U.S. DEPARTMENT OF ENERGY

Fossil Energy Roadmap

Report to Congress
September 2020

United States Department of Energy
Washington, DC 20585

Message from the Assistant Secretary for Fossil Energy

Many of the energy market successes we observe today trace back to historic investments made by programs in the U.S. Department of Energy's (DOE) Office of Fossil Energy (FE). FE data shows that our achievements include advances in the recovery of critical rare earth elements (REEs) from coal and coal by-products; highly efficient coal technologies that achieve near-zero emissions; reduction of acid rain and mercury emissions from power plants; horizontal drilling and stimulation methods that supported oil and gas operators as they spurred the shale revolution; authorization of liquefied natural gas (LNG) exports of 45.89 billion cubic feet per day of natural gas from over a dozen and a half export facilities in the United States; and effective maintenance and operation of the Strategic Petroleum Reserve. These technology advances are foundational to the development of new industries, commercial deployment of new technologies in a competitive market, and the creation of good jobs in America's coal country and throughout the United States.

The shale revolution is a quintessential example of strategic technology development and cooperation between Federal investment and the private market. The result of this technology pursuit is that the Nation is on the pathway to true energy independence for the first time in decades, and the United States is now the top worldwide producer of both oil and natural gas. Additionally, from 2005 to 2018, the United States was a global leader in carbon dioxide (CO_2) emission reductions (by nearly 14 percent).[1] At the same time, our cultivation of carbon capture technologies has resulted in plants like Petra Nova, where CO_2 utilization and storage research has resulted in the capture of more than 2 million tons of CO_2 from

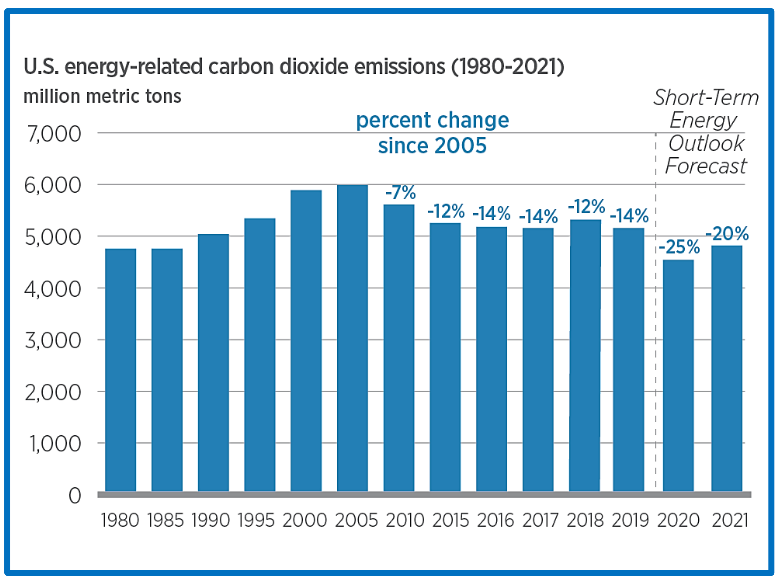


Figure 1 – U.S. Energy-Related CO_2 Emissions [1]

[1] U.S. Energy Information Administration, *Short-Term Energy Outlook,* July 2020, https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf.

a coal-fired power plant that is subsequently used for enhanced oil recovery. FE's management of the Strategic Petroleum Reserve also lets us stand ready to provide needed crude oil in times of emergency and supply disruption, as seen during Hurricane Harvey in 2017.

DOE's FE is focused on promoting resiliency, reliability, and stability throughout the Nation's entire energy system—and is committed to delivering exceptional technology solutions today and preparing advanced technologies for commercialization tomorrow. To that end, FE's key research and development (R&D) priorities are to (1) develop the coal plants of the future; (2) modernize the existing coal fleet; (3) reduce the cost and risk of carbon capture, utilization, and storage (CCUS); (4) expand the use of big data by leveraging artificial intelligence; (5) address the energy-water nexus; and (6) advance REEs, critical materials, and coal products technologies. Advancing R&D of these technologies depends on a strong economy and manufacturing sector that will serve as an incubator for them to grow and become ready for commercial use.

Above all, FE will expand fossil fuel and energy production, conversion, and utilization in an environmentally sustainable manner. It is my pleasure to lead FE as we are solving these challenges, and to secure the Nation's energy future and maintain prosperity for future generations.

Pursuant to statutory requirements, this report is being provided to the following Members of Congress:

- **The Honorable Richard Shelby**
  Chairman, Senate Committee on Appropriations

- **The Honorable Patrick Leahy**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Lamar Alexander**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Nita M. Lowey**
  Chairwoman, House Committee on Appropriations

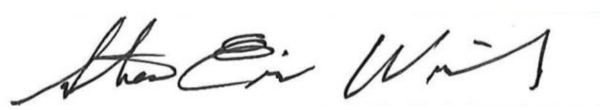
- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies
  House Committee on Appropriations

If you have any questions or need additional information, please contact me or Ms. Katie Donley, Deputy Director for External Coordination, Office of the Chief Financial Officer, at (202) 586-0176.

