Office of
Clean Coal and Carbon Management

STRATEGIC VISION 2020-2024

U.S. DEPARTMENT OF ENERGY | Office of FOSSIL ENERGY

AUGUST 2020

Preface

The Office of Clean Coal and Carbon Management (OCCCM) supports research and development (R&D) on advanced technologies to ensure the availability of clean, affordable products from coal. R&D focuses on the discovery and development of technologies that improve the efficiency, emissions, and performance of current and future coal-based power plants; reduce the cost of carbon capture, utilization, and storage (CCUS); ensure efficient use and management of water resources; and create new markets for coal and coal products through innovative conversion processes and the utilization of carbon dioxide to create added value.

OCCCM supports the larger goals and performance measures articulated in the *Office of Fossil Energy (FE) 2018-2022 Strategic Vision* informed by longer-term goals for planning purposes. This *OCCCM Strategic Vision for 2020–2024* clarifies the priorities and strategies that will guide the Office's R&D investments in alignment with the FE vision and key directions.

Note to Readers

The focus areas and strategies or directions outlined in this document are not intended to supersede Department of Energy budget submissions for the Office of Fossil Energy. Rather, these are visionary aspirations that support and reinforce those submissions. Details of the official budget can be found in the Department of Energy FY 2021 Congressional Budget Request, located at: www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-2.pdf

Cover:

Background image, Adobe Stock 129033427; top hexagon: vials containing fluorescent graphene quantum dots from coal, DOE/NETL; second hexagon from top: hydrogen energy storage, Adobe Stock 182859327; third hexagon: Petra-Nova-8 carbon capture facility, credit NRG, www.nrg.com/assets/documents/case-studies/petra-nova/Petra-Nova-8.jpg; fourth hexagon: two NETL scientists develop solvent for extracting rare earth elements from coal, DOE/NETL, https://cen.acs.org/materials/inorganic-chemistry/coal-new-source-rare-earths/96/i28?utm_source=YouTube&utm_medium=Social&utm_campaign=CEN; fifth hexagon: high-voltage transmission towers, Adobe Stock 48646447

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Perspective

Dear Stakeholders,

The U.S. fossil energy sector is becoming more agile and innovative in response to continuing economic and environmental challenges. The past decade has thrown multiple hurdles at the coal industry, including stagnant electricity demand, growing climate concerns, increased competition from other energy sources, and a pandemic-induced recession. Bold pursuit of opportunities to more fully leverage this abundant natural resource will contribute to a robust economic and energy future across America.

The Office of Clean Coal and Carbon Management (OCCCM) is uniquely equipped to expedite the transition to a low-carbon economy while maintaining U.S. energy dominance. Carbon reduction is a global issue, and OCCCM leads the world in technologies for reducing greenhouse gas emissions as cost-effectively as possible. Our flagship program CoalFIRST is developing coal power plants to serve the 21st century electricity grid, generating zero or near-zero emissions of carbon dioxide—or net-negative emissions when co-fired with biomass. These small, modular plants will adapt to changing power demand, produce hydrogen and other critical products, and provide energy storage to enhance grid reliability and resilience.

Hydrogen from fossil fuels, including coal, is expected to play a key role in the U.S. transition to clean, low-carbon energy systems. The International Energy Agency predicts the United States and other advanced countries that develop a successful hydrogen economy will rely primarily on fossil fuels along with carbon capture, utilization, and storage (CCUS). OCCCM is already a world leader in this technology and is working to remove cost as a barrier to its widespread use.

To provide good jobs for Americans in coal-rich regions, OCCCM continues to extract critical minerals and develop new products from coal, such as quantum dots for use in medicine and electronics. To expedite progress, the research leverages cross-cutting technologies like advanced manufacturing and artificial intelligence.

OCCCM has the specialized expertise to address current challenges and explore promising new uses for coal. I believe our team has identified exciting opportunities to build on our strengths and boost program impacts in support of national goals. I invite you to learn more about our program and new directions.

Lou Hrkman
Deputy Assistant Secretary (DAS)
Clean Coal and Carbon Management

Welcome to the Office of Clean Coal and Carbon Management

Coal is as an abundant U.S. natural resource with a long history as a reliable source of low-cost electricity. Within the U.S. Department of Energy (DOE) Office of Fossil Energy (FE), the Office of Clean Coal and Carbon Management (OCCCM) conducts research, development, and demonstration (RD&D) of advanced technologies that increase the socio-economic value of coal—while avoiding adverse impacts on health, climate, and the environment. OCCCM's world-class scientific analyses guide its RD&D, domestic and international partnerships, and education and outreach activities.

OCCCM manages a portfolio of groundbreaking RD&D to expand the role of coal in building a robust, low-carbon economy. The Office is structured to efficiently conduct this research.

RD&D of Advanced Fossil Technology Systems

- A*dvanced energy systems.* Innovative technologies will improve the efficiency of existing and future coal-based power systems, enabling affordable carbon dioxide (CO_2) capture and maintaining the highest environmental standards. OCCCM supports gasification R&D to convert coal into synthesis gas, which can then be converted into electricity, chemicals, hydrogen, fuels, and other products. The program also works on advanced hydrogen turbine designs and supports advanced combustion systems.
- *Emissions Control and Carbon Capture, Utilization, and Storage (CCUS).* Novel technologies and business models will enable low-cost CCUS to improve the environmental performance of fossil power plants and industrial systems across America; support secure, long-term, regional carbon storage; enhance oil recovery; and provide feedstocks for valuable new products. Related innovations achieved through RD&D and technology partnerships will capture CO_2 directly from the air, provide a reliable U.S. supply of critical minerals, and support a successful hydrogen economy. Advanced treatment technologies reduce solid and liquid waste streams, decrease pollutants, conserve water, and preserve ecosystems.

Photo: NETL

Rare Earth Elements (REEs) and Other Critical Minerals from Coal in the Near Term

OCCCM is piloting multiple projects to avoid reliance on imports of REEs and other critical minerals vital to modern technology. For example, the University of Kentucky and Virginia Tech are testing a novel, plasma-based process that could make U.S. coal country a significant new supplier of these critical minerals.

www.energy.gov/fe/articles/power-plasma-extracting-rees-coal

- *Cross-Cutting RD&D and Systems.* OCCCM works with other DOE programs to accelerate progress on technologies that address shared challenges. For example, the Office leads the Artificial Intelligence Intra-Agency Cross-Cutting Team for the Subsurface and participates on the Energy Systems Integration Facility (ESIF) Steering Committee, the AI RTIC subcommittee, and the Technology Transfer Policy Board, among others. The Office also leverages resources and expertise with other program offices like the Advanced Manufacturing Office, as described in a recent report on *The Intersection of Advanced Manufacturing with Clean Coal and Carbon Capture Technologies*.

Strategic Planning, Analysis, and Engagement

OCCCM conducts expert energy and economic analyses to support its RD&D activities; advise policy and regulatory development; and inform a range of local, state, tribal, national, and international projects, initiatives, and partnerships. These analytic activities tend to fit into three broad categories:

- *Market and benefits analysis*. Analyses estimate relative RD&D impacts and identify trends, issues, or gaps likely to affect outcomes. Domestic and global bodies often seek OCCCM's technical input on proposed policies and regulations.
- *Technical support*. OCCCM conducts definitive analyses of potential projects, policies, and partnerships in response to requests received from other offices within DOE, other agencies, national and regional organizations, state and local governments, tribes, territories, or international groups.
- *Strategic engagement*. The Office also participates in multilateral forums, conducts educational outreach activities, and facilitates dialogs to inform critical decisions by a variety of organizations (from states and utilities to international bodies). To address national needs, OCCCM actively works with the National Coal Council and other stakeholder groups and cooperates with other federal agencies (e.g., through the Inter Agency Power Group) and with other governmental and non-governmental organizations to coordinate on important issues.

Model of a "desk-sized" sCO_2 turbine *Photo:* GTI

Supercritical Carbon Dioxide (sCO_2) Power Cycles

In contrast to power cycles in use today, those that use sCO_2 as the working fluid will have a smaller footprint and can use any heat source (fossil, geothermal, nuclear, concentrating solar) to achieve 10% higher efficiency at lower cost. DOE and industry partners are building a 10-MW pilot plant in San Antonio, Texas, to demonstrate this technology.

www.swri.org/sites/default/files/step-infographic.pdf

CARBON CAPTURE, UTILIZATION & STORAGE

ACCELERATING CCUS TOGETHER

Accelerating CCUS Together (ACT)

DOE leads U.S. participation in the international ACT Initiative, which leverages the resources and capabilities of 15 countries to accelerate research on CCUS. As part of this effort, DOE national laboratories are now working on three carbon capture projects and four carbon storage projects.

www.energy.gov/fe/articles/us-department-energy-announces-4m-projects-collaborate-internationally-and-accelerate

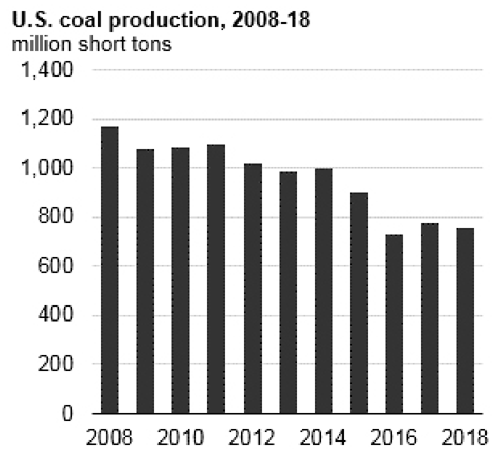
Coal and Carbon Management Trends

America's vast coal resources have provided reliable, low-cost energy to drive the U.S. economy for more than a century. Over the past decade, coal-based power plants have faced rising operating costs, pressures to decarbonize, stagnant electricity demand exacerbated by a global pandemic,[1] and stiff price competition from natural gas and renewables. Large coal plants designed to supply steady baseload power must also cope with the rapid cycling now required to offset the grid's increased use of intermittent renewable energy. The U.S. coal industry needs novel technology solutions to transform these challenges into viable opportunities. The path forward begins with an honest accounting of the current situation.

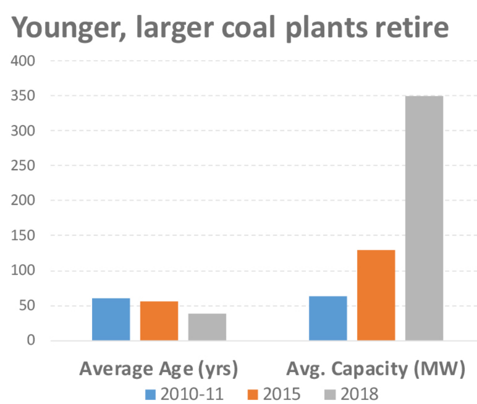
"There is still a bright future for coal, we just have to continue to develop it."

Energy Secretary Dan Brouillette
February 10, 2020

Coal plant retirements, mine closures, bankruptcies. U.S. coal plant capacity peaked at 318 gigawatts (GW) in 2011 and has declined since then as plants retire or switch to other fuels. By the end of 2019, capacity had dropped to 229 GW, and utilization rates had declined from 67% in 2010 to 48% in 2019.[2] Many of the shuttered plants were more than 60 years old, but some utilities have begun closing newer coal plants. Environmental, social, and governance (ESG) pressures are likely to cause more closures or bankruptcies in 2021 and 2022.[3] Some utilities plan to hang on by co-firing with biomass or operating only during peak seasons.[4]



Source: U.S. Energy Information Administration (EIA)



Source: U.S. Energy Information Administration (EIA)

The Energy Information Administration (EIA) projects that coal will provide only 13% of U.S. power in 2050 [reference case], down from 24% in 2019. Morgan Stanley's base-case scenario projects coal will be just 8% of the U.S. power mix by 2030.[5]

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1 International Energy Agency, *Global Energy Review 2020*, www.iea.org/reports/global-energy-review-2020?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email

2 EIA, U.S. coal-fired electricity generation in 2019 falls to 42-year low, May 11, 2020. www.eia.gov/todayinenergy/detail.php?id=43675

3 Kalb, Olivia, "More coal mine closures, bankruptcies to come as demand drops during coronavirus pandemic: Moody's, March 26, 2020. www.spglobal.com/platts/en/market-insights/latest-news/coal/032620-more-coal-mine-closures-bankruptcies-to-come-as-demand-drops-during-coronavirus-pandemic-moodys

4 Duquiatan, Anna, et al. "US power generators set for another big year in coal plant closures in 2020," S&P Global, Jan 13, 2020 www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/56496107

5 S&P Global Market Intelligence, December 23, 2019. https://ieefa.org/morgan-stanley-analysis-sees-coals-share-of-u-s-electric-generation-dropping-to-8-by-2030/

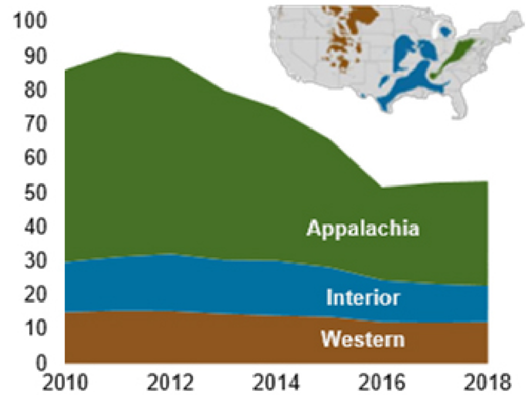
Growing pressure for carbon reductions. In response to stakeholder concerns, many states, tribes, companies, cities, and utilities plan to achieve carbon neutrality by 2050 or sooner. To survive, coal-fired power plants will need to invest in and adopt a range of new operating methods, equipment, and strategies.

Coal market trends. Domestic coal markets are expected to continue declining as a result of reduced demand.[6] Recent rule rollbacks may help coal plants lower operating costs, but the industry will continue to face daunting hurdles without low-cost, proven technologies to generate power with carbon neutral or net-negative emissions. Further challenges appear on the horizon as the long-term impacts of COVID-19 remain uncertain,[7] and states, utilities, and others continue to discuss mechanisms for carbon pricing.[8]

Around the globe, coal remains the world's single largest source of electricity, even with the collapse of European coal markets—a result of country-level efforts to set and deliver contributions to the Paris Agreement. The highest demand for coal is now in the developing economies of Asia, driven by strong economic growth and expanded household access to electricity.[9] However, increases in coal production within China and India are expected to dampen growth in coal imports by those countries.[10]

The promise of technology innovation. Research efforts currently funded by OCCCM are reimagining and reengineering coal plants for the future, developing low-cost CCUS technologies, and developing novel products from coal and its byproducts.

U.S. coal mining employment by region (thousands)



Coal mining jobs have decreased due to declining coal use and industry automation.

Source: U.S. Energy Information Administration (EIA) www.eia.gov/todayinenergy/detail.php?id=42275

"Investing in R&D for cleaner coal technologies will allow us to develop the next generation of coal plants for countries to use this valuable natural resource in an environmentally responsible manner."

Energy Secretary Dan Brouillette

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[6] Morehouse, Catherine, "2020 Outlook: Coal faces headwinds from aging plants, adverse market signals and high remediation costs," *Utility Dive*, January 14, 2020. www.utilitydive.com/news/2020-outlook-coal-faces-headwinds-from-aging-plants-adverse-market-signal/569732/

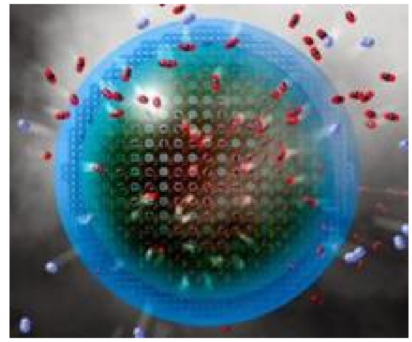
[7] IEA, *Global Energy Review 2020*. Impacts of the Covid-19 crisis on global energy demand, April. www.iea.org/reports/global-energy-review-2020?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email

[8] Skibell, Arianna, "Groups push FERC on carbon price," *EnergyWire*, April 15, 2020. www.eenews.net/energywire/2020/04/15/stories/1062876543

[9] Ambrose, Jillian, "World demand for coal falls despite growth in Asia," *The Guardian Weekly*, December 16, 2019. www.theguardian.com/environment/2019/dec/17/world-demand-for-coal-falls-despite-growth-in-asia

[10] *Mining Review*. "Thermal coal markets: 5 trends to watch out for in 2020," January 31, 2020. www.hellenicshippingnews.com/thermal-coal-markets-5-trends-to-watch-out-for-in-2020/

Reinventing coal plants. Modular, flexible, and highly efficient, coal-based power units are being designed to operate with carbon-neutral or net-negative (if combined with biomass) emissions and integrate easily with the modern power grid (responsive to fluctuations in the availability of renewables). Preliminary front-end engineering design (FEED) studies now in progress could lead to new domestic markets for coal in resilient microgrids and secure U.S. technology leadership in foreign markets that rely on coal.



Carbon Capture Membranes

Artist rendering of a highly permeable and selective membrane as it separates carbon dioxide from nitrogen.

Image: Mike Gipple, NETL

Capturing carbon profitably. Innovative technologies and systems are being developed to cost-effectively capture and store even dilute streams of CO_2. OCCCM RD&D projects are improving the efficiency and lowering the cost of membranes, solvents, sorbents, and other novel concepts for pre- and post-combustion capture. Recent OCCCM achievements in CCUS have generated global interest as these technologies handle emissions from coal and natural gas power plants—*and* industrial systems. Novel direct air capture (DAC) technologies are also attracting notice as a tool that may be widely applied to mitigate climate impacts.

Value-Added Products from Coal

Graphene quantum dots made from coal show potential for use in medical imaging and other areas.

Photo: Coal Beneficiation Program, NETL

To expedite progress on CCUS, OCCCM is adapting and using advanced tools and capabilities from other disciplines. For example, advanced manufacturing processes like 3D printing enable novel configurations that increase heat and mass transfer rates, while artificial intelligence (AI) and machine learning (ML) can speed materials discovery and optimize processing.

Transforming coal and its byproducts into value-added goods. Innovative technologies are converting coal, captured emissions, and other coal byproducts into unique and useful products and materials. Novel products now in development offer advantages over traditional materials, potentially opening new markets. For example, coal-derived building materials provide unique insulation and conduction properties. Other products show promise for use in coatings, composites, foams, textiles, electronics, plastics, and high-value materials (e.g., rare earth elements) critical to the U.S. economy. Products from ash may also address environmental issues.

