CCS, CDR, CMs and hydrogen with carbon management (Larsen, Herndon, & Hiltbrand, 2020) (Initial Report, 2021). Importantly, industries arising from these technologies have the potential to help diversify the job market for energy transition communities due to the overlap in location and skills of the fossil energy workforce. Carbon transport and storage technologies, for example, must scale up dramatically over the next decade and will require significant expertise that currently exists in the oil and gas sector (Abramson, McFarlane, & Brown, 2020) (LEP, 2021) (NASEM, 2021) (NPC, 2019). CDR can also employ individuals in the agricultural, forestry, mining and manufacturing sectors. Mining skillsets are of high importance in developing domestic CM supply chains.

FECM is well positioned to influence future energy and climate change solution industries, including in regions that have historically hosted fossil assets, and will work across the following areas to ensure that worker and community needs and the creation of good quality jobs are prioritized in the transition: place-based strategies, stakeholder engagement and workforce development and technical assistance.

1.2.1 Place-based Strategies

Communities across the United States vary greatly in their existing energy systems, economic and natural resources and desires for the future. Place-based solutions that account for the unique circumstances and assets in each community will be successful, long-lasting and can create good quality jobs in addition to resilient and carbon-free energy. FECM will enable these place-based solutions by continuing to invest in a diverse RDD&D portfolio that relies on varying resources, skillsets and siting considerations, informed by frequent and meaningful engagement with communities impacted by energy transitions.

Developing effective place-based strategies requires a holistic approach that includes meaningful engagement with communities and coordination across the federal government, as different communities will choose unique solutions and technologies to anchor their economic transition strategies. Additionally, successful place-based solutions will address both immediate job needs, as well as support long-term and adaptive community development. For example, FECM could support a carbon storage pilot project in a community and later facilitate a transition to CO_2 storage coupled to an on-site DAC system in that same community.

1.2.2 Stakeholder Engagement

Meaningful engagement with labor stakeholders and labor unions underpins all efforts to center workers, support diversified economies and place-based energy solutions and accelerate the growth of good-paying jobs. Stakeholder engagement can help communities identify and implement clean energy technologies and create jobs. Engagement can also help FECM learn about workforce needs and existing worker training resources that include labor apprenticeships. These programs can be quickly adapted to the rapidly changing energy landscape.

Looking forward, and guided by a strategic engagement plan, FECM will proactively engage with the labor community, including workers, tribal leaders, labor unions and labor organizations, as well as relevant community- and place-based organizations. Communities with reliance on fossil fuels and disadvantaged communities should be prioritized in these efforts. FECM should work to establish communication directly with these communities and relevant, trusted leaders and community partners, as many have expressed a desire for direct federal engagement (NETL, 2021). FECM can play a key role in coordinating these efforts across DOE and other federal agencies, as it is already doing through the Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization.

1.2.3 Workforce Development and Technical Assistance

For technologies in FECM's portfolio to meaningfully contribute to our clean energy goals, the United States must build up a skilled domestic workforce. FECM must support a wide array of training programs at technical schools, community colleges and universities while continuing to host students and interns through programs like the Mickey Leland Energy Fellowship. Existing activities such as the University Training and Research programs should be updated to reflect the technologies needed to meet the net-zero future with focused support for HBCU and MSI. At the community level, FECM can also support the job-readiness programs that will be essential for recruiting people into the many apprenticeship programs that will be created for frontline workers in CCS, CDR, hydrogen and other sectors.

Technical assistance to help communities implement clean energy technologies is critical to assist in the transition away from unabated fossil fuels and to revitalize local economies. One avenue to do so would be for FECM to expand the technical assistance efforts through programs like the Communities Local Energy Action Program (LEAP). Across workforce development and technical assistance activities, FECM will target energy communities and disadvantaged communities and track and report these efforts to ensure assistance reaches communities that need it the most.

1.3 International Collaboration

Scaling up the technologies and approaches highlighted in this Strategic Vision is a global challenge that requires concerted global actions. International engagement is key to the success of such efforts. FECM leads DOE's engagement with partners on these topics and has developed an international reputation for both policy and technical expertise.

FECM accomplishes this work through strategic partnerships with other governments, research organizations, bilateral and multilateral stakeholder efforts and through technical support and capacity building assistance provided to other countries. FECM also serves as a focal point across the U.S. government for interagency collaboration on technical, policy and regulatory issues related to CCS and CDR, in addition to mitigating and remediating the environmental impacts of fossil fuels. FECM works with DOE'S Office of International Affairs, DOE overseas offices, other DOE program offices, the National Laboratories, the EPA, the U.S. Department of Agriculture (USDA), the U.S. Department of the Interior (DOI), U.S. Department of Treasury (USDT) and others.

As FECM refocuses its mission on climate and decarbonization, the Office's decades of experience in working successfully with a variety of global communities can be leveraged to help accelerate the responsible deployment of these technologies. Prioritizing efforts in the following areas can significantly deliver on FECM's Strategic Vision in a global context, better inform its engagement strategy and boost synergies with international partners:

1. **Identify and prioritize potential international partnerships:** Monitor international development and identify potential partners who are committed to the decarbonization of the fossil fuel value chain as a long-term climate strategy and international partnerships that prioritize such strategy. These partners must be willing and able to work with FECM to move their countries and regions toward net-zero goals.
2. **Lead efforts to develop transparent emissions accounting methodologies and platforms for U.S. energy exports, including Liquefied Natural Gas (LNG) and hydrogen with carbon management.** Develop universal life cycle assessment (LCA) standards to accurately account for the environmental impact and GHG footprints of U.S. energy-related exports and imports, from the point of production to the point of consumption. Coordinate with HFTO and other offices, agencies and countries on developing a common emissions accounting methodology for hydrogen across all feedstocks and resources (renewables, fossil, nuclear, etc.) and facilitate international trade.
3. **Track international RDD&D:** Understand and track international partners' RDD&D priorities, successes and failures to identify opportunities for collaboration as well as inform FECM RD&D investment decisions such as countries in the Global South for tech transfer of FECM-funded technologies.
4. **Identify opportunities for, and execute as appropriate, international collaboration on the following:** Infrastructure development (including feasibility studies on hubs and clusters for CCS and the clean hydrogen/ammonia supply, international market development, methane mitigation and trade), human capital development and capacity building for sustained growth of CCS, CDR, methane reduction and hydrogen production coupled to carbon management.
5. **Advise on FECM priorities domestically and internationally:** Elevate collaboration with other DOE and U.S. government partners on carbon management issues in the international context. Leverage expertise to serve as a resource on issues that are new to many throughout the U.S. government and regularly engage in exchanges of information and insights with international partners and stakeholders on R&D progress and needs. Promote regular knowledge and best practices sharing and harmonization of standards for equipment, safety and certification of life-cycle GHG emissions for decarbonization technologies.

1.4 Domestic Collaboration

The collaborations between U.S. government agencies and within various DOE offices are crucial in meeting U.S. decarbonization goals. Partnerships with other agencies will enhance DOE's ability to deploy carbon management technologies successfully. The complex policy, legal and regulatory considerations for CCS projects require sustained interagency coordination between DOE, EPA, DOI, the U.S. Department of Defense (DOD), the U.S. Department of Transportation (DOT), USDT, the U.S. Department of State (DOS) and other federal agencies. DOE is continually working to build and maintain these cross-agency relationships, share technical information and expertise and work with other departments on CCS and other climate mitigation efforts. These efforts include, but are not limited to: federal RDD&D; regulatory frameworks; tax credits; permitting and siting; analysis of the benefits and potential impacts of climate mitigation technologies and policies; and public outreach and engagement. Another facet of this domestic partnership will include collaboration with National Oceanic and Atmospheric Administration (NOAA), the National Space Agency (NASA), the National Science and Technology Council (NSTC), etc.

1.4.1 Leveraging the National Energy Technology Laboratory's Expertise to Help Meet Net-zero GHG Emissions Goals

FECM is home to the National Energy Technology Laboratory (NETL), one of DOE's 17 National Laboratories. NETL is at the center of technological development to enable a zero-carbon future. NETL delivers integrated solutions to enable the transformation to a sustainable energy future. NETL is the only government-owned, government-operated laboratory in the DOE complex, and possesses the competency, capability and authority to grasp strategic imperatives and lead initiatives that advance the U.S. energy, economic and manufacturing priorities. NETL supports DOE goals by:

- Leveraging nationally recognized technical competencies in Applied Materials Science and Engineering, Chemical Engineering, Computational Science, Decision Science and Analysis, Environmental Subsurface Science and Systems Engineering and Integration, including preeminent project management, to advance knowledge and technology to fulfill the missions of the Lab, FECM and DOE.
- Collaborating with partners in industry, academia and other state, regional, national and international research organizations to nurture emerging technologies through the maturation cycle from discovery to commercialization.
- Implementing mission-driven programs for multiple DOE offices and performing objective technical and economic analyses to inform technology readiness and decision-making across the entire energy value chain.
- Serving the nation in times of emergency, including service as a DOE devolution center in the continuity of operations planning.

Notable NETL successes over the decades include the development and demonstration of technologies that have directly reduced CO_2 emissions from power and heavy industry, in addition to many that are likely to be crucial for reaching net-zero goals. These include deployment of pollution control technologies that reduced nitrogen oxide (NO_X) and sulfur oxide (SO_X) emissions; generation of technology solutions for capture, use and storage of CO_2, including CDR technologies, such as DAC; creation of advanced materials for aggressive energy conversion, storage and transport environments; and technologies that enabled recovery of the nation's critical materials and rare earth elements (REEs).

NETL is in a unique position to accelerate the development of technology solutions through mission-driven R&D projects for DOE/FECM. In addition, NETL supports, through program management services, EERE, the Office of Cybersecurity, Energy Security and Emergency Response and the Office of Electricity (OE). The laboratory's research portfolio includes more than 1,000 projects—totalling an award value of nearly $5 billion and a cost-share of more than $1.3 billion—with more than 600 partners from small and large U.S. businesses, national research organizations, colleges and universities and other government laboratories, including nine of NETL's sister DOE national laboratories.

1.5 Operational Excellence to Accelerate FECM Mission

FECM will drive an enterprise-wide culture of innovation and empowerment, promote knowledge sharing and transparent communication and foster responsible stewardship of people, resources and facilities. The FECM workforce is highly technical. Successful recruitment for technical positions with a high level of required education requires effective planning to attract highly qualified candidates while fostering diversity. There are opportunities to increase diversity within the workforce, and FECM will employ innovative strategies and programs to cultivate and maintain a world class workforce. These workforce development strategies will include social science fields that include environmental and energy justice and have the capacity to achieve current FECM mission and future objectives.

FECM will develop a media strategy highlighting the important impacts that our work in fossil energy and carbon management will have on achieving net-zero GHG emissions goals. The national media strategy will be driven by educating internal and external audiences while capitalizing on the news of the day and including FECM leadership in the conversation. Key elements of the national strategy will include education about decarbonizing the economy, FECM's role and the importance of the Office's RDD&D, expansion of the potential RDD&D performer base, expanding access to information regarding FECM's opportunities and explicit attention to reaching disadvantaged communities and groups underrepresented in enacting the energy transition.

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CHAPTER 2 | POINT-SOURCE CARBON CAPTURE (PSC)

Vision Statement

Demonstrate first-of-a-kind carbon capture on power and industrial sectors coupled to dedicated and reliable carbon storage, that will lead to commercially viable nth-of-a-kind opportunities for widescale deployment and facilitate a carbon-free economy by 2050.

FECM's PSC program will play a key role in decarbonizing committed emissions associated with the power sector and enabling long-term industrial decarbonization, particularly for industries like cement production that have non-energy CO_2 emissions. The PSC program will also play a key role in enabling certain types of CDR, particularly BiCRS for hydrogen, power and other applications. This vision emphasizes the need to prepare commercial-scale capture technologies that are flexible to complement the ever-changing U.S. power grid while simultaneously capable of complete or near-complete abatement at emission sources. Mitigation of CO_2 emissions from point sources requires coupling carbon capture with dedicated and reliable geological storage, carbon mineralization and/or carbon conversion. This vision cannot occur without considering communities that have been harmed by fossil fuel projects.

This vision is organized around both near-term opportunities with a primary focus on decarbonization of the power sector and longer-term opportunities with a primary focus on the industrial sector. Both cases will leverage developed and developing public-private partnerships.

Lastly, to achieve this vision, PSC must be integrated with other carbon management technologies – especially carbon transport, storage, conversion and CDR.

2.1 Background

Capture, transport and geologic storage of CO_2 have been practiced at the commercial scale since the early 1970s when the Val Verde natural gas processing facilities in West Texas began supplying separated CO_2 to enhanced oil recovery (EOR) operations in the region. As of 2020, 28 CCS facilities have been built and operated globally, storing over 200 million tonnes of CO_2 as part of EOR operations and in dedicated saline storage sites (GCCSI, 2020). Many of those efforts have involved the capture of CO_2 from high concentration (i.e., > 98 percent) sources, including twelve natural gas processing operations; four fertilization production facilities; three facilities each from ethanol production, gasification-based chemical production and hydrogen production; and one steel production facility. Only two facilities have been completed capturing CO_2 from low concentration (i.e., < 20 percent) gas streams: the Boundary Dam and Petra Nova coal-fired power production facilities in Saskatchewan and Texas, respectively.

The prevalence of operating capture facilities among high-concentration sources is driven by cost. Capture costs increase with decreasing concentration. Driving down costs for capture from low-concentration sources is an essential element in driving the deployment of CCS. The more dilute a gas mixture is in CO_2, the more expensive the separation process becomes. This is demonstrated for the various sectors ranging from ambient air at roughly 400 ppm to natural gas, which is 100 times more concentrated at 3-5 percent CO_2, and ultimately to industrial emissions sources, which are a combination of process and combustion exhaust emissions that range from 20 percent up to more than 99 percent CO_2 concentration. FECM's focus is on the demonstration of the more costly first-of-a-kind projects so that by "learning by doing," lower nth-of-a-kind costs can be realized, ultimately leading to wide-scale commercial deployment of CCS across several sectors.

2.2 Cost Reductions

Reduced capture cost has long been acknowledged as a critical component to spur the deployment of carbon capture for low-concentration sources. Since DOE R&D efforts for carbon capture began in the early 2000s, cost estimates have fallen by 60 percent through the implementation of energy and process efficiencies and the development of advanced capture media (e.g., solvents, sorbents and membranes). These developments have led to a reduction in both capital and operating costs. Additionally, ongoing efforts to develop transformational technologies have identified and are targeting opportunities for further cost reductions. These continuing RD&D efforts are critical in the effort to drive the eventual deployment of capture technologies.

With ongoing improvements in the performance of carbon capture technologies, the cost of capital is now becoming the dominant factor in overall CO_2 captured cost. The process industry has relied heavily on economies of scale to reduce costs, which means that as equipment sizes decrease, costs increase non-linearly. Much of the successful CCS RD&D to date has shown favorable reductions in capture costs for natural gas combined cycle (NGCC) power blocks producing approximately 2 million tonnes of CO_2/year. However, approximately 65 percent of NGCC power blocks in the United States produce less than 2 million tonnes of CO_2/year, making many of the country's NGCC gas plants unattractive targets for CCS. Emissions from individual industrial sources vary widely, with representative volumes ranging from just over 100,000 tonnes of CO_2/year to over 3.7 million tonnes of CO_2/year. Given the importance of scale, DOE will explore multiple R&D opportunities which aim to transcend the classical reliance on economies of scale, such as process intensification, modularization and advanced manufacturing.

Complementing the RD&D effort in the drive for cost reduction is the act of "learning by doing" – i.e., construction and operation of pilot- and demonstration-scale facilities. Cost reductions in technologies novel for their time are common and well-documented in the evolution of environmental control processes and systems. Taylor et al. (2005) analyzed cost reductions in flue gas desulfurization (FGD) installations over time (Taylor, Rubin, & Hounshell, 2005). Their findings showed that the maturation of FGD technology over a 20-year period led to a 50 percent decrease in capital costs arising from improvements in reliability. Increased reliability allowed designers to eliminate costly redundancies such as spare absorber modules. Additional capital cost savings resulted from technological trends that provided economies of scale, lowered unit costs and reduced reagent preparation costs. In addition, the analysis showed that operating costs were reduced, on average, to 83 percent of their original values for each doubling of cumulative power generation. This value of 83 percent is known as the "progress ratio" and is comparable to progress ratios found in many other industries through the "learning by doing" model of tacit knowledge acquisition. Current experience strongly suggests that similar cost reductions can be achieved as more experience is gained deploying and operating carbon capture technology.

Examples of cost reductions can be made by moving beyond first-of-a-kind installations, such as the two low-concentration source demonstrations noted previously (Boundary Dam and Petra Nova). Project developers conducted quantitative analyses following construction and operation that estimated total capital cost reductions of 67 percent in the case of Boundary Dam (CCS Knowledge, 2018) and a 30 percent reduction in total engineering, procurement and construction cost for Petra Nova (Tanaka, et al., 2018). In both cases, the elimination of redundancies played a major role in reducing costs for future projects, as would economies of scale and modularization of process units. These projected cost improvements provide real-world support for the use of demonstration-scale testing to play an important role in ultimately achieving nth-of-a-kind cost reductions for CO_2 capture systems similar to those described above for FGD systems.

By strategically investing in technologies that lead to commercial deployment, the PSC program can move technologies to nth-of-a-kind. In fact, within the Bipartisan Infrastructure Law Section 41004(b), Congress directs DOE to fund six CCS demonstrations projects. The investments in these integrated CCS demonstration projects will facilitate "learning by doing" cost decreases.

The current carbon capture front-end engineering design (FEED) studies and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) projects are the most mature technologies in their respective portfolios. The objective of CarbonSAFE is to "prove/validate" several saline storage sites across the United States that have a CO_2 storage capacity of up to 50 million tonnes. Five carbon capture FEED studies coupled to CarbonSAFE projects have been completed for the power sector. By leveraging the work from these two programs, a near-term opportunity exists for the deployment of large-scale CCS systems and advancement toward nth-of-a-kind costs.