Sincerely,



Steven E. Winberg

Executive Summary

The *Fossil Energy Roadmap* (FE Roadmap) was written to satisfy the congressional request in the explanatory statement accompanying the Consolidated Appropriations Act, 2018:[2]

> *The Department is directed to develop a cohesive policy and technology strategy and supporting roadmap or long-term plan for its Fossil Energy Research and Development portfolio and supporting infrastructure to guide the discovery or advancement of technological solutions that incorporate lessons learned for the future of research, development, and demonstration efforts on advanced carbon capture and storage (CCS) technologies, advanced fossil energy systems, and crosscutting fossil energy research, as well as guide the discovery or advancement of technological solutions for the prudent and sustainable development of unconventional oil and gas. The Department is directed to deliver the "Fossil Energy Roadmap" to the Committees on Appropriations of both Houses of Congress not later than 1 year after the enactment of this Act.*

In accordance with the congressional request, the FE Roadmap addresses critical needs that are integral to unleashing American resources and technology. The purpose of the FE Roadmap is to:

- Define the FE program and technology pathways required to meet the goals, objectives, and measures of near-term research and development (R&D).
- Describe enduring technical challenges and fossil energy R&D activities that enhance U.S. economic growth, energy security, and environmental stewardship.

The conclusions of this effort provide strategic guidance to the Office of Fossil Energy to effectively plan and execute development and deployment promoting resiliency, reliability, and stability throughout the Nation's entire energy system, delivering exceptional technology solutions today, and preparing advanced technologies for commercialization tomorrow.[3]

It should be noted that this FE Roadmap was completed prior to the COVID-19 pandemic and does not contain information related to FE and its National Energy Technology Laboratory (NETL) capabilities or technologies that either have been or could be brought to bear in supporting the Nation's efforts to address the crisis. NETL has responded to the COVID-19

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[2] Explanatory Statement Submitted by Mr. Frelinghuysen, Chairman of the House Committee on Appropriations, Regarding the House Amendment to Senate Amendment on H.R. 1625, 164 Cong. Rec. H2045, H2483 (March 22, 2018), *available at*: https://www.congress.gov/115/crec/2018/03/22/CREC-2018-03-22.pdf-bk2.
[3] Executive Office of the President, *America First Energy Plan* (Washington, DC: White House: 2017), https://www.whitehouse.gov/issues/energy-environment/.

crisis, along with the Department's other 16 national laboratories, as a part of the National Virtual Biotechnology Laboratory (NVBL) consortium. NETL's capabilities in materials science, reaction chemistry, geospatial data analysis, and computational science and engineering have played a key role in its contributions, and these activities are key drivers in the multi-lab interface.

Alignment with the Administration and DOE

The FE Roadmap represents an integral part of FE's R&D planning process. The FE Roadmap is guided by the Administration's *America First Energy Plan*, the U.S. Congress and DOE priorities, and is informed by FE's *Strategic Vision*, scientists, engineers, stakeholders, and customers. The *FE Strategic Vision* includes strategic programmatic and research goals. The FE Roadmap addresses the strategic research goals and related objectives in the *FE Strategic Vision*, targeted dates for achievement and necessary competency investments, and it provides a clear path toward those goals. The FE Roadmap also aligns with multi-year and annual planning efforts and describes near- and long-term research pathways that address both the Nation's needs and enduring technical challenges. The specific goals and objectives that are documented in the *FE Strategic Vision* and addressed in the FE Roadmap are as follows:

FE Goal 1 – Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources.

- **Objective 1.1** – Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future;
- **Objective 1.2** – Develop technologies to maximize the value from fossil energy resources, including their production and use;
- **Objective 1.3** – Engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship; and
- **Objective 1.4** – Create smart infrastructure technologies for fossil energy.

FE Goal 2 – Enhance U.S. economic and energy security through prudent policy, advanced technology, and the use of strategic reserves.

- **Objective 2.2** – Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation.

By achieving these goals and objectives, FE will contribute to realizing the mission-critical focus areas outlined above.

Research and Development Priority Areas

FE has identified six key FE R&D priority areas requiring concentrated investments to realize American energy dominance: (1) develop the coal plants of the future; (2) modernize the existing coal fleet; (3) reduce the cost and risk of carbon, capture, utilization & storage (CCUS); (4) expand the use of big data by leveraging artificial intelligence; (5) address the energy-water nexus; and (6) advance rare earth elements (REEs), critical materials, and coal products technologies.

Near-Term Research and Development Program Categories

This roadmap outlines the supporting infrastructure needed to guide the discovery and advancement of technological solutions. It incorporates lessons learned for future R&D efforts in six near-term R&D program categories:

1. Advanced Energy Systems
2. Crosscutting Research
3. CCUS
4. Supercritical Transformational Electric Power (STEP)
5. REEs
6. Oil and Natural Gas Research.

Enduring Technical Challenges

In the near term, the FE Roadmap outlines how continued competency development and intellectual and physical asset investment across the six DOE-appropriated FE R&D program categories can support enduring technical challenges represented by four strategic, concentrated FE R&D initiatives: (1) High-Efficiency, Low-Emissions (HELE) Power Generation Power Systems; (2) Fossil Energy Integration, Optimization, and Resiliency; (3) Real-Time Decision Science for the Subsurface; and (4) Manufacturing High-Value Carbon Products from Domestic Coal.