Hydrogen is one of the most important products from coal. It offers the highest energy content by weight of any known fuel, and hydrogen fuel cells emit only heat and water. Hydrogen produced from fossil fuel using CCUS, known as *blue hydrogen*, could be a key enabler in the transition to a low-carbon economy. Whereas hydrogen made with renewable energy can be carbon neutral, hydrogen produced using biomass gasification *and* CCUS has the potential to be a negative emissions technology.

Opportunities ahead. OCCCM is developing a portfolio of advanced technologies to provide more compact, flexible, affordable, and sustainable power generation. Supported by a secure energy storage infrastructure, these technologies can deliver reliable and resilient power to all sectors of the economy.

Strategic Vision Overview

The strategy for OCCCM is based on a strong mission and vision to enable a vibrant, resilient coal industry characterized by diverse uses for America's coal resources. This strategy envisions new opportunities for modular, highly efficient coal plants to produce electricity with near-zero CO_2 emissions and integrate seamlessly with renewables on the modern grid. The strategy represents a rethinking of coal and coal resources to create a diverse set of valuable products and generate cleaner hydrogen for industry. Technologies developed to capture and utilize carbon from coal can also be applied to natural gas, biomass, and industrial sources of carbon to achieve carbon-neutral or net-negative emissions.

Emerging technical advances in coal-fired power and carbon capture technology will leverage innovations in high-performance computing, AI, ML, smart manufacturing, and other high-tech fields. Building strong domestic and global partnerships with other governments and organizations involved with coal and carbon management will enhance information exchange and accelerate technology deployment. Analyses of key issues will lay the groundwork for an effective R&D portfolio that addresses both technical and market needs.

OCCCM expertise in technologies such as carbon capture and geologic storage is essential to reducing carbon emissions. The Office will conduct outreach that elevates public awareness of OCCCM contributions to national energy and economic security and expands access to premier DOE experts in clean coal and CCUS. Foundational work conducted through programs like University Coal Research and the Mickey Leland Energy Fellowship will advance knowledge and help develop a skilled future workforce. OCCCM fosters educational opportunities with Historically Black Colleges and Universities (HBCUs) and Minority Serving Institutions (MSIs) to build greater diversity in future generations of energy scientists and engineers. The Office also provides technical assistance and resources for tribes and tribal energy resource development organizations, including grants for Native American educational projects.

The four focus areas and supporting activity directions listed in Figure 1 (see following page) summarize the technology pathways to be pursued. The focus areas align closely with the goals laid out in FE's *2018-2022 Strategic Vision*.[11] Utilization of carbon—whether from coal, coal byproducts, or carbon dioxide—is a key focus, covered in both Areas 2 and 3. Production and use of hydrogen are similarly integral to both advanced generation and products. The areas and directions outlined in this document are visionary and reinforce (rather than supersede) DOE budget submissions.[12]

This vision document was developed through a collaborative process involving all OCCCM programs. It is organized by the four major areas of focus, with additional information provided on the state of the industry, cross-cutting programs, and program evaluation methods. This is a dynamic document that will be revisited as progress is made and outlooks evolve.

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[11] U.S. Department of Energy, *Office of Fossil Energy 2018-2022 Strategic Vision. 2018.* www.energy.gov/sites/prod/files/2019/12/f69/FE%20Strategic%20Vision.pdf

[12] Department of Energy FY 2021 Congressional Budget Request. www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-2.pdf

Powering the Future

Vision

Advanced, affordable, 21st century U.S. fossil energy systems and products stimulate a robust global energy economy with carbon-neutral or net-negative emissions.

Mission

Drive R&D and adoption of advanced, affordable, reliable energy systems and products from coal and other fossil resources with carbon-neutral or net-negative emissions.

Focus Areas and Directions (▪)

Transforming Fossil Energy Systems for the Future

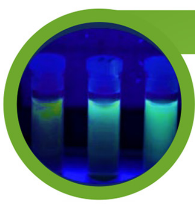
Drive technology solutions for a resilient 21st century grid.

- Develop technologies to enable highly flexible and reliable power systems with carbon-neutral or net-negative emissions.
- Modernize existing coal plants to achieve far greater efficiency, flexibility, and resilience.
- Integrate hydrogen production and storage to support grid flexibility and resilience.
- Optimize the environmental performance of energy systems, reducing impacts on water and other resources.

Managing Carbon with Confidence

Advance technologies to cost-effectively capture and securely store carbon across the economy.

- Accelerate the development of transformational carbon capture and storage technologies.
- Build and advance the capabilities needed to measure, scale, and validate CCUS technologies.
- Advance direct air capture, storage, and negative emissions technologies to extend the reach of carbon management.
- Pursue new products and uses for captured CO_2.



Reimagining Coal

Create valuable new products from coal and its byproducts.

- Explore new, high-value products and uses for coal and coal-based resources across the economy.
- Accelerate pathways to valuable products via coal-produced hydrogen.

Creating Opportunities with Analysis & Engagement

Generate opportunities for advanced coal and carbon management technologies using expert analysis and strategic engagement.

- Inform and educate stakeholders based on strategic analysis.
- Engage with the international community to elevate awareness and accelerate global technology progress.
- Build strategic partnerships with domestic government and industry.

Figure 1. OCCCM Strategic Focus Areas and Directions

Photos: 1. Adobe Stock 67795826, 2. Petra Nova www.energy.gov/fe/articles/happy-third-operating-anniversary-petra-nova www.olcf.ornl.gov/2008/01/17/simulation-aids-development-of-first-coal-plants-with-near-zero-emissions/ 3. Rice University, L. McDonald, The American Ceramic Society, May 14, 2019. https://ceramics.org/ceramic-techtoday/medical/coal-derived-quantum-dots-offerbasis-for-effective-antioxidant 4. Shutterstock 223150981

Area 1. Transforming Fossil Energy Systems for the Future

Drive technology solutions for a resilient 21st century grid.

The advanced fossil energy power plants of the future will need to be flexible, reliable, highly efficient, environmentally sound, and disassociated from large-scale greenhouse gas (GHG) emissions. To be globally competitive, new coal power technologies will need to generate electricity at lower cost with near-zero CO_2 emissions. Coal plants will increasingly need fast cycling and rapid ramp-up capabilities to integrate seamlessly with a modern, resilient, and highly connected energy grid that uses intermittent or distributed power sources.

CoalFIRST (Flexible, Innovative, Resilient, Small, Transformative)

The CoalFIRST initiative is developing technologies for future power plants at smaller scale (50 to 350 megawatts). The vision is for highly efficient, flexible, reliable, and environmentally responsible power that is cost-competitive with other generation sources. Technologies developed through CoalFIRST will benefit domestic coal fleets but also deliver export opportunities in Asia, Africa, and small market economies, such as island nations.

Source: NETL

OCCCM is committed to advancing the technologies needed to transform existing coal plants and enable the development of future, high-performing, advanced coal plants. Concepts for small, flexible, low-emission coal plants are under development. The aim is to produce power at more than 40% efficiency at higher heating value (HHV) with load following and reduced startup time. Groundbreaking coal power concepts now on the verge of large-scale demonstration could yield overall efficiencies close to 45%. Research will focus on improving foundational technologies, components, systems, and operations within existing plants, such as advanced topping cycles, new high-temperature materials, and improved control systems. Investments will focus on technologies that facilitate efficient energy storage to increase the flexibility and resilience of future plants and technologies that affordably produce and utilize hydrogen in both legacy and advanced coal plants.

OCCCM will invest in ways to improve environmental performance, which is vital to both future and legacy power plants. These improvements include reducing emissions to air, land, and water; minimizing the use of water for waste heat removal; and reusing coal ash and wastes. Improved environmental performance will enhance the overall reliability and cost-effectiveness of modern coal power plants.

Strategic investments will leverage advanced computational technologies, including big data analytics, AI, ML, and high-performance computing. Integration of technologies capable of managing massive datasets will be critical to enabling seamless integration with a modern smart grid.

Direction 1.1. Develop technologies to enable highly flexible and reliable power systems with carbon-neutral or net-negative emissions.

Situation Analysis

Historically, the United States has been a world leader in developing efficient coal power technologies. Today, the Nation trails Japan, China, and the European Union in coal plant efficiency.[13] Technology advances under development in the United States have significant potential to shift efficiency higher while providing benefits in reliability, flexibility, carbon management, and environmental performance. High-efficiency coal plants have been built in the United States to demonstrate technologies such as an advanced supercritical boiler and high-efficiency turbine generator.[14] High-efficiency, low-emission coal plants are an important pathway to reaching carbon-neutral or net-negative emissions. The World Coal Organization indicates that using advanced technology to increase global coal plant efficiency could reduce CO_2 emissions by 2 gigatons per year.[15] Market downsizing and regulatory challenges are impediments to investment in advanced coal plant technology.[16] Technical challenges to improving efficiency and achieving future enhancements for advanced coal power include the cost of technology (capital and development), materials limitations, and viable carbon capture approaches. Major R&D investments by DOE and the private sector are helping to accelerate development of a new suite of technologies that will help transform coal power generation.

Grid modernization and energy supply changes are creating a further paradigm shift in how U.S. generating assets operate. Greater demand for dispatchable generation and grid reliability is creating opportunities for advanced coal-fired generation, both domestically and globally. Advances beyond today's utility-scale, centralized power plant concept (e.g. base-load units) and state-of-the-art technologies are needed, along with innovative approaches for design and construction.

Demand for a dynamic grid has increased the construction of energy storage projects and spurred development of advanced storage solutions. Energy storage enhances grid flexibility, enabling distributors to purchase electricity during off-peak times, when energy is cheaper, and sell it back when demand is greater. Energy storage options such as pumped hydro have been in use for over a century. With increased grid uptake of renewable power over the past decade, other forms of cost-effective storage are being more widely developed and deployed, including compressed air energy storage, molten salts, battery technology, hydrogen fuel cells, and others. Some solutions (e.g., lithium ion batteries) have only short-term storage capacity (hours). R&D is needed to develop advanced utility-scale and small-scale storage solutions with improved longevity, cost-effectiveness, and flexibility.

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[13] Power. Who Has the World's Most Efficient Coal Power Plant Fleet? 2017. www.powermag.com/who-has-the-worlds-most-efficient-coal-power-plant-fleet/

[14] Longview Power Clean Coal Technology. https://longviewpower.com/our-technology

[15] World Coal Association. High efficiency low emission coal. www.worldcoal.org/reducing-co2-emissions/high-efficiency-low-emission-coal

[16] Process Baron. How Does U.S. Coal Power Plant Efficiency Stack Up? https://processbarron.com/news/u-s-coal-power-plant-efficiency-stack/

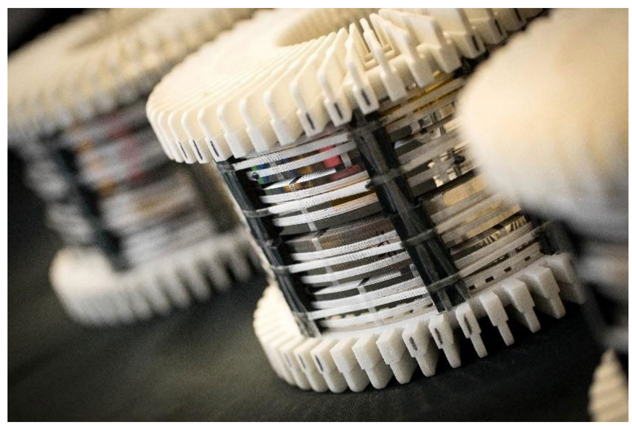
Strategic Response for Transformative Energy Systems

OCCCM is laying the groundwork for developing and operating a new generation of advanced coal plants for the 21st century. Investments in technology R&D will achieve substantial improvements in overall plant efficiency, including designs that produce carbon-neutral or net-negative emissions and integrate effectively with the modern grid.

Strategies for Transformative Energy Systems

- Achieve high overall plant efficiency (40% or more) at full load, with minimal reductions in efficiency over the required generation range.

OCCCM continues to push the limits of turbine performance through research on combustion, aerodynamics, heat transfer, and materials for advanced turbines and turbine-based power cycles. R&D focuses on enabling turbines to operate in excess of 3100˚F with low nitrogen oxide (NOx) emissions, increased power output, and efficiencies above 65%. Examples of advanced technologies include ceramic matrix composites for airfoils and combustion components, advanced low-NOx micro-mixer combustion systems, and pressure-gain combustion.



A cobalt-based nanocrystalline alloy and strain anneal manufacturing process developed by a lab-industry partnership supports next-generation solid-state transformers, grid-tied inverters, and power flow controllers. *Image:* NETL

OCCCM will also continue to pursue new, modular concepts that offer ultra-high efficiency, rapid ramp rates, minimal water consumption, and carbon-neutral or net-negative emissions. R&D under the CoalFIRST initiative will support flexible, 21st century power plants that meet the needs of the modern grid and incorporate component innovations that improve efficiency, resilience, and emissions performance. Modular units will be smaller than conventional utility-scale coal plants, transforming the design and manufacture of coal systems and technologies. The focus is on multiple technologies (e.g., advanced combustion and power cycles, advanced gasification, cutting-edge manufacturing, fabrication, etc.) for use with different coal types and regions throughout the United States and across the coal and power industries. Advanced modular units must also be able to co-fire with natural gas and integrate with coal upgrading processes and new product value streams.

> "CoalFIRST is the only R&D effort in the world that is working to develop coal-powered plants of the future that will have zero or near-zero CO_2 emissions."
>
> Steven Winberg
> Assistant Secretary for Fossil Energy

Process engineering and virtual design methods for new units will help minimize design, construction, and commissioning schedules compared to conventional plants—reducing deployment costs. Holistic approaches will enhance monitoring and maintenance diagnostics and reduce forced outages and disruptions, facilitating greater efficiency and cost-effectiveness in overall plant operations. Systems that are flexible and integrate effectively with a modern, highly connected grid are a critical focus.

R&D for integrating energy storage will focus on concepts at utility scale, including thermal, chemical, and electrolytic or battery storage technology. Energy storage provides an additional source of revenue while supporting a modern, resilient grid. The Office is participating in the DOE Energy Storage Grand Challenge, with funding planned for cost-shared research and development projects, including innovative, early-stage concepts and technologies that offer game-changing benefits for fossil power. Supercritical carbon dioxide (sCO_2) energy storage, for example, provides high energy efficiency and a low carbon footprint, and the carbon dioxide (CO_2) can be sold or paired with methanol production. Hydrogen storage concepts also have great potential to improve plant flexibility and resilience; these are discussed under Direction 1.3.

Research directions will include the following:

- Advanced, innovative power generation systems
  - Modular, flexible, and resilient systems (CoalFIRST), including advanced component and engineering design and advanced combustion technologies
  - Advanced manufacturing methods to reduce fabrication costs
  - Advanced turbines: pressure-gain combustion, direct CO_2 cycles (Allam cycle), indirect supercritical CO_2 cycles, advanced ultra-supercritical (AUSC) power cycles, direct power extraction systems
  - Gasification cycles to produce power and hydrogen
  - Hybrid coal power (e.g., biomass and other renewables)
  - Co-firing of coal, biomass, mixed plastics, or municipal solid waste (MSW)
  - Oxy-fired systems that improve efficiency
  - Fuel-agnostic power system technologies

Solving the Plastics Crisis

About eight million metric tons of plastics enter the oceans each year and break down into microplastics that collect bacteria and pollutants and are eaten by fish and shellfish.

People now consume thousands of microplastics each year in seafood, sugar, honey, salt, and water.* Tens of thousands of microplastics are also in the air—and the full health impacts are not yet known.**

Near Term: *Power from Plastics*

To support CoalFIRST design efforts, OCCCM will conduct RD&D on coal gasifiers capable of co-firing biomass and other co-feedstocks like plastics and municipal waste. The syngas processing and carbon capture systems will safely manage byproducts and emissions produced by flexible coal gasifiers.

By 2030: *Plastics Innovation Challenge*

This DOE challenge aims to develop biological and chemical means for deconstructing plastic wastes into useful chemicals; upcycle waste streams into higher-value products; and develop plastics that are recyclable by design.

*Cox, K.D. et al; "Human Consumption of Microplastics," *Environ. Sci. Technol. 2019, 53, 12, 7068–7074.* ACS, Jun 1, 2019.

** Stokstad, Erik, "Plastic dust is blowing into U.S. national parks—more than 1000 tons each year," *Science*, June 11, 2020.

- Technologies for hydrogen generation to support transportation and chemicals sectors

- Materials development and design
  - New alloy materials with the potential to improve performance, reduce costs, and enable efficient operation (e.g., in AUSC systems)
  - Materials for new energy systems and capabilities (e.g., gas separation membranes, oxy-combustion, gasifiers) that can lower emissions of NOx and CO_2
  - Technology base for synthesis, processing, life-cycle analysis, and performance characterization of advanced materials
- Flexible grid-integrated systems
  - Rapid, efficient, economic, and sustainable ramping to accommodate grid operations
  - Integration with variable/intermittent generation, load balancing, and bulk storage
  - Distributed generation systems with rapid (seconds/minutes) and deep ramp rates (fast cold starts)
- Utility-scale integrated energy storage
  - Participation in the Energy Storage Grand Challenge at tens of GWs scale
  - Thermal (waste heat) storage
  - Liquid air storage (i.e., cryogenic energy storage to compress and liquefy dried/CO_2-free air)
  - Supercritical compressed CO_2 energy storage (SC-CCES)
  - Hydrogen storage (see Direction 1.3).

The Energy Storage Grand Challenge

DOE is spearheading an Energy Storage Grand Challenge to create and sustain global leadership in energy storage utilization and technology exports. The objective is to create flexible storage solutions that use secure, domestic resources, eliminating reliance on foreign supplies of critical materials. The Grand Challenge builds on the $158 million Advanced Energy Storage Initiative announced in President Trump's Fiscal Year 2020 budget request. Under this challenge, OCCCM plans to support feasibility studies and pre-front-end engineering designs, component-level R&D, and innovative concepts and technologies.

Image: Adobe Stock 198290164

> "Through our CoalFIRST initiative, we're accelerating the development of transformational technologies that will pave the way for the coal plants of the future."
>
> Steven Winberg
> Assistant Secretary for Fossil Energy

Direction 1.2. Modernize existing coal plants to achieve far greater efficiency, flexibility, and resilience.

Situation Analysis

While the average efficiency of the most recently constructed U.S. coal plants is about 38% (2017 baseline heat rate), the efficiencies of older coal power plants can be much lower.[17] Construction of new coal power plants virtually stopped over the past two decades due to competition from other fuels and permitting/regulatory requirements, resulting in an older, less efficient operating fleet. Most U.S. coal plants operate at subcritical conditions, as opposed to more efficient supercritical and ultra-supercritical plants. Operating at higher temperatures and pressures yields a cleaner process, more energy, and less pollution, but moving from one stage to the next is capital intensive.