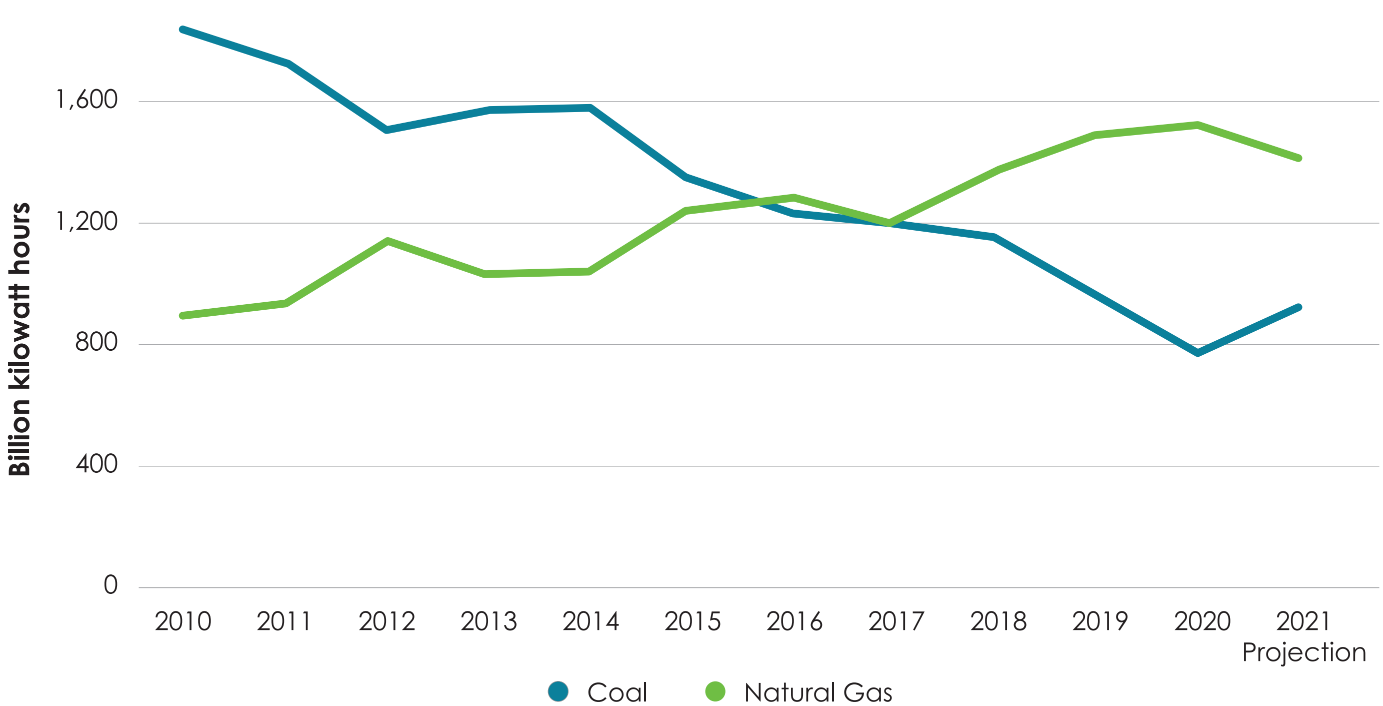
2.3 PSC for Natural Gas Power Generation

Investments made in the United States to move down the cost curve for PSC may be leveraged in other regions with similar fossil dependencies to enable a global path to achieve net-zero GHG emissions. Going forward, FECM's priority will be on additional FEED studies for emissions expected to persist through mid-century, such as from natural-gas-fired power plants. As Figure 2.1 shows, coal-fired electricity generation continues to fall while electricity generated from natural gas continues to increase in market share. While the need for carbon capture on coal-fired units seems less likely than even five years ago, the potential value of CCS on some units producing electricity from natural gas appears even more clear.

2.3.1 R&D Gaps

Full decarbonization of the electricity sector while ensuring reliability and minimizing cost will require a combination of clean resources that together provide the services necessary to ensure a reliable, affordable power system. Natural gas power plants with CCS could lower the cost of a decarbonized electricity generation system by providing clean, flexible, firm capacity. This is especially true if the PSC technologies capture carbon very efficiently (i.e., ≥95 percent capture efficiency), notwithstanding low utilization factors. (Note that addressing the final uncaptured emissions would require either fossil carbon phase-out or compensatory CDR.) However, increases in percent carbon capture significantly above 90 percent and

Figure 2.1 | Annual U.S. electric power sector generation by fuel (EIA, 2021).



decreases in utilization factor could lead to substantial increases in the cost of capture for the current generation of carbon capture technologies, especially when applied to natural gas power plants flue gas. Also, the dilute concentration of CO_2 in natural gas power plants (4 percent compared to about 12 percent for coal-fired utilities), as well as higher water and oxygen content in the natural gas flue gas, makes CO_2 capture from natural gas power plants more technically and economically challenging compared to coal.

To maximize scale-up/demonstration opportunities on natural gas-based power units, carbon capture projects (pre-FEED, FEED) must target emission sources that are co-located or located near reliable long-term storage or transport options (pipelines). This was begun in 2019 with the linkage of capture FEED projects with CarbonSAFE projects. In the future, this linkage will continue by partnering with CCS hub entities. This highlights a need for FECM to thoroughly understand domestic CCS hubs as they begin developing across the United States. Funding limitations will restrict FECM's capture projects to just a few key hub locations, but the private/public partnership opportunities can be used as a decision-making tool for where to spend valuable point-source capture resources. Near-, mid- and long-term R&D priorities for the power sector are outlined in Figure 2.2.

2.3.2 R&D Directions

To address the specific goals, DOE FECM will:

(1) Invest in additional FEED studies coupled with CarbonSAFE projects for existing natural gas power plants or CCS hubs.

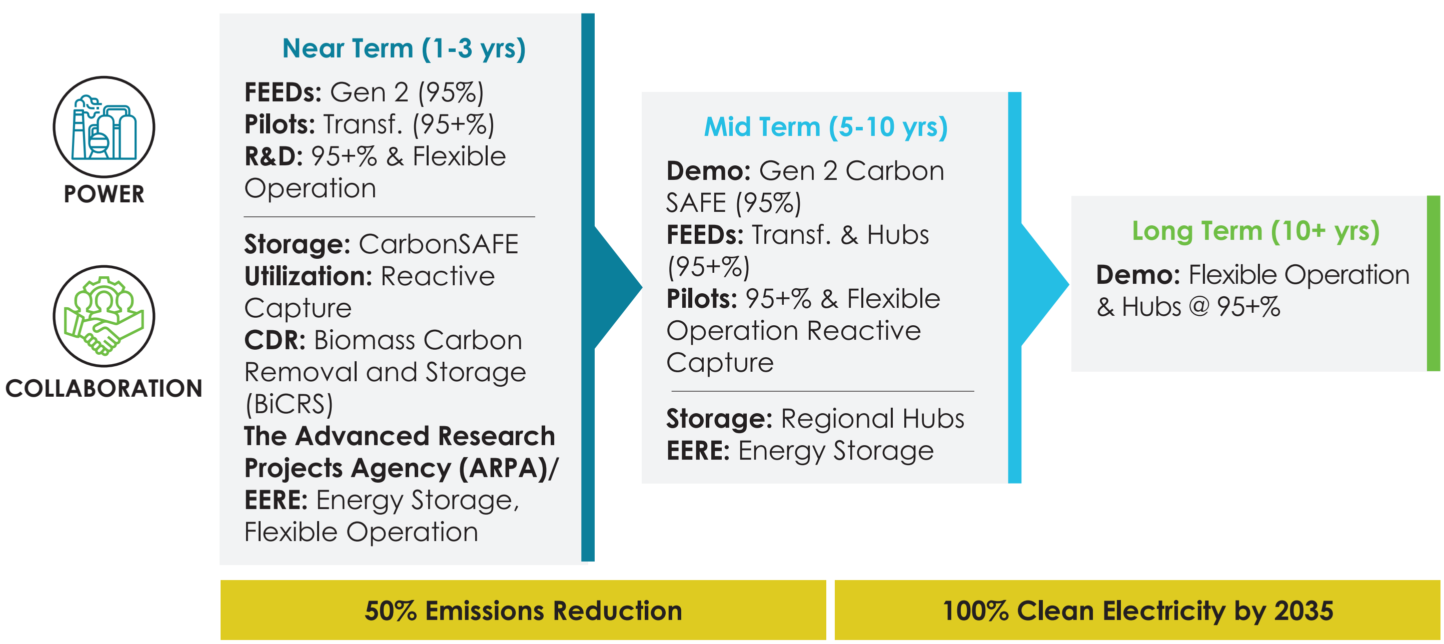
(2) Leverage the broad portfolio of PSC technologies to improve cost and performance; validate performance in small- and large-scale pilot projects.

(3) Support development and scale-up of PSC technologies that leverage low-carbon supply chains and generate low-carbon construction materials (cement, concrete, steel) coupled with advanced gas-fired power plants utilizing lower carbon fuels (i.e., natural gas with renewable natural gas, hydrogen (H_2)).

(4) Foster cross-cutting projects (i.e., within FECM and within DOE) to scale-up PSC technologies at natural gas power plants integrated with long-duration carbon storage or CO_2 conversion (i.e., reactive capture, mineralization), CDR (i.e., BiCRS) and energy storage to support DOE's FECM integrated carbon management strategy; and

(5) Expand capabilities in dynamic process modeling (CCS Knowledge, 2018), techno-economic assessment (TEA) and LCA.

Figure 2.2 | Near-, mid- and long-term R&D PSC priorities for the power sector.



2.4 PSC for Industrial Applications

The International Energy Agency projects that 45 percent of the CO_2 captured and stored globally via CCS would come from industrial applications such as steel manufacturing, cement plants, refineries, ethanol and hydrogen plants. Currently, it is not feasible to avoid process emissions from these industrial sectors when CO_2 may be produced as a result of a chemical reaction outside of fossil fuel combustion, as in the case of calcining limestone for cement production, (e.g., $CaCO_3$ (limestone) -> CaO (lime) + CO_2). Renewable and nuclear energy sources may be used to provide the heat required for some processes, but process emissions are difficult to avoid in the absence of PSC. Some industrial sectors also rely on high-temperature processes that are difficult to electrify within the desired timeframe.

Many PSC technologies developed by DOE/FECM over the last 20 years for power sector applications can be applied to mitigate CO_2 emissions from industrial facilities. However, more research is needed to optimize these technologies for the specific flue gas conditions found in industrial manufacturing processes. Different from the power plants, industrial facilities have multiple, distributed, smaller emission sources with different composition profiles that will require stream integration and/or multiple technologies to meet the deep decarbonization goals.

Similar to the capture program's objectives for natural gas-based power systems, partnering with CCS hubs is a primary focus for the industrial capture program. In fact, it may be even more critical for the PSC program when looking at decarbonizing the industrial sector. This is because the majority of industrial sector emission sources are numerous but smaller and therefore lose the "economy of scale" benefit realized by the power sector. Leveraging the multi-party hub concept can spread the cost of the transport and storage component of CCS to multiple parties, thereby decreasing the overall cost of CCS for these industrial sources. Near-, mid- and long-term R&D priorities for industrial sectors are outlined in Figure 2.3.

2.4.1 R&D Gaps

Full decarbonization of the industrial sector while assuring minimum impact on the product quality and cost will require a combination of (i) improvements in process energy intensity through process intensification and (waste) heat integration, (ii) reducing unfavorable economies of scale for industrially relevant PSC system sizes and (iii) reduction of carbon intensity through the integration of point-source carbon and storage, low-carbon raw material substitution, integration with renewable energy and electrification. These objectives can be accomplished by pilot testing carbon capture technologies at the specific industrial facilities. Within the Bipartisan Infrastructure Law Section 41004(a), Congress provides funding to DOE for the development of large-scale carbon capture pilot projects. These investments will de-risk CCS associated with industrial operations in the cement, steel, hydrogen, ammonia and ethanol sectors.

2.4.2 R&D Directions

To address the specific goals, DOE FECM will:

(i) Support FEEDs for projects coupled to CarbonSAFE projects (short-term) or regional hubs (long-term)

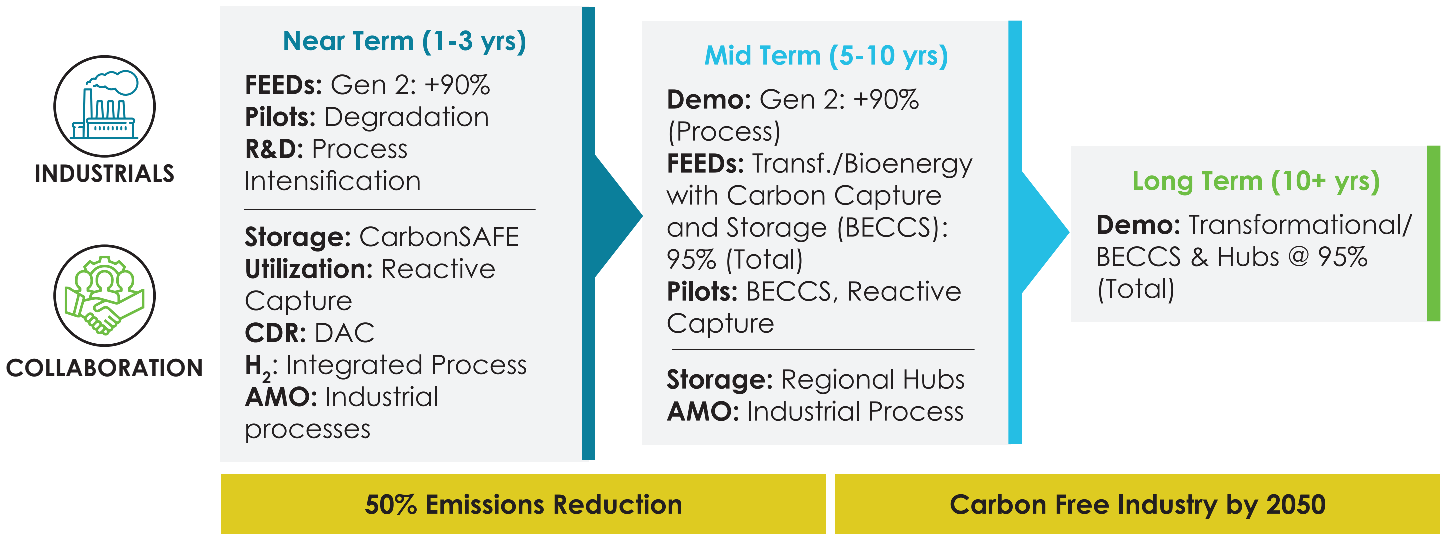
(ii) Validate transformational pre- and post-combustion PSC technologies at industrial facilities with pilot testing to improve cost and performance; quantify co-benefits (i.e., criteria pollutant removal)

(iii) Pursue fully integrated industrial-PSC processes that utilize low carbon feedstock and fuels (H_2, sustainable biomass, biofuels)

(iv) Foster cross-cutting projects (i.e., within FECM and within DOE) to scale PSC technologies at industrial facilities integrated with industrial processes (FECM/H_2, Advanced Manufacturing Office (AMO)), long-duration carbon storage, CO_2 conversion and CDR to support the DOE FECM integrated carbon management strategy

(v) Leverage the demand for low-carbon supply chains by producing low-carbon construction materials (cement, steel).

Figure 2.3 | Near-, mid- and long-term R&D PSC priorities for the industrial sectors.



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CHAPTER 3 | CARBON DIOXIDE (CO_2) CONVERSION

Vision Statement

Research, develop and demonstrate a broad suite of technologies that convert CO_2 into environmentally responsible, equitable and economically valuable products, and enable low-carbon supply chains to meet the goal of a decarbonized economy by 2050.

3.1 Introduction

FECM's Carbon Conversion (CC) Program invests in RD&D and supports the ecosystem that enables technologies to recycle CO_2 into value-added products on an economic scale. Conversion technologies can integrate into various stages of the PSC and CDR supply chains and contribute to opportunities in a decarbonized future.

To achieve the outlined goals of the FECM CC Program listed in Figure 3.1, evaluating the efficacy of conversion technologies must include understanding the viability of the technologies or products. Viability is indicated by commercially competitive or economically attractive pathways as a function of technology and policy development. Technical viability for conversion includes developing systems with access to incrementally scaled testing, secure supply chains, off-takes, defined end-use

Figure 3.1 | Overview of near-, mid- and long-term goals for FECM's CO_2 conversion program.

Near-term (<5 yrs)

- R&D and pilot-scale testing of conversion technologies to evaluate performance and pathways
- Product and market-oriented analysis

Mid-term (5-10 yrs)

- Demonstrate five viable pathways/technologies
- Analysis of decarbonization potential

Long-term (10+ yrs)

- ***Conversion technologies deployed that achieve Y tonnes of CO_2 removed/stored/utilized***
- Design and redesign viability
- Carbon conversion products cannot have an emissive end-of-life if alternatives exist
- Pathways/technologies should be adaptive to cultural shifts such as modular manufacturing or on-demand production

applications and marketable products. Finally, environmental viability is grounded in principles of LCA to validate that CO_2-derived products have fewer net environmental impacts than incumbent products.

3.2 Sustainability & Climate Mitigation Strategy

First, it is imperative to understand the limitations of carbon conversion technologies to understand possible goals and significance. Carbon conversion to products is an approach among a portfolio of approaches that will be required to manage the gigatonne-scale of CO_2 emissions that will be avoided or removed from the atmosphere annually. Many of the products that store CO_2 are either on a scale too small to have a significant impact or are short-lived such that CO_2 re-enters the atmosphere. Despite these limitations, conversion of CO_2 into products does have a place, but the overall carbon accounting of the materials and energy required is a critical component to ensuring that the efforts are additive and ultimately lead to climate benefits. Finally, a practical, sustainable strategy should not be linear but more of a holistic approach.

Conversion technologies can play a catalyzing role in the CCS supply chain during the implementation of future decarbonization scenarios. Conversion technologies can target locations that may not have storage capacity or CO_2 sources that are too distributed for centralized capture. Also, reactive capture and conversion, which couples the CO_2 separation process to its conversion, may reduce costs through process intensification and potentially benefit from regenerating carbon capture materials while simultaneously creating products. Finally, investing in open source, publicly available LCA tools creates veritable carbon accounting foundations for technology development and policies like 45Q tax credits.