Supporting Infrastructure (2030)

Infrastructure investments are targeted to create, sustain, and recapitalize facilities that support the goals of near-term R&D programs, as well as to mature capabilities critical to meeting enduring technical challenges. Capital investments are identified, planned, and prioritized to enhance technical capabilities; to meet specific programmatic mission requirements; to upgrade and maintain critical infrastructure; and to meet operational efficiency goals of Executive Order 13834 that relate to building energy use, water consumption, and other efficiency elements.[4]

The FE Roadmap identifies infrastructure projects and gaps that highlight required capital investments needed to execute FE R&D program activities, as well as current and future strategic initiatives that support the mission-critical FE R&D focus areas.

Conclusion

The FE Roadmap connects near-term R&D goals encompassed in existing programs and the ongoing technical challenges facing the Nation to infrastructure investments. Those investments will ensure uninterrupted delivery of the technical innovations that undergird American energy innovation and economic prosperity.

The FE Roadmap outlines actions that can result in a more prosperous, secure, and reliable domestic system of energy production, transfer, delivery, and end use. Following this roadmap will accelerate American leadership within the global energy economy, support economic freedom and prosperity, and preserve this country's stature as the global leader at the intersection of technology innovation and commerce.

[4] Executive Office of the President of the United States, Council on Environmental Quality, Office of Federal Sustainability, *Implementing Instructions for Executive Order 13834 – Efficient Federal Operations* (Washington, DC: April 2019).

Fossil Energy Roadmap

Table of Contents

I. Legislative Language

The *Fossil Energy Roadmap* (FE Roadmap) was written to satisfy the congressional request in the explanatory statement accompanying the Consolidated Appropriations Act, 2018:[5]

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The conclusions of this roadmap provide strategic guidance to the Office of Fossil Energy (FE) to effectively plan and execute development and deployment promoting resiliency, reliability, and stability throughout the Nation's entire energy system, delivering exceptional technology solutions today and preparing advanced technologies for commercialization tomorrow.[6]

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[5] Explanatory Statement Submitted by Mr. Frelinghuysen, Chairman of the House Committee on Appropriations, Regarding the House Amendment to Senate Amendment on H.R. 1625, 164 Cong. Rec. H2045, H2483 (March 22, 2018), *available at*: https://www.congress.gov/115/crec/2018/03/22/CREC-2018-03-22.pdf-bk2.

[6] Executive Office of the President, *America First Energy Plan* (Washington, DC: White House: 2017), https://www.whitehouse.gov/issues/energy-environment/.

II. Introduction

This *Fossil Energy Roadmap* connects the strategic goals of the Administration and the U.S. Department of Energy (DOE) to enduring technical challenges and associated initiatives, existing programs, and infrastructure investments that will ensure uninterrupted delivery of the technical innovations that undergird American economic prosperity. The FE Roadmap is divided into the following sections:

- **U.S. Landscape 2030 and Beyond** – This section describes the current technical and economic context, especially emphasizing the transformation of the domestic energy economy over the past decade. It also describes the *America First Energy Plan*[7] and reviews other relevant Administration priorities.

- **Technology Landscape** – This section provides details of available technology development opportunities. It outlines a middle- and long-term technical development approach, pursuit of which will produce continuous innovation to penetrate the commercial energy technology markets.

- **Goal, Objectives, and Sub-Objectives** – This section outlines near-term R&D and the associated priority goals of DOE and the connection to FE's research goals.

Figure 2 – America First Energy Plan

7 Executive Office of the President, *America First Energy Plan* (Washington, DC: White House: 2017), https://www.whitehouse.gov/issues/energy-environment/.

- **FE R&D Portfolio** – This section connects the specific elements of FE programs to the overarching strategic goals and to enduring technical challenges.

- **Supporting Infrastructure (2030)** – This section outlines the critical investments necessary to maintain core competency in areas critical to the achievement of near-term R&D and to meet enduring technical challenges in fossil energy.

III. U.S. Landscape 2030 and Beyond

Technical and Economic Context

America's role in the global energy sector has been transformed from a net energy importer to a net energy exporter as a result of large increases in production of crude oil and natural gas.[8] This has significantly affected related downstream industries and consumers. The FE Roadmap seeks to identify ways to leverage the Nation's fossil energy production and supply advantages to increase its strength in manufacturing, enhance national security, and sustain its economy well into the future.

America First Energy Plan

The *America First Energy Plan*[9] is the guiding policy for FE and NETL. FE's research programs develop transformative science and technology solutions to address the challenges facing the Nation, ensuring the responsible development and use of the Nation's domestic fossil energy resources.

The Trump Administration is committed to energy policies that lower energy costs for Americans and maximize the use of American resources for industry, freeing the United States from dependence on foreign oil. Further, the Administration is committed to developing domestic energy production so that U.S. energy needs are never held hostage by nations hostile to U.S. interests.