Maintenance issues, disruptions, and inefficient operations also lower coal plant efficiency and reliability, especially in older plants. Legacy plants need greater resilience and flexibility to integrate successfully into a modern grid. With more intermittent and distributed sources, existing grid infrastructures are increasingly switching from traditional base load to load-following profiles, putting significant pressures on the aging coal fleet. Systems and materials in legacy plants are older and not designed for the fast ramp rates, low load operation, and more frequent cold starts characteristic of load following. Coal plants are now being used to provide non-baseload power, which requires more frequent cycling. Increased cycling, in turn, damages components by subjecting them to fatigue, microstructural damage, and other thermal and pressure stresses, ultimately shortening component life.

Technology Characteristics

Subcritical plants operate below the critical point of water, which is 705°F and 3,208 pounds/square inch (psi).

Supercritical plants operate above 1,000°F and at more than 3,200 psi.

Ultra-supercritical plants operate at hotter temperatures—up to 1,400°F and 5,000 psi.

Advanced sensors and controls increasingly monitor and diagnose systems to help plant operators increase efficiency and flexibility, reduce forced outages, and avoid component failure and downtime. Challenges for sensors and controls include harsh environments, optimal placement, data analytics and optimization, and cybersecurity.

[17] U.S. DOE, *FY 2021 Congressional Budget Request*, DOE/CF-0164, February 2020, page 209. www.energy.gov/sites/prod/files/2020/04/f73/doe-fy2021-budget-volume-3-part-2.pdf

Strategic Response for Legacy Coal Power Systems

> **Strategy for Legacy Coal Power Systems**
>
> - Increase the efficiency of existing coal plants 5% by 2022.[18]

OCCCM will invest in RD&D to improve the reliability, resilience, and efficiency of legacy coal-based power systems. High-performance computing (HPC) and advanced optimization will be used to design and evaluate technology options that maximize efficiency and/or output under a variety of operating scenarios. Computational system dynamics activities support the development of immersive, interactive, and distributed visualization technology for designing next-generation advanced power systems. This visualization technology is based on validated models and highly detailed representations of equipment and processes. It should lead to a suite of products that can simulate the operations of carbon-neutral power plant systems (e.g., gasification and oxy-combustion). Broad areas of interest include topping cycles, boiler operation optimization, sliding pressure operation, and steam-cycle modifications.

> **Artificial Intelligence for Coal Power Plants**
>
> DOE is funding a project to develop a *Deep Analysis Net with Causal Embedding for Coal-Fired Power Plant Fault Detection and Diagnosis*. The aim is to create a computational system for fault detection and diagnosis in coal-fired power plants.
>
> Cost-shared by General Electric Company and GE Research (Niskayuna, NY), the project will develop a novel, end-to-end, trainable, AI-based multivariate time series learning system for flexible and scalable fault detection and root cause analysis (i.e., diagnosis) in coal power plants.
>
> *Source:* U.S. Department of Energy. www.power-eng.com/2019/06/10/doe-providing-39-million-for-coal-fired-power-fleet-research/

OCCCM analysis tools and methods will also help to improve the operation and efficiencies of the existing coal-fired power fleet. These tools will help make coal-fueled facilities environmentally and economically competitive in the energy markets of today and tomorrow.

Advanced materials are foundational, and they will continue as an important focus of technology development. The extreme environment materials (EEM) and harsh environment materials initiatives (HEMI) will address new materials development as well as materials durability and wear during service. Aggressive service environments involve high temperatures and thermal cycling, high pressures, corrosive chemicals, dust and particulates, mechanical wear, high-temperature oxidation, and hydrogen attack. These aggressive environments and the associated materials durability challenges occur across multiple applications and sectors.

Advanced manufacturing and computational methods will also be leveraged to help modernize coal plant maintenance and operational practices, improve data analytics, and support development of advanced, more durable materials. Advances in sensors and controls will be pursued as important enabler of optimized coal plant efficiency, flexibility, and reliability. The emphasis is on sensors and controls that can operate in harsh environments, improve the overall efficiency of plant operations, and facilitate integration with the modern grid.

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[18] In effect, increase the efficiency of a typical plant in the existing fleet to 32.5% from the 2017 baseline of 31%.

Directions for research will include the following:

- Advanced materials for severe environments (high temperatures and pressures)
  - EEM for cost-effective structural and functional materials
  - HEMI to address high temperatures and aggressive environments in oxy-fuel, hydrogen, and syngas turbines
  - Advanced data analytics and controls development for condition-based maintenance (CBM)
- Advanced manufacturing and operations methods
  - Advanced maintenance and repair for coal plant boilers via technologies for rapid, low-cost repair of coal plant boilers, leveraging insight afforded by robotic inspection
- Reliable, low-cost sensors and controls specific to efficiency, performance, flexibility, and resilience
  - New control systems analogs
  - Monitoring, measuring, and verifying technology performance/environmental outputs
  - Condition-based, big data-capable sensors for management and maintenance
- Computational analysis and technology
  - Data-driven power plant modeling, such as digital twin maintenance approaches[19]
  - Algorithms to shift from preventive- to condition-based maintenance
  - Big data analytics for plant management
  - Computational science and system dynamics
  - Economic analysis to examine new opportunities for predictive maintenance and cycling
  - Analysis to understand the value of resiliency and reliability in the existing fleet
- Increased flexibility and capability for more rapid cycling[20]
  - Identification of challenges and options for enabling greater flexibility (including decreased turndown times, dispatch)
  - Effective tools to help operators understand decision trade-offs under variable operational environments
- Technology optimization
  - Compression systems development
  - Recuperative heat recovery to achieve higher efficiencies
  - Heat addition and cooling
  - Advancements in energy storage to improve cycling performance.

[19] Digital twin-based predictive maintenance software uses real-time sensor records about the health and working conditions and analyzes those records in the context of historical data about failure modes and relevant impacts.

[20] Cycling is the act of varying the output of generation to meet dispatch requirements. Cycling causes changes in temperature and pressure outside of the original design specifications, altering operational characteristics (e.g., heat rate, cooling needs, emissions control, and maintenance).

Direction 1.3. Integrate hydrogen production and storage to support grid flexibility and resilience.

Situation Analysis

Industrial hydrogen is a major global market and demand is expected to rise, which would enable wide-scale decarbonization and global emissions reduction. Today, hydrogen is used primarily in oil refining, ammonia and methanol production, and steel making. Hydrogen holds potential as a carbon-neutral transport fuel in heavy-duty vehicles (e.g., electric trucks) as the weight of battery-driven propulsion systems creates technical and cost challenges. Hydrogen can also be combined with ammonia in gas turbines to increase system flexibility. In addition, hydrogen is a leading option for storing renewable energy.[21] Excess renewable energy created during low-demand periods can power electrolysis to separate hydrogen from water. The hydrogen can then be used in stationary or vehicle fuel cells to generate power, or it can be stored as a compressed gas or cryogenic liquid for later use.

Currently, dedicated hydrogen production facilities around the world rely primarily on fossil fuels (76% natural gas, 22% coal), generating about 830 million metric tons of CO_2 annually.[22] The most common hydrogen production process is steam methane reforming (SMR),[23] though it is also produced via coal gasification or, in small quantities, by the electrolysis of water.

Given its many uses, hydrogen from coal-based, integrated combined cycle (IGCC) gasification has a potentially important role in the future economy. In gasification, coal is reacted with oxygen and steam under high pressures and temperatures to form synthesis gas (syngas), comprising mostly hydrogen and carbon monoxide. Coal-derived syngas can be converted into gasoline and diesel via additional reactions (Fischer Tropsch Liquids) or into chemicals. [Area 3, Reimagining Coal, discusses chemical products from coal-derived hydrogen syngas.] IGCC combined with CCUS represents a low-carbon alternative with potentially higher thermal efficiencies, lower costs, fewer emissions, and reduced water use. IGCC technology is proven for heavy oils and residues, petroleum coke, and bituminous coals.

Co-firing coal with biomass, petroleum, or waste products (e.g., plastics) using CCUS can produce cleaner hydrogen for use in energy storage, transportation, or power generation. DOE currently supports R&D on these innovative, mixed-stream processes. Other hydrogen-producing technologies under development (primarily for fuel cells) include high-temperature water splitting, microbial photobiological water splitting, and photoelectrochemical water splitting.[24]

Challenges for gasifying coal to produce and utilize hydrogen include more efficient combustors; hydrogen yields/purity; advanced turbines and materials for 100% hydrogen firing; effective integration as a product stream for traditional coal plants; and reliable hydrogen supply and storage infrastructure. Capital and operating costs also remain key challenges.

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[21] Unlocking the Potential of Hydrogen Energy Storage. Fuel Cell and Hydrogen Energy Association. July 2019. www.fchea.org/in-transition/2019/7/22/unlocking-the-potential-of-hydrogen-energy-storage#:~:text=Hydrogen%20energy%20storage%20is%20a,in%20order%20to%20separate%20hydrogen.

[22] The Future of Hydrogen. June 2019. International Energy Agency (IEA). www.iea.org/reports/the-future-of-hydrogen

[23] Types of Coal-Derived Chemicals. National Energy Technology Laboratory. Accessed 4/21/2020. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/coal-derived-chem

[24] Alternative Fuels Data Center. Department of Energy. https://afdc.energy.gov/fuels/hydrogen_production.html Accessed 4/21/2020.

Strategic Response for Hydrogen Production and Storage

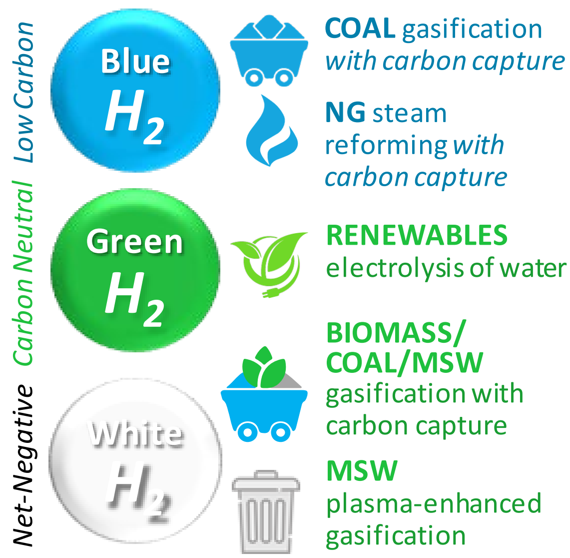
OCCCM will support activities to advance coal-to-hydrogen technologies, specifically through the process of coal gasification with CCUS. OCCCM has pioneered the direct use of hydrogen to generate power over the past 20 years, resulting in commercial combustors widely used in natural gas turbines. Opportunities exist to leverage prior work to improve the economics of hydrogen production from natural gas SMR and coal gasification and to enhance the supporting infrastructure for existing and future hydrogen markets.

Strategies for Hydrogen Production and Storage

- Produce blue or white hydrogen from coal or blends (biomass, coal, MSW) at commercial scale by 2035.
- Develop turbines capable of 100% hydrogen combustion by 2030.

Research is accelerating progress on technologies to produce hydrogen from coal-derived synthesis gas and to build and operate a carbon-neutral, high-efficiency power plant that produces both hydrogen and electricity from coal. Researchers are also working on hydrogen derived from various blends of biomass, coal, and/or MSW to achieve net-negative CO_2 emissions (i.e., *white hydrogen*). Major turbine producers have committed to developing turbines capable of at least 20% hydrogen combustion by 2020 and 100% hydrogen combustion by 2030; however, a significant amount of work remains (e.g., additional combustor development) before 100% hydrogen-fueled turbines become fully commercialized.

Modern/Future Hydrogen Sources



Sources: World Energy Council, "New Hydrogen Economy—Hope or Hype?" 2019. Proctor, D., "Group says it will launch world's largest green hydrogen project," POWER Magazine, May 2020.

OCCCM is also exploring poly-generation approaches to integrate the production and use of hydrogen in coal plants. In poly-generation, coal is gasified to produce hydrogen for multiple purposes, including 1) efficient power generation, either directly or blended with natural gas; 2) energy storage; 3) fuel-grade hydrogen (e.g., for transportation uses); and/or 4) production of chemicals like methanol or ammonia.

Solid oxide fuel cells (SOFCs) are being developed as a source of efficient, low-cost electricity from natural gas or hydrogen from distributed power generation. The high operating temperatures of SOFCs offer the possibility of internal methane reforming, providing additional sources for hydrogen production. SOFCs with internal reforming can produce hydrogen at scale within a carbon capture-ready paradigm through simple condensation of the SOFC exhaust.

Investments in innovative, flexible, modular designs will enable early adoption of small-scale systems for coal/biomass/waste mixture gasification and other syngas-based technologies for producing hydrogen. The aim is to increase the use of abundant domestic coal in strategic or targeted high-value applications and contribute to energy security as well as the revival of depressed economies in traditional coal-producing regions of the United States.

R&D directions for gasifying coal to produce hydrogen at target costs and with carbon-neutral or net-negative emissions include the following:

The University of Alaska-Fairbanks is testing a modular gasification system design for producing syngas from local coal resources in challenging environments. *Photo:* NETL

- Improvements in hydrogen production from coal and other fuels (e.g., biomass waste), integrated with power
  - New components, configurations, and sensor technologies combined with AI for real-time operational monitoring and fault prediction and for transport and use of coal-produced hydrogen
  - Economics of design, capital and operating costs
  - Advanced and/or modular methane reforming systems, such as SOFCs for modular- and large-scale power generation
  - Updating of relevant codes and standards related to production and supply
  - Solid oxide fuel cell improvements
  - Efficient mechanisms for delivering hydrogen to end users and optimizing supply chains
  - Technology for hydrogen-fueled turbines as retrofits for industrial gas turbines and combustion systems for power generation
- Advanced materials for hydrogen
  - Materials for the transport and long-term storage of hydrogen in a confined space under high temperature and pressure conditions, e.g., utility-scale hydrogen storage or pipelines
  - Innovative materials for reversible hydrogen storage, including high-surface-area adsorbents, metal organic frameworks, metal and chemical hydrides, and liquid carriers
- Poly-generation approaches in existing and new power plants
  - Integration of gasification, hydrogen turbines, and hydrogen storage systems as grid-scale energy storage
- Utility-scale energy storage
  - Hydrogen energy storage
  - Potential for regional utility-scale geologic storage of hydrogen.

Direction 1.4. Optimize the environmental performance of energy systems, reducing impacts on water and other resources.

Situation Analysis

The environmental performance of coal power plants is measured by air and water-based emissions, water use and management, and recycling or other strategies to conserve resources.[25] The Clean Air Act and Clean Water Act require all industries, including coal power, to control pollutants released into the air and water. Power plants use flue gas desulfurization equipment (scrubbers) to clean sulfur and other pollutants in gases emitted from smokestacks. The coal industry also employs technologies that can remove impurities from coal. Higher-efficiency power generation systems lower emissions and water use by reducing the amount of coal that is burned per unit of useful energy produced.

The largest use of water in coal plants is for cooling condensed steam before reuse. Various methods are used to cool/recycle water (once-through, wet recirculating, and dry cooling); each method has trade-offs in terms of water draw, use, and overall costs. The cooling system affects water requirements as well as the overall efficiency of the power plant. Scrubbers also use water mixed with limestone to absorb pollutants (creating a wet waste stream). Efficiency increases (e.g., via waste heat recovery or other approaches) can reduce water requirements. Advanced power technologies, such as IGCC or supercritical CO_2 fuel cycles, offer water-saving advantages over conventional coal power systems. Other strategies for water management include advanced multi-stage filtration, water treatment concepts, and reuse of coal ash. Cost and lack of demonstrations remain the key technical challenges.

Strategic Response for Environmental Performance

Transformative next-generation coal power technologies will inherently improve environmental performance via higher overall efficiency. OCCCM will further invest in technologies and strategies to enable high environmental performance and conserve water resources. In addition to emissions controls, this focus includes technologies directly related to water management and waste recycling, reuse, or similar strategies. A broad portfolio of technologies is envisioned to lower costs, address technical barriers, and enable integration with current plants. Examples include alternative materials of construction and advanced manufacturing strategies.

Strategies for Environmental Performance

- Accelerate development/use of efficient technologies for fresh water use and reuse.
- Reduce non-CO_2 criteria pollutants and solid and liquid emissions.
- Achieve in-practice use of advanced emissions reduction technologies by 2025.

R&D will focus on ways to reduce fresh water use and improve water efficiency in thermoelectric plants, focusing on the treatment and use of non-traditional waters and improving the plant's cooling processes. New water treatment technologies that economically derive clean water from alternative

[25] Air emissions include sulfur dioxide (SO_2), nitrogen oxides (NOx), particulates, carbon dioxide (CO_2), mercury, other heavy metals, and coal ash residues (fly ash, bottom ash).

sources could increase water recycling during energy extraction and conversion—reducing total water demand. OCCCM will also participate in the Water Security Grand Challenge, a White House initiated, DOE-led framework to advance transformational technology and innovation to meet the global need for a safe, secure, and affordable water supply.[26]

Innovative technologies will be developed to reduce and recover byproducts from coal combustion. The intention is to build a suite of enhanced, cost-effective emission control technologies that can be applied across the power generation sector. Utilization of coal ash and captured carbon is discussed in more detail in Area 3.

Research on environmental performance will pursue the following directions:

Water efficiency, use, and security

- Water Security Grand Challenge participation to accelerate RD&D on treatments of produced water from power generation to address water scarcity; thermoelectric cooling
- Water-limited cooling provided by supercritical CO_2 fuel cycles and innovative multi-stage filtration technologies (e.g., membrane, evaporative, chemical, electrochemical, biological)
- Sensors to measure parameters for more accurate water control/management
- Techno-economic assessments of promising technologies to guide development
- Effluent separations
  - Economic treatment technologies for selective removal of low-level contaminants in wastewater streams (e.g., selenium, boron) and for water reuse to minimize compliance volume
- Collaboration with the U.S. Department of Agriculture on energy-water analysis

Emissions reduction and control

- Reduction of capital and operating costs via process optimization and application of data analytics
- Advanced monitoring techniques, focused on a point and on plant throughput

Recycling and reuse

- Waste heat recovery
- Transformative technologies resulting in decreased emissions or creation of valuable byproduct streams (see Area 3, Reimagining Coal)

Modeling and simulation

- Modeling and analysis of existing regional water availability data
- Life cycle analysis, including water
- Simulations to address the energy-water nexus (water needs of power plants).

[26] DOE Water Security Grand Challenge. www.energy.gov/eere/water-security-grand-challenge

Area 2. Managing Carbon with Confidence

Advance technologies to cost-effectively capture and securely store carbon across the economy.