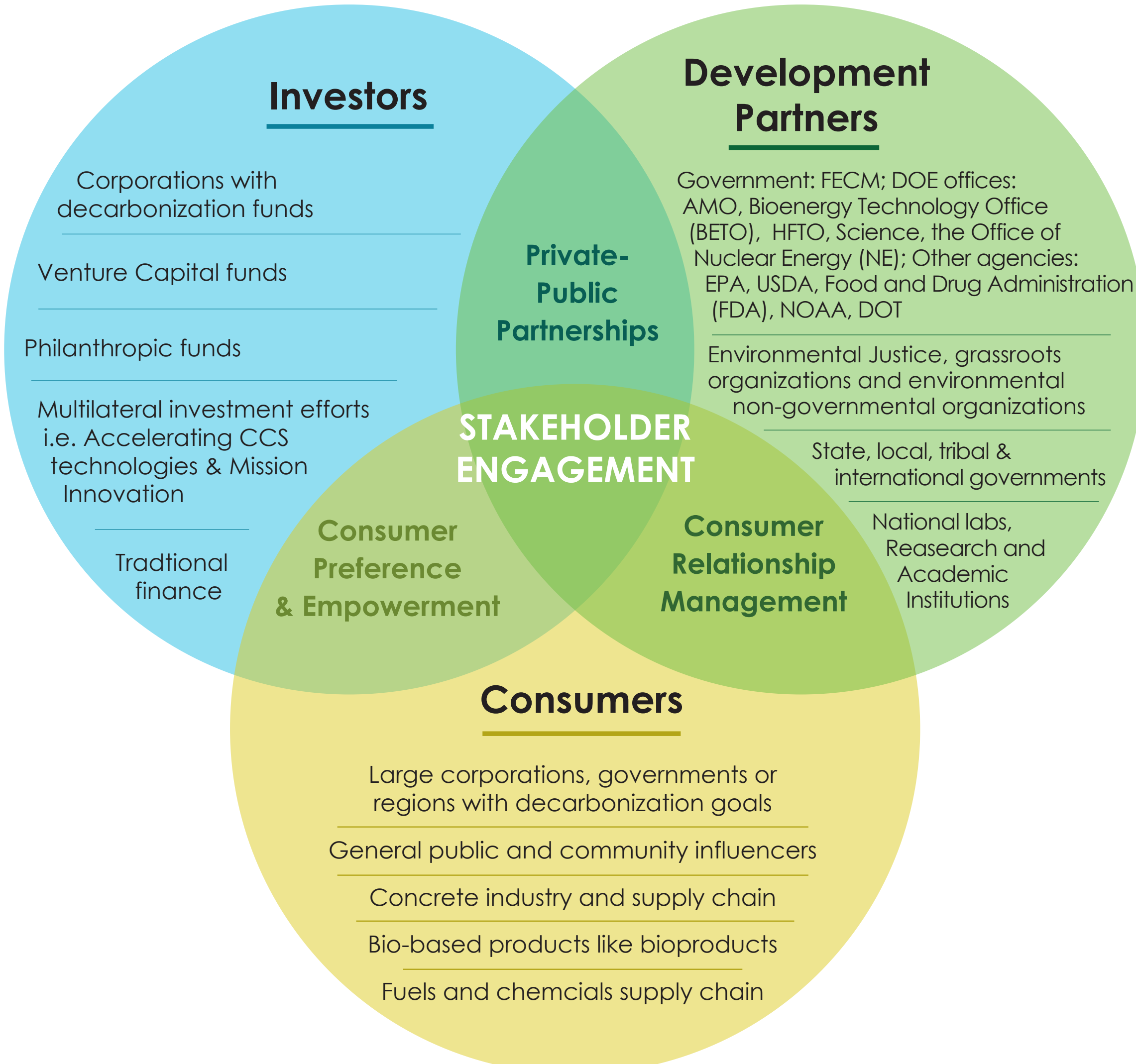
For the greatest impact, conversion technologies should emphasize CO_2-based products that accelerate future decarbonization scenarios.

3.3 Stakeholder and Policy Engagement

There are diverse stakeholders given the variety of products, CO_2 feedstocks and technologies within the conversion program. These stakeholders can be viewed as investors, development partners and consumers, as shown in Figure 3.2.

Stakeholders may fall into different categories for various pathways or at other times along the technology's maturation. This is not a rigid, lasting classification. The purpose of the categories is to help filter communications into a few core goals and meaningful "asks" to shape future stakeholder engagement (Figure 3.2). Effective communication relies heavily on providing accurate information and requesting specific information/actions in return. The CC Program leverages existing information and studies but recognizes that there are gaps in data and opportunities for more research. For example, startups have discussed the difficulty of addressing the "tri-location challenge," which is the distributed location of CO_2 sources, inexpensive renewable electricity and optimal product transport or market. Providing data and spatial understanding on this tri-location challenge is a valuable space for government programs to engage the broader industry.

Figure 3.2| Venn Diagram (top) provides illustrative examples of entities that may classified through one of three lenses or perspectives of consumers, investor and/or development partner. The overlapping areas are potential mechanisms to pursue collaborative engagement between entities. Table (bottom) lists core goals and meaningful "asks" to frame engagement.



Investors	**Goals:** Translate technology competency, provide efficient LCA and TEA evaluation tools and increase awareness
	Asks: How can the program de-risk technologies? What are requirements to provide commercial funding?
Development Partners	**Goals:** Improve knowledge transfer; accelerate R&D maturation; provide common use facilities, provide benchmarking and standarization; understand job impacts and considerations; create strategic partnerships
	Asks: What technical resources will move projects up TRL levels? What barriers are technology developers facing
Consumers	**Goals:** Understand market-specific barriers like standards, permits or regionality; ensure product quality and control; ensure decarbonization potential
	Asks: How can the program improve consumer demand? How can the program foster off-take agreements even for potential products?

The mechanisms listed in the overlapping regions in Figure 3.2 are targeted approaches to facilitate collaboration between different stakeholders.

- In the center is community engagement. This includes environmental justice and job implications, which should underpin all efforts.
- Public-private partnerships are also necessary to develop the technology pipeline to deliver a sustainable market with a broad deployment. In addition, certain entities such as corporations may handle the initial price premium associated with CO_2-based products. Developers must also work with investors to convey technology safety and address investors' needs in terms of risk and economic viability.
- Customer relationship management is another mechanism that will focus on building consumer trust while also factoring in consumer interests in the development cycle. For example, are there opportunities for technologies to result in improved and better products for consumers?

Consumer empowerment and preference is a mechanism to foster communication between investors and consumers. Often changes in consumer behavior can change the path of technology deployment (i.e., investment in renewables driven by power purchasers requesting clean energy). There is an opportunity for the federal government to use its procurement power and create policies to support early markets for CO_2 conversion and provide security to consumers that CO_2-based products in the market provide verifiable carbon reductions. As an example, under Section 40302 of the Bipartisan Infrastructure Law, FECM will establish and implement a grant program for state governments, local governments and public utilities or agencies to procure and use commercial or industrial products that are derived from anthropogenic carbon oxides.

Underpinning federal government procurement policies or regulations on carbon conversion is a need for continued improvement of LCA implementation. Guidance on LCA for utilization has been developed for DOE-supported projects, and the latest 45Q tax credit guidance references this LCA guidance. Providing technical expertise in creating transparent and accurate LCA application for policy efforts is the near-term goal for the program.

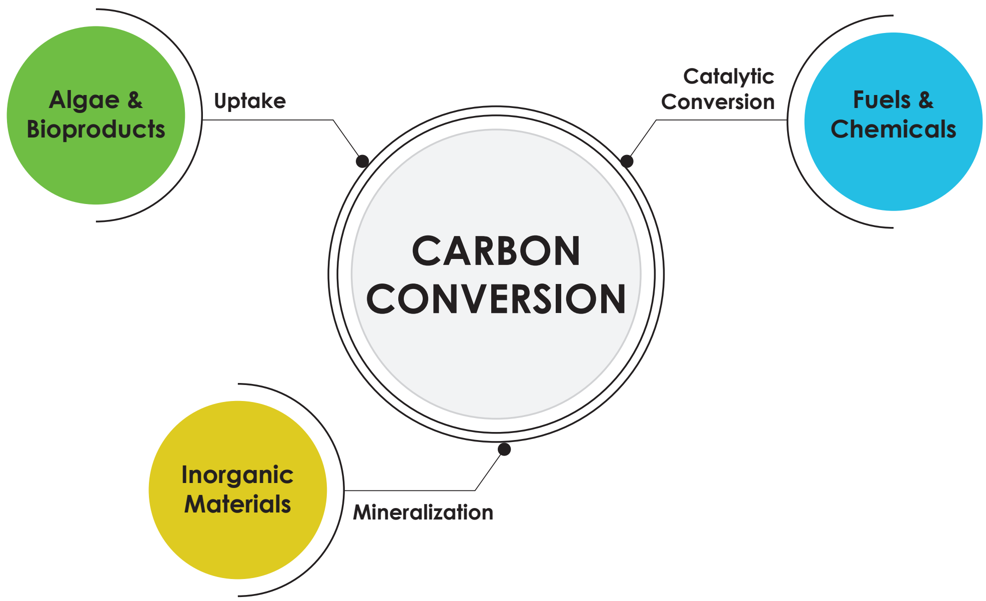
There are also LCA provisions in other policies, such as the federal renewable fuels standard (RFS) program. The RFS program currently has approved pathways for fuels produced from algae-derived oil. These LCA guidelines and provisions could be expanded and improved to address a broader range of technologies. In addition to the inclusion of fuels produced from CO_2 conversion, there are provisions under renewable fuels programs for facilities capturing CO_2 to potentially receive credits under the program. However, companies interested in such pathways must submit petitions to add new pathways.

3.4 Technical Strategy

Figure 3.3 depicts CO_2 products. CO_2 can be utilized without conversion, for example as a working fluid in contexts like EOR, but such non-conversion pathways where the CO_2 is used rather than converted are not of interest to the CC program. The R&D focus of this program is to address critical technology challenges associated with CO_2 conversion and improve overall system performance by decreasing energy requirements and validating carbon reduction compared to conventionally produced analogs.

To achieve these objectives, RD&D projects must address challenges specific to one of the three pathways below.

Figure 3.3 | Diagram of carbon conversion and utilization (physical services) pathways.



3.4.1 Carbon Uptake in Algal Systems

Algae are efficient photosynthetic organisms. The biomass produced in algal systems can be processed and converted to fuels; chemicals; food for fish, animals or humans; soil supplements; and other specialty and fine products.

Priority Research Items:

1. Development of novel CO_2 delivery mechanisms by integrating carbon capture or intermediate delivery to increase productivity and improve the carbon utilization efficiency of the delivered CO_2.
2. In partnership with BETO's Advanced Algal Systems program, better analysis of existing algal systems, including costs, delivery, purity and rates of consumption. This will ensure CO_2 delivery technology is compatible and can grow to commercial scale.
3. In partnership with BETO, accelerate the market penetration of a range of bioproducts from more efficient product yield to facilitating permitting and addressing consumer concerns.

Objectives for RD&D on this pathway include:

Near-Term (<5 years):

- Field test and scale-up advanced algal approaches with enhanced carbon capture which are commercially viable or integrated into existing commercial systems.
- Improve LCA and TEA tools and harmonize with existing tools such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model.

Mid-Term (5-10 years):

- Demonstrate integrated carbon capture and advanced algal concepts on a field scale to validate performance and economics.

3.4.2 Catalytic Conversion

Catalytic conversion can include thermochemical, electrochemical, photochemical and microbially-mediated approaches. The utilization of catalysts or integrated processes lowers the energy needed to drive these systems. Via this pathway, CO_2 can be transformed into synthetic fuels, chemicals, plastics and solid carbon products like carbon fibers.

Priority Research Items:

1. Increased focus on conversion pathways that leverage existing supply chains (e.g., translating a platform technology like polymer electrolyte membrane electrolyzers).
   a. Discover new catalysts or improve current catalysts with a focus on industrial viability.
   b. Integrate catalysis research while considering reactor design for large-scale production.
   c. Create benchmarks to standardize catalyst scale-up and use existing industry experience to develop benchmarks i.e., chloro-alkali systems for electrochemical conversion.
2. Production of non-traditional products from CO_2 conversion like those with C-C bonds (carbon nanotube, polymers and ethylene).

Objectives include:

Near-Term (<5 years):

- Test and evaluate different catalytic conversion pathways and technologies that show promise for conversion of CO_2 into products; determine applicable benchmarking standards for various pathways.
- Conduct pre-feasibility studies of first-generation concepts to define engineering, technical and financial parameters of CO_2 conversion technologies.

Mid-Term (5-10 years):

- Conduct integrated field tests of advanced catalytic conversion technologies to validate approaches.
- Conduct FEED studies, construction and operation/demonstration of first-generation technologies.
- Establish supply chains and leverage existing fuels and chemicals infrastructure.

Long-Term (10-15 years):

- Demonstrate second generation, commercially viable, catalytic conversion technologies.
- Establish integrated systems that couple CO_2 conversion and hydrogen production for product generation.

3.4.3 Mineralization

CO_2 mineralizes with alkaline reactants to produce inorganic materials, such as aggregates, bicarbonates and associated inorganic chemicals. Carbonate materials may be an effective long-term storage option for CO_2 especially for use in the built environment.

Priority Research Items:

1. Further understand relative rates of carbonation and hydration to control carbonation or curing reactions.
2. Investigate waste products such as mining wastes and produced waters for alkalinity sources for mineralization reactions.
3. Process designs that can integrate CO_2 capture with mineral carbonation technologies.
4. Facilitate testing and gain approvals for codes and standards such as ASTM or American Association of State Highway and Transportation Officials (AASHTO).

Objectives include:

Near-Term (<5 years):

- Deploy more "plug and play" technology solutions for improved CO_2 curing in building materials.
- Conduct field tests of novel concepts to understand integration and engineering challenges.
- Conduct lab- and bench-scale R&D to increase understanding and validate carbonation rates, crystal growth and reactions at the solid-liquid-gas interface.

Mid-Term (5-10 years):

- Demonstrate mineralization concepts coupled with capture technologies to validate technologies and production of marketable products.
- Establish viable supply chain models for mineralization concepts.

Long-Term (10-15 years):

- Demonstrate second-generation mineralization products, including novel composites, built from CO_2.

Cross-cutting Opportunities: There are several opportunities to leverage advancements in cross-cutting areas that could apply to carbon conversion technologies. For example, LCA and TEA tools and capabilities are necessary to ensure the environmental and economic viability of carbon conversion technologies and approaches. There are also opportunities to leverage advanced capabilities such as high-performance computing and advanced manufacturing, leading to new, innovative catalysts, materials and reactor systems that can optimize carbon conversion.

Existing testing facilities and infrastructure can also facilitate field testing technologies under real-world conditions to validate integrated concepts. This includes broadening the scope beyond domestic capabilities and exploring opportunities internationally where capabilities, resources and knowledge can be leveraged. Investments in the broader "carbontech" ecosystem can also impact carbon conversion technology development and deployment by leveraging incubators and hubs. This includes engaging with the investment community early in development and exploring collaborative opportunities with broader CCS development activities such as regional hubs and infrastructure development. Finally, collaboration with other agencies will have benefits by ensuring these agencies have sound science and technical basis when making policy decisions. These relationships can facilitate the deployment of carbon conversion technologies by developing codes, standards, regulations and procurement policies that can impact market acceptance and development for products made with CO_2.

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CHAPTER 4 | CARBON DIOXIDE REMOVAL (CDR)

Vision Statement

Advance diverse CDR approaches in service of facilitating gigaton-scale removal by 2050, emphasizing robust analysis of life cycle impacts of various CDR approaches and a deep commitment to environmental justice, including rigorously evaluating CDR, defining conditions for success and leveraging leadership and expertise.

4.1 Core Goals and Relevant Efforts

CDR refers to the permanent removal of CO_2 from the atmosphere, which is a core element of both the Administration's climate goals and FECM's Strategic Vision. FECM's CDR vision is to advance diverse CDR approaches in service of facilitating gigatonne-scale removal by mid-century, emphasizing rigorous analysis of life cycle impacts and a deep commitment to environmental justice. FECM's RDD&D efforts aim to advance diverse CDR approaches in service of facilitating gigatonne-scale removal by mid-century, with particular emphasis on demonstration and analysis efforts that reduce uncertainty about performance, costs and environmental impacts, including the impacts of life cycle GHG emissions.

Key areas of integration across FECM's Strategic Vision areas include Point-Source Carbon Capture (PSC), Dedicated and Reliable Storage and Methane Mitigation (for natural gas-fired CDR). For example, PSC technologies overlap with some CDR approaches, like direct air capture coupled to dedicated and reliable storage and BECCS. Dedicated and Reliable Storage, for example, in geologic and mineralization contexts, is core to successful carbon removal, and any natural gas-fired CDR will be more effective with Methane Mitigation. We anticipate that some of the biological pathways for CDR could prompt additional interaction with the Dedicated and Reliable Storage strategic area in the context of soil carbon and standing biomass sequestration and verification. Key areas of integration across DOE include the Carbon Earthshot, with a goal of achieving \$100/ton net CO_2e removal for diverse and highly scalable CDR applications by 2032. Key areas of integration across the U.S. government include the CDR Task Force. Critical areas of integration internationally include the newly launched Mission Innovation for CDR.

In the near term, FECM's most critical goal is to lay the groundwork for a sustainable and just CDR industry built on rigorous analysis. As the CDR industry essentially does not yet exist, near-term activities will dramatically shape not only the industry but expectations for structure, accountability and other institutional factors. As such, FECM's near-term objectives include becoming a trusted resource on CDR, evaluating both technology and institutional structures during R&D activities and developing analytical resources to ensure rigor in evaluating sustainability and justice for the CDR industry. Further, FECM will advance CDR methods and components that are most related to our historical core expertise areas (e.g., DAC and geologic storage). For example, under the Bipartisan Infrastructure Law, FECM is directed to support Regional Clean Direct Air Capture Hubs (section 40308) in addition to prizes for both precommercial and commercial DAC technologies (section 41005).

The amount of CDR needed to be deployed to reach net-zero, then potentially net negative, is contingent on the success of emissions avoidance and mitigation efforts. Since that avoidance is the strong priority over removal, FECM does not set explicit quantitative targets for CDR deployment levels but, rather, emphasizes developing expertise across diverse CDR methods. Thus, in the medium term, in addition to refining standards and analytical capacity for evaluating CDR, FECM will build expertise in the entire range of CDR methods—including land- and ocean-based methods. FECM will also advance early-stage technologies across various TRLs while focusing on justice and sustainability. In the long term, with the relative maturity of the CDR industry, FECM will concentrate on both novel technologies and advancing existing technologies, e.g., via improvements to socio-environmental impacts and costs.