It is recognized that American energy independence must go hand-in-hand with responsible stewardship of the environment. Protecting clean air and clean water, conserving natural habitats, and preserving natural reserves and resources will remain a top priority. Prudent energy policy begins with recognizing the untapped domestic

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[8] U.S. Energy Information Administration, 2019, *Annual Energy Outlook 2019: with Projections to 2050*, AEO2019, https://www.eia.gov/outlooks/aeo/pdf/AEO2019.pdf.

[9] Executive Office of the President, *America First Energy Plan* (Washington, DC: White House: 2017), https://www.whitehouse.gov/issues/energy-environment/.

energy reserves in America, such as the estimated $50 trillion in untapped shale, oil, and natural gas reserves, including those on Federal lands.

U.S. Fossil Energy Production Growth

Providing affordable, reliable, and secure energy is one of today's preeminent challenges. A primary goal of DOE is advancing energy technologies to help meet this challenge. Fossil fuels provided over 80 percent of the Nation's primary energy in 2019, and they are projected to be a part of America's energy future for several decades.[10] Fossil energy production growth is supported by growing demand from large natural gas-intensive chemical projects and from the development of liquefaction export terminals in an environment of low natural gas prices. FE is working with industry to develop innovative and cost-effective technologies for the environmentally sound production and use of fossil fuels that support economic growth, energy security, and U.S. competitiveness.

According to the U.S. Energy Information Administration (EIA), 61 percent of all electricity in the United States came from fossil fuels in 2019, with natural gas contributing 37 percent of total U.S. generation and coal contributing 24 percent.[11] Fossil fuels also accounted for about 80 percent of global primary energy consumption in 2019—a figure that has remained relatively unchanged for the last three decades.[12] Notwithstanding significant growth in renewable energy and efforts to decarbonize the energy system, total fossil fuel use will continue to increase as global energy demand continues to grow.

EIA projects U.S. coal demand will decline through 2050 in the Annual Energy Outlook 2020 (AEO2020) Reference Case.[13] Coal production decreases through 2025 due to retiring coal-fired electric generating capacity, but Federal rule compliance and higher natural gas prices lead to coal production leveling off afterwards. U.S. coal-fired capacity peaked at 318 gigawatts (GW) in 2011 and has been declining since then because many plants retired or switched to other fuels and few new coal-fired plants came online. By the end of 2019, U.S. coal-generating capacity totaled 229 GW. The coal fleet's rate of operation, or utilization, has also decreased. The U.S. coal fleet generated as much as 67 percent of its capacity in 2010, based on the operating

[10] U.S. Energy Information Administration (EIA), *U.S. Energy Facts Explained* (Washington, DC: EIA 2020).
[11] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020: with Projections to 2050* (Washington, DC: EIA, 2020), https://www.eia.gov/outlooks/aeo/pdf/AEO2020.pdf.
[12] U.S. Energy Information Administration (EIA), *International Energy Outlook 2019* (Washington, DC: EIA, 2019).
[13] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020: with Projections to 2050* (Washington, DC: EIA, 2020), https://www.eia.gov/outlooks/aeo/pdf/AEO2020.pdf.

capacity at the time. Coal's utilization rate has declined since then, and in 2019, it fell to 48 percent.[14]

In addition to decreases as a result of competitively priced natural gas and increasing renewables generation, coal-fired generating capacity is projected to decrease by 109 GW (or 46 percent) between 2019 and 2025 to comply with the Affordable Clean Energy (ACE) rule before leveling off near 127 GW in the AEO2020 Reference Case by 2050. By 2030, the utilization rate of the remaining coal-fired capacity returns to 65 percent, which is slightly less than in the early 2000s. Coal-fired generating capacity retires at a faster pace than total generation in the AEO2020 Reference case as capacity factors increase for the more efficient coal-fired units that remain in service. Coal plant retirements are expected to slow starting in 2025. The remaining coal plants are more efficient and continue to operate throughout the projection period. Low natural gas prices in the early years also contribute to the retirements of coal-fired and nuclear plants because both coal and nuclear generators are less profitable in these years. Coal's share of total U.S. electricity generation is projected to decline from 25 percent in 2019 to approximately 14.5 percent in 2050 as natural gas and renewable generation sources increase their generation shares.

In 2019, for the first time since 1957, domestic energy production exceeded energy consumption in the United States on an annual basis. The United States continues to produce historically high levels of crude oil and natural gas. Slow growth in domestic consumption of these fuels leads to increasing exports of crude oil, petroleum products, and liquefied natural gas. U.S. natural gas and oil production is projected to be driven by the development of shale gas and tight oil resources in the future. However, future production remains highly uncertain; it will be based on the quality of the resources and the evolution of technological and operational improvements to increase productivity and reduce costs. Accordingly, the AEO2020's outlook for domestic natural gas and crude oil production is highly sensitive to resource and technology assumptions.

In the AEO2020 Reference Case, growth in production of U.S. crude oil and natural gas plant liquids generally continues through 2025, mainly as a result of the continued development of tight oil resources. During the same period, domestic consumption falls, making the United States a net exporter of liquid fuels in the Reference case and in many of the side cases. Domestic dry natural gas production increases at an average annual rate of just under 1 percent through 2050, from approximately 34 trillion cubic feet (Tcf) in 2019 to 45 Tcf in 2050. Natural gas dry production in the AEO2020 Reference case grows 1.9 percent per year from 2020 to 2025, which is considerably slower than the 5.1 percent-per-year average growth rate from 2015 to 2020.