Carbon capture, utilization, and storage (CCUS) is critical to managing carbon emissions in a wide spectrum of industries, from fossil-fueled power generation to manufacturing and heavy industry—including oil refineries and facilities that produce hydrogen, ethanol, cement, or steel. CCUS can enable advanced power systems to adapt to changing operational requirements, such as the growing need for fossil-fueled power plants to be load-following, demand-responsive electricity generators. Negative emissions technologies (NETs), such as direct air capture and storage (DACS), bioenergy with CCUS (BECCS), and mineralization, will play pivotal roles in managing carbon emissions in the long term. In the near term, taking advantage of opportunities to utilize CO_2 and make products can partially offset the costs of capture systems while supporting flexible, clean coal and natural gas plants. Similarly, making products from CO_2 can increase the value of deploying carbon capture.

CCUS starts with trapping CO_2 at its source, followed by utilizing the carbon for valuable products or transporting and storing it at an underground location. Utilization of the carbon in CO_2 is discussed in this section as part of carbon capture and management; utilization of carbon from coal and coal byproducts or wastes is covered in Area 3, Reimagining Coal. To manage carbon with confidence, OCCCM will develop innovative technologies that improve the operations and economics of CCUS so that power plants and industry could achieve carbon-neutral or net-negative emissions; improve plant and process efficiency; reduce the costs and environmental impacts of non-CO_2 emissions from coal power plants (e.g., trace metals emissions in solid, liquid, and gaseous effluents); and ensure that CO_2 is utilized for valuable products or securely stored.

The technologies developed through CCUS programs will enable both existing and advanced fossil-fueled power plants to move toward effective carbon management and will provide valuable solutions for a wide range of industrial producers of CO_2 seeking to control GHG emissions. The valuable advances and scientific information developed through OCCCM research can be applied globally to inform technology development.

Direction 2.1. Accelerate the development of transformational carbon capture and storage technologies.

Carbon Capture

Situation Analysis

CCUS has many potential benefits and can be a cost-competitive option for managing carbon relative to other low-carbon sources of electricity and products. Carbon capture involves the separation of CO_2 into a pure stream and (in many cases) compression to a supercritical fluid for transport via pipeline. Industry has a rich history of CO_2 separation, although few large-scale CCUS power plants are currently in operation worldwide. Successful examples of carbon capture at scale have been achieved with government support and policy incentives. Challenges include the increased capital and operating costs of carbon capture relative to comparable plants with unabated carbon emissions and the possible reduction in net generating capacity.[27,28] Investments in transformative technology can help to overcome these challenges.

The DOE post-combustion capture program addresses both capital and operating costs to improve the economics of carbon capture and provide a solution for the power sector. Over the last decade, the program has developed pilot-scale, second-generation technologies that are on a development path to capture carbon at a cost of $40/metric ton, and efforts are ongoing for larger scale up. Transformational technologies that capture carbon at approximately $30/metric ton are at earlier stages of development. Plants associated with the DOE program are operating at various scales around the United States:

- Air Products operates a state-of-the-art system in Port Arthur, Texas, to capture more than 90% of the CO_2 from two SMRs used in large-scale hydrogen production. This project represents the first commercial-scale use of CCUS to decarbonize this process in the United States, where SMRs produce 95% of hydrogen. The project achieved full-scale operations on-time and on-budget in 2013 and, as of June 30, 2020, had captured more than 6.9 million metric tons of CO_2 for use in enhanced oil recovery (EOR).
- The Archer Daniels Midland (ADM) project in Decatur, Illinois, captures CO_2 from its ethanol biofuels production process and stores it in a deep saline reservoir.[29] Between April 2017 and June 30, 2020, the project captured 1.8 million metric tons of CO_2. This first-of-a-kind carbon storage project is an example of BECCS, an approach deemed essential to achieve global carbon reduction goals.
- The Petra Nova project captures more than 90% of the CO_2 emitted from a coal-fired boiler flue gas stream at the W.A. Parish Generating Station in Thompson, Texas. Led by NRG Energy and JX Nippon Oil, this project opened in 2016 as the largest post-combustion, carbon-capture facility in the world. It captures and uses 1.4 million metric tons of CO_2 per year to enhance oil production at the West Ranch Oil Field in Jackson County, Texas.[30] By the end of June 2020, the project had captured 3.8 million metric tons of CO_2 for EOR.

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27 Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4. NETL. August 2019. https://netl.doe.gov/sites/default/files/netl-file/A-Zoelle-NETL-Baseline-Volume-1_r1.pdf

28 Peter Folger. Carbon Capture and Sequestration (CCS) in the United States. Congressional Research Service. August 2018. 7-5700 www.crs.gov R44902. Accessed March 13, 2020. https://fas.org/sgp/crs/misc/R44902.pdf

29 Watch for ADM to pioneer biofuels, more carbon capture projects. GreenBIZ. May 13, 2020. www.greenbiz.com/article/watch-adm-pioneer-biofuels-more-carbon-capture-projects

30 Texas Petra Nova is the world's largest and only US coal power plant with the capacity to capture over 90% of carbon emissions at large scale (over 1 million pounds); post-combustion capture technology offsets cost by selling captured CO_2 for enhanced oil recovery. Large-scale carbon emissions recovery is also in place at the Boundary Dam plant in Canada.

U.S. industry has used solvents to capture CO_2 since the 1930s. Investments in R&D have led to improvements, and continued R&D could lower the cost and increase the scale of carbon capture technology. Recent efforts to effectively scale up and apply the technology to power plants underscore the need for further research and policy incentives. Tax credit programs offer opportunities but may not be enough to make the technology cost competitive.[31]

Research is needed to improve economies of scale and address the technical challenges posed by increased capture efficiency, such as improved thermodynamics (reduced energetic requirements, lower pressure drops, lower temperature, process optimization) and kinetics (faster, more selective chemical/physical separation pathways). Process intensification and advanced manufacturing can reduce capital and operating costs. Scalability, durability, and flexibility are challenges that must be met to ensure long-term performance and the ability to work with variable power and capture rates.

Strategic Response for Carbon Capture

Strategies for Carbon Capture

- Pursue second-generation and long-term transformational carbon capture technologies to achieve a cost of electricity at least 30% less than the state of the art.

Capturing CO_2 from coal or gas power plants and industrial sources requires steam and electricity, reducing the plant's electricity output and/or increasing its fuel input. This energy penalty or parasitic load increases operating costs. Research investments in advanced carbon capture technologies have the potential to provide step-change reductions in both cost and energy penalties compared to currently available technologies. These advancements would create viable pathways for future power plants and industrial facilities to capture carbon and operate under strict GHG constraints. The technologies are wide-ranging and include research directed at the use of solvents, solid sorbents, membranes, hybrid approaches, and cryogenics.[32]

NETL researchers are studying coal chemical looping, which enables combustion of fuels in nearly pure oxygen, presenting an opportunity to simplify CO_2 capture in power plants.

Photo: NETL

OCCCM research has taken new approaches to carbon capture from bench- to pilot-scale demonstrations. The program leverages progress in advanced manufacturing to make novel sorbents and uses ML and computational tools to better design research. The Carbon Capture Simulation for Industry Impact ($CCSI^2$) project uses ML to optimize the generation and analysis of experimental data.

[31] 45Q Tax Credit. Carbon Capture Coalition. https://carboncapturecoalition.org/45q-legislation/

[32] 2019 Proceedings - Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting - Capture And Utilization Sessions. https://netl.doe.gov/node/9032

To achieve its aims, OCCCM is pursuing advances in process chemistry, process equipment design, chemical production methods, and gas cleanup and separation technologies. Transformational advances will be facilitated by advanced computational tools for rational materials discovery, design of advanced capture system components, and synthesis of materials to characterize physical properties.

The front-end engineering design (FEED) and Carbon Storage Assurance Facility Enterprise (CarbonSAFE) programs (described further in Direction 2.2) together provide foundational research in CCUS infrastructure and capabilities to support carbon capture at commercial coal and natural gas projects. The essential engineering studies conducted by these programs closely intersect with private-sector interests, fostering and spurring investment in future CCUS projects.

Carbon Capture Simulation for Industry Impact

The open-source, R&D 100 Award-winning computational toolset from the CCSI^2 project provides industry end users with a comprehensive, integrated suite of scientifically validated models and tools for risk analysis, uncertainty quantification, optimization, and intelligent decision-making. The National Energy Technology Laboratory (NETL) leads CCSI^2 in partnership with Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Pacific Northwest National Laboratory, West Virginia University, and the University of Texas, Austin.

www.netl.doe.gov/sites/default/files/2017-11/R-D211.pdf

R&D activities include the following:

- Early-stage R&D on transformative CO_2 separation technologies such as non-aqueous solvents, advanced polymeric membranes, advanced sorbents, and cryogenic processes; reactive capture of carbon, e.g., electrolysis and absorption
- Manufacturing and design technologies (e.g., additive manufacturing, advanced models, direct printing) applied to carbon capture system components, such as membranes and absorber packings
- Carbon capture systems for advanced power systems, such as chemical looping, oxygen combustion, DACS, BECCS, and direct supercritical CO_2 cycles
- Improved catalytic conversion of CO_2
- Flue gas testing of technologies at the National Carbon Capture Center
- Computational modeling and simulation tools for data generation, evaluation, and design (e.g., ML, materials design).

Post-Combustion Capture Test Facilities at the National Carbon Capture Center (NCCC) have supported testing of over 37 technologies, including new membranes, enzymes, sorbents, solvents, hybrids, and associated systems.

Photo: DOE NCCC

Carbon Storage

Situation Analysis

Carbon storage involves isolating captured carbon emissions in underground geologic formations, such as saline formations and depleted oil and gas reservoirs (Figure 2). The suitability of these sites depends on geological factors, including porosity, permeability, and the presence of overlying rock formation(s) that are not permeable and lack potentially transmissive faults and fractures. Storage in depleted oil fields is technically and economically viable as CO_2 interacts with remaining oil, making it easier to remove. This type of storage has been done commercially in the United States since the 1970s. DOE programs have successfully deployed various large-scale CCUS pilot and demonstration projects. These projects provide a useful foundation for further testing, maturing, and proving these technologies at a million-ton-per-year or greater scale.[33] A recent study by Science of the Total Environment found DOE to be the "most productive organization in the world" in the field of CCUS.[34]

CO_2 has been injected into saline formations for long-term storage since the 1990s, first in Norway and later in the United States. DOE demonstration programs have injected over 16 million metric tons of CO_2. Technical challenges include scale-up, optimization of operations, storage efficiency, risk monitoring and mitigation, and long-term stewardship.

Strategic Response for Carbon Storage

Federal government-sponsored R&D is critical to validating and increasing confidence in the safety, affordability, and permanence of CO_2 injection and storage. Further advances in CO_2 storage technology will provide industry the verifiable information needed to economically and safely assess and monitor long-term storage of CO_2. Carbon capture and geologic storage must be demonstrated as an effective and reliable solution before being widely implemented. Carbon storage investments will focus on early-stage R&D to develop coupled simulation tools, characterization methods, and monitoring technologies to improve storage efficiency, reduce cost and risk, decrease subsurface uncertainties, and identify ways to ensure that operations are safe, economically viable, and secure. This effort will include a spectrum of deep underground geologic storage approaches.

Strategies for Carbon Storage

- Develop and prepare at least five commercial-scale saline storage sites for permitting by 2025.
- Complete Phase I, Development and Prototyping, of the Science-Informed Machine Learning to Accelerate Real Time Decisions for Carbon Storage (SMART-CS) Initiative by 2022.

R&D focus areas will include the following:

- Wellbore integrity assessment, monitoring, and mitigation, including legacy well detection
- Scale-up for large-scale (50+ million metric tons of CO_2) geologic storage sites

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33 www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage

34 Hui Li, Hong-Dian Jiang, Bo Yang, and Hua Liao. "An analysis of research hotspots and modeling techniques on carbon capture and storage." Science of The Total Environment. Volume 687, 15 October 2019, Pages 687-701

- Geo-mechanical studies for assessing state of stress and induced seismicity risk
- New methods for plume imaging and leak quantification
- Transformational sensing and monitoring systems
- Unconventional CO_2 storage
  - Residual oil zones
  - Offshore CO_2-EOR and storage
  - Injection and storage in shales combined with recovery of shale gas
  - Basalt formations
  - Unmineable coal seams
- Monitoring tools and advanced computational platforms such as ML to enable real-time decision-making
- Analysis of markets, policies, and financial drivers for CCUS and underground storage.

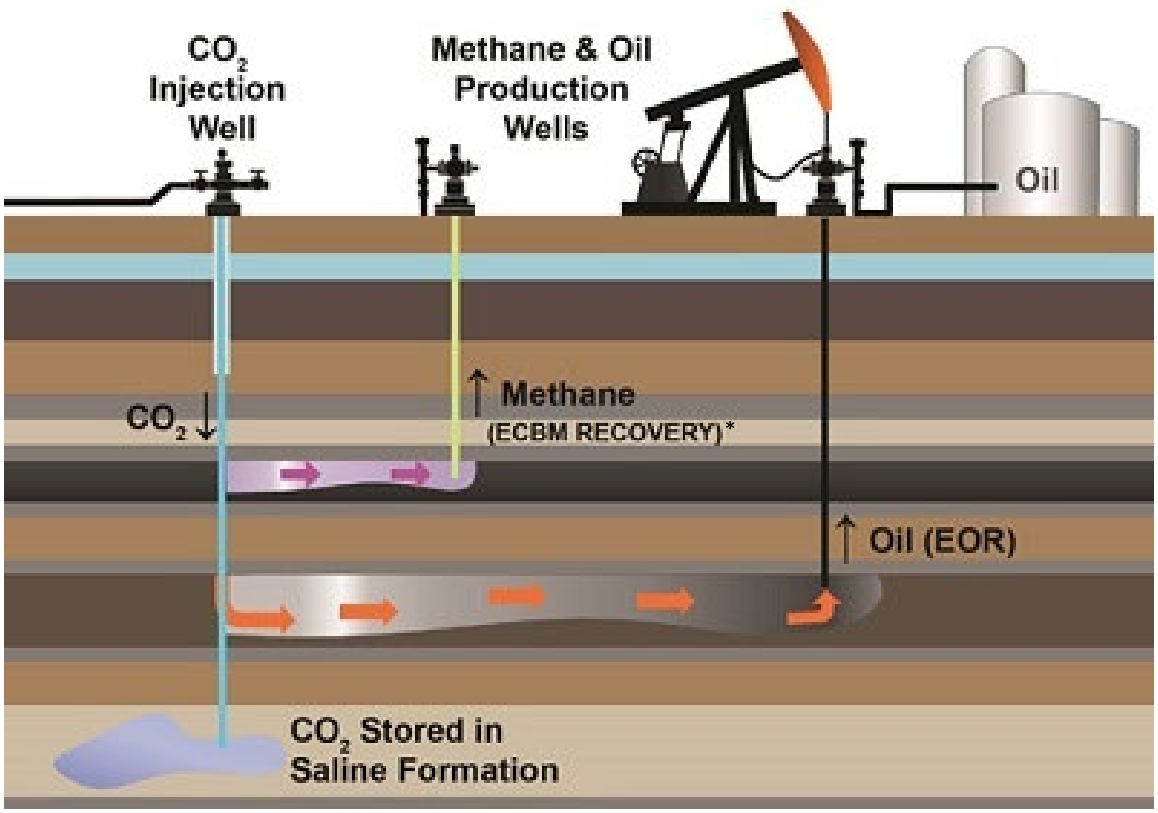

Figure 2. Options for Carbon Storage * ECBM: Enhanced Coal Bed Methane

Image: **NETL** www.netl.doe.gov/coal/carbon-storage/faqs/carbon-storage-faqs

Direction 2.2. Build and advance the capabilities needed to measure, scale, and validate CCUS technologies.

Situation Analysis

Geologic carbon storage involves designing an industrial facility with integrated operations, geologic site characterization, diverse modeling and simulation capabilities, feasibility studies, risk assessment, and demonstrations or field testing. A significant amount of geological site characterization has been undertaken worldwide. DOE has estimated total storage capacity in the United States to range between about 2.6 trillion and 22 trillion tons of CO_2, with the vast majority of that capacity in saline formations.[35] Many factors impact the suitability of an underground site for carbon storage, including proximity to the source of carbon and site-specific characteristics, such as porosity, permeability, and potential for leakage. The intent is to store carbon underground in perpetuity, with no migration back to the atmosphere.

Significant research has been conducted to test and model the behavior of large quantities of injected CO_2 in underground reservoirs. Research shows that the United States theoretically has the capability to store all CO_2 from large stationary sources underground for centuries. Additional large-scale testing and field demonstrations are needed to further validate reservoir capacity and characteristics, as well as permanence.

Strategic Response for CCUS Capabilities

OCCCM will pursue foundational research in the areas of geologic site validation, computational tool and data development, and science-based methods for risk assessment. R&D will support the development and testing of advanced sensing and data telemetry capabilities to characterize fault/fracture networks, stress state, fluid/pressure migration, and wellbore integrity to facilitate real-time decision-making capabilities. [35]

Strategies for CCUS Infrastructure

- Launch multiple CCUS hubs for U.S. power and industrial sectors, each operational by 2030 and capturing, storing, or utilizing 5 million metric tons of CO_2 per year, with scale-up capability.

The CarbonSAFE Site Characterization and CO_2 Capture Assessment program is vital to the broad deployment of carbon storage. The focus is on assessing and verifying safe and cost-effective carbon capture and/or purification technologies and commercial-scale storage sites for anthropogenic CO_2. Projects under CarbonSAFE will accelerate wide-scale deployment of CCUS by conducting the work needed to permit a commercial-scale project. OCCCM also continues to invest in the FEED program, which is necessary to more fully understand the costs of CCUS systems and support wide-scale deployment of the technology. The integration of results emerging from the CarbonSAFE and FEED programs is providing the foundational information, experience, and engineering design needed to stimulate industrial investment and facilitate the success of commercial CCUS. New projects are being

[35] Ibid. 2. Folger, Congressional Research Service.

announced in the power sector, and those considering saline storage are largely premised on work conducted through the CarbonSAFE and FEED studies (Figure 3). FEED projects also include use of CCUS at industrial facilities.[36]

OCCCM will continue to invest in the Regional Partnerships Initiative to address key challenges in large-scale storage; facilitate data collection, sharing, and analysis; evaluate regional infrastructure; and promote regional technology transfer.