4.2 The Need for CDR

Given slow progress on mitigation over the past several decades, including a failure to cut global GHG emissions rapidly, CDR is now recognized as a core requirement for achieving ambitious climate goals, including those described in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC, 2021). Although avoiding GHG emissions is the top priority, CDR is important for mitigating difficult-to-avoid emissions in multiple sectors (like those associated with food production) and for drawing down legacy GHG pollution from the accumulated atmospheric pool. Due to its potential for addressing historic emissions, and given the deep harms observed and anticipated from climate change, responsible and appropriate CDR is potentially an important strategy for enacting global environmental and climate justice goals. Further, CDR is integral to the Administration's goal of reaching net-zero GHG emissions economy-wide by 2050: the use of "net-zero" rather than "zero" reflects the recognition for the need for negative emissions technologies.

CDR is relevant for net-zero and net-negative GHG emissions trajectories, as outlined in the Intergovernmental Panel on Climate Change's (IPCC's) Assessment Report 6 (IPCC, 2021). For net-zero GHG emissions goals, CDR could be deployed to mitigate ongoing emissions from difficult-to-decarbonize sectors like those that cannot be effectively electrified or controlled today (e.g., aviation) and those with non-CO_2 non-energy GHG emissions (e.g., nitrous oxide from agriculture). However, these efforts must be made with the recognition that removing one tonne of CO_2 from the atmosphere cools the planet less than emitting one tonne of CO_2 warms it. For net-negative emissions goals, CDR could be deployed for atmospheric CO_2 drawdown, remediating past climate pollution. CDR will be essentially a brand-new industry, the scale of which depends substantially on the balance of CDR-as-mitigation, compensating for ongoing emissions to reduce "net" emissions and CDR-as-drawdown that addresses legacy emissions. Policy, and a careful emphasis on justice and responsible deployment, will be crucial for the way CDR is deployed in the United States and across the world. Questions about ownership (e.g., CDR as a for-profit private service versus CDR as a public utility, and real or perceived ties to fossil fuel extraction and use), siting, co-benefits and dis-benefits will be critical for designing a new industry capable of providing affordable, effective, sustainable and just actions. One key risk, and a focus area for FECM, is that poor implementation of CDR could lead to withdrawal of, or failure to grant, social license. Challenges exist at multiple scales, from local disbenefits (e.g., noise; land use; industrialization) to international governance challenges (e.g., discharge of post-removal ocean water associated with direct ocean capture). The role of the federal government relative to private, state and other actors is not yet fully defined. Similarly, the role of intellectual property sharing and technology transfer in global climate efforts is critical and likely to be increasingly defined as demonstration projects and early commercial projects come online.

4.3 Technology Focus Areas

FECM works on diverse CDR approaches. Areas of focus include DAC, enhanced mineralization, BiCRS and BECCS, direct ocean capture and other ocean-based approaches, terrestrial sequestration and geologic storage as an enabling technology. FECM works across technology readiness levels and aims to be a leader in rigorously evaluating and testing multiple technologies. FECM's CDR vision also includes looking for new areas of CDR research that have not historically been part of its programs, with the goal of being a credible and reliable source of high-quality information on CDR. Further, FECM aims to leverage past work on abatement technologies to unlock rapid and responsible CDR.

4.3.1 Priorities for Leadership Efforts

FECM intends to focus its leadership efforts in several important areas: RDD&D, including the development of system-scale[1] hubs and regional deployment; facilitating an integrated system of CDR efforts, including with a whole-of-government approach that emphasizes transparent, consistent and rigorous approaches to measurement, reporting and verification (MRV); and facilitating the responsible, just development of the CDR industry.

4.3.2 RDD&D

FECM is highly focused on RDD&D for CDR. Work at different TRLs and on diverse CDR approaches are intended to provide optionality for the country's net-zero goals. Also important is FECM's role in de-risking technologies, improving transparency around costs and performance, and leveraging expertise to evaluate potentially transformative CDR pathways. As the CDR industry develops, emphasizing facility-scale and system-scale design and deployment will become increasingly core to FECM's work and vision. Particularly related to hub development and regional deployment, FECM's analytical, design and experimental work will be critical in understanding CDR from component through system scale. One major area of emphasis is understanding diverse sociotechnical contexts for CDR using a place-based lens, considering how constraints and opportunities vary geologically, geographically, socially and economically, and how those different contexts might alter deployment choices. System-scale analysis that includes host community context and needs is a major focus for deployment-oriented work in FECM. FECM intends to be a leader not only in technological development for CDR, but also in the responsible and appropriate deployment of CDR that understands it to be a new sociotechnical system.

4.4 Convening Government and Other Actors for a Systems Approach to CDR

FECM intends to demonstrate leadership in a systems approach to CDR by leveraging expertise and convening power within the U.S. government and all CDR actors. Within the U.S. government, FECM will especially focus on transparent and communicative approaches to enable true removal, including designing, testing and implementing rigorous and easy-to-use analysis and MRV approaches to validate quantitative measures of CDR. Within the U.S. government, FECM recognizes the need to work closely across multiple agencies. These agencies include: EPA, for Class VI wells and life cycle GHG accounting; DOT, for CO_2 pipeline planning and deployment; USDA, for biomass sourcing, land access and other efforts mainly focused on land-based and biomass CDR; DOI, for land access including pore space for CO_2 storage; DOS, for international governance and cooperation goals; NOAA, for better understanding of the prospects for ocean-based CDR; and the White House, serving an ongoing coordinating role that can benefit from FECM advice and leadership.

Outside of government, FECM's convening power is an opportunity for leadership. FECM can leverage its expertise in CDR and other areas (like industrial point-source CCS for decarbonization) to enable intentional, effective and responsible deployment of CDR. For example, FECM can serve as a trusted source of expertise and convening opportunities to help companies with net-zero goals think about CDR versus alternative methods of supply chain decarbonization. By leveraging other areas of its expertise, FECM can serve as a leader in enabling a responsible and appropriate path to net-zero that includes, but does not solely rely on, CDR. Leveraging investments in other spaces to identify where ongoing RDD&D efforts can unlock additional CDR opportunities, such as when specific technologies are relevant for both mitigation and removal strategies, FECM can inform efficient decarbonization. Analytical capabilities, including systems modeling, can provide leadership in identifying where path dependencies at a system scale might emerge. As an example, potential carbon management futures might compete for similar resources like pore space, biomass or transportation infrastructure. FECM can act in an integrative leadership role by being very intentional about obtaining and sharing information about early CDR efforts,

[1] System-scale refers to the analysis, design, operation or demonstration of a complete system that includes multiple interacting components, often with feedback and control. System-scale can refer to a process system (such as a power plant with carbon capture or industrial plant) or an infrastructure system (such as the electrical grid, pipeline network or supply chain system). System-scale models are critical for integrating technologies.

providing data, lessons learned and other information that can facilitate success both in government and nongovernment CDR investments. Developing clear metrics and communicating how and why certain goals are set can be a way that FECM shows leadership that provides transparent benchmarking for other actors. For example, CDR investments might optimize around cost per CO_2e removed rather than maximizing capture, as is more common for mitigative point-source removal, and being transparent about the effect of differing objectives for technologies that seem similar can provide value across the system.

4.5 Justice and Responsibility in CDR Development

FECM's CDR vision includes a deep commitment to justice and responsible CDR deployment, particularly given that CDR is a nascent industry that is expected to become a necessary component of responding to the climate crisis. For all CDR approaches, from primarily nature-based to primarily technological, the scale of expected deployment requires extreme care in the responsible and appropriate development of facilities, systems and governance and ownership structures. FECM intends to facilitate efforts across the U.S. government to enable excellent stakeholder engagement with a strong focus on justice in both domestic and international contexts. This will include working to communicate effectively and transparently what CDR is and why it is needed. Particularly for early demonstrations, it is critical to be clear about why particular choices are made and how they will lead to intended outcomes. For instance, early demonstrations might not enact true life cycle GHG removal, particularly before the energy sector is fully decarbonized. It is also critical to be clear about why tests are important and how the value chain through RDD&D ultimately facilitates responsible and just action on the climate crisis. Being committed to transparency, safety and swift mitigation of any potential harms is crucial for CDR deployment. Work to build capacity in communities and other groups to enable thoughtful participation is also an area where FECM intends to be proactive. Given the expertise, FECM's vision includes careful analysis and identification of potential future harms from CDR and approaches for mitigation. These approaches include considering the distributional disparities associated with both co- and dis-benefits. Designing engagement approaches that are conscious of diverse contexts and needs can provide both opportunities and challenges for CDR, and this should be a core area of focus.

FECM can also show leadership in implementing policy expected to lead to responsible, appropriate and just uptake of CDR. As an RDD&D organization, FECM can work both with our agency partners and congressional leaders to recommend policy guard rails and transparently communicate examples of appropriate implementation pathways. FECM can also provide transparent information to inform policy about when and how to use technologies that the office tests and proves, both for national and international contexts. By being transparent about "what good looks like" and about what FECM is doing to reach those goals, FECM can help demonstrate policy leadership via rigorous and responsible technical efforts. This effort will include acknowledging when specific pathways pose risks that might need additional care and evaluation (e.g., when interim efforts rely on existing fossil fuel systems that could lead to long term lock-in).

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CHAPTER 5 | DEDICATED AND RELIABLE CARBON STORAGE AND TRANSPORT

Vision Statement

Establish the foundation for a successful carbon storage and transport industry by making key investments in RD&D, large-scale transport and storage facilities and regional hubs to support rapid deployment of carbon storage necessary to enable the decarbonization of the U.S. economy.

5.1 Carbon Storage and Transport Today – Foundation for Growth

Two decades of DOE FECM-directed research, development and field demonstration (NETL, 2020), together with industry investment and technical involvement of states and other federal organizations, have demonstrated that CO_2 can be reliably transported and stored in geologic formations. These efforts include:

- **Carbon Storage Atlas** – An estimate of the prospective CO_2 storage resource for onshore saline formations that total 8.328 billion tonnes (NETL, 2015).
- **Regional Carbon Sequestration Partnerships (RCSP)** – Completed six large-scale field projects cumulatively storing over 11 million tonnes of capture CO_2, which validated monitoring technologies and demonstrated secure and reliable storage. (NETL RWFI, 2021) (NETL, 2020)
- **Regional Initiative projects** – Successors to the RCSPs that accelerate efficient and equitable carbon capture, utilization and storage (CCUS) deployment by engaging with regional stakeholders and communities, providing technical assistance for project development.
- **CarbonSAFE** – A program that began in 2016 to characterize, permit and construct commercial-scale storage facilities, each with the capacity to store 50+ million tonnes of CO_2. Five Phase III projects are currently active and aligned with capture FEED studies supported by the DOE CC Program.
- **Core R&D** – The advancement of geologic storage site characterization methods, monitoring systems, modeling and simulation capabilities and risk assessment and management tools to support permitting and demonstrate reliable storage.
- **Pipelines** – A mature and established U.S. CO_2 transportation industry operating over 5,000 miles of CO_2 pipeline infrastructure across thirteen states, with established construction and operational best practices that are well understood.
- **Regulatory** – The United States has in place regulatory structures for carbon storage and transport that some of the states are seeking primacy to manage.

Today, various industry stakeholders are pursuing CO_2 storage in saline formations, motivated in part by incentives such as the 45Q tax credit and California's Low Carbon Fuel Standard. Of the 22 carbon storage projects in development in the United States, at least 10 are pursuing storage projects in saline formations and will be active by 2030 (GCCSI, 2021). But to meet the Administration's decarbonization targets, future investments in the dedicated transport and storage industry must be accelerated to build the infrastructure needed for carbon storage and transport over the next decade.

5.2 Demand for Reliable Carbon Storage and Transport Industry – The Future

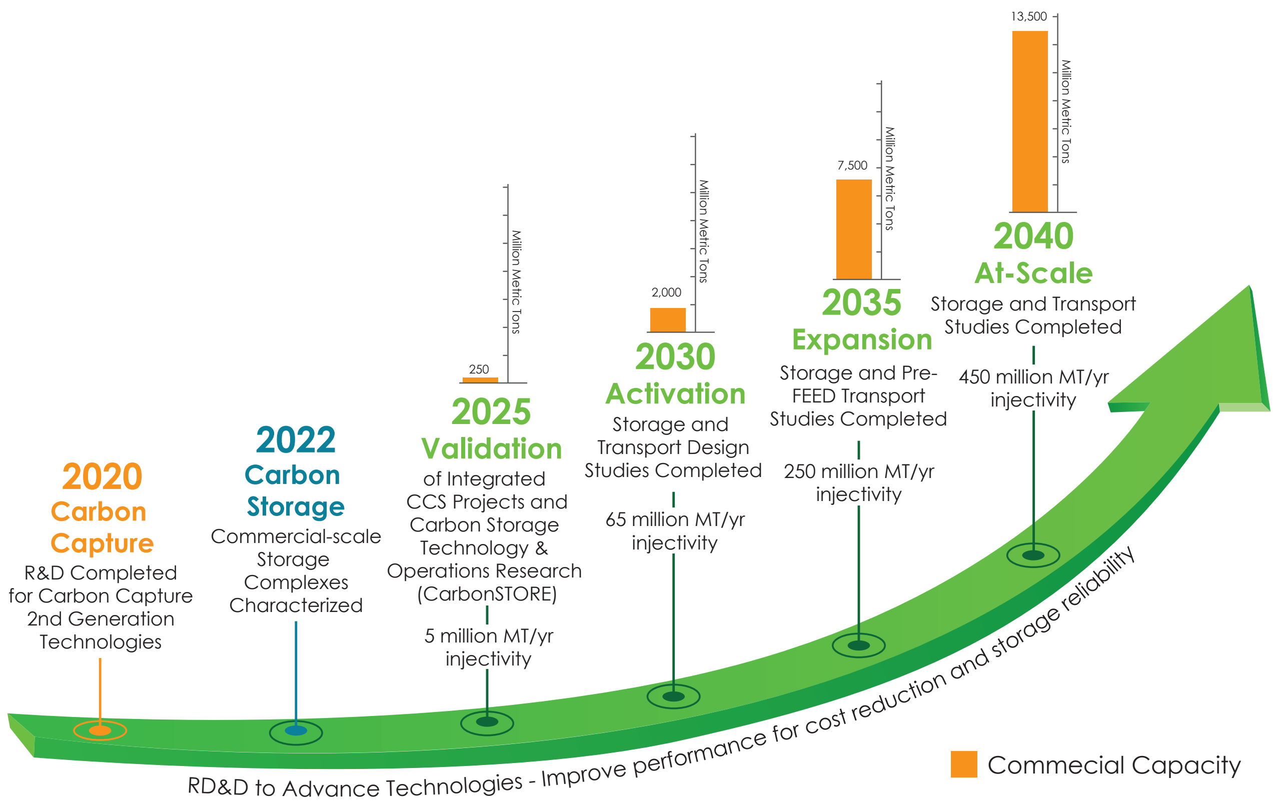
Building the infrastructure for carbon storage and transport over the next decade is necessary to support the full decarbonization of carbon-intensive industrial sectors and to enable CDR strategies like direct air capture coupled to dedicated and reliable storage and BiCRS.

Over the next decade, several billion dollars of strategic investment in RD&D, stakeholder and community engagement and the advancement of "commercial" storage resources will be needed to ensure that this critical infrastructure is in place to meet the nation's carbon management goals (Larson, et al., 2020). These early investments are needed to establish the foundation for the rest of the industry.

Recent studies show geologic transport and storage capacity infrastructure must accommodate at least 65 million tonnes of CO_2 per year by 2030. This rate is roughly equivalent to the demand of the entire CO_2 EOR industry, a well-established industry built over the past 50 years (Larson, et al., 2020). Injection of CO_2 at this rate over 30 years will require two billion tonnes of commercial storage capacity by 2030.

Expansion of the existing CO_2 transportation network and conversion of existing infrastructure will be needed to move hundreds of millions of tonnes of CO_2 per year to facilities for reliable storage (IEA, 2021). Robust plans for the build-out of a national-scale network of pipelines must be developed to inform and facilitate the rapid, secure and widespread deployment of CCS and CDR, with particular attention to justice and consultation. Studies estimate a national

Figure 5.1 | Reliable storage and transportation pathway towards decarbonization.



Note: MT means metric tonnes

network of carbon transport and storage facilities that will require investments of tens to hundreds of billions of dollars, creating hundreds of thousands of jobs (LEP, 2021) (NPC, 2019) (Abramson, McFarlane, & Brown, 2020) (NASEM, 2021). While national studies differ on some approaches, they agree that massive investment is needed to meet the nation's decarbonization goals.

To spur this level of growth, DOE and FECM will make key investments in large-scale storage facilities and regional hubs to catalyze the rapid deployment of carbon storage necessary to meet decarbonization goals, as shown in Figure 5.1. These can be allocated across three phases: activation, expansion and at-scale.