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[14] U.S. Energy Information Administration (EIA), "*U.S. coal-fired generation in 2019 falls to 42-year low.*" (Washington, DC: EIA, 2020), https://www.eia.gov/todayinenergy/detail.php?id=43675.

Domestic crude oil production increases during 2019 through 2025 at an average annual rate of approximately 2.6 percent and then flattens after 2025, staying at about 14 million barrels per day during 2026-2042 and decreases at an average annual rate of 1.95 percent thereafter, down to about 12 million barrels per day in 2050. In the AEO2020 Reference case, U.S. crude oil production reaches 14.0 million barrels per day by 2022 and remains near this level through 2045 as tight oil development moves into less productive areas and well productivity declines. Onshore tight oil development in the Lower 48 states continues to be the main driver of total U.S. crude oil production, accounting for about 70 percent of cumulative domestic production in the AEO2020 Reference case during the projection period.

> *The United States was the largest global crude oil producer in 2018 and 2019.*
> ***– U.S. Energy Information Administration***

The sensitivity of AEO2020 projections to changes in assumptions regarding domestic crude oil and natural gas resources and technological progress is examined in two cases, which provide a framework to examine the effects of higher and lower domestic supply on energy demand, imports, and prices.
In the High Oil and Gas Resource and Technology case, the resource assumptions are adjusted to allow for more domestic crude oil production than in the Reference case. This case includes 50 percent higher estimated ultimate recovery (EUR) per tight oil, tight gas, or shale gas well; additional unidentified tight oil and shale gas resources to reflect the possibility that additional layers or new areas of low-permeability zones will be identified and developed; 50 percent higher assumed rates of technological improvement that reduce costs and increase productivity in the United States than in the Reference case; 50 percent higher technically recoverable undiscovered resources in Alaska and in the offshore Lower 48 states than in the Reference case. Therefore, under the High Oil and Gas Resource and Technology Case, domestic natural gas and oil production increases through 2050, reaching 55.4 trillion cubic feet per year and 19.0 million barrels per day respectively, in 2050.[15]

In the Low Oil and Gas Resource and Technology case, the estimated ultimate recovery per well for tight oil, tight gas, or shale gas in the United States and the undiscovered resources in Alaska and the offshore Lower 48 states are assumed to be 50 percent lower than in the Reference case. Rates of technological improvement that reduce costs and increase productivity in the United States are also 50 percent lower than in the Reference case. These assumptions increase the per-unit cost of crude oil and natural gas development in the United States.

[15] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020, Projections Tables for Side Cases*, https://www.eia.gov/outlooks/aeo/tables_side.php.

Under such conditions, the Low Oil and Gas Resource and Technology Case forecasts natural gas production to stay at an average rate of about 33 Tcf per year from 2020 through 2050, and crude oil production to decrease after 2028 for most of the projection period to about 8 million barrels per day in 2050.[16]

Higher natural gas prices in the Low Oil and Gas Supply case slow the pace of coal power plant retirements by about 23 GW through 2025 compared with the Reference case. The Low Oil and Gas Supply case has 155 GW of coal-fired capacity still in service in 2050. Conversely, lower natural gas prices in the High Oil and Gas Supply case increase coal-fired power plant retirements by 28 GW in 2025, and 96 GW of remaining coal-fired capacity remains by 2050. By 2050, in the High Oil and Gas Supply case, fossil fuel-fired electric power generation is 25 percent higher than in the Reference case. In the Low Oil and Gas Supply case it is 34 percent lower than in the Reference case.[17]

As a result of projected lower natural gas prices in the High Oil and Gas Supply case, natural gas-fired generation increases 1.9 percent per year through the projection period, reaching a 51 percent share of the generation mix by 2050. In contrast, under the projected higher natural gas prices in the Low Oil and Gas Supply case, natural gas-fired generation declines 1.4 percent per year through 2050, reaching a 19 percent share of the generation mix by 2050.[18]

Production growth dovetails with another factor in America's future energy independence—energy imports. The United States has been a net energy importer since 1953, but due to declining energy imports and growing energy exports, EIA projects that the United States, for the first time since the 1950s, will export more energy than it imports by 2020 as increases in crude oil, natural gas, and natural gas plant liquids production outpace growth in U.S. energy consumption.[19] Increases in energy exports will result in continued job growth across multiple sectors and will position America to reduce trade deficits through the responsible export of its abundant energy resources.

The FE Roadmap establishes a path to ensure the Nation's access to secure, affordable, and reliable fossil energy resources and strategic reserves in a way that is economically beneficial to the United States, and it outlines opportunities to increase America's importance on the world energy stage. Additionally, the FE Roadmap will explain a key

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[16] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020, Projections Tables for Side Cases,* https://www.eia.gov/outlooks/aeo/tables_side.php.

[17] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020: with Projections to 2050* (Washington, DC: EIA, 2020), https://www.eia.gov/outlooks/aeo/pdf/AEO2020.pdf.

[18] U.S. Energy Information Administration (EIA), *Annual Energy Outlook 2020: with Projections to 2050* (Washington, DC: EIA, 2020), https://www.eia.gov/outlooks/aeo/pdf/AEO2020.pdf.