The OCCCM focus areas for building capabilities include:

- Small and large-scale storage testing and validation
  - Adequate injectivity, available storage resource, and storage permanence across a range of formation classes and storage types
  - Reservoir response, e.g., impacts of brine extraction on reservoir capacity and operations
  - Approaches such as stacked storage, multiple well injections
  - Participation in storage demonstrations worldwide
- FEED program for carbon capture systems[37]
  - Commercial-scale carbon capture units on existing (retrofit) or new coal- or gas-fired power plants
  - Prefeasibility and FEED studies for industrial sources of CO_2
- CarbonSAFE site characterization and injection testing

DOE Carbon Storage Testing and Validation Projects

Carbon Storage Assurance Facility Enterprise (CarbonSAFE) – Early-stage development of integrated CCS complexes with future potential for commercial operation. Since 2016, 13 sites have conducted pre-feasibility studies addressing regulatory, legislative, technical, public policy, commercial, financial, and other challenges to commercial-scale deployment. Three are in advanced phases, performing geologic analysis and subsurface modeling for geologic characterization, risk assessment, and monitoring.

Brine Extraction Storage Tests (BEST) – Field tests to demonstrate feasible brine extraction and injection strategies for managing reservoir pressure and CO_2 flow. In a process called plume steering, salty water, known as brine, from the CO_2 storage reservoir can be extracted to change the reservoir pressure and the flow of the stored CO_2. The aim is to improve storage efficiency in future saline formation storage sites.

Regional Carbon Sequestration Partnerships (RCSP) – Study of the best geologic storage approaches and technologies to safely and permanently store CO_2 in seven regions. Operating since 2003, current partnerships focus on large-scale field testing (one million metric tons of CO_2) to confirm that injection and storage can be achieved safely, permanently, and economically.

DOE Science and Computational Infrastructure

National Risk Assessment Partnership (NRAP) – Partnership to develop an integrated science and data foundation for the risk assessment of long-term CO_2 storage. Five DOE national laboratories are participating: NETL, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory.

Carbon Storage Atlas and National Carbon Sequestration Database (NATCARB) –Coordinated update of carbon capture and storage potential across the United States and other portions of North America. NATCARB provides access to datasets generated by the RCSPs and other DOE projects as well as links to other publicly available data repositories.

[36] http://ethanolproducer.com/articles/17119/doe-funds-ccus-project-at-ethanol-plant-opens-new-ccus-foa

[37] Front-End Engineering Design (FEED) Studies for Carbon Capture Systems on Coal and Natural Gas Power Plants, nine DOE-funded projects in commercial-scale carbon capture. www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage

- Continued efforts by Regional Partnerships[38]
- Improvements to computational capabilities
  - Simulation/risk assessment and monitoring capabilities via NRAP and other activities; tools and methods to extend predictive capabilities for managing risks related to CO_2 storage
  - Leveraging AI to exploit the use of big data in optimizing CCUS
  - Development and coordination of critical datasets for geologic storage, such as NATCARB
  - Incorporation of CCUS into integrated resource planning (IRP) models and software.

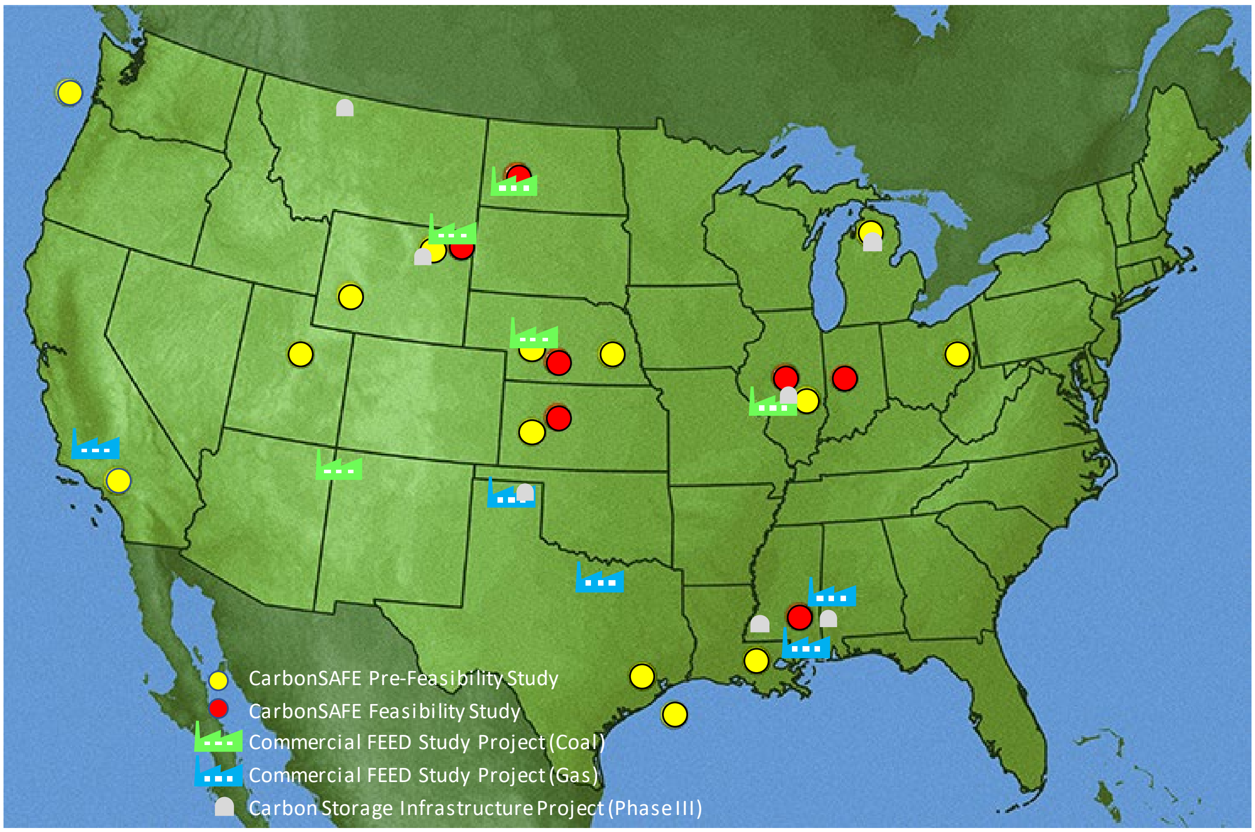

Figure 3. CarbonSAFE and FEED Studies for Carbon Capture

Sources: https://netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe, https://netl.doe.gov/coal/carbon-storage/storage-infrastructure-projects, and www.kgs.ku.edu/PRS/IMSCSH/pdfs/ccus_conference_3/Jarad_Daniels.pdf

[38] Regional Initiative to Accelerate CCUS Deployment. www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage

Direction 2.3. Advance direct air capture, storage, and negative emissions technologies to extend the reach of carbon management.

Situation Analysis

Negative emissions technologies (NETs) remove CO_2 from the atmosphere and store or use it. Removing CO_2 directly from the atmosphere is not new. It has long been applied in models showing theoretical pathways for reducing CO_2 emissions. NETs include, for example, DACS, BECCS, and fixing of carbon in soil. Recent developments in DAC combined with carbon storage have increased the potential viability of this concept. DAC pulls CO_2 directly from the air by using large fans, filters, and chemical reactions to produce a pure CO_2 stream that can be stored or utilized.[39] A DAC plant scheduled to begin construction in British Columbia in 2021 is designed to extract about one million metric tons of CO_2 from the air annually for the production of synthetic fuels.[40] Recent reports cite the need for DAC alongside other carbon removal and mitigation strategies. As a result, DAC technology is gaining greater attention.[41,42] The costs for removing and storing CO_2 via DAC vary and could be up to $600 per metric ton.[43] Cost and demonstrated viability at scale remain the primary impediments to DAC.

Strategic Response for DAC and NETs

Along with the DOE Office of Science, OCCCM is participating in a new DOE initiative focusing on DAC and plans to provide up to $10 million in fiscal year 2020 funds for a spectrum of DAC projects.[44] Research in DAC will focus on both applied development and field testing of prototypes. New activities will build on existing research in materials and systems development and will seek to improve first-generation materials and process technologies. In addition, projects will explore novel, second-generation concepts and components. Lab, bench, and pilot-scale testing of first-generation DAC systems and materials was completed in 2020.

Strategies for Direct Air Capture and NETs

- Complete bench-scale testing of second-generation DAC systems and novel materials and components.
- Integrate co-firing biomass with coal and other MSW to improve the carbon footprint and move toward net-negative emissions.
- Build analytical capacity (models and data) to support BECCS.

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39 Direct Air Capture Technology Factsheet. May 24, 2018. Geoengineering Monitor. www.geoengineeringmonitor.org/2018/05/direct-air-capture/

40 Carbon Engineering expanding capacity of commercial Direct Air Capture plant. September 2019. https://carbonengineering.com/news-updates/expanding-dac-plant/

41 Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. NAS. https://nas-sites.org/dels/studies/cdr/

42 Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology. Rhodium Group. May 9, 2019. https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/

43 Jon Gertner, "The Tiny Swiss Company That Thinks It Can Help Stop Climate Change," New York Times, Feb. 12, 2019.

44 Department of Energy to Provide $22 Million for Research on Capturing Carbon Dioxide from Air. March 30, 2020. www.energy.gov/articles/department-energy-provide-22-million-research-capturing-carbon-dioxide-air

OCCCM will explore other NETs with the potential to support advanced fossil energy plants with carbon-neutral and net-negative emissions. This is a strategic opportunity to leverage fossil energy R&D toward BECCS demonstration and deployment as well as other techniques that reduce GHG emissions.

R&D focus areas will include:

- DAC technologies
  - First-generation systems: New materials and alternative capture media with a focus on improved concentration of CO_2, process optimization, and novel components
  - Second-generation systems: New system concepts, with bench-scale testing of materials and components
  - Selection of a DAC pilot-scale test center
  - Transformative NETs with fossil energy applications
- Bio-based technologies such as BECCS; biomass co-firing with coal, CO_2 capture, and carbon-negative routes through the adoption of biomass gasification or combustion coupled with CCUS.

DOE is working with Carbon Engineering and other partners on Direct Air Capture technology.

Image: Carbon Engineering (graphical representation)

" While Direct Air Capture (DAC) is often described as a new technology, it bears many similarities to systems developed as part of our CCUS technology program. We're enthusiastic about leveraging our existing R&D to accelerate technology progress on DAC systems."

Steven Winberg
Assistant Secretary for Fossil Energy

Direction 2.4. Pursue new products and uses for captured carbon dioxide.

Situation Analysis

Globally, diverse processes are being investigated to utilize CO_2 for high-value products. For example, an emerging molten electrolysis process converts CO_2 directly into carbon fibers or nanotubes. CO_2 can also be combined with fly ash, produced from coal combustion or petroleum coke, to create nanoparticles that serve as additives to enhance the performance and efficiency of concrete, plastic, and coatings. Photosynthesis or microbial reactions can convert CO_2 into methanol or ethanol, which can then be used to make resins, pharmaceuticals, and other products.

Some of the challenges in using CO_2 for chemicals, fibers, and plastics include improving catalyst selectivity and the underlying science; scaling up hydrogen production; driving CO_2 reactions; and achieving advances in process and reaction engineering and design.[45]

When CO_2 is mineralized with alkaline reactants, it produces carbonates that can be used in cements, aggregates, construction fill, bicarbonates, and other inorganic chemicals. Carbonates used for materials of construction are a potential long-term storage option for CO_2 in the built environment. CO_2 can also be substituted for water in curing concrete with a similar mineralization effect, making the concrete stronger and reducing water use.[46] Cement manufacturing is a significant source of CO_2; these emissions can be captured and purified, then re-injected as a mineralizing bonding agent to be mixed with CO_2-based aggregates.[47]

Current challenges are that these processes require energy-intensive preparation of reactants to achieve feasible conversion or they require additives that must be regenerated and recycled, which requires energy. The result is an energy penalty for the power plant.[48] Other hurdles include higher cost for novel processes, general aversion to change in the building sector, and limited field trials and demonstrations to prove viability. To ensure safety, structural materials must also meet strict performance codes, which are difficult to update as innovations become available.

DOE recently selected 11 carbon utilization projects to receive close to $17 million in federal funding to develop and test technologies that can utilize CO_2 from power systems or other industrial sources as the primary feedstock.[49] The aim of these projects is to reduce carbon emissions and transform waste carbon streams into value-added products.

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45 The potential and limitations of using carbon dioxide. The Royal Society. May 2017. https://royalsociety.org/-/media/policy/projects/carbon-dioxide/policy-briefing-potential-and-limitations-of-using-carbon-dioxide.pdf

46 Blue Planet Materials from CO_2. 2020. www.blueplanet-ltd.com/ Solidia. Sustainable Cement and Concrete Production. 2020. www.solidiatech.com/

47 Low Emissions Intensity Lime and Cement. European Union Horizon 2020. www.project-leilac.eu/

48 IPCC Special Report on Carbon dioxide Capture and Storage, Chapter 7. Mineral carbonation and industrial uses of carbon dioxide. 2018. www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter7-1.pdf

49 DOE Invests $17 Million to Advance Carbon Utilization Projects, June 16, 2020. www.energy.gov/articles/doe-invests-17-million-advance-carbon-utilization-projects

Strategic Response for Products from Captured CO_2

A key aspect of reimagining coal is the development of new, high-value products that make use of captured CO_2 (Figure 4). The aim is to find new products that are cost-effective, capture and store CO_2 indefinitely, and provide a new revenue stream.

> **Strategies for Products from Captured CO_2**
>
> - Develop technologies to support markets for CO_2-derived carbon fibers by 2030.
> - Advance mineralization processes for cement and similar solids using CO_2.

OCCCM will invest in multiple research pathways to develop technologies for CO_2-based products. These pathways will yield carbon nanomaterials and fibers, cements and other inorganic materials (via mineralization reactions), and chemicals or fuels. R&D will include mineralization concepts, both *in* and *ex situ*, that utilize mine waste, tailings, and rocks (etc.) with an affinity for reacting with CO_2 and storing it as a solid mineral. For example, alkaline waste generated from mining of magnesium silicate rocks reacts spontaneously with CO_2 to precipitate solid carbon. Globally, mining waste has the capacity to sequester 100-200 metric tons of CO_2 annually.[50] Thermo-chemical, electrochemical, photochemical, and microbially mediated approaches will be applied to transform carbon into synthetic fuels, chemicals, plastics, and solid carbon products like carbon fibers.

Microalgal capture is one interesting approach. Algae are efficient photosynthetic organisms that can 'eat' CO_2, and the biomass produced in algal systems can be processed and converted to fuels; chemicals; food for fish, animals, and humans; soil supplements; and other specialty products.

With the large potential of CO_2-derived products, all pathways are in various stages of development globally. OCCCM will continue its current activities in this area, taking advantage of research advances and international collaboration where feasible.

R&D areas include the following:

- Mineralization of CO_2
  - Reduced costs for mineral carbonization through higher conversion or other improvements
  - Mapping of resources and potential markets for mineralized products
  - Innovative cement products using CO_2, including aggregates, building tiles, simulated stone facings, and other innovative applications[51]
  - Acceleration of natural processes for CO_2 mineralization
- Innovative products from captured carbon
  - Fiber board, nanofibers, or other fiber products
  - Fibers produced directly from CO_2 using electrolysis
  - Plastics and bioplastics

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[50] Gregory M. Dipple, Ian Power, Kate Carroll, and Bart De Baere. University of British Columbia, Canada. "Pathways to Accelerated Carbon Mineralization in Mine Tailings." CO_2 Summit III: Pathways to Carbon Capture, Utilization, and Storage Deployment. Calabria, Italy. May 2017. https://dc.engconfintl.org/co2_summit3/16/

[51] XPrize for Carbon Dioxide. https://carbon.xprize.org/prizes/carbon/products

- Creation of synthetic fuels and chemical monomers using CO_2 as a feedstock
  - Electrochemical or other pathways for synthetic or chemicals from CO_2
  - Microalgal capture for biofuel and bioproduct generation.

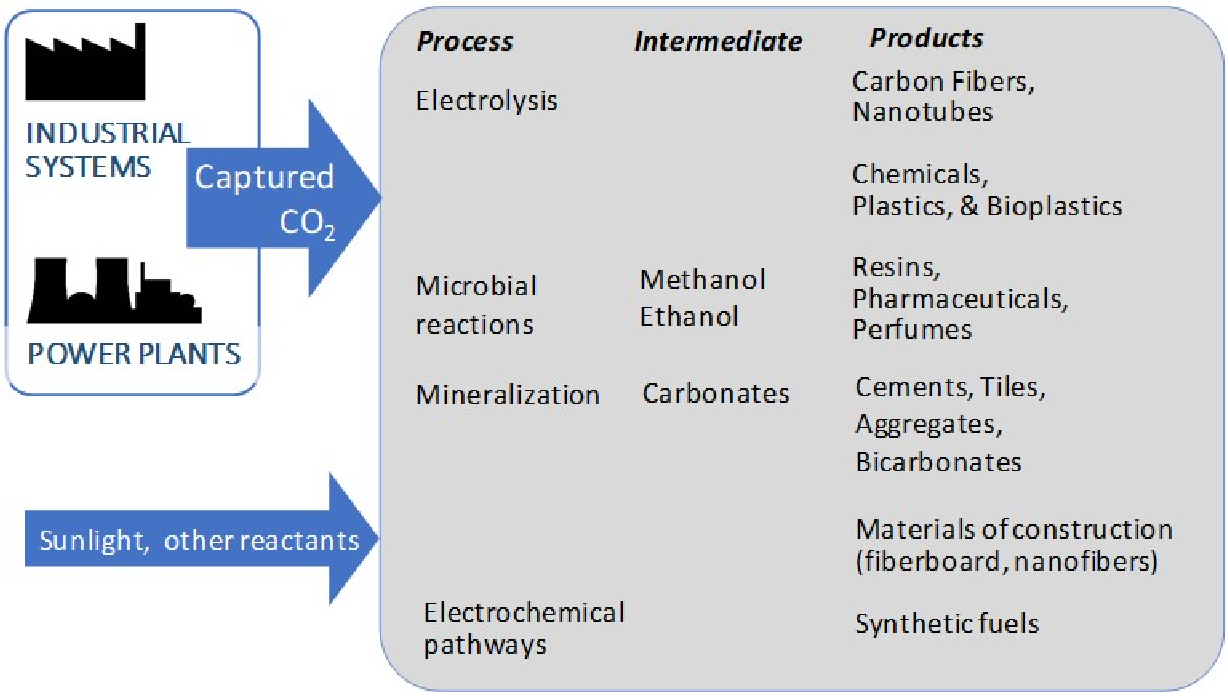

Figure 4. Products from Captured Carbon Dioxide

Area 3. Reimagining Coal

Create valuable new products from coal and its byproducts.