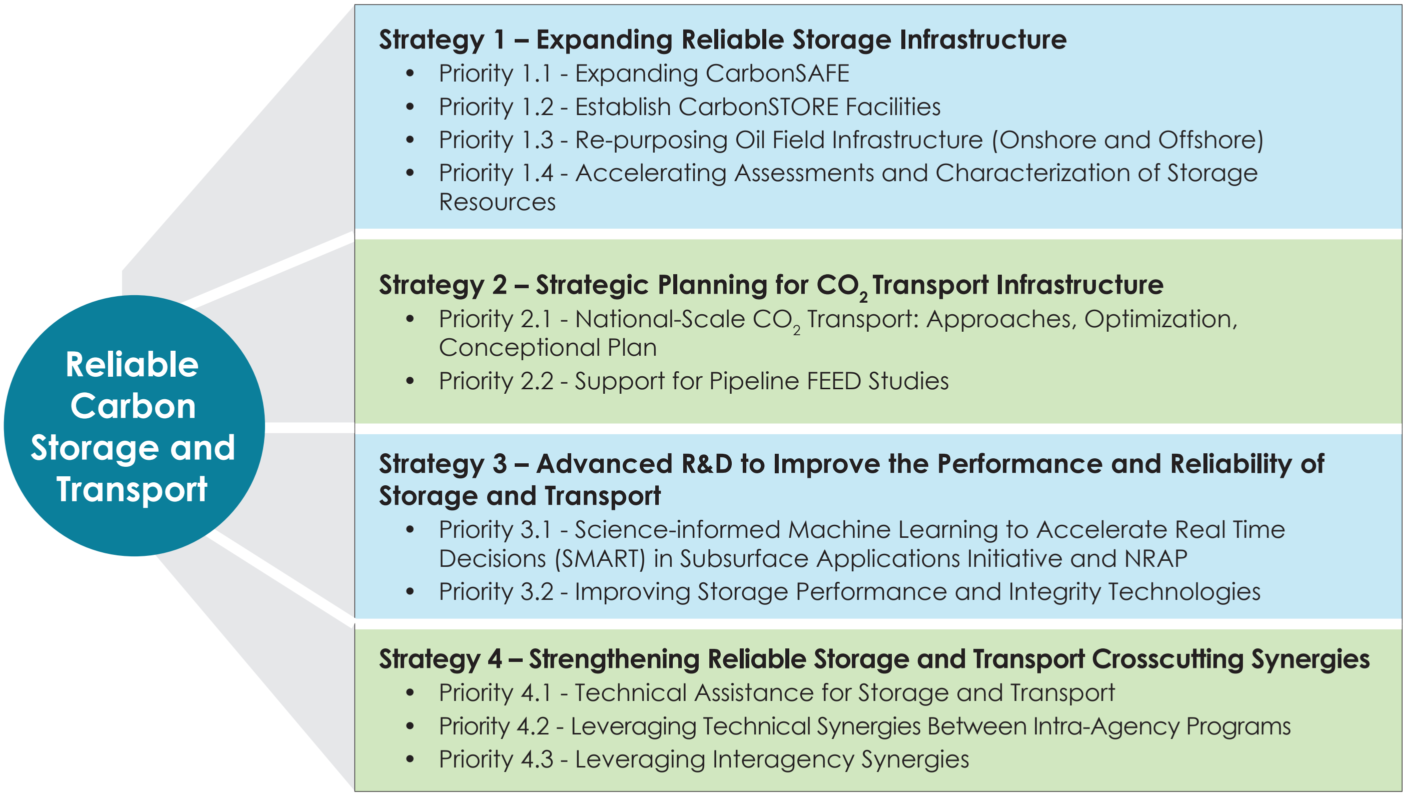
5.3 Goals to Expedite Reliable Storage and Transport

The nation's decarbonization commitment drives FECM to promote the expedited deployment of CCS and storage-based CDR. Forecasted growth in demand for reliable geologic storage resources and transport infrastructure requires that FECM make strategic investments now and over the coming years to meet this challenge. Strong, proactive engagement with disadvantaged communities and other key stakeholders will ensure that these goals are met in an environmentally sustainable and just manner. The goals in Figure 5.2 were identified as critical areas where program support can catalyze "at-scale" deployment.

Figure 5.2 | Strategies and research priorities to support reliable storage and transport.

		5 Year Goal 2030 ACTIVATION	10 Year Goal 2035 EXPANSION	15 Year Goal 2040 AT SCALE
Carbon-SAFE	Commercial Storage Capacity	2,000 Million MT over 30 years	7,500 Million MT over 30 years	13,500 Million MT over 30 years
	Injectivity	Injection of 65 Million MT/yr	Injection of 250 Million MT/yr	Injection of 450 Million MT/yr
Contingent Storage Resource		Identify 5,500 Million MT	Identify 6,000 Million MT	Identify 7,500 Million MT
Repurposing Storage Infrastructure		FEED studies for repurposing onshore and offshore infrastructure (depleted oil/gas fields, wells, pipelines, etc.)		
CO_2 Transport Infrastructure		Support design studies of regional infrastructure; feasibility studies of national network	Support pre-FEED studies of trunk lines to interconnect regional hubs	Support development of trunk lines and feeder lines
Advanced R&D		Develop tools for basin-scale management of storage resources Develop and deploy tools to reduce cost, risk and uncertainty in storage projects Establish CarbonSTORE facilities in multiple different geologic settings Integration of Science-informed Machine learning to Accelerate Real Time decisions for Carbon Storage (SMART-CS) and National Risk Assessment Partnership (NRAP) tools into commercial storage applications		
Crosscutting Synergies		Develop programs to provide technical assistance and make information readily available to agencies and stakeholders		

Figure 5.3 | Strategies and priorities to support reliable storage and transport.



5.4 Strategies and Priorities

To achieve the goals for carbon transport and storage, FECM is focused on four key strategies and associated research priorities to accelerate the development and deployment of reliable carbon storage and transport technologies, as illustrated in Figure 5.3.

5.4.1 Strategy 1 – Expanding Reliable Storage Infrastructure

Reliable storage infrastructure will be key to the deployment of CCS technologies in the United States. Hundreds of capture and storage facilities will be necessary to meet the goals shown in Figure 5.3. "At-scale" deployment of a large-scale carbon storage industry necessary to decarbonize the U.S. economy requires immediate investments to expand CarbonSAFE, establish CarbonSTORE, repurpose infrastructure and provide technical assistance. Under the Bipartisan Infrastructure Law Section 40305, FECM is directed to support Carbon Storage Validation and Testing of large-scale of CO_2 geologic storage facilities.

Priority 1.1 – Expanding CarbonSAFE: CarbonSAFE was initiated to develop integrated carbon storage projects from the pre-feasibility level through the authorization to inject while addressing subsurface technical challenges in the development of carbon storage complexes with commercial capacities of 50+ million tonnes of CO_2.

Key expansions of the CarbonSAFE initiative will be central to advancing storage projects along the pathway toward commerciality and development of secure storage hubs. Key program needs include:

- Support for Phase IV project construction to attain authorization to inject and categorize the storage resource as commercial capacity.
- Development of additional CarbonSAFE Phase I, II and III facilities both onshore and offshore, targeting storage facilities that are significantly larger than 50 million tonnes of CO_2.
- Incorporation of all types of CO_2 sources (power, industrial, DAC).

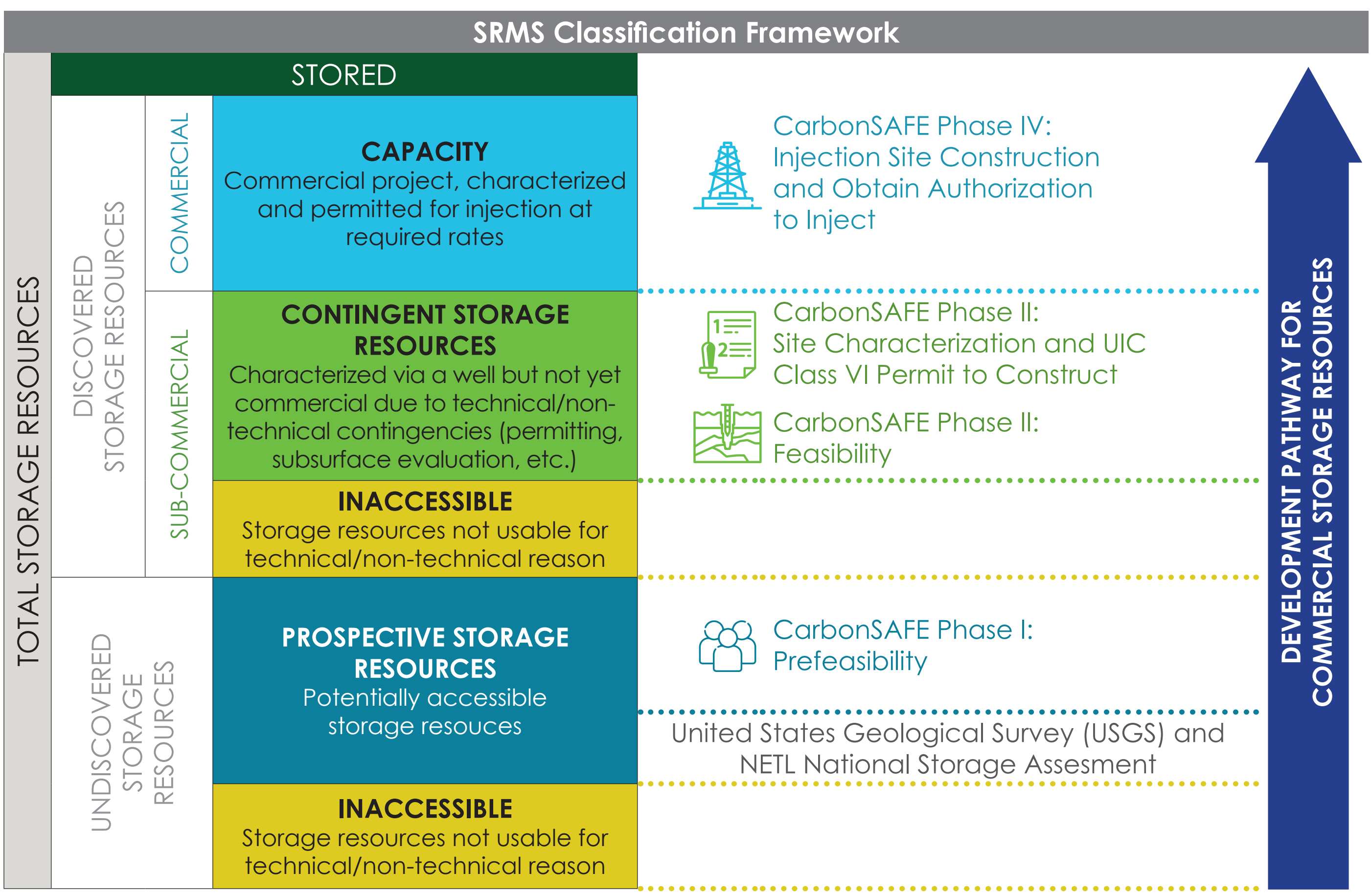
- Development of storage hubs with CarbonSAFE facilities as anchors for storage.

Priority 1.2 – Establish Carbon Storage Technology & Operations Research (CarbonSTORE) Facilities: The CarbonSTORE initiative will establish long-term carbon storage field laboratories to align with the operations of the CarbonSAFE facilities. These field laboratories will allow unprecedented access for researchers to test new monitoring technologies, validate simulation tools and demonstrate machine learning approaches for advanced operational control and decision support.

Priority 1.3 – Repurposing Oil Field Infrastructure (Onshore and Offshore): The oil and gas industry's trillions of dollars of existing investments (Statista, 2021) (EIA, 2011) and extensive technical expertise represent a major opportunity to expedite the development of storage resources. DOE will draw on its knowledge and experience to understand how oil and gas infrastructure can be repurposed to support CO_2 transport and storage. This understanding will focus on the characterization, assessment and management of existing wellbores; repurposing sour gas pipelines; characterizing reservoirs for storage; and instrumenting facilities for monitoring CO_2 plume, reservoir pressure and wellbore integrity.

Priority 1.4 – Accelerating Assessments and Characterization of Storage Resources: The commercial viability of billions of tonnes of storage needs to be increased to the level of contingent storage resource (see Figure 5.4) by reducing the uncertainty and refining existing national and regional storage resource estimates. These resources will include storage complexes not previously assessed as well as non-traditional formations. Some non-traditional formations such as basalts and serpentines have unique properties that CO_2 will react with, causing the minerals in the formation to form carbonates that can permanently store CO_2 as a solid. Some of these materials also outcrop at the surface and could be used as feed materials for enhanced weathering to support CDR approaches.

Figure 5.4 | CO_2 storage resources management system – adapted from [SRMS] (SPE, 2017).



5.4.2 Strategy 2 – Strategic Planning for CO_2 Transport Infrastructure

DOE is well-positioned to support the planning of a national-scale CO_2 transport network by carrying out analyses and modeling studies for an optimized pipeline network connecting sources to deep subsurface storage sites. Under the Bipartisan Infrastructure Law (section 40304), FECM is directed to work with the Loan Programs Office (LPO) to support carbon transport financing and innovation. In addition, under section 40303 FECM is directed to support FEED studies for CO_2 pipelines.

DOE has also supported the development of tools for planning transport infrastructure, including the FECM/NETL CO_2 Transport Cost Model and the Los Alamos National Laboratory's SimCCS model for resource planning.

Priority 2.1 – National-Scale CO_2 Transport: Approaches, Optimization and Conceptual Plan: The program will conduct detailed studies to develop an optimal conceptual plan for a robust, safe and efficient national-scale CO_2 transport infrastructure. This planning process will incorporate broad stakeholder engagement, including interaction with members of coal, power plant-neighboring and other disadvantaged communities to identify and address environmental justice concerns. In this way, CO_2 pipeline infrastructure modeling studies will yield designs for right-sized, optimized and prioritized trunk line routes and build-out timelines to serve the equitable, efficient and effective expansion of CCS operations.

Priority 2.2 – Support for Pipeline Design Studies: Design studies are necessary for the national-scale integrated pipeline system to create the backbone of a national storage industry (Larson, et al., 2020). These studies will start with community engagement to address additional technical issues for optimized, prioritized pipeline routes, identify R&D gaps related to materials and leak mitigation and estimate investment cost.

5.4.3 Strategy 3 – Advanced R&D to Improve Performance and Reliability of Storage and Transport

Advanced R&D is necessary to develop transformational technologies and simulation-based tools to improve performance and reduce the cost of reliable carbon storage at project and basin scales.

Priority 3.1 – Science-informed Machine Learning to Accelerate Real Time Decisions for Carbon Storage (SMART-CS) and National Risk Assessment Partnership (NRAP): Available carbon storage project data coupled with machine learning presents a compelling opportunity to advance the design, operation and safety of carbon storage and transport at a project and basin scale. The SMART-CS initiative focuses on enhancing real-time visualization and forecasting and virtual learning capabilities to improve project performance and inform decision-making. NRAP's tools and workflows offer the means to demonstrate that risks associated with geologic storage are manageable for carefully selected and well-characterized storage sites, leading to an increase in operator, regulator and public confidence. The SMART-CS and NRAP projects leverage the FECM Energy Data Exchange (EDX) as a secure virtual platform to support research collaboration and curation of research data and tools. These capabilities will continue to be developed and support the program's objectives to understand the geologic interfaces of many projects across a geologic basin, ensuring that basin-scale hydrologic and geomechanical risks are effectively managed.

Priority 3.2 – Improving Storage Performance and Integrity Technologies: The following technology areas have been identified for future development, with the goal of deploying and validating these improvements at a commercial scale:

- High-resolution sub-surface imaging to improve characterization of the geologic storage complex.
- A new understanding of subsurface stress conditions that influence seismicity.
- Sensing and interpretation of CO_2 migration near wellbores and above the caprock.
- Improving strategies for subsurface pressure management.

5.4.4 Strategy 4 — Strengthening Reliable Storage and Transport Crosscutting Synergies

Priority 4.1 – Technical Assistance for Storage and Transport: The success of the carbon storage and transport industry will depend upon the development of hundreds of thousands of good-paying domestic jobs to support this massive deployment by 2030 and continuing through 2050 (EFI, 2020). To help ensure that success, DOE/FECM will focus on the following key efforts:

- Support training programs at technical schools, community colleges and universities.
- Provide simulation models to evaluate i) permits and leasing applications for individual projects and ii) basin storage resource management for regulators and resource management communities.
- Transfer simulation-based tools and technologies to industries that are developing storage projects and transitioning their existing oil and gas operations to storage operations.

Priority 4.2 – Leveraging Technical Synergies Between Intra-Agency Programs: The FECM Carbon Storage Program will leverage expertise and learnings from other programs and agencies to advance carbon storage and transport. For example:

- Other programs within DOE FECM are pursuing complementary R&D focused on well integrity, pipeline transport with a focus on liners and coatings to improve CO_2 transport infrastructure longevity and hydrogen storage and transport.
- FECM's Carbon Utilization Program on mineralization of CO_2 will leverage the science and R&D conducted on both in-situ and ex-situ mineralization processes and geologic feedstocks.
- The EERE Geothermal Office Program and FECM's Minerals Sustainability Program are performing R&D in brine recovery and water treatment which can inform decisions about active reservoir management and extraction of valuable resources such as CMs.
- The Office of Science (SC) sponsors basic research and supercomputing facilities at the national laboratories, which will be leveraged to improve monitoring and simulation capabilities.

Priority 4.3 – Leveraging Interagency Synergies: Several federal agencies proactively coordinate to accelerate the development and deployment of reliable carbon and transport systems within the next decade. Specific coordination opportunities between federal agencies (shown in Table 5-1) are further highlighted in the Council on Environmental Quality (CEQ) Report to Congress on Carbon Capture, Utilization, and Sequestration (CEQ, 2021).

At the state level, geologic surveys, departments of transportation, environmental protection, oil and gas permitting agencies and offshore state water oversight entities would provide significant resources for safe storage and transport of carbon. The Carbon Storage Program's Regional Initiatives will be critical in the effort to foster those relationships to ensure their input and expertise.

Table 5-1 | Complementary federal agency roles for carbon storage and transport.

Federal Agency/Organization	Role(s)	Collaboration
Environmental Protection Agency	Regulatory Permitting	Inform regulatory development process with lessons learned from RD&D
Department of Transportation	CO_2 Transportation Safety	Support R&D on materials and safe operations of CO_2 pipelines
Bureau of Land Management, Fish and Wildlife Service, and the United States Forestry Service	Stewards of Federal Land and Minerals	Provide best practices and tools to assess project development and tools to manage resources
Bureau of Ocean Energy Management and Bureau of Safety and Environmental Enforcement	Steward, permitting and leasing offshore resources	Provide data needed to set up an offshore CO_2 injection well permitting and resource system.

FECM also engages with international partners to leverage program dollars and advance CCS globally

Multi-national partnerships include

- IEA
- Carbon Sequestration Leadership Forum (CSLF)
- Clean Energy Ministerial (CEM) - CCUS Initiative
- Mission Innovation CCUS Initiative

Highlight

FECM is a member of the Accelerating CCUS Technologies Consortium, an international initiative of 16 member countries investing jointly in RD&D and innovation within CCUS. (ACT, 2021)

Active Bilateral Partnerships

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CHAPTER 6 | HYDROGEN WITH CARBON MANAGEMENT

Vision Statement

FECM's vision for a future U.S. hydrogen economy aligns with the comprehensive DOE strategy for clean hydrogen production and use, specifically supported by FECM in developing hydrogen use technologies and clean hydrogen production pathways using responsibly sourced carbon-based feedstocks with carbon management. Carbon abatement and mitigation of environmental impacts from resource recovery and use are integral to clean hydrogen production with net-zero GHG emissions.

6.1 Goals

The fundamental goal of the FECM Hydrogen program is to develop clean hydrogen as a cost-competitive alternative to traditional carbon-based fuels. The current cost of $1.50 per kilogram for hydrogen produced from SMR with 90 percent carbon capture (IEA, 2019) is too high to spur rapid market acceptance as a base fuel for power generation, energy storage and industrial heat. Additionally, low-carbon hydrogen is not currently produced at the scale required to decarbonize large segments of the U.S. economy. Hydrogen from SMR, coupled with CCS, is currently the most economical means of generating clean hydrogen (IEA, 2019) as a way to "kickstart" the nascent industry until the cost of clean hydrogen from electrolysis, BiCRS and other means becomes competitive. Hydrogen production coupled to carbon management is an integral part of the recently launched DOE Hydrogen Energy Earth Shot Initiative (DOE, Hydrogen Shot, 2021). This initiative intends to define a pathway and achieve a cost of hydrogen with carbon management of $1/kg within one decade (1-1-1) and with life cycle GHG emissions reductions (including from methane) of 90 percent versus current levels, while maintaining and expanding the employment of the U.S. energy workforce.