[19] U.S. Energy Information Administration (EIA), *The United States is expected to export more energy than it imports by 2020* (Washington, DC: EIA, 2019).

catalyst in this effort—the scientific basis for FE research investments that enable future scientific breakthroughs in the energy field.

Executive Orders and Other Policies

Clean coal technology is a cornerstone of the *America First Energy Plan*. Removing regulatory burdens facing the energy industry could help promote the use of coal and innovative coal technologies in the electricity sector. Other legislatively driven incentives, including the United States Code title 26 section 45Q tax credit, could also impact coal and oil and gas investments.

In 2017, President Trump issued two Executive Orders initiating the regulatory reform process:

- Executive Order 13777, initiating a process of regulatory reform "to lower regulatory burdens on the American people."[20]
- Executive Order 13783, addressing increased production of domestic energy and directing Federal agencies to review current policies and rules that potentially deterred development or use of such domestic energy.[21]

Executive Order 13783, Section 4, directed the Administrator of the U.S. Environmental Protection Agency (EPA) to review its Clean Power Plan (CPP) and related rules and agency actions for consistency with the policy set forth in Section 1 of the Order, and stated, "*if appropriate, shall, as soon as practicable, suspend, revise, or rescind the guidance, or publish for notice and comment proposed rules suspending, revising, or rescinding those rules*." EPA proposed to repeal the CPP and finalized the Affordable Clean Energy (ACE) rule, which established emission guidelines for states to develop plans to address greenhouse gas (GHG) emissions from coal-fired power plants. The ACE rule would replace the CPP and has several components:

- Establishes heat rate improvement as the 'best system of emission reduction' for carbon dioxide (CO_2) emissions from coal-fired power plants;
- Provides states with a list of 'candidate technologies' as well as operating and maintenance practices that can be used to establish unit-specific standards of performance and incorporate into their state plans; and

[20] Exec. Order 13777: Enforcing the Regulatory Reform Agenda, 82 FR 12285 (2017), https://www.gpo.gov/fdsys/pkg/DCPD-201700139/pdf/DCPD-201700139.pdf.
[21] Exec. Order 13783: Promoting Energy Independence and Economic Growth, 82 FR 16093 (2017), https://www.gpo.gov/fdsys/pkg/FR-2017-03-31/pdf/2017-06576.pdf.

- States will submit plans to EPA within three years. The states' plans establish standards of performance and include measures for implementation and enforcement of the standards.

These policies are likely to impact fossil energy. Tax credits may also impact fossil energy deployment. For example, the current 45Q tax credit provides a tax credit for sequestered CO_2 on a per-ton basis that can be used for enhanced oil recovery projects, non-enhanced oil recovery geologic CO_2 storage projects, and CO_2 utilization. These tax credits seek to encourage the development of new carbon capture, utilization, and storage (CCUS) technologies, further adding to the value of U.S. fossil energy resources. This development process is discussed in the following section.

IV. Technology Landscape

Introduction

FE's science and technology strategy focuses on the development of technologies that will secure America's energy future. By collaborating with industry and university partners to develop and deploy technology solutions to maximize the value of U.S. fossil energy resources—including their production and use—FE works to ensure American energy dominance, while an emphasis on the efficient use of resources solidifies American stewardship of the environment for years to come. Such advanced technologies will enable the continued use of fossil fuels to produce cost-effective, reliable, and clean domestic energy, while also extending the market for American energy resources and technologies throughout the world.

FE strives to integrate and grow research and technology transfer activities in the public and private sectors through collaborative partnerships with National Laboratories, academia, and industry that continuously feed America's technology development pipeline. Through a broad R&D portfolio, FE pursues new concepts with the potential to revolutionize fossil energy production and utilization, develops technologies for market adoption, and supports industry partnerships to demonstrate new technologies.

FE's near-term goals, enduring technical challenges, and foundational DOE goals drive the R&D priorities. FE will support research and technology development efforts in key priority areas that:

1. Develop the coal plants of the future
2. Modernize the existing coal fleet
3. Reduce the cost and risk of CCUS
4. Expand the use of big data by leveraging artificial intelligence

5. Address the energy-water nexus
6. Advance REEs, critical materials, and coal products technologies.

The FE research portfolio reflects the spirit of DOE's history of bringing together pioneering multidisciplinary teams to meet the Nation's most important challenges. These initiatives rely on FE's core competencies and experimental and computational capabilities at the DOE National Laboratories, coupled with strategic partnerships to accelerate the rate of technical innovation from fundamental discovery to deployment. By enhancing the value and productivity of domestic natural resources, these enduring research initiatives will be catalysts for economic growth, increased national security, and global energy leadership.

The near-term R&D categories critical to immediate goals are also components of enduring technical challenges that cross current program boundaries; they integrate and extend the technical competencies that have been developed to meet near-term goals. The enduring technical challenges are characterized as broad strategic research efforts that align with DOE's and FE's strategic goals and are comprehensive in scope. They integrate complementary competencies already in existence within FE.