While 90% of U.S. coal is used for electricity production, electricity demand is stagnant and coal consumption is declining. Exploring new markets for coal-derived products can offset some of this decline. Coal gasification combined with CCUS, for example, can yield an excellent and economical feedstock for hydrogen. Coal byproducts have remarkable uses today, such as manufacturing chemicals and plastics. Some coal by-products are incorporated in aspirin, soap, dyes, and fabrics. Activated carbon from coal is used in the manufacture of water filters, air purifiers, and kidney dialysis machines.

Opportunities are emerging to reimagine coal in the form of new and valuable products. Coal and coal-based resources could yield a secure supply of rare earth elements (REEs) and critical minerals, which are essential to health care, electric vehicle motors, jet engines, lithium ion batteries, cell phones, hard drives, and defense technology. Coal can also serve as the feedstock for carbon-based materials such as carbon fibers, graphene, graphite, or nanomaterials.

Hydrogen from coal can be used to make products such as ammonia and fertilizer or produce gasoline and diesel fuel. Conversion of hydrogen into chemicals is another way of storing energy, which is important to a modern grid that uses an increasing share of intermittent renewable energy sources.

Many benefits accrue from utilizing coal to make valuable products beyond electricity. Creating new coal- and carbon-based products and markets will help to build a bright future for the coal industry.

OCCCM is fully committed to exploring new opportunities for valuable products from coal and coal resources. Strategic investments in targeted research will focus on the direct conversion of coal or coal-derived carbon and CO_2 to innovative products as well as on the economic production of chemicals from hydrogen.

National Coal Council – *Coal in a New Carbon Age*

The National Coal Council (NCC) recently released a report outlining the significant opportunities for coal beyond power generation, steelmaking, and other industrial uses. As a carbon source, coal can potentially fuel a new wave of innovative and advanced products and manufacturing. The report identifies markets for a multitude of coal-derived products, such as solid carbon products (carbon fiber, graphite, electrodes, graphene, carbon foam, etc.), REEs, biotech and medical products, agricultural uses, and others.

Based on NCC market analysis, the most significant opportunities are cost-effective, high-value specialty materials and products that could spur market growth. Coal could become a critical, low-cost carbon asset for many sectors, such as automobiles, defense, aerospace, electronics, construction, agriculture, and life sciences.

Source: NCC, *Coal in a New Carbon Age*, May 2019. www.nationalcoalcouncil.org/studies/2019/NCC-COAL-IN-A-NEW-CARBON-AGE.pdf

Direction 3.1. Explore new, high-value products and uses for coal and coal-based resources across the economy.

Situation Analysis

One of the major uses of coal today beyond electricity is steel (metallurgical or coking coal).[52] Other uses are found in alumina refining, paper manufacture, and chemicals. A surprising number of consumer products include components from coal or coal by-products.

As many as 200 minerals have been identified in coal and its byproducts, including REEs and other critical minerals,[53] which are potentially high-value products. REEs include metallic elements (lanthanides on the periodic table plus scandium and yttrium) essential to many high-tech devices such as cell phones, computers, and electric vehicles. Critical minerals comprise a broad spectrum, including lithium, cobalt, selenium, silicon, tellurium, titanium, platinum, and others. REEs are vital to national security and many defense applications, including guidance systems, lasers, electronic displays, and radar and sonar systems.

While a small amount of REEs are mined in the United States, processing and separation occur primarily in other countries,[54] with most supplies coming primarily from China, Australia, and elsewhere. This situation poses potential risks for the economy and national security. In 2019, President Trump issued a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals to ensure reliable supplies of REEs and other important materials.[55] DOE has been conducting research on extraction, separation, and recovery technologies for production of REEs and other critical minerals from coal and by-product streams (e.g., coal refuse, coal ash, coal sediments, etc.).

Coal pitch-based carbon fibers have been around since the 1960s and are used commercially for aerospace and space projects in which stiffness is a critical material property. Commercial coal-based fibers come from metallurgical coking coal, which has fewer impurities. Research is ongoing to produce carbon fiber from less costly non-coking coal. Under a DOE grant, the Western Research Institute, Ramaco Carbon LLC mining company, and a group from the composites industry are developing low-cost carbon fiber using various feedstocks and precursors, including non-coking Wyoming coal.[56] A DOE project at the University of Kentucky Center for Applied Energy Research (CAER) is focusing on transforming coal tar into carbon fiber for use in aircraft, automobiles, and other applications.[57]

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[52] How is Steel Produced? World Coal Association. 2020. www.worldcoal.org/coal/uses-coal/how-steel-produced

[53] Robert B.Finkelman, Shifeng Dai, and David French. "The importance of minerals in coal as the hosts of chemical elements: A review" Intl. Journal of Coal Geology. Vol. 212, August 2019. www.sciencedirect.com/science/article/pii/S0166516219306251

[54] U.S. Geological Survey, *Mineral Commodity Summaries, 2020*. https://urldefense.com/v2/url?u=https-3A__pubs.er.usgs.gov_publication_mcs2020&d=DwIFAg&c=qtSr2lo3xh19jSoNXq96-b_j2zKvnyYOjwVJNv4R9Is&r=3fXXq9KQ07-5Abj8wAd6r4KagWD9B4PhKYJZeIPdhh8&m=-GpZTYscSstEI3ucEzxqnISsRinZd3lSJRA6LA0-klc&s=toUC0o-7rDKIBpSkuuOMHWL9kaYI8QIoNtZz9ykj4OQ&e=

[55] A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals. 2019. www.commerce.gov/news/reports/2019/06/federal-strategy-ensure-secure-and-reliable-supplies-critical-minerals and Executive Order 13817 www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals

[56] Research of developing coal, oil into low-cost carbon fiber advances. April 2, 2019. *Composites World*. www.compositesworld.com/news/research-of-developing-coal-oil-into-low-cost-carbon-fiber-advances

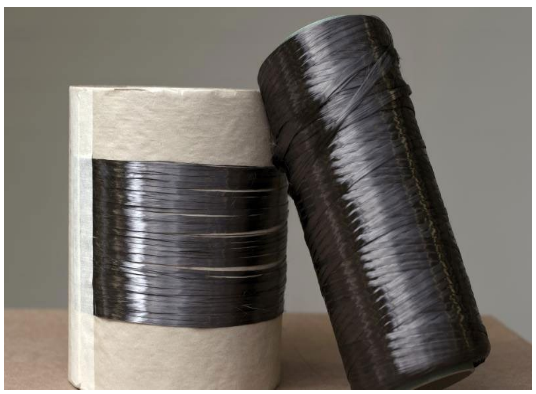
[57] New CAER Grant Seeks to Turn Coal into Carbon Fiber. University of Kentucky. December 19, 2019. https://uknow.uky.edu/research/new-caer-grant-seeks-turn-coal-carbon-fiber

Strategic Response for High-Value Coal Uses

OCCCM is committed to investing in research to develop strategic and innovative uses for coal beyond electricity generation. Technologies are being explored to facilitate conversion of coal (or coal combined with biomass and/or MSW) to materials, chemicals, and fuels. Research is focused on creating high-value products such as structural materials, carbon fiber, and carbon nanomaterials; extracting REEs and other critical minerals; and incorporating valuable coal product streams into existing or future coal plant configurations (Figure 5).

Strategies for High-Value Coal Uses

- Stand up commercial facilities that can produce 1-3 metric tons/day of REE/critical minerals from coal waste products.
- Develop technologies to support markets for coal-derived solid carbon products by 2030.



Carbon fibers (shown on spools) are lighter and stronger in comparison to traditional metals.

Source: ORNL

There are numerous advantages to using coal in carbon-based products or building materials. Carbon fiber, for example, is half the weight of aluminum but has four times the strength. In comparison to steel, carbon fiber is one-fourth the weight but twice as strong. Today's carbon fibers used to make products lighter in weight are made mostly from petroleum products—and could potentially be made less expensively from coal. In building materials, carbon fiber rebar, for example, can provide flexibility to concrete structures, is lighter than iron, and does not rust.[58] Carbon foams, another significant product pathway, have been produced in batch processes from coal or pitch for use in structural products. OCCCM is investing in new research to develop continuous processes for making building materials and infrastructure components that incorporate carbon foam from coal-derived feedstocks.[59] Office research will also evaluate prototype carbon building designs, materials, and applications.

"A mature coal-to-products manufacturing industry could employ hundreds of thousands of people and create over 100 billion dollars in valuable products from coal. Our coal-to-products R&D portfolio is critical to offering coal communities an alternative market for coal."

Steven Winberg
Assistant Secretary for Fossil Energy

OCCCM research on emissions reduction and control technologies includes recovery of valuable combustion byproducts, such as

[58] Coal to Products: A Carbon Valley for Coal. Ramaco Carbon. 2018. www.nationalcoalcouncil.org/NCC-Events/2018/Atkins-NCC-Spring-2018.pdf

[59] U.S. Department of Energy Announces Up to $14M for Advanced Coal Processing Technologies. April 13, 2020. www.energy.gov/fe/articles/us-department-energy-announces-14m-advanced-coal-processing-technologies

coal combustion residuals (CCRs), which include boiler bottom ash and fly ash. CCR can be used as structural fill, for layering unpaved roads, to strengthen concrete, and as a soil additive, among other beneficial uses.

Research on REEs and other critical minerals is specifically designed to develop a viable domestic supply of these materials. Research success will achieve multiple objectives, including high-value uses for coal, reliable supplies for U.S. industry, and increased national security. A variety of thermochemical, electrochemical, photochemical, and microbially mediated approaches will be applied for materials production with an emphasis on minimal environmental impacts.

R&D directions include:

- REEs and critical minerals from coal
  - Geologic and chemical characterization of REEs and critical minerals found in materials associated with domestic sources of coal, coal by-products, and other streams
  - Design, development, and testing of more novel and environmentally benign separation and processing technologies for REEs and critical minerals, including purification and extractive metallurgy
  - Novel extraction technologies that minimize the environmental footprint
  - Sustainable technologies for future coal use and for the extraction of REEs and critical minerals from legacy ash ponds, acid mine drainage, and other residual streams
- Materials from coal, coal pitch, CCR, and other coal-based resources
  - Coal-based building materials (e.g., graphitic or non-graphitic carbon foams, roofing tiles, siding, decking, insulation, joists/studs, sheathing, tiles and carpet, architectural blocks)
  - Infrastructure components (e.g., structural components for mass transit, sewers/tunnels, wastewater management or solid-waste treatment, and materials for roads and bridges)
  - High-value, coal-derived, solid carbon products/materials, such as carbon fibers and nanomaterials (e.g., graphene, quantum dots, conductive inks, 3D printing materials, energy storage/battery anodes, carbon composites, and supercapacitor materials)

Recovery of Rare Earth Elements (REE) from Acid Mine Drainage

Acid mine drainage (AMD) has occurred in coal mining regions of Appalachia since the early 18th century. In 2017, West Virginia University's Water Research Institute initiated work with an industry partner to identify and quantify potential sources of REEs in existing Appalachian AMD. Geotextile tubes modified to provide specific containment, dewatering, and capture properties proved cost-effective at recovering more than 90% of available REEs—showing the potential to deliver tremendous economic and environmental benefits to the Appalachian region.

TenCate Geotube® technology for the recovery of REEs from AMD.

Photo: T. Stephens, TenCate Geosynthetics Americas https://geosyntheticsmagazine.com/2019/10/01/recovery-of-rare-earth-elements-from-acid-mine-drainage-using-geotextile-tubes/

- Recovery of valuable products from CCRs and legacy ash facilities to increase beneficial utilization of CCR and improve management of legacy CCR impoundments

- Foundational products research
  - Foundational research on materials discovery and component/composite development
  - Synthetic biology applications, such as microbial conversion of coal to biogenic methane[60]
  - Analytical tools for market assessment of non-power products from coal and carbon
  - Use of AI and other advanced computational techniques to advance products research.

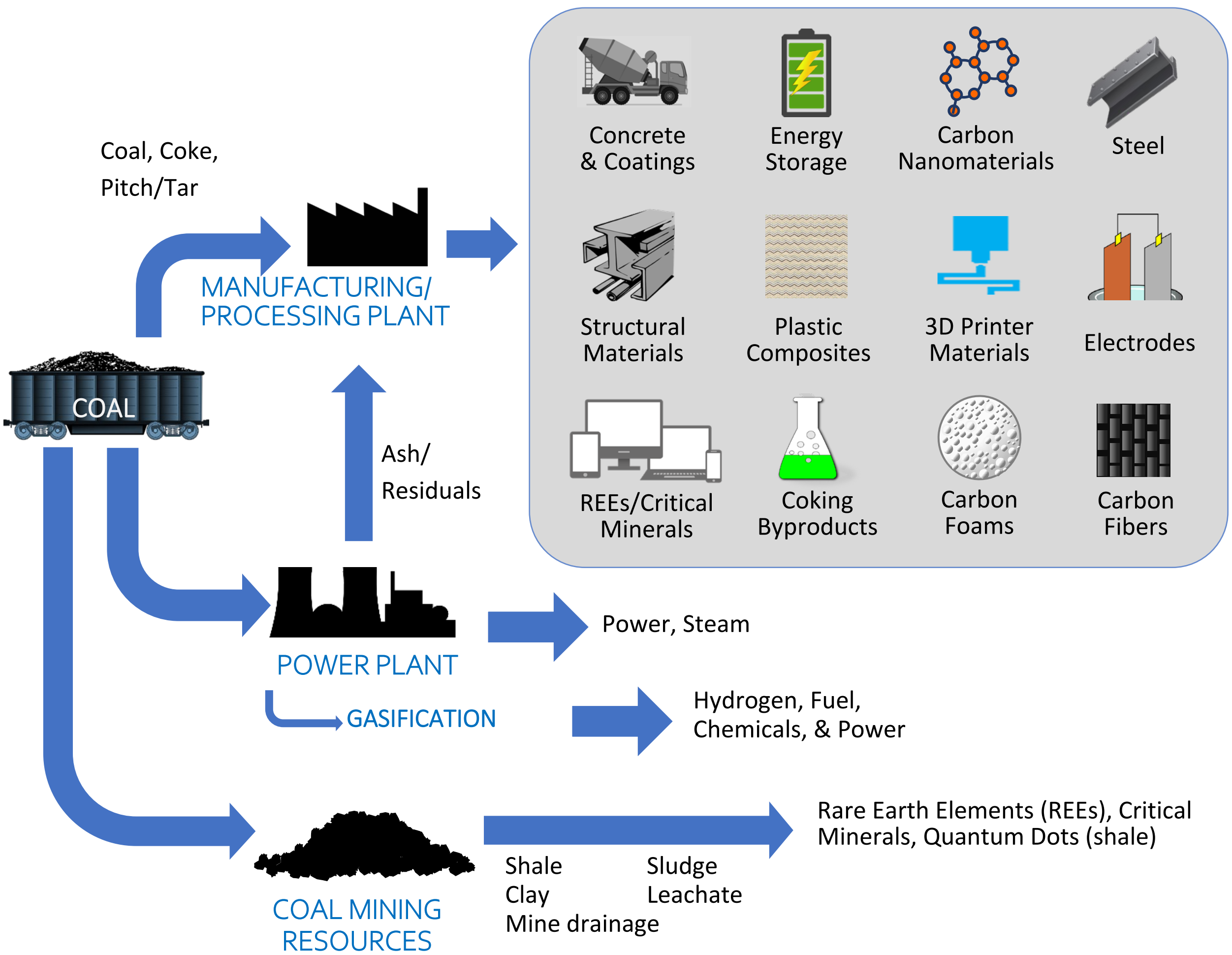


Figure 5. Products from Coal, Coal Resources, Ash, and Byproducts

[Note: Products from captured carbon dioxide are shown in Figure 4.]

[60] Distribution of the methanotrophic bacteria in the Western part of the Upper Silesian Coal Basin (Borynia-Zofiówka and Budryk coal mines). International Journal of Coal Geology. Volume 130, 15 August 2014, Pages 70-78. www.sciencedirect.com/science/article/abs/pii/S0166516214001013

Direction 3.2 Accelerate pathways to valuable products via coal-produced hydrogen.

Situation Analysis

Coal gasification has been used to produce chemicals since the 1950s, and the process currently holds a modest share of the global chemicals market. According to the Gasification and Syngas Technologies Council, a significant number of planned/future gasification capacity will include chemicals production.[61]

The largest dedicated use of hydrogen today is to desulfurize or crack petroleum fractions, and much of this hydrogen is produced onsite at petroleum refineries. The next largest use of hydrogen is ammonia production for use in ammonium nitrate fertilizer and many household cleaning products. Other uses of hydrogen include hydrogenation, which can be used to turn unsaturated fats into saturated oils and fats (e.g., hydrogenated vegetable oils, such as margarine and butter). Hydrogen is also used as a reducing agent and in many chemical reactions.

Syngas produced from IGCC with CCUS provides not just power and hydrogen fuels but enables production of higher-value chemical products with a lower carbon footprint than traditional processes and without petroleum feedstocks (Figure 3). As described earlier, hydrogen in coal-derived syngas can be converted into transport fuels as well as valuable chemical products, such as methanol and ammonia. Carbon monoxide from gasification can also be converted to hydrogen via the water-gas shift reaction, and to acetic acid and other chemicals (Figure 6).[62]

Conversion of hydrogen into chemicals offers a valuable and flexible solution for storing energy. Ammonia, for example, can be stored and later used to produce electricity in a fuel cell or further reacted to separate the hydrogen, which can then be used in a hydrogen fuel cell. Captured CO_2 can be combined with hydrogen to produce methanol through a series of process steps, and the methanol can be stored and used as a fuel, as a chemical reagent, or in a fuel cell to produce electricity.

Challenges to producing chemicals from coal are the same as those for gasification, including cost (capital and operating/maintenance) and availability. Effective integration of chemical processes into power plant configurations presents another challenge. Specific processes for the production of chemicals require purified hydrogen and/or CO_2, which can be costly. Electrolysis may also have conversion efficiency limits, which need to be addressed for the process to become technically and economically viable.