Specific RD&D goals for hydrogen production systems within FECM, in coordination with other offices, include:

- Decreasing the cost of CCS while increasing carbon capture rates.
- Enabling lower methane emissions from upstream, midstream and downstream gas transportation.
- Increasing understanding of hydrogen leakage potential from both climate and safety perspectives.
- Decreasing the cost of clean hydrogen production associated with pathways that use carbon-based feedstocks.
- Increasing the commercial viability of hydrogen production from a full lifecycle cost perspective.
- Facilitating public confidence and welfare by supporting safety analyses regarding hydrogen blending, development of materials compatible with hydrogen and adoption of industry codes and standards that ensure the safe generation, storage, transportation and use of hydrogen.
- Improving living and economic conditions of disadvantaged communities by addressing environmental justice needs for those that have traditionally borne the negative consequences of carbon-based fuels
- Creating steady, good-paying jobs in the clean energy sector.

6.2 Pathways to Hydrogen Production with Carbon Management

There are several methods for the production of hydrogen from carbon-based feedstocks, including:

- Point-source pre-combustion capture from gasification and reforming processes that can achieve hydrogen with carbon management with >95 percent CO_2 capture. These methods utilize waste coal, natural gas, coal mine methane, waste plastics and sustainably sourced biomass as feedstocks.
- Gasification of blended municipal solid waste (MSW), sustainable biomass, waste plastics and waste coal with CCS to produce hydrogen with carbon management and high hydrogen syngas. Implementing gasification technology in a distributed, modular fashion will cut the lifecycle carbon emissions associated with transporting dispersed feedstock resources.
- The reforming of natural gas to produce hydrogen with integrated carbon management, including SMR with CCS retrofits, and autothermal reforming (ATR), while minimizing methane leakage to the maximum extent possible.
- Methane conversion to hydrogen and a solid carbon product. In this case, both hydrogen and carbon black can be utilized. Carbon black can be used for applications in building materials, cement and concrete. Current studies are underway to support these technological developments (NETL, 2021).
- Additional advanced methods, such as plasma reforming and partial oxidation of natural gas, are included in the pathway analysis.

6.3 Hydrogen Utilization

Because of its high reactivity, clean hydrogen can play an important role in the conversion of CO_2 to valuable products such as synthetic fuels, chemicals and plastics via many conversion pathways, including electrochemical, electrocatalytic, photochemical, non-equilibrium plasma chemistry and microbially-mediated approaches. Table 6-1 highlights some of the major applications of hydrogen along with the current and projected future demands for hydrogen in each sector.

Table 6-1 | Existing and emerging hydrogen demand areas (DOE, 2020).

	Transport Applications	Chemicals and Industrial Applications	Stationary and Power Generation Applications	Integrated/ Hybrid Energy Systems
Existing Growing Demands	Material Handling Equipment Buses Light-Duty Vehicles	Oil Refining Ammonia Methanol	Distributed Generation: Primary and Backup Power	Renewable Grid Integration (with storage and other ancillary services)
Projected Future Demands	Medium and Heavy-Duty Vehicles Rail Maritime Aviation Construction Equipment	Steel and Cement Manufacturing Industrial Heat Bio/Synthetic Fuels	Reversible Fuel Cells Hydrogen Combustion Long-Duration Energy Storage	Nuclear/ Hydrogen Hybrids Natural Gas/ Hydrogen Hybrids with carbon capture, utilization and storage (CCUS) Hydrogen Blending

6.4 Regional, National or Global Considerations and Strategies

6.4.1 Hydrogen Storage and Distribution Infrastructure

6.4.1.1 Hydrogen Safety Study (Near-Term, 6 Months)

The safety of new hydrogen generation, distribution and storage infrastructure is of paramount concern. FECM initiated a hydrogen safety study in August 2021 to support the widespread and large-scale production, storage, transport and utilization of hydrogen as a carbon-free energy source. The study's initial objective is to produce a publishable review of safety issues anticipated for hydrogen turbines, hydrogen-fueled SOFCs and bulk production of hydrogen by natural gas reforming, solid fuel gasification or solid oxide electrolysis cells (SOECs). This work will be coordinated with Hydrogen and Fuel Cell Technology Office's (HFTO's) congressional budget activities and direction on safety, codes and standards. The study also intends to identify technology advancement opportunities to improve the cost and safety performance of these systems, particularly with consideration of advancements in sensor technology and artificial intelligence (AI).

6.4.1.2 Underground Storage of Hydrogen for Long-Duration Energy Storage (Mid-Term, 5 Years)

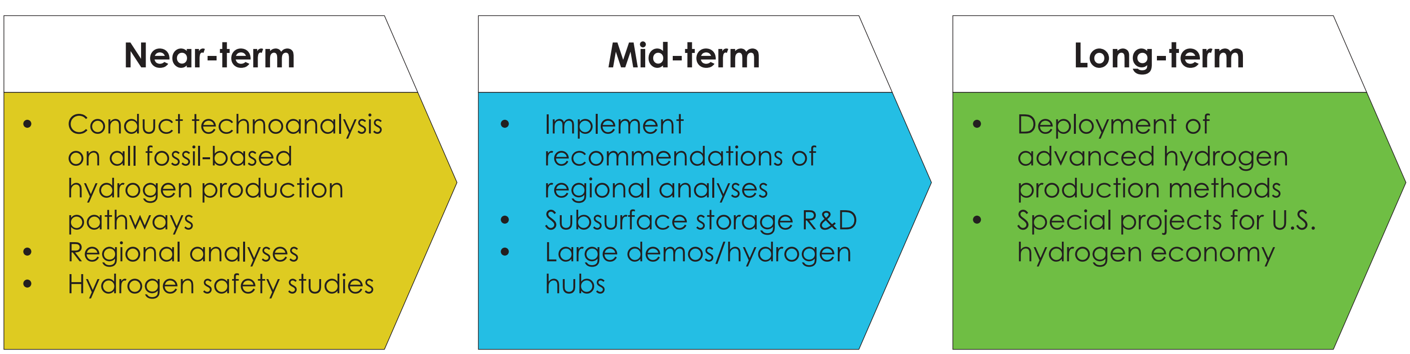
FECM will collaborate with EERE, OE and other offices on ongoing R&D efforts that support energy storage, including analysis of materials of construction, geological characterization, safety regulations and TEAs. FECM will characterize existing geologic underground natural gas storage facilities for potential hydrogen storage, and will coordinate closely with HFTO, particularly for siting and delivery to end use applications such as transportation and industrial use applications.

6.4.1.3 Regional Hub Solutions for Clean Hydrogen (Mid-Term, 10 Years)

It is expected that regional hubs that concentrate hydrogen infrastructure can provide significant economies of scale. Various studies and analyses suggest that the production, transport and storage of CO_2, hydrogen and value-added chemicals can accelerate carbon-based clean hydrogen's viability as a resource. Industry cost-shared pilot and demonstration-scale facilities will validate the technology and economics of clean hydrogen and help generate market demand for hydrogen as a feedstock, an energy carrier and within industrial sectors. Regional clean hydrogen hub activities will be coordinated with other offices as part of the Infrastructure Investment and Jobs Act Hydrogen Hub activities.

6.4.1.4 Deployment of Advanced Hydrogen Production Methods (Longer-Term, 20 Years)

FECM will align significant resources towards developing advanced hydrogen production methods from carbon-based feedstocks with CCS, such as BiCRS. This alignment will begin with RD&D investments in FY22 and will prepare for advanced hydrogen production technology deployment in the 2035-2040 timeframe. Research to meet this goal will include process intensification enhancements, improved materials and system integration. In addition, FECM will coordinate with HFTO and other EERE offices on potential hybrid approaches such as coupling variable renewables with clean dispatchable power to enable low cost, clean hydrogen.



6.5 Challenges for Hydrogen with Carbon Management from Carbon-Based Waste Resources

On June 7, 2021, DOE launched the Hydrogen Shot to reduce the cost of clean hydrogen by 80 percent to $1/kg within one decade. Challenges to meet the cost and milestones include:

- Proactive policy support with a clear vision for clean hydrogen deployment, including simplified permitting for large-scale transport and storage, as well as incentives for clean hydrogen production and use.
- Better alignment of the regulatory framework in regions involving multiple states.
- Funding uncertainty. This uncertainty poses significant risks such as scale-up risk, the high amount of initial capital investment, low investment risk tolerance and long periods for a return on investment.
- Lack of clean hydrogen standards or certification processes in place, and strong regulatory analysis for transport and storage.
- Lack of climate and safety regulations related to hydrogen transport, storage and use.
- Technical challenges such as improved process intensification, safety monitoring, feedstock flexibility, sub-surface storage, pipeline component interactions, improved methane mitigation and increased pre-combustion CO_2 capture to lower the carbon footprint of clean hydrogen.
- Training or re-training of a highly qualified labor force to maintain good-paying jobs.
- Reinvigoration of the domestic industrial manufacturing supply chain to ensure that the equipment and services required for the clean energy transition are available and sourced in the United States, using American labor. The "invent here, make overseas" strategy forfeits the knowledge and technology associated with the direct manufacture of products and forgoes the opportunity to create large numbers of good-paying domestic jobs.
- Public acceptance and outreach for successful clean hydrogen technology deployment.

6.6 Key Partnerships to Foster Success

FECM regularly interacts with other DOE offices to maximize knowledge sharing and ensure that there is no duplication of effort. To achieve our hydrogen program goals, FECM will continue to collaborate with:

- EERE (particularly HFTO), OE, NE, the Office of Science and the Advanced Research Projects Agency–Energy (ARPA–E) in the areas of hydrogen safety, fuel cells, SOECs, ammonia production, methane mitigation and advanced materials. These offices recently collaborated with FECM on the congressionally-mandated Report to Congress on Opportunities for R&D in integrating blue hydrogen technology in the industrial power sector—enhancing the deployment and adoption of CCS (report under review with Executive Secretariat).
- The DOT's Pipeline and Hazardous Materials Safety Administration for hydrogen pipeline and storage safety and the EPA to discuss CCUS opportunities. FECM also collaborates with the USGS to better understand subsurface hydrogen storage.
- Partnerships with industry, national laboratories, academia and non-profit organizations regarding hydrogen R&D developments.
- Other countries, including the United Kingdom, Japan, Saudi Arabia, Turkey, Norway and India, on their hydrogen efforts.

6.7 Investment Considerations and Strategies

To drive the decarbonization of the power and transportation sectors (the largest contributors of CO_2 emissions), the total cost of hydrogen production, transportation, use and storage must be lower than its value in relevant applications.

FECM has two major programs related to clean hydrogen use that address both the power and transportation sectors: turbines and fuel cells, respectively. Turbines using 100 percent hydrogen or ammonia have not yet been developed for utility or industrial-scale power generation and the combustion dynamics of these carbon-free fuels differ from natural gas.

However, several turbine developers and power companies are working on firing existing natural gas turbines with natural gas and hydrogen blends. Developers and power companies are favorable candidates for large-scale hydrogen or ammonia-fired turbine demonstrations.

A 200-kilowatt equivalent (kWe) SOFC prototype power system, integrated into the electrical grid, has been designed, built and field-tested on pipeline natural gas. The scale-up of such systems is the means to incorporate technology improvements made under the SOFC program for various applications. Several developers are currently testing innovative, small-scale (5-25 kWe) natural gas-fueled SOFC systems that are gaining confidence and acceptance in a variety of new markets. These markets include data centers which have power needs at both small (10 kilowatt) and large-scale (1 megawatt) SOFC system ratings, and where resilience and reliability are critical. Further applications for small-scale SOFCs include charging stations for electric vehicles, cell phone towers, information technology repeater stations, distributed generators for disadvantaged communities and natural gas wellheads. Additional funding would enable the development and testing of SOFC systems fueled by hydrogen/natural gas blends or 100 percent hydrogen.

Multiple demonstration projects are needed to drive momentum in the research community. Investments by the government can lower technology risk, and public/private partnerships are critical for the funding of large demonstrations. Additionally, hydrogen consumers are needed to off-take hydrogen from large demonstration projects. Policy incentives are needed to offset cost differences during early-stage clean hydrogen production. Under the Bipartisan Infrastructure Law section 40314, FECM is directed to support Regional Hydrogen Hubs, which presents a unique opportunity to fund multiple demonstrations and deployments of emerging and proven hydrogen technologies.

Desirable characteristics of locations for hydrogen demonstration projects are:

- A committed off-taker for the clean hydrogen.
- Existing hydrogen pipeline access or a nearby off-taker, thus reducing hydrogen transportation and storage costs.
- Readily available access to geological CO_2 storage or a CO_2/carbon black off-taker that ensures the carbon is isolated from the atmosphere.
- Readily available existing large-scale hydrogen or ammonia storage.
- Local incentives for clean hydrogen use.
- High industry cost-share.
- A site that could demonstrate an Integrated Energy Complex incorporating an optimized collaboration among carbon-based fuels with CCUS, renewable energy and nuclear energy. These combined efforts may demonstrate low-cost energy with good energy storage and load-following capability.
- Limited job opportunities, such that a large infrastructure project will create or maintain good-paying jobs.

6.8 Strategic Objectives and Outcomes to Support the Vision

FECM envisions achieving its clean hydrogen goals in collaboration with its partners through the ambitious development and deployment of pilot/demonstration projects in four key areas:

6.8.1 Modular Gasification with CCS

In collaboration with EERE, industry, academia and the National Labs, FECM will demonstrate a modular biomass gasification system and a waste feedstock-fed gasification process using advanced design techniques to achieve a hydrogen production cost of $1 per kilogram with >95 percent carbon capture efficiency.

FECM will conduct further R&D of co-gasification of waste plastics (or MSW), biomass and waste coal for cost reduction and modularity through process intensification. FECM will demonstrate a 10-50 megawatt co-gasification for clean hydrogen production, achieving net-zero or net-negative GHG emissions with carbon capture to achieve a net-zero carbon economy by 2050.

- 2022-2025: The near-term plan for gasification is to reduce the cost and improve the efficiency of new modular gasification plants through process intensification. Process intensification R&D will develop more efficient and compact systems through the optimization of critical parameters or combining multiple systems into a single unit. Specific technologies include selective hydrogen extraction, gasifiers optimized for mixed feedstocks, syngas cleanup systems, water gas shift reactors and oxygen separation from air.

- 2025-2030: After FECM develops more efficient gasification system processes, a pilot-scale demonstration is planned to verify that those processes truly reduce capital and operation costs to produce clean hydrogen from wastes with CCS for net-zero or net-negative GHG emissions. Further technical gaps will be identified, and new control strategies developed.
- 2030-2040: FECM envisions funding a commercial scale (several hundred megawatts) gasification plant for hydrogen production from wastes with CCS at an existing facility where feedstocks are locally available or can be obtained easily and cheaply.

6.8.2 Reversible Solid Oxide Fuel Cells (R-SOFC)

R-SOFCs can both store and produce energy in a single system and contribute to clean energy generation/storage. Hydrogen created from R-SOFCs is a promising production source and can be stored for future use when renewable energy sources are not available. When the grid demands power, the R-SOFC consumes the stored hydrogen to produce electricity. FECM will collaborate with HFTO which has funded more than $55 million related to R-SOFCs over the last few years, and will demonstrate a modular R-SOFC system to produce either hydrogen or power depending on grid demand.

6.8.3 Hydrogen Turbines

In collaboration with EERE, national labs and turbine and electrolyzer manufacturers, FECM will demonstrate the use of clean hydrogen in the power sector by utilizing existing assets at a thermal power plant to validate next-generation clean hydrogen production and combustion technologies.

Electricity production from hydrogen-fired turbines, with hydrogen/natural gas blends or pure hydrogen, is the focus of many utility and turbine manufacturer-supported projects. Research is underway to retrofit existing natural gas turbines to support ever-increasing volumes of hydrogen in blends with natural gas. The ultimate goal is to fire turbines with 100 percent hydrogen. There is also interest in converting existing assets into direct hydrogen production and utilization facilities. A key priority will be to demonstrate low NOx from turbines operating on blends and on pure hydrogen, and widely disseminate the results, particularly due to concerns expressed by the environmental justice community regarding criteria pollutants from turbines.

6.8.4 Clean Hydrogen Hubs

Hydrogen hubs are networks of clean hydrogen producers, potential clean hydrogen consumers and connective infrastructure located in close proximity. Under the Bipartisan Infrastructure Law, at least four regional clean hydrogen hubs are to be selected for development—including at least one that demonstrates the production of hydrogen from carbon-based fuels with CCS. FECM will work with other offices involved in the clean hydrogen hub activities to ensure maximum success and to meet congressional deliverables.

- 2022-2025: Developing a carbon-based hydrogen hub with carbon management under the requirements of the recently passed Bipartisan Infrastructure Law provides a major opportunity to carefully consider the needs of 2050 from the vantage point of 2022. One anticipated advantage of carbon-based hydrogen with carbon management is that it is likely to be available in the near term at lower costs than zero- or negative-carbon hydrogen. In contexts like industrial use, where capital investments are often fuel-specific, costly and long-lived, near-term availability of carbon-based hydrogen with carbon management could de-risk near-term investments in hydrogen-utilizing equipment. As such, FECM's vision for the carbon-based hydrogen hub with carbon management is to identify opportunities where

1) substantial carbon-based fuel demand is clustered that could be transitioned to hydrogen; 2) carbon-based hydrogen with carbon management is feasible today; and 3) long-term, hydrogen support infrastructure could be used for zero- or negative-carbon hydrogen production. As an example, a natural gas-intensive industrial park that is proximate to CO_2 storage resources and abundant biomass supplies could be an ideal location for a hydrogen hub that uses natural gas today.