High-Efficiency, Low-Emissions (HELE) Power Generation – Innovating coal-fired power plants that feature flexible operations to improve efficiency and reduce emissions, provide resilient power to Americans, are small compared to today's conventional utility-scale coal, and will transform how coal technologies are designed and manufactured. This challenge is an extension of addressing near-term goals related to key priority areas 1 and 2 noted above.

Fossil Energy Integration, Optimization, and Resiliency – Improving the efficiency of the existing coal and natural gas fleet and reducing emissions from transmission and generation, as well as enabling the next generation of smaller and more flexible fossil-fuel systems that are highly integrated, stable, and reliable sources of power. This challenge is an extension of addressing near-term goals related to key priority areas 1 and 2 noted above.

Real-Time Decision Science for the Subsurface – Creating the tools needed to double the available domestic subsurface fossil-based resources (i.e., coal, oil, and natural gas) while improving environmental performance. This challenge is an extension of addressing near-term goals related to the key priority area 4 noted above.

Manufacturing High-Value Carbon Products from Domestic Coal – Cultivating additional value streams throughout the fossil energy life cycle and developing the capability to generate high-value, carbon-based products (e.g., nanomaterials and carbon fiber) from coal. This challenge is an extension of addressing near-term goals related to key priority areas 3, 5, and 6 noted above.

To address these enduring technical challenges, FE is pursuing infrastructure projects that are aligned with existing core capabilities.

HELE Power Generation

The first enduring technical challenge is focused on **HELE Power Generation** using coal. Through the Coal flexible, innovative, resilient, small, transformative (FIRST) initiative, FE seeks to enable U.S. manufacturers to create the cleanest, highest-performing, and most cost-effective coal-fired power plants in the world. This initiative aims to develop mid-term technology options (2030 timeframe) that will improve the efficiency and flexibility of modern coal power plants over the next decade. FE will utilize a diverse and coordinated approach to identify and perform research with National Laboratories, academia, and industry.

Changes to the U.S. electricity industry are forcing a paradigm shift in how the Nation's generating assets are operated. Coal-fired power plants that were originally designed and optimized as baseload resources are now increasingly expected to provide critical ancillary services to the grid and to accommodate greater generation of electricity from intermittent renewable sources.

In addition, wide-scale retirements of the Nation's existing fleet of coal-fired power plants—without replacement—may lead to a significant undermining of the resiliency of America's electricity supply. Nevertheless, the need for considerable dispatchable generation, critical ancillary services, and grid reliability—combined with potentially higher future natural gas prices and energy security concerns, such as the availability of onsite fuel during extreme weather events—creates the opportunity for advanced coal-fired generation for both domestic and international deployment. These fundamental changes to the operating and economic environment in which coal plants function are expected to persist into the next decade and beyond.

Fossil Energy Approach

The HELE Power Generation initiative encompasses technology innovation in the near- and mid-term. FE's core capabilities will guide technology development and system integration while assessing life cycle costs and market potential. Existing high-efficiency technologies for power generation will enhance conversion efficiencies and lower emissions. Advanced combustion technologies include ultra-supercritical and advanced ultra-supercritical technologies for pulverized coal (PC) or circulating fluidized bed combustion boiler concepts. Advanced combustion technologies are also required for air-fired indirect supercritical carbon dioxide (sCO_2) cycle plants without carbon capture.

Challenges include identifying combustor designs to accommodate new working fluids such as sCO_2 and reducing associated materials costs to achieve the efficiency and cost of electricity goals.

Advanced coal combustion technology systems will not be limited to achieving high efficiency for baseload operation. The new combustion technology systems will be required to achieve high efficiency over the full range of plant operating conditions—e.g., baseload, cycling load, two-shift operation, and high ramp rate demands. These electric market requirements will require advances beyond today's technology to achieve high plant efficiency over the full range of operating demands. Specific technical requirements of a HELE Power Generation system are outlined in Figure 3.

In addition to advances in existing plant combustion concepts, there are opportunities to achieve improvements in efficiency through advanced combustion power concepts. Examples include:

- Development of a coal combustion reactor concept to apply indirect sCO_2 power cycles.
- Advanced combustion concepts potentially leading to efficiency advances: for example, through flameless combustion and pressure gain combustion.
- Potential applications for small-scale modular coal combustion systems leading to opportunities for advanced combustion concepts to achieve high efficiency.

Other low-emissions power plant concepts will also be considered. Low CO_2 intensity can be realized through the development of advanced materials for extreme environments that enable higher-efficiency power plant concepts (e.g., advanced ultra-supercritical boiler technologies) fueled with coal and natural gas. Designs will need to maintain state-of-the-art emissions control capability.

Water consumption is also an important market driver in selected regions. Advanced high-efficiency plants that use less water will be needed in the future.