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61 Overview of Gasification. NETL www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/chemicals

62 Types of Coal-Derived Chemicals. National Energy Technology Laboratory. Accessed 4/21/2020. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/coal-derived-chem

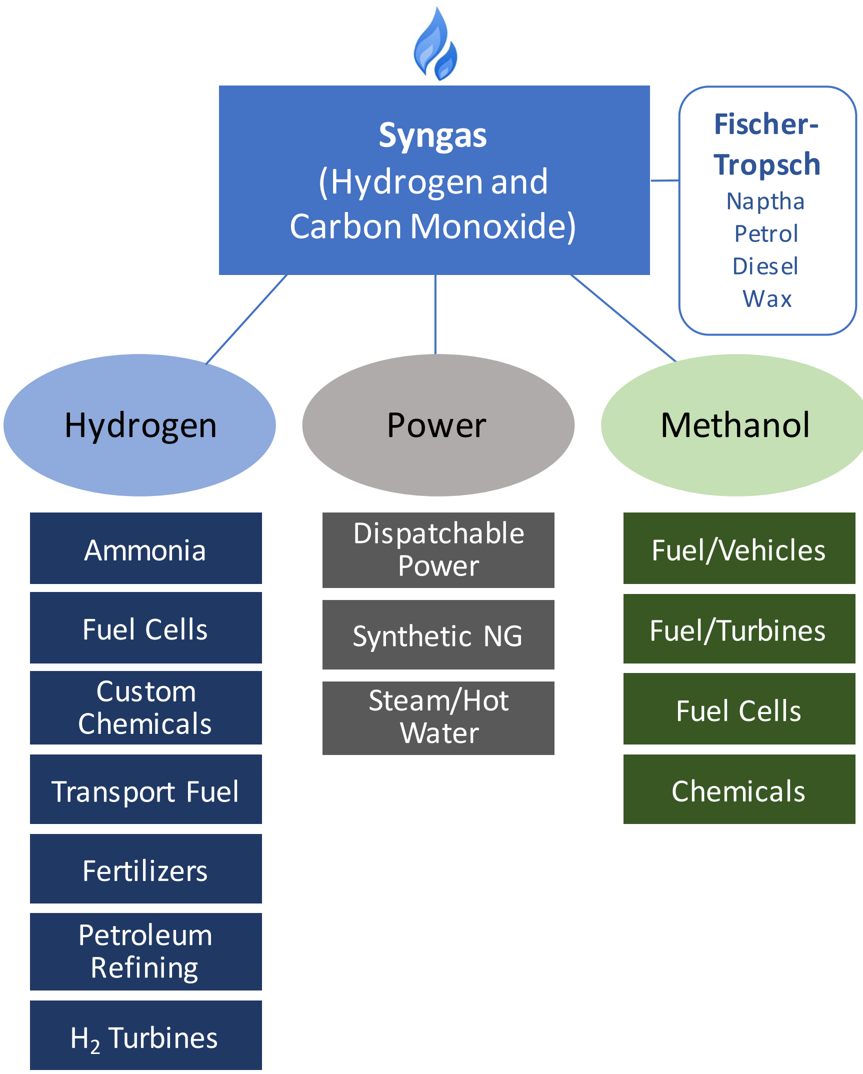


Figure 6. Products/Uses of Coal-Produced Syngas

Strategic Response for Hydrogen Products and Flexible Storage Concepts

OCCCM is pursuing the use of coal-derived syngas to convert hydrogen, carbon monoxide, and other carbon streams into valuable products that can be directly utilized or stored/transported for multiple uses. Conversion of hydrogen to chemicals mitigates the need to store hydrogen and creates valuable product streams that can be used to generate electricity in fuel cells or be stored/shipped to external markets.

Strategies for Hydrogen Products and Flexible Storage

- Establish coal-produced hydrogen as an economic and available feedstock stream for chemicals.
- Develop and validate flexible hydrogen energy storage concepts.

R&D topic areas include:

- Ammonia from hydrogen
  - Poly-generation pathways for production from coal-produced hydrogen
  - Development of auxiliary processes for onsite use, such as ammonia fuel cells or cracking ammonia and passing the resulting hydrogen across a hydrogen fuel cell
  - Innovative ammonia production processes (e.g., electrolysis); utilization of waste heat
  - Ammonia as an energy storage option
- Methanol from hydrogen
  - Methanol from the combination of hydrogen and captured, purified CO_2
  - Development of auxiliary processes for onsite use, such as higher efficiency, less complex methanol fuel cells
- Improvements in hydrogen preparation and processing
  - Hydrogen purification
  - Efficient mechanisms for delivering hydrogen-produced chemicals to end users and optimization of supply chains.

"We're leveraging our investment, lessons learned, and expertise in CCUS technology to jump start a low-cost and carbon-free hydrogen economy."

Steven Winberg
Assistant Secretary for Fossil Energy

Area 4. Creating Opportunities with Analysis and Engagement

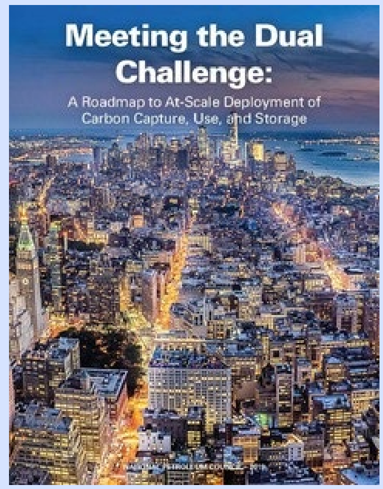
Generate opportunities for advanced coal and carbon management technologies using expert analysis and strategic engagement.

Beyond research, OCCCM seeks to accelerate technology development by conducting analysis, outreach, and international engagement activities that create opportunities for strategic collaboration and information exchange. OCCCM applies its extensive expertise in coal technologies and carbon management to provide thought leadership, lead and implement change, and deliver technical assistance to government and private-sector partners.

Organizations around the world have tapped into OCCCM's considerable expertise in clean coal and carbon management. Technologies under development by OCCCM can often be applied beyond the coal industry, such as CCUS strategies that apply to most large emitters of CO_2. OCCCM's analytical work supports fact-based, science-based policy decisions on technologies that are needed for the future. Many organizations turn to OCCCM for factually correct analysis and rely on Office participation in key international dialogs to communicate an accurate picture of U.S. energy technology development in context.

The OCCCM R&D portfolio requires robust analytical capabilities as well as accurate and timely data to guide the research, support industry partners in addressing financial risks, and inform regulatory and policy decisions. Strategic engagement on both domestic and international fronts is a key means for OCCCM to stay abreast of and contribute to progress in clean coal and related technologies worldwide—and to identify critical opportunities for collaboration and information exchange.

National Petroleum Council (NPC) Report



Meeting the Dual Challenge:
A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage

About 80% of the world's CO_2 capture capacity is deployed in the United States, uniquely positioning the Nation as a world leader in CCUS capability. In December 2019, the NPC delivered a report on the actions needed to deploy CCUS at scale nationwide. This NPC roadmap lays out three phases of deployment—activation, expansion, and at-scale—to support the growth of CCUS over the next 25 years.

Source: NPC

Direction 4.1. Inform and educate stakeholders based on strategic analysis.

Situation Analysis

The successful deployment of CCUS and transformational clean coal technologies is affected by many factors beyond research, including costs, energy markets, regulations, and the overall energy and environmental policy landscape. Analysis of global trends and emerging data provides a critical foundation for understanding the economics and markets and for informing and responding to new policies and regulations.

Analysis is needed to demonstrate how more flexible clean coal plants and carbon management strategies can best complement and integrate with the 21st century grid. With a modernized electricity grid, new paradigms will emerge for the smooth integration of both future and legacy power plants. The modern grid will be characterized by the integration of more intermittent and distributed resources, different load balancing models, energy storage, and carbon capture or use systems.

Navigating global and domestic policies and regulations for fossil energy can be a challenge for advancing new clean coal and carbon management technologies. Technologies may be close to entering the market, but policies and regulations may represent barriers—or provide incentives. For example, while there are many potential benefits to U.S. exports, quantifying global incentives and benefits is difficult. Policy actions like Executive Order 13783[63] provide opportunities, but additional guidance is needed to facilitate implementation.

Understanding potential markets and the benefits of advanced technology is vital to supporting research and development decisions. Purposeful, targeted analysis is needed to support OCCCM technology deployment by answering questions about risk and techno-economics, including return on investments, long-term benefits, and commercial acceptance. The challenges include access to accurate and up-to-date field data; estimating economics of earlier-stage technology; and projecting benefits in markets impacted by long-term uncertainties.

[63] Executive Order 13783. Presidential Executive Order Promoting Energy Independence and Economic Growth. March 28, 2017. www.whitehouse.gov/presidential-actions/presidential-executive-order-promoting-energy-independence-economic-growth/

Strategic Response for Analysis

> **Strategies for Analysis**
>
> - Conduct analysis to provide feedback on benefits and direction of R&D.
>   - Determine impacts of R&D to economy, plant efficiency, carbon, CCUS efficiency, etc.
> - Perform policy and regulatory analysis.
>   - Support for EPA, IRS, and other federal regulatory processes with technical due diligence
>   - Analysis to inform domestic and global policy discussions and support proposed/ new regulation or laws
> - Increase public awareness of analysis results to better inform and educate global partners.
> - Lead process to develop and update OCCCM strategic planning documents.

The OCCCM program leads U.S. expert analysis and strategic engagement to inform clean energy policy development and guide RD&D on reliable energy systems based on coal and other fossil resources. This R&D guidance extends to emissions control technologies and product development to achieve carbon-neutral use of fossil energy.

OCCCM will continue to invest and expand analysis activities that are vital to effective R&D portfolio management and its external stakeholders. Data collection and analysis support all OCCCM strategic areas and directions, as well as the strategic planning process. OCCCM activities will provide insights on techno-economics and benefits to the Nation, including job creation and competitive advantage. Analysis will inform responses to high-priority regulatory reform and incentives, such as Executive Order 13783 and 45Q,[64,65] by providing accurate technical information and data synthesis. All of these analytical elements enable effective management and promote awareness of important OCCCM programs and initiatives.

OCCCM's strategy is to build and maintain the capability for rapid, world-class analysis to answer questions that require fast response, as well as those that require long-term, complex study. This effort includes building internal and external relationships with key analytical groups at the national laboratories and other organizations. Further, OCCCM works to maintain its position as a premier source of analysis and data to ensure an accurate, fair depiction of the technology portfolio and inform optimal allocation of resources within the Office.

To accomplish its vision, OCCCM is focused on several important topic areas, including:

Regulation and Policy

- Assessment of various policy instruments and relevant priorities for R&D
- Monitoring of emerging domestic and international policies and regulations

[64] IRS issues guidance on carbon capture tax credit. The Hill. February 19, 2020. https://thehill.com/policy/energy-environment/483735-irs-issues-guidances-on-carbon-capture-tax-credit

[65] The Tax Credit for Carbon Sequestration (Section 45Q). Congressional Research Service. March 12, 2020. https://crsreports.congress.gov/product/pdf/IF/IF11455

Markets and Benefits

- Research, analysis, and modeling to support the OCCCM vision, including jobs and economic benefits
  - Baseline and future carbon-constrained scenarios
  - Market-based analysis to support transformative energy systems
- Techno-economic analysis to assess economic benefits and opportunities for exports
- Market evaluation of advanced or innovative products from coal and CO_2
- Life-cycle analysis of OCCCM technologies, including carbon dioxide utilization.

Energy Modeling Forum (EMF) Working Group on 45Q Carbon Credits

Congress passed the Bipartisan Budget Act of 2018 and reformed tax code § 45Q to provide credits of up to $35 per ton for CO_2 captured and utilized in qualifying applications (e.g., EOR) and up to $50 per ton for CO_2 captured and permanently stored in a geologic repository.

An EMF group was formed to study how 45Q would affect business models for CCUS and energy system decisions. A range of issues were analyzed, including impacts on CCUS deployment, the types of capture technology and markets, and potential impacts. Five modeling teams participated:

- The Global Change Assessment Model (GCAM) from the Pacific Northwest National Laboratory
- The National Energy Modeling System modified by OnLocation (CTUS-NEMS),
- The MARKet ALlocation (MARKAL) Model available from the IEA
- The U.S. Regional Economy, GHG, and Energy (US-REGEN) Model from EPRI
- EPA's Application of the Integrated Planning Model (IPM).

The EMF, established at Stanford University in 1976, brings together leading experts from government, industry, and academia to improve the use of energy and environmental policy models to support sound decision making.

Direction 4.2. Engage with the international community to elevate awareness and accelerate global technology progress.

Situation Analysis

The international community is a key partner and collaborator in helping to accelerate progress on clean coal and carbon management worldwide.

OCCCM works directly with the International Energy Agency, leads CCUS work under the Clean Energy Ministerial, and conducts minister-facing dialogs to advance awareness, understanding, and support of CCUS. Activities for the Carbon Sequestration Leadership Forum (CSLF) include leading technical and policy efforts and serving as the Secretariat for this multilateral initiative that provides a platform for countries to coordinate research on better and more cost-effective technologies for carbon capture and storage.[66] OCCCM also leads and participates in multi-lateral organizations working on carbon management and clean coal. For example, the Office serves on executive committees of the IEA's Greenhouse Gas Programme and Clean Coal Centre; leads relevant groups under the Asia Pacific Economic Cooperation (APEC) forum; and participates in developing standards for carbon capture and storage with the International Standards Organization (ISO). The Office leads DOE research under the Accelerating Carbon Capture and Storage Technologies (ACT) Initiative, through which a consortium of countries (Canada, Denmark, France, Germany, Greece, India, Italy, the Netherlands, Norway, Romania, Spain, Switzerland, Turkey, the United Kingdom, and the United States) collaborate on RD&D projects to accelerate and mature CCUS technologies worldwide.

In addition, OCCCM engages with international stakeholders, governments, and research organizations through bilateral agreements. OCCCM collaborates bilaterally with numerous countries (e.g., Japan, India, Norway, China, and the United Kingdom), some under formal ministry-level or lab-to-lab agreements, others without formal agreements. The Office also has a trilateral cooperation agreement with Canada and Mexico. These international collaborations are designed to ensure coordination, avoid duplication of effort, enhance information accessibility, and address intellectual property issues.

[66] The Carbon Sequestration Leadership Forum brings together 26 member governments representing over 3.5 billion people and comprising over 80% total global anthropogenic CO_2 emissions. www.cslforum.org/cslf/

Strategic Response for International Engagement

International outreach and engagement with key partner organizations is critical to achieving OCCCM's mission and strategic vision. These connections provide key insights on global R&D and technology innovations; deepen understanding of the unique challenges facing clean coal and carbon management in diverse countries; and create opportunities to increase awareness of the major advances emerging from OCCCM R&D programs.

OCCCM's international engagement program aims to monitor, evaluate, and advise international efforts; serve as liaison in global conversations for related R&D; and support, inform, and collaborate with the DOE Office of International Affairs and the OCCCM R&D programs. These efforts enhance overall functionality and coordination across FE and with the rest of DOE.

OCCCM will continue activities to support multi-lateral and bilateral efforts through technical and policy/ministerial level engagements across the globe, leveraging policy collaboration and regulatory discussions to educate and inform decision makers as appropriate. In addition, OCCCM monitors and evaluates worldwide demand and markets for coal and carbon management technologies. Market demand information is essential to help OCCCM programs identify new areas for research and invest wisely in technology RD&D. Understanding global market demand for coal and coal products is critical as the industry is undergoing major changes worldwide. Markets for raw commodity exports, technology exports, and foreign investments in U.S. technology will all impact the future coal industry.

Strategies for International Engagement

- Proactively identify, track, and evaluate global markets and RD&D for fossil energy and carbon management technology to speed development and deployment.
- Leverage international collaboration to advance technology development (better, faster, cheaper) through targeted multi-lateral and bilateral cooperative activities.
- Ensure advanced, affordable coal energy systems and products are part of the global technology and policy dialog.

Clean Energy Ministerial (CEM) CCUS Initiative

This CEM initiative strengthens public-private collaboration on CCUS and adds value to related efforts such as the Carbon Sequestration Leadership Forum (CSLF), IEA Greenhouse Gas R&D Programme (IEA GHG), Mission Innovation, and Global CCS Institute (GCCSI).

CEM hopes to accelerate CCUS as a viable option for mitigation of CO_2 and foster information exchange on key technologies, regulations, and policies while building strategic partnerships for CCUS and advancing global deployment.

The initiative utilizes CEM ministerial events and outreach tools to reach a wider audience that includes both country ministers and high-level policymakers.

www.cleanenergyministerial.org/initiative-clean-energy-ministerial/carbon-captureutilization-and-storage-ccus-initiative

OCCCM's International group plays a lead role in engaging on global issues related to coal and in successfully building relationships to leverage the effectiveness of the Office. OCCCM can serve as a broker between domestic and international fossil research activities and relevant policies by staying abreast of the major issues and markets, R&D portfolios, and policy conversations.

The United States develops technologies that the rest of the world needs—and does it better, faster, and cheaper when supported by international collaboration, policies, and regulations. OCCCM engages with influential global entities and organizations to ensure that dialogs and events consider U.S. interests. Activities that enhance international engagement include the following:

Global markets and RD&D opportunities

- Assess worldwide markets of importance to coal technology and CCUS
- Track international engagement in coal and CCUS technology development, policies, and regulations; elevate awareness of international analyses and resources

Other Key Multilateral Activities

The International Energy Agency. OCCCM coordinates with the CCUS unit and participates in dialogs related to technology analysis and roadmapping.

The Carbon Sequestration Leadership Forum: This multilateral initiative provides a platform for countries to coordinate research activities that will lead to better and more cost-effective technologies for carbon capture and storage.

Asia Pacific Economic Cooperation: APEC's Energy Working Group seeks to maximize energy contributions to economic and social well-being while mitigating the environmental effects of energy supply and use.

Leveraging international collaboration

- Identify, participate in, and leverage multilateral and bilateral agreements to optimize collaboration on technology and policy development
- Monitor/assess international policy developments on climate change
- Participate in dialogs to advance awareness and understanding of CCUS, including the Clean Energy Ministerial (CEM), IEA GHG, and IEA Clean Coal Centre, and support higher-level activities such as the G20[67]

Technical information dissemination

- Distribute reports and information on fossil energy technologies and their value (articles, fact sheets, infographics)
- Broaden outreach and elevate awareness of U.S. fossil energy systems and products
- Support the technology transfer of U.S.-developed concepts to coal-focused countries to foster export markets.

[67] The G20 (Group of Twenty), an international forum for governments and central bank governors including 19 countries and the European Union.

Direction 4.3. Build strategic partnerships with domestic government and industry.