- In addition to hub development that prioritizes building systems that reinforce decarbonization, near-term opportunities for hydrogen with carbon management include existing carbon-based hydrogen production sites that also have prospective CO_2 off-take opportunities. For such facilities, the incremental investment to transform the hydrogen produced without CCS into clean hydrogen involves finding a suitable storage/disposal option for the CO_2 byproduct that is currently released to the environment.
- Near-term, FECM, in partnership with industry, will perform a large-scale demonstration of gasification, SMR or ATR with CCS. A particular focus of this demonstration will be to maximize hydrogen output and CCS.
- 2025-2030: During this period, FECM expects to fund demonstrations on advanced hydrogen production techniques such as methane pyrolysis, chemical looping or plasma reforming that could lead to net-negative hydrogen production over time. These pathways may produce clean hydrogen at a lower cost or create valuable byproducts, offsetting the cost of clean hydrogen. After successful demonstrations, the industry will take the lead on building processes based on these advanced techniques. Ideal demonstrations are located around the source of feedstocks, both those available in the near- to medium-term and those expected to be used under full decarbonization. The location of demonstration projects will also depend on CO_2 storage availability and the potential buyers of hydrogen who currently rely on carbon-based fuels and have low electrification potential.
- 2030-2040: A major demonstration is expected to prove the feasibility of sub-surface hydrogen storage in geologies not previously known to hold hydrogen, such as depleted oil and gas reservoirs with suitable impermeable caprocks. An ideal location would be near a 100 percent hydrogen-firing turbine for dispatchable energy where renewables may not be available but where future electrolytic production of hydrogen for storage and later use might be possible. A successful demonstration will likely enable hydrogen storage deployment in geological formations other than traditional salt domes.

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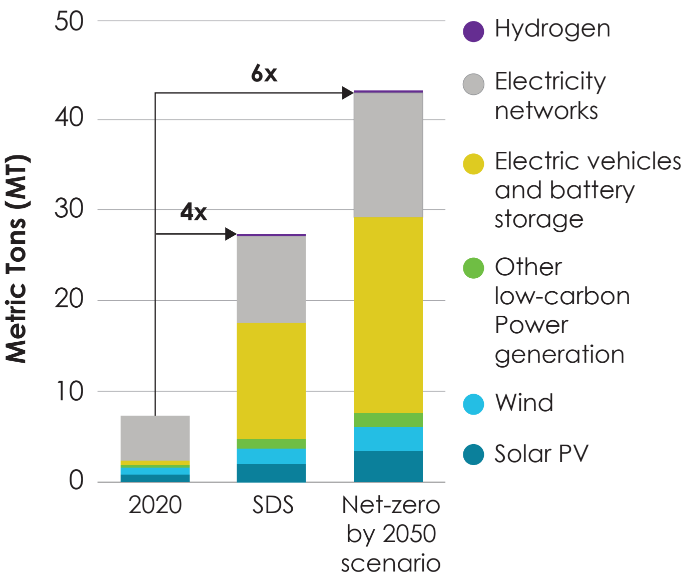
CHAPTER 7 | CRITICAL MINERALS (CMs)

Vision Statement

Catalyze an environmentally and economically sustainable CMs and carbon ore resource recovery industry in the United States that will support clean energy deployment. This effort will include creating domestic manufacturing jobs; secure, diverse, resilient, domestic CM supply chains; and environmental and social justice stewardship through co-production- and reclamation-based research and technology development.

Based on USGS calculations, the total U.S. domestic consumption of REEs in 2017 was about 16,000 tons. Meeting the goals of decarbonizing the U.S. economy by 2050 will require at least quadrupling the demand for mineral supplies for clean energy technologies by 2040 (Figure 7.1). The expected growth for some of the CMs and REEs is significantly larger than the average value (4x), for instance: lithium (42x), graphite (25x), cobalt (21x), nickel (19x) and REEs (7x).

Figure 7.1 | Mineral demand for clean energy technologies. PV: Photovoltaic; SDS: Sustainable Development Scenario (IEA, 2021).



Developing domestic CM supply chains for meeting current and future demand has become a national priority. The domestic industry is a tiny fraction of what it once was. Much of the extraction, processing, refining and manufacturing of CMs is currently occurring overseas (e.g., China), where such industries may be subject to lower environmental quality standards than in the United States. Labor standards and wages may also differ substantially. A combination of international market forces, domestic regulations and financial incentives (or lack thereof) make it difficult for the industry to get a foothold. Current conventional mining and extraction projects require a substantial lead time to initiate (often more than a decade) due to permitting and other processes required. Domestic (e.g., EPA, the Office of Surface Mining Reclamation and Enforcement (OSMRE)) and international organizations (e.g., the International Standards Organization (ISO)) are currently assessing standards for sustainable production of such resources across the supply chain.

To date, technology development and validation efforts in FECM have shown that it is technically feasible to produce relatively high purity minerals and metals from diffuse feedstocks. However, economic viability is uncertain, and economics can be improved with technological advancement. Extraction techniques proven viable for coal and coal byproducts could be applied to similar unconventional and secondary resources from non-carbon-based sources (e.g., hard rock mine tailings, mineral sands wastes, steel production byproducts, landfill leachates). Together, these unconventional and secondary resources may produce enough REEs/CMs to meet a significant part of future demand, but data on the geographic distribution and quality of such resources is highly irregular and incomplete at the current time. Often, such resources may have characteristics (e.g., alkalinity) that could help with carbon removal or industrial decarbonization, which complement other major FECM strategies. Additionally, all extraction technologies should be applied in such a way as to improve environmental quality rather than impacting it negatively.

7.1 Technical Strategy

Over the course of the next five-plus years, FECM will focus on optimizing the advancement of existing extraction, separation and processing technologies to accelerate the production REEs and other CMs from the unconventional and secondary sources described above. Advancing these projects will enable large-scale pilots that will produce high purity mixed rare earth oxides by the middle of the decade, in large part through existing public-private partnerships. This strategy will create more robust public-private partnerships, which will de-risk the establishment of flexible use portions of the domestic supply chains and encourages the high value of downstream products that can be incorporated into cost structures for upstream facilities. Such a strategy will reclaim or remediate land and waters impacted by fossil energy activities and other legacy actions (e.g., mining, impoundments), thus improving the environment and the health and safety of local populations, especially poor and highly impacted communities. An additional benefit should be alleviating the long wait times required for permitting new mining and extraction projects. However, because the REE/CMs associated with these unconventional and secondary sources are such a small fraction of the source materials, economically successful projects will almost always be required to find beneficial use from the remaining fraction of the source material. These beneficial uses can include the development of high-value carbon products, fertilizer, cement additives and concrete composites.

This strategy is supported by three primary technical pillars: 1) resource characterization and technology development, 2) sustainable resource extraction technology development and 3) processing, refining and alloying technology development.

7.1.1 Resource Characterization and Technology Development

Although preliminary (U.S. DOE, 2017) estimates suggest a significant CM/REE resource associated with carbon-based waste and byproduct materials, a much more refined picture of the landscape is needed to provide a significant enough set of feedstocks to catalyze the development of a domestic CM industry. In addition, the tools used for fossil waste characterization can also be used for non-fossil waste with potentially similar characteristics, e.g., produced water from CO_2 storage, hydrogen storage or geothermal production. FECM R&D will create new methodologies, tools and technologies required for identifying and assessing the quality (e.g., composition and impurities) and quantities of CMs and carbon ore available for sustainable commercial production from unconventional and secondary sources in different regions across the United States, particularly those associated with fossil energy communities.

Data collection, integration and curation technologies will be of critical importance to assess resources and reserves for CMs on a national, regional and local scale. Collaboration and data sharing with other federal agencies (i.e., USGS, OSMRE, EPA), state agencies (e.g., state geologic surveys) and industrial organizations will be necessary to enable rapid and reliable assessments of sufficient quality. New advanced characterization, analysis and assessment technologies, including geophysical methods, novel geochemical sensors, geospatial statistical approaches, data analytics and AI and machine learning techniques, will be developed to enable quantitative assessment of site-specific resources. These developments will improve the design of environmentally beneficial, cost-effective extraction (and remediation) technologies and facilities.

7.1.2 Sustainable Resource Extraction Technology Development

FECM's research, development, deployment and commercial application (RDD&CA) will focus significant future efforts on the development of novel and advanced technologies to enable cost-effective and sustainable extraction of REE/CMs from unconventional and secondary sources. These efforts will include the advancement, improvement and optimization (Anastas & Zimmerman, 2003) of conventional extraction technologies to improve the environmental, cost performance and health and safety of such technologies at a large scale within the next few years.

Additionally, transformational extraction technologies (e.g., microbial processes, in situ mineral extraction, CO_2-aided separations) will be assessed and developed to produce the next generation of extraction technologies from unconventional and secondary sources. These technologies will be ready for deployment at scale by 2032 and will be tailored to site-specific sources as characterized by the technologies described in the preceding section. FECM will coordinate with other organizations within DOE (i.e., the Critical Minerals Institute (CMI)) and other agencies (e.g., DOD, OSMRE) who are developing and assessing novel extraction, recycling and treatment technologies for secondary sources. FECM will work with industry to develop techniques that maximize the value of all materials (i.e., fit for beneficial use) contained within the resource while generating high purity REEs/CMs and minimizing environmental impacts.

7.1.3 Processing, Refining and Alloying Technology Development

The domestic midstream supply chain for REEs and many CMs is nearly non-existent in the United States today, so the success of this program to the broader nation depends on catalyzing the establishment of domestic processing and manufacturing facilities across the supply chain. The FECM program has shown that it is possible to extract and process, through advancing conventional technologies, high purity CM/REE resources from low concentration unconventional and secondary sources, something that was considered impractical only five years ago. FECM RDD&CA will advance environmentally benign and economically efficient processing, including extraction, purification and reduction, refining and alloying techniques and technologies to produce high-purity CMs, including rare earth metals, as well as the manufacturing of high-value carbon products. These technologies will need to be upscaled from the lab and bench scales to small- and large-scale pilots and larger field demonstrations. In some cases, this may be a part of a vertically integrated processing supply chain that goes from source to metal making and manufacturing. Such integrated supply chains could serve as pillars for the development of robust domestic supply chains within the United States if the facilities along the chain are flexible enough to: 1) accept raw and processed materials from multiple sources and also 2) supply processed materials to other entities.

FECM will focus on developing cost-effective and environmentally benign processing facilities that can accept raw and processed materials from unconventional and secondary sources but are flexible enough to work with other feedstocks and generate materials for multiple valuable end uses. The Office will explore approaches, such as simulation-based techniques, that will help accelerate the optimization and upscaling of such facilities and help model the full supply chain to understand where the greatest challenges and opportunities lie. Key to the success of this effort will be the ability to collaborate and coordinate with other governmental offices (e.g., DOE-AMO/CMI, DOD) and with industrial players to minimize duplication, accelerate development and identify new markets. Where possible, FECM will seek to connect industrial organizations along different parts of the supply chain where connections may be synergistic and catalyze new end uses for the materials coming from unconventional and secondary sources. As with the extraction technologies, the approach will be to further advance conventional and near-commercial novel technologies in the next few years. This will spur the development of transformational processing technologies that have the potential to be the next generation processing technologies, with improved and better targeted environmental and cost goals, by the end of the decade. In so doing, FECM will encourage the open sharing of data and novel technologies, and encourage the development of new end uses, which can in turn influence processing, refining and alloying.

7.1.4 Standards and Supply Chains Development

Resilient, sustainable, domestic CM supply chains not only require technological advances; modifications to national and international standards and trading policies will necessarily have a significant role to. FECM will engage in cross-cutting activities that promote international collaboration and cooperation with organizations that address CM standards (i.e., ISO) and trade policy that are essential to all three technical pillars described above. Development of international standards and partnerships are the tools the United States can use to address current CM supply and high-value product manufacturing challenges.

FECM will seek to inform policy, not make policy, around CMs and associated mining, remediation, reclamation, extraction, processing, refining and manufacturing. Strategies that create public-private partnerships de-risk the establishment of flexible-use portions of the domestic supply chains and encourage the high value of downstream products that need to be incorporated into cost structures for upstream facilities. FECM will continue to play a lead role in working with ISO and other international players to establish high standards for all parts of the CM supply chain. This will include reclamation, extraction and manufacturing, as well as the consideration of labor standards and other non-technical factors that may have an impact on environmental justice and workforce communities. Additionally, FECM will work with other DOE offices and government agencies to develop and inform national standards, such as EPA's Electronic Product Environmental Assessment Tool, and engage with others considering standards or labeling approaches. To this end, FECM will work with other technology offices to evaluate the technologies (e.g., blockchain, fingerprinting) that could help track CMs and materials across all stages of the supply chains, regardless of the original feedstock. Additionally, standards for regulations related to reclamation will be considered in order to incentivize new or established companies to remediate the environment and extract CMs from the waste without bearing the full liability of those who have come before them.

7.2 Markets and Building Supply Chains

Robust markets for CMs and materials are essential to stand up to domestic supply chains. As mentioned, the latest studies project a rapid rise in the need for several CMs and REEs over the next 10-30 years. However, the outlook for individual CMs remains highly uncertain. Through the remediation and reclamation of legacy carbon-based energy wastes and byproducts, FECM has an opportunity to make a significant contribution to the supply of many CMs, perhaps enabling the transition away from an economy that is mostly dependent on foreign countries for a vast supply of CMs. FECM will leverage existing information and studies and work closely with others within the DOE and the U.S. government (especially the USGS and EPA) to understand how many unconventional and secondary resources can contribute to the future market capacity (e.g., batteries, superconductors, solar cells) and capability, both domestically and internationally.

Building such market capacity requires initiating facilities, capabilities and workforces all along the supply chains. Supply swings can create price bubbles that encourage the creation of new extraction technologies and facilities, only to have the bubbles burst and the industrial facilities and workforce unable to compete in the marketplace. Reducing the uncertainty around future prices and demand for CMs and materials will have a major impact on the success of these products. FECM will need to interact with EERE, as well as multiple industry groups, to develop a better understanding of the end-use and future supply needs of the wide range of CMs that could be supplied by unconventional and secondary sources. At the same time, FECM will seek opportunities to catalyze the growth of newly manufactured products by helping to provide a guaranteed sustainable supply of high-quality, cost-effective CMs. Utilizing a regional approach through the Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) initiatives will be a key enabler to evaluating resources (mineral, facilities and workforce) across the supply chain.

One of the biggest challenges with regard to combined reclamation of waste or byproducts (i.e., secondary and unconventional sources) is the high liability associated with the waste materials and the perceived low value of the extracted raw materials. This challenge can be addressed by encouraging regulations and permitting procedures that take a science-based approach to improve the quality of the environment, possibly taking the form of joint public-private cleanup activities with combined CM extraction.

7.3 Engagement Strategy

For over a decade, DOE has been a leader in addressing critical supply chain challenges, with demand increasing in scope and magnitude. FECM will work with other DOE offices to support DOE's five technical priorities: (1) Diversifying Supply, (2) Developing Substitutes, (3) Recycling and Reuse, (4) Systems Analysis, and (5) Demonstrations. In particular, the Division of Minerals Sustainability collaborates closely with EERE to support applied RDD&CA across most topics, while SC provides the necessary fundamental research and world-class user facilities necessary to complete much of the related work. The Division also collaborates closely with IA, the LPO and the Office of Technology Transitions to effectively engage with both foreign and domestic stakeholders. Additionally, FECM will engage with the National Lab complex, which possesses a wealth of technical capability in all of the technical pillars previously outlined.

DOE plays a leadership role in the federal government's efforts in the area of CM, including (1) the NSTC CM subcommittee, which regularly interacts with interagency partners (DOI, DOD, the Department of Commerce (DOC), DOS and the Department of Homeland Security) to advise on policies relating to CM; and (2) the Committee on Homeland and National Security that oversees the CM Subcommittee. As such, FECM works with DOE colleagues to contribute to both subcommittees. Additionally, the Division seeks to identify strategic opportunities to collaborate with external agencies outside of the NSTC. In particular, FECM will seek a multiagency collaboration with the DOI (USGS and OSMRE) and the EPA on issues related to the characterization and sustainable extraction of CMs from unconventional and secondary sources. FECM will engage with other technology developers in this space, such as DOD, by sharing information on novel technologies, engaging in reciprocity for review of funding opportunities and exploring joint funding opportunities. The Division will continue to engage with other federal, industry and international organizations, such as the National Institute of Standards and Technology and DOC on the development of sustainable standards for CMs and REEs through ISO Standards development.

Finally, FECM seeks to engage beyond government and international entities to industry, academia and other technology developers and domestic stakeholders who are needed to facilitate the development of domestic CM supply chains. FECM will need to engage with a variety of different industry players regarding:

- Joint technology development
- Resource identification
- Information sharing (e.g., technical data, reclamation opportunities, uses of other associated materials)
- Remediation technologies
- Technology end use/manufacturing (consumption needs)
- Regional Innovation Centers

Engagement with academic institutions will be important for technology development and workforce training needed to develop, manage and maintain CM supply chains. Academic and regional/local institutions of all types will provide trusted sources for national, regional and local communities. One of the most critical engagements will be with local and regional communities to help gather more relevant data on resources within the regions—materials, facilities, workforce and others—and to instill trust and promote stakeholder buy-in for the aims and benefits of the program's goals. Inclusion and engagement are vital to develop and maintain the trust, participation and support of the communities that will most likely be impacted and benefit from this work. Engagements will be made most effective by interacting with a wide range of stakeholders, such as trade organizations, professional societies, unions, community groups, non-governmental organizations and schools, presenting science-based data from trusted sources.

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CHAPTER 8 | METHANE MITIGATION

Vision Statement

Minimizing emissions of methane during production, processing, transportation and use across the coal, oil and gas industry, eliminating non-trivial methane emissions from carbon-based fuel supply chains by 2030.

8.1 Background: Fossil Energy Sources of Methane Emissions in the United States

In implementing FECM's efforts to minimize the climate and To minimize the climate and environmental impacts of U.S. dependence on carbon-based fuels, FECM is working towards mitigating methane emissions associated across the oil and gas supply chain (e.g., production, processing, transportation, storage and end-use). Second to CO_2 emissions, methane emissions are the largest contributor to climate change. Among other sources, approximately 8 million metric tonnes (MMT) of methane are emitted across the oil and natural gas value chain, which consists of more than two million miles of pipelines; more than two million wells that are abandoned, actively producing and/or used for storage; and more than 100,000-unit operations consisting of processing plants, compressor stations and gathering stations. Due to the distributed nature of methane emissions sources, FECM is focused on developing accurate, cost-effective, efficient technology solutions and best practices to identify, measure, monitor and eliminate methane emissions from these sources.

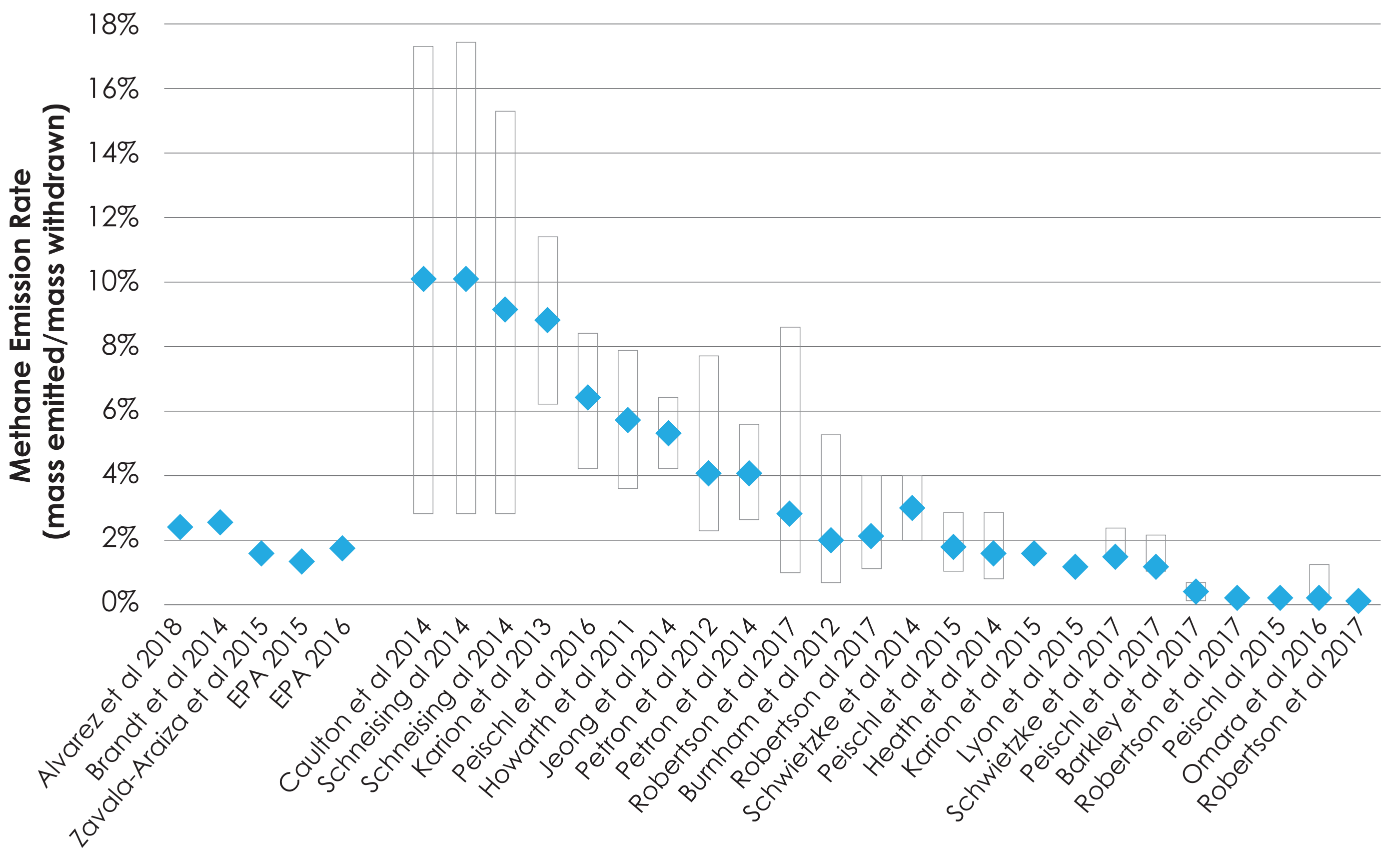
Methane mitigation R&D efforts include advanced materials of construction, monitoring sensors, data management systems and more efficient and flexible compressor stations. A companion set of research efforts for methane emissions quantification will focus on developing technologies to detect, locate and measure emissions. This includes the development and validation of measurement sensor technologies for the collection, dissemination and analysis of emissions data, which will inform efforts such as the GHGI and orphan well remediation programs of the EPA and DOI, respectively. FECM's Office of Resource Sustainability is also working on creating innovative solutions to reduce associated gas flaring and venting, including alternative uses for the "stranded" natural gas. It is possible through modular technologies to convert the gas to higher-value solid and liquid products that can be transported efficiently. In addition, modular conversion technologies designed to generate hydrogen as a clean, distributed energy carrier is also being pursued.

EPA reports that in 2019 (latest data available), total emissions of GHGs in the United States totaled 6,558 MMT of CO_2e (EPA, 2021c). About eight percent of this total, or 656 MMT CO_2e, was due to methane emissions, which can occur during the production and transport of coal, crude oil and natural gas, as well as from livestock management and other agricultural practices, and from the decay of organic waste in municipal solid waste landfills. Of this amount, about 197 MMT CO_2e (30 percent) can be attributed to the oil and natural gas sector (EPA, 2021a). It is important to note that EPA uses a GWP-100 of 25 (EPA, 2021d) in its GHGI, which is lower than the current best estimate of about 30 (IPCC, 2021). As such, reported 100-year CO_2e values for methane are underestimates relative to the current understanding of climate effects from methane.

EPA also estimates that, in 2019, U.S. coal mining contributed approximately 110 billion cubic feet of methane emissions (EPA, 2021c), recorded as roughly 50 MMT CO_2e or about eight percent of the total for methane emissions (EPA, 2021b). It is important to note that there are ongoing efforts within FECM to increase the availability of methane measurements associated with production, transport and use of carbon-based fuels and additionally invest in approaches to minimize the emissions today.

In addition, hundreds of researchers have published dozens of studies attempting to estimate the percentage of methane emissions from the nation's natural gas production, transportation and delivery systems. Estimates of methane emissions in some regions have been as low as 0.1 percent, and, in others, as high as 10 percent or more (Raimi & Aldana, 2018) in terms of mass emitted per unit of mass withdrawn. Figure 8.1 includes numerous recent studies that examine either the full natural gas supply chain or individual oil and gas producing regions, where most emissions appear to occur. At the left side of the figure, results from three of the most comprehensive studies (each a meta-analysis in its own right) appear alongside two relatively recent EPA estimates, while the right side of the figure demonstrates the range of studies carried out for specific regions.

Figure 8.1 | Methane emissions rates from recent studies. Diamonds represent central estimates. Bars represent confidence intervals or high/low estimates (reproduced from Raimi & Aldana, 2018).



According to the EPA's GHGI (EPA, 2021a), the largest source of methane emissions from oil and gas production are pneumatic controllers. These are gas pressure-driven valve controllers designed to release small amounts of methane during normal gas control operation (e.g., valve opening and closing). The second leading cause of methane emissions associated with natural gas and oil production comes from natural gas gathering and boosting stations consisting of in-field pipelines and associated compressor stations that collect natural gas and boost its pressure to move it towards a centralized gas processing facility. A relatively large number of individual types of equipment and operating activities account for the rest of the emissions. In addition, CO_2 emitted from the combustion of gas flared during oil and gas production is not included in these totals.

The overall accuracy of EPA's methodology for calculating oil and gas production operations-related methane emissions is based on an inventory of equipment elements and assigned emission factors that have been the subject of debate. Other methodologies for directly measuring and quantifying these methane emissions have been proposed and tested. There is also some question as to the degree to which "high bleed" pneumatic controllers have been replaced with lower emission systems in recent years. DOE's objective is to work with EPA, where appropriate, to further refine its methodology and provide data and measurements that can improve the overall accuracy of how methane emissions across oil and gas production and supply chain elements are determined.

The natural gas processing, gas distribution and transmission and storage sectors account for relatively small portions of methane emissions estimated by EPA, about 12, 37 and 14 MMT CO_2e, respectively (EPA, 2021a). The primary sources of emissions within gas processing and transmission are from compressors and their driving engines. Within the natural gas distribution sector, the primary sources of emissions are line leaks and meter leaks.

There are also risks of methane emissions from any industrial process where natural gas is produced as a byproduct or held under pressure within a process stream. Relevant examples include crude oil refineries (e.g., safety flares, gas supply lines, processing units); biogas generation and collection systems at renewable natural gas, renewable diesel or biodiesel production facilities; and liquefied natural gas liquefaction, storage and loading facilities, along with chemical processing plants.

In all these examples, the equipment elements and process operations prone to emissions are more-or-less similar (or identical) to those within the oil and natural gas production, processing and transportation sectors (e.g., valves, valve controllers, compressors, pipelines, flares, etc.).

8.2 DOE Methane Emissions Mitigation Strategy

DOE's strategy for addressing methane emissions from the hydrocarbon fuel sector includes efforts to improve emissions detection, quantification and mitigation capabilities across the entire fuel value chain (e.g., production, transportation, storage and utilization). Specifically, through an Integrated Methane Monitoring Characterization Center, FECM will develop and deploy technologies to accurately detect, quantify and report methane emissions from methane point sources in real time. In addition, to accurately characterize methane emission sources, the real-time aspect of identifying and measuring emissions will enable rapid mitigation (e.g., repair) of large point sources referred to as "super-emitters." To minimize emissions from the natural gas pipeline system, FECM will accelerate the development of low-cost, efficient pipeline inspection, repair and monitoring technologies designed for new and legacy pipeline systems.

In addition, FECM will coordinate and work with States and Rural and Tribal Communities to implement the provisions of the Bipartisan Infrastructure Law, as related to plugging, remediation and restoration of orphaned oil and gas wells on federal lands (Section 40601). FECM activities will focus on the following four areas: (1) identifying, characterizing, and inventorying orphaned wells and associated pipelines, facilities and infrastructure; (2) measuring or estimating and tracking of emissions of methane and other gases associated with orphaned wells; (3) ranking of orphaned wells for priority in plugging, remediation and reclamation; and (4) reporting of costs associated with plugging, remediation and reclamation of orphaned wells.

Parallel DOE activities seeking to effectively utilize natural gas for decarbonization through conversion to low-carbon chemicals and hydrogen are also underway. These activities have aggressive cost reduction goals for hydrogen production and the development of storage and transport infrastructure. They also include RD&D elements that are suitable for application to mitigate associated natural gas (e.g., gas produced with oil), fugitive emissions and flaring (NETL, 2020). Strategic RD&D activities along these pathways can be categorized as near-term, mid-term and long-term according to their expected implementation periods, as shown below.

8.2.1 Near-Term Activities (2022-2030) or (0-5 Years)

- Improve capabilities for detecting and monitoring emissions across the oil and gas production, processing, transportation and storage sectors and renewable gas production (e.g., improved sensors, low-cost leak indicators, more accurate remote sensing methods).
- Develop more accurate and representative quantification of methane emissions factors for specific equipment components across the United States.
- Reconcile the differences between top-down (satellite, towers and aerial remote sensing) and bottom-up (equipment counts) estimates of emissions for all hydrocarbon fuel sectors.
- Develop more effective, lower-cost retrofits of equipment components prone to leaks or chronic emissions (e.g., pneumatic valve controllers, compressor seals and packing, distribution lines).
- Develop strategies for enhancing natural gas flare combustion efficiency.
- Develop improved, safe, cost-effective inline pipeline repair tools and methods.
- Develop cost-effective methods for locating orphaned oil and gas wells, quantifying their emissions in order to prioritize their management for plugging.
- Develop AI tools and machine learning and predictive data analytic methods for identifying likely anthropogenic sources of "super-emitters" and proactively reducing the risk of emissions.
- Develop rigorous CO_2e accounting methods of all hydrocarbon-based fuel sources (oil, gas, coal, LNG, renewable liquified petroleum gas, biodiesel, etc.) from production (wells, mines, landfills, digesters) to conversion (hydrogen, ammonia, hythane (a mixture of hydrogen and methane)) to storage and end-use.

8.2.2 Mid-Term Activities (2030-2035) or (5-10 Years)

- Develop and test technologies (TRL 5) and support the improvement of best practices that will drastically reduce the volume of methane emissions associated with abandoned and orphaned wells. Advance strategies for working across state and local government to accelerate the proper plugging and possibly remediation of such wells.
- Employ improved methods for detecting, quantifying and mitigating methane emissions from both active and abandoned coal mines (e.g., gob well-venting control systems, mine mouth capture systems, mine air ventilation systems).
- Develop tools and methods for detecting and mitigating fluid migration between productive natural gas reservoirs or subsurface natural gas storage horizons, potable water aquifers and other sensitive receptors (e.g., improved characterization of the long-term effects of natural gas storage on wellbore materials, advanced subsurface monitoring, improved wellbore integrity monitoring and remediation tools).
- Coordinate with other relevant entities on the full implementation of effort for locating orphaned oil and gas wells, quantifying their emissions in order to prioritize their management and cost-effectively plugging and abandoning them. Some activities are being done in both near-term and mid-term time frames.

The matrix provided in Table 8-1 consolidates these strategic activities across the industry sectors.

DOE's strategy will be closely coordinated with other government and inter-governmental entities that are tasked with similar decarbonization efforts. For example, DOE efforts to develop more accurate and representative methane emissions factors for equipment components and efforts to reconcile differences between top-down and bottom-up emissions estimates will be coordinated with the EPA's GHGI objectives. Similarly, DOE efforts to develop improved inline pipeline repair tools will be coordinated with DOT's Pipeline and Hazardous Materials Safety Agency R&D objectives to avoid duplication and maximize synergies.

Within DOE, FECM will maintain an open dialogue with ARPA-E on methane detection and quantification technologies research. Also, discussions underway with NOAA on leveraging their satellite sensing capabilities for methane emission and other trace gas detection will be advanced. Similarly, coordination with NASA will be considered for similar sensing and data collection collaborations. Finally, initial talks being held with DOI on providing technical assistance and guidance for potential upcoming orphaned well remediation initiatives will be advanced. Coordination on this issue would also involve the States through the Interstate Oil and Gas Compact Commission. As stated above, FECM will also coordinate with Rural and Tribal Communities for plugging, remediation and reclamation of orphaned wells, per Section 40601 of the Bipartisan Infrastructure Law.

These efforts include research focused on developing ways to make hydrogen production and transport less costly and more environmentally positive (production of "blue" hydrogen with CCS, and "green" hydrogen through electrolysis using renewable energy). To the degree that natural gas remains a feedstock for hydrogen production, reducing methane emissions will lower the environmental impact of hydrogen production. DOE will seek to leverage technologies that can be utilized to both reduce methane emissions and accelerate the availability and use of hydrogen fuel. For example, sensing technologies that can be utilized for both methane and hydrogen detection, AI and machine learning technologies utilized to reduce leaks from equipment handling either methane or hydrogen, and the integration of LCA emissions analysis to minimize emissions associated with blue hydrogen.

Table 8-1 | Near- and mid-term DOE methane emissions technology development matrix.

Sources	Methane Emissions Technology Solutions		
	Detection	Quantification	Mitigation
Oil and Natural Gas Drilling, Production and Field Processing	• Enhanced capability of methane leak monitoring sensors • Data Analytics methods for predicting high volume "super-emitters" ▫ Coordination with other relevant entities on the full implementation of efforts to locate orphaned wells ▫ Methods for detection of subsurface communication with potable water sources and other sensitive receptors	• Improved estimates of equipment emission factors • Methods for reconciling top-down vs. bottom-up methane concentration measurements • Develop cradle-to-grave LCA of all hydrocarbon-based fuel sources from production to conversion to storage and end-use ▫ Coordination with other relevant entities on the full implementation of efforts to develop improved estimates of abandoned and orphan well emissions	• Lower cost retrofits of emitting devices (valves, etc.) • Enhanced efficiency flares with capture technologies • Modular Capture/conversion technologies to reduce flaring • Low emission compressor seal technologies • Subsurface communication remediation technologies ▫ Predictive data analytic methods for proactively reducing the risk of emissions from production, transportation and storage systems ▫ Coordination with other relevant entities on the full implementation of efforts for cost-effectively plugging and abandoning orphaned wells ▫ Develop and test technologies and support the improvement of best practices that will drastically reduce the volume of methane emissions associated with orphaned wells and advance strategies for working across state and local government to accelerate the proper plugging and abandonment of such wells

Key: • Near-Term (2025-2030) ▫ Mid-Term (2030-2035)

Continues on next page

<table>
<tr><th rowspan="2">Sources</th><th colspan="3">Methane Emissions Technology Solutions</th></tr>
<tr><th>Detection</th><th>Quantification</th><th>Mitigation</th></tr>
<tr><td>Natural Gas Gathering and Compression</td><td>• Enhanced capability of methane leak monitoring sensors
▫ Methods for detecting abandoned gathering lines</td><td rowspan="2">• Improved estimates of equipment emission factors
• Methods for reconciling top-down vs. bottom-up methane concentration measurements
• Develop cradle-to-grave LCA of all hydrocarbon-based fuel sources from production to conversion to storage and end-use</td><td>• Lower cost retrofits of emitting
• devices (valves, etc.)
• Enhanced efficiency flares
• Capture/conversion technologies to reduce flaring
• Low emission compressor seal technologies</td></tr>
<tr><td>Pipeline Transportation and Natural Gas Storage</td><td>• Enhanced inline sensors for real-time monitoring
▫ Methods for detection of surface leakage from storage reservoirs
▫ Methods for detection of subsurface communication with potable water sources and other sensitive receptors</td><td>• Lower cost retrofits of emitting devices (valves, etc.)
• Inline pipeline repair technologies
• Low emission compressor seal technologies
▫ Advanced materials for improved wellbore stability and integrity for subsurface storage</td></tr>
<tr><td>LNG Liquefaction and Transportation</td><td></td><td></td><td>• Lower cost retrofits of emitting devices (valves, etc.)</td></tr>
<tr><td>Natural Gas Distribution and End-Use</td><td rowspan="4">• Enhanced capability for methane leak monitoring sensors</td><td rowspan="5"></td><td>• Lower cost retrofits of emitting devices (valves, etc.)
• Inline pipeline repair technologies</td></tr>
<tr><td>Crude Oil Refining</td><td>• Lower cost retrofits of emitting devices (valves, etc.)
• Enhanced efficiency flares
• Capture/conversion technologies to reduce flaring</td></tr>
<tr><td>Refined Products Distribution and Use</td><td rowspan="2">• Lower cost retrofits of emitting devices (valves, etc.)</td></tr>
<tr><td>Renewable Natural Gas Production</td></tr>
<tr><td>Coal Mining, Transport and Storage</td><td>▫ Methods for detecting emissions from existing or abandoned coal mines
▫ Methods for detecting emissions from coal transport and storage</td><td>▫ Mine-mouth methane capture systems
▫ Gob well methane capture systems
▫ Mine air ventilation systems</td></tr>
</table>

Key: • Near-Term (2025-2030) ▫ Mid-Term (2030-2035)

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