Situation Analysis

Over the last decade, OCCCM has worked closely with other federal and state/local organizations to coordinate work on advanced coal technologies and CCUS. These partnerships include such organizations as the Carbon Utilization Research Council (CURC), Energy Council, National Association of State Energy Officials (NASEO), National Association of Regulatory Utility Commissioners (NARUC), National Conference of State Legislatures (NCSL), the National Governors Association (NGA), National Rural Electric Cooperative Association (NRECA), the Regional Carbon Capture Deployment Initiative, Southern States Energy Board (SSEB), United States Energy Association (USEA), Western Governors' Association (WGA), and many more. Activities include reviewing and providing technical input for studies and other reports as well as participation in national conferences, committees, forums, and annual meetings to discuss emerging issues and challenges facing the coal industry. OCCCM also convenes an interagency working group on CCUS that holds meetings quarterly. The Office engages with industry stakeholders to understand R&D needs, the commercial readiness and viability of advanced coal systems, and progress on demonstration projects.

Strategic Response for Building Partnerships

Strategic engagement ensures that R&D opportunities and supporting analysis emerging from OCCCM are communicated to a broad range of stakeholders, including Congress, the private sector, other federal agencies, state and local governments, and nongovernmental organizations.

Strategies for Building Partnerships

- Expand cross-agency collaboration and information exchange via stronger partnerships.
- Participate in DOE initiatives and programs, such as GMI and the DOE-wide AITO.
- Build partnerships with industry and academia, informing efforts through technical expertise and strategic collaboration.

OCCCM has the analytical capabilities and technical knowledge to help shape coal-related policy decisions across the federal government, including tax policies, regulations, permitting, and other programs that impact coal production, use, and technology deployment. OCCCM will continue interagency collaboration to enhance federal coordination on CCUS. This activity helps to ensure communication and awareness among government agencies and stakeholders on issues such as federal funding opportunities, tax incentives, project milestones, regulatory development, and permitting. As discussed in the next section (Cross-Cutting Activities), OCCCM also participates in several initiatives and cross-cutting teams within DOE, such as the Grid Modernization Initiative (GMI) and the Artificial Intelligence Intra-Agency Cross-Cutting Team for the Subsurface.

Industry engagement enables OCCCM to better understand industry views on regulatory and policy incentives and barriers. The adoption of new regulations, for example, may impact market dynamics and RD&D program strategies. OCCCM conducts and participates in many technical workshops, forums, and other events to gain the perspective of industry stakeholders on key issues and challenges.

Focus activities to enhance strategic partnerships with government and industry include:

- Pursue targeted strategic engagement with state and other federal partners, including cross-cutting teams within DOE (see Cross-Cutting Activities section), to coordinate and leverage capabilities and resources and to collaborate on technology development and deployment, for example:
  - Proactively engage with government organizations through bilateral partnerships with states and regions
  - Work with other federal agencies on important initiatives to the Nation (e.g., critical minerals, REEs, water resources, and CCUS)
- Form or maintain strategic relationships with domestic government and industry on development of new products and materials from coal and coal resources
- Hold workshops, forums, and conferences to proactively obtain industry perspectives on technology and other emerging topics.

Critical Cross-Cutting Activities

OCCCM's investments in cross-cutting technologies and activities provide important foundational support across the carbon management and coal R&D programs. OCCCM participates in the six R&D Cross-Cut Teams established across DOE to address high-priority research areas. These teams work at the cutting edge of technology and help to integrate new discoveries and advances into diverse R&D programs:

- **Advanced Materials Manufacturing:** OCCCM participates in coordinated R&D for advanced materials in multiple applications, including materials under extreme environments and critical materials. Activities include exploring the use of HPC for materials design and discovery and materials for the harsh environments of power systems. The Extreme Environment Materials (EEM) and Harsh Environment Materials Initiatives, which are funded as part of advanced coal systems research (Area 1), address new, durable materials for use in aggressive service environments.

- **Energy-Water Nexus**: Through projects that address sustainable coal plant water use, treatment and recovery, and conservation, OCCCM helps support the Nation's transition to more resilient energy-water systems.[68] OCCCM R&D activities seek to reduce freshwater usage and improve water efficiency in thermoelectric plants. The Office also participates in the DOE-wide Water Security Grand Challenge, focusing on treatments of produced water from power plants.

- **Exascale Computing**: OCCCM supports various computational activities relevant to the joint Office of Science-National Nuclear Security Administration collaboration, which aims to significantly accelerate the development and deployment of next-generation, high-performance computing systems. For example, OCCCM is supporting research on MFiX, an advanced multiphase computational fluid dynamics code, to run on exascale computing systems. The MFiX code can help solve problems in coal gasification, carbon capture, chemical looping, and many other areas. MFiX-Exa will leverage future exascale machines to optimize and scale up chemical looping reactors (CLRs), a technology that could greatly reduce the costs associated with CO_2 capture.[69],[70]

- **Grid Modernization:** For this DOE-wide activity, OCCCM contributes toward modernization of the future grid through projects such as CoalFIRST. OCCCM also works within DOE on the GMI, which focuses on implementing a modern grid with greater resilience, improved reliability, enhanced physical and cyber security, affordability, and superior flexibility.

- **Subsurface Science Technology, Engineering, and Research**: OCCCM supports several projects that characterize the subsurface for carbon management applications and contribute foundational science and engineering advances in this cross-cutting area.[71] A key activity is the AI Intra-Agency

68 www.energy.gov/energy-water-nexus-crosscut

69 Optimizing a New Technology to Reduce Power Plant Carbon Dioxide Emissions. 01/18/19. Exascale Computing Project. www.exascaleproject.org/optimizing-a-new-technology-to-reduce-power-plant-carbon-dioxide-emissions/

70 NETL, MFiX-Exa. https://mfix.netl.doe.gov/mfix-exa-optimizing-a-new-technology-to-reduce-power-plant-carbon-dioxide-emissions/

71 www.energy.gov/subsurface-science-technology-engineering-and-rd-crosscut-subter

Coordinating Team (IACT) for the Subsurface, which examines the use of artificial intelligence on subsurface data.

- **Supercritical Carbon Dioxide (sCO_2) Technology:** OCCCM is supporting a 10-MW pilot facility to integrate this compact, highly efficient technology into fossil energy power configurations. Beyond offering higher efficiency than conventional steam turbine Rankine cycles, sCO_2 technology using the Brayton cycle can ramp up and down rapidly to enable smooth integration with modern grid systems that incorporate a growing share of intermittent renewable power. Industry partners are on board to expedite technology progress toward commercialization.

In addition to the DOE-wide activities noted, OCCCM supports cross-cutting research in advanced manufacturing technologies and advanced computing and analytics.

The Grid Modernization Initiative (GMI)

The DOE-wide Grid Modernization Initiative is a cross-cutting effort to help create and enable the modern grid of the future. In 2019, FE announced approximately $8 million in federal funding for three projects through DOE's 2019 Grid Modernization Lab Call. The projects aim to strengthen, transform, and improve the resilience of energy infrastructure to ensure the Nation's access to reliable and secure electric power now and in the future.

The GMI focuses on new architectural concepts, tools, and technologies to measure, analyze, predict, protect, and control the modern grid, as well as on the infrastructure to enable rapid development and widespread adoption of tools and technologies.

www.energy.gov/grid-modernization-initiative

Advanced Manufacturing. OCCCM is drawing upon some of the advanced techniques emerging from the manufacturing sector to develop innovations for future coal and carbon management technologies. According to a recent report, OCCCM is working with the DOE Advanced Manufacturing Office (AMO) to leverage novel manufacturing capabilities to improve components for coal plants and products. Cross-cutting projects are similarly leveraging advanced manufacturing techniques to improve plant performance and component design/ production.[72] Topics include the following:

- Robotic inspection techniques with the capabilities to create, replace, or repair components in place, e.g., micro robotics to make repairs inside turbines
- In-plant robotics systems to perform inspections, maintenance, and repairs
- Improved metals and metallurgy
- Sensors
  - Novel sensors and data-driven models to improve thermal management and integrate plant operations with environmental controls

[72] Special Report: *Intersection of Advanced Manufacturing with Clean Coal and Carbon Management Technologies*. DOE Office of Fossil Energy, Office of Clean Coal and Carbon Management. October 2019. www.energy.gov/sites/prod/files/2019/10/f67/Special%20Report%20on%20Coal.pdf

- Models and sensors for predictive maintenance
- Wireless embedded sensors for *in-situ* monitoring of advanced energy systems
- Additive manufacturing and direct printing for smart equipment sensors (e.g., wireless sensors in refractories, autonomous smart sensors)

- 3D printing and micro-fabrication
- Advanced manufacturing for system components (isostatic pressed techniques, advanced casting) such as turbine blades

OCCCM is also drawing on work conducted through the AMO Research Consortia (Regional Manufacturing Institutes) to develop novel, high-performance components; advanced materials; and transformational diagnostics and maintenance systems.[73]

Advanced Computing and Analytics: OCCCM collaborates with the Artificial Intelligence and Technology Office (AITO), DOE's center for AI. The Office is working to accelerate the delivery of AI-enabled capabilities, scale R&D efforts, and synchronize AI activities to advance core missions and support U.S. leadership in this field. Areas of focus will include the following:

- AI, big data analytics, and ML approaches to enable real-time decision making
- Virtual and augmented reality tools
- High-performance computing to optimize advanced energy system performance
- Existing capabilities to manipulate, store, and share large data bases for AI and ML
- Applications of quantum information science in addressing challenges for advanced energy systems and carbon management.

[73] AMO Research and Development Consortia. 2020. www.energy.gov/eere/amo/research-development-consortia

Program Metrics and Evaluation

Programs to advance clean coal and carbon management have a long history at DOE and have produced many benefits to the Nation. The recently completed analysis *A Retrospective Analysis of the Costs, Impacts, and Benefits of the U.S. Department of Energy Coal RD&D Program* looks at economic, environmental, and other impacts of DOE's coal RD&D program from 1976 through 2019. As shown in Table 1, the economic benefit of the program over this period, excluding CO_2, is estimated at $237 billion (2019 dollars). This estimated benefit far exceeds program costs during the same period, about $29 billion (2019 dollars), as shown in Figure 7.[74] The greater than eight-fold benefit-to-cost ratio suggests an impressive return on investment.

Table 1. Impacts of the DOE Coal R&D Program Through 2019

Category	Impacts (billions of 2019 dollars)
Realized Savings Through 2000	$7.3
Reduced CAPEX	$7.6
Efficiency Savings	$2.9
Clean Coal Technology Exports	$42.6
SO_2	$68.5
NO_x	$35.9
CO_2	42.1Mt
Public Health	$36.9
NETL Operations	$35.0
Jobs	78,600 jobs/yr.*
Total	$236.7
Total, including CO_2	$239.1

*Annual average for the period 2008 – 2019.

Source: Management Information Services, Inc.

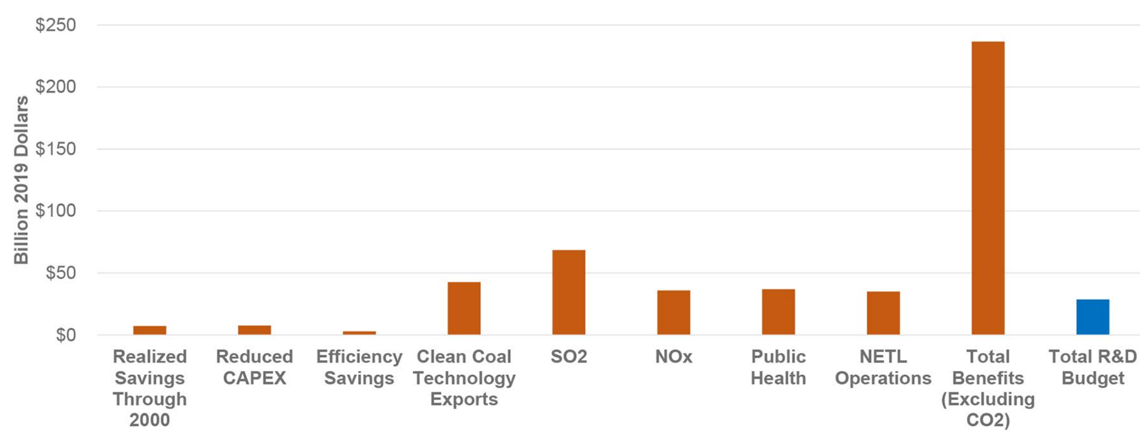


Figure 7. Impacts and Benefits of the DOE Coal RD&D Program through 2019

Source: Management Information Services, Inc.

DOE coal RD&D programs reduced the cost of envirionmental control systems by more than $100 billion and generated public health benefits worth nearly $40 billion. In addition, these programs facilitated creation of about 1.6 million jobs over the period 2000–2019. This significant job creation provided important economic benefits in rural areas and in coal-related sectors, industries, and occupations. The

[74] Management Information Services, Inc. *A Retrospective Analysis of the Costs, Impacts, and Benefits of the U.S. Department of Energy Coal RD&D Program*. 2020.

job impacts of DOE programs are especially noteworthy in the current environment, when job losses and unemployment are at record levels and the coal industry has been hit particularly hard.

Coal RD&D program funding priorities have changed substantially over the last decade in response to shifts in the energy sector and environmental and climate issues. Over 80% of the DOE FY 2020 coal RD&D budget is devoted to programs (primarily CCUS) that are expected to yield public health, economic, and GHG emissions reduction benefits well into the future. The OCCCM vision continues to strategically focus on technologies for the future.

OCCCM evaluates and measures progress and the value of its investments on an ongoing basis. Going forward, the Office will develop and refine its methodologies to evaluate the success and impacts of R&D related to the four major focus areas outlined in this Vision document. Given the potential global reach of OCCCM efforts in carbon management and advanced energy systems, the Office will examine both the domestic and international impacts of its activities.

The program is shaped by many factors, including the dynamic state of the energy industry; the emergence of a modernized grid; a strong national motivation for economic prosperity and growth; and the need to provide clean, affordable energy. The underlying foundation is built on rapid and continuing advances in computational technologies, which affect every aspect of discovery, invention, applied research, system manufacturing and installation, and operations and maintenance. With many factors for consideration, OCCCM will focus valuation of its programs using these key metrics:

- Carbon mitigation and utilization in both the power and industrial sectors
- Public health benefits, including lower emissions, environmental impacts, and carbon footprint
- Economic impacts, such as jobs, exports, industrial investments, and other factors
- Product development and associated markets and benefits
- Impacts on grid security and resilience, including flexibility and load management
- Reach of analytical information and advances generated by various programs
- Impacts on ancillary and critical industries and supply chains, such as manufacturing and critical materials.

OCCCM will continue its robust, long-standing program to expand the Nation’s options for cleaner technologies, strategies to mitigate carbon emissions, and economic growth in coal regions.

Appendix A. Acknowledgements

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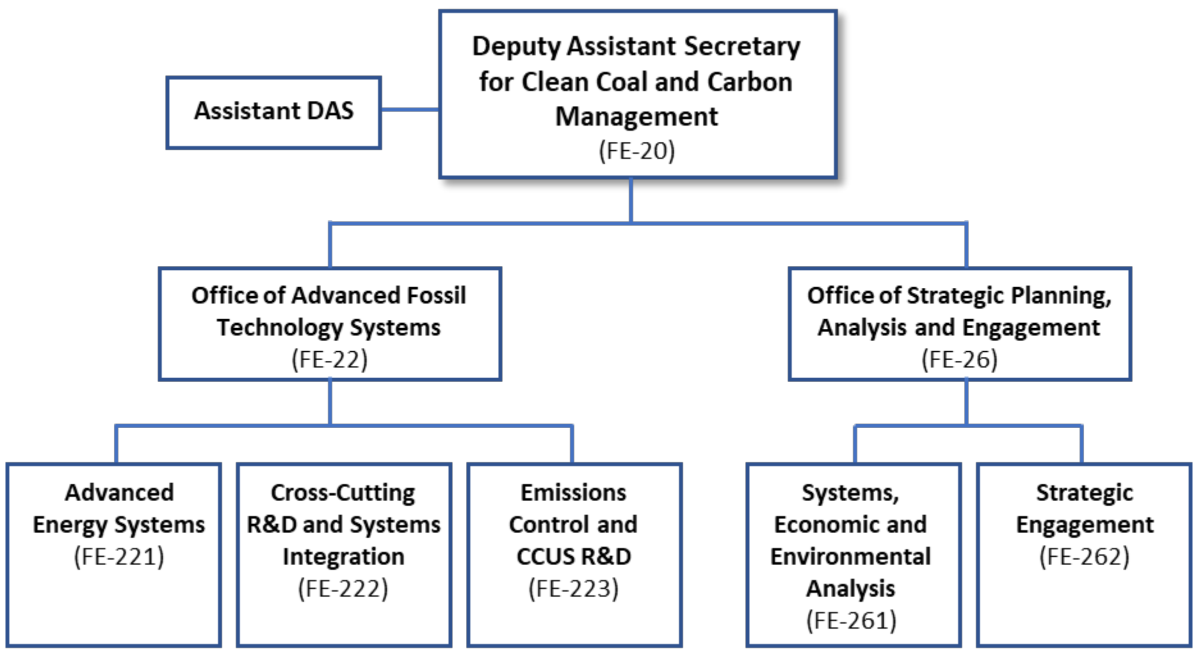
Appendix B. Organization Chart

Fossil Energy

Office of Clean Coal and Carbon Management



Appendix C. List of Acronyms

ACT	Accelerating CCUS Together, international CEM initiative
AMD	Acid mine drainage
AMO	Advanced Manufacturing Office
AI	Artificial intelligence
AITO	Artificial Intelligence and Technology Office of DOE
AUSC	Advanced ultra-supercritical
BECCS	Bioenergy with carbon capture and storage
CCR	Coal combustion residuals
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CCSI2	Carbon Capture Simulation for Industry Impact
CEM	Clean Energy Ministerial
CO_2	Carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
DAC	Direct air capture
DACS	Direct air capture with storage
DOE	U.S. Department of Energy
ECBM	Enhanced coal bed methane
EIA	Energy Information Administration (of the DOE)
EEM	Extreme environment materials
EOR	Enhanced oil recovery
FE	Fossil Energy
FEED	Front-end engineering design
GHG	Greenhouse gas
GMI	Grid Modernization Initiative
GW	Gigawatts
HEMI	Harsh environment materials initiative
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
ML	Machine learning
MSW	Municipal solid waste
NATCARB	National Carbon Sequestration Database
NETL	National Energy Technology Laboratory
NET	Negative emissions technology
NOx	Nitrogen oxide
NRAP	National Risk Assessment Partnership

OCCCM	Office of Clean Coal and Carbon Management
ORNL	Oak Ridge National Laboratory
RCSP	Regional Carbon Sequestration Partnerships
R&D	Research and development
RD&D	Research, development, and demonstration
REE	Rare earth elements
RTIC	DOE's Research and Technology Investment Committee
sCO_2	Supercritical carbon dioxide (power cycle)
SMR	Steam methane reforming
SO2	Sulfur dioxide
SOFC	Solid oxide fuel cells

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