SPECIFIC DESIGN CRITERIA
• **Employ Efficiency Improvement Technologies –** (40+% higher-heating value) • **4% Minimum Ramp Rate (Up to 30% Natural Gas)** • **Cold/Warm Start** – Less than 2 hours (provide concepts using energy storage) • **5:1 Turndown** – Full environmental compliance • **Compound Cycles** – High efficiency and flexibility from combinations of turbine/piston/fuel cells that provide high efficiency in small systems • **Zero Liquid Discharge** • **CO_2 Capture Ready or Inherently Capture** • **Solids Disposal** – Mostly saleable product • **Dry Bottom and Fly Ash Discharge**

Figure 3 – Specific Design Criteria of HELE Power Generation System

Fossil Energy Integration, Optimization, and Resiliency

DOE supports science and technology developments leading to the commercialization of low-cost, reliable power for the American people that spurs economic development while mitigating technical and environmental risks. Key to this mission is maintaining leadership in the development of new technologies for energy generation, energy transmission, and fossil resource utilization, which are all critical to domestic economic competitiveness and energy security.

FE is pursuing the enduring technical challenge of **Fossil Energy Integration and Optimization, and Resiliency,** which combines advanced systems engineering with the detailed development of sub-systems and components to optimize production, delivery, and integrated system performance while enhancing environmental stewardship. Fossil energy plays an important role in reliable, baseload power generation and in meeting our nation's electricity demand. In the area of resiliency, FE's efforts support DOE's Grid Modernization Initiative (GMI), which links key program offices, including FE, and works toward creating the modern electricity grid infrastructure of the future that is reliable and resilient.

KEY OUTCOMES
This research will address deployment scenarios for advanced power generation that include determining: 1. Optimal fossil energy configurations that integrate with other power sources 2. Optimal mix of fossil energy generation, energy storage, and renewable power 3. Options to provide greater turn-down and energy storage for fossil systems 4. Improved energy transmission and conversion technologies that support supply and grid resiliency 5. Identification of novel energy conversion systems.

For more than 40 years, commercial electricity production and distribution business models have relied on base generating capacity supplied by fossil power plants. However, the role of fossil energy is rapidly shifting as variable and intermittent generation become more prevalent. Thus, many fossil-based power plants are cycling more frequently, which often accelerates equipment degradation. This reality, coupled with the age of the existing fleet, is leading to the retirement of many existing assets.

In addition to addressing issues surrounding the existing fleet, attention must also be paid to advancing the next generation of fossil energy power plants. To achieve these goals, new technologies must be developed that enable more flexible operations to meet changing market conditions on both the supply and demand side.

Fossil fuels are critical to assuring the resiliency, reliability, and stability of interconnected fuel supply networks (pipelines) and energy conversion and delivery networks (the electrical grid). Next-generation materials, sensors, controls, and flexible fossil-based power systems may decrease energy intensity and decrease emissions per energy unit delivered. Key attributes of new fossil-based power systems are described in Figure 4.

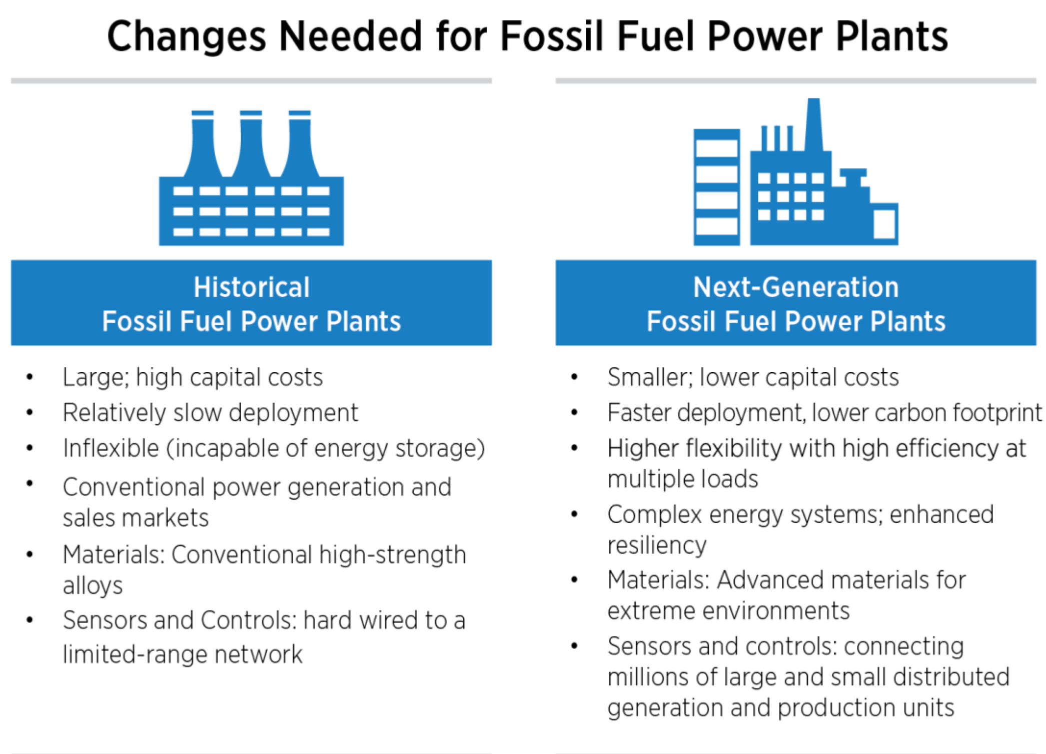

Figure 4 – Changes Needed for Fossil Fuel Power Plants

For these technologies to support an efficient, affordable, and reliable energy future, transformational technologies must be identified, rapidly advanced to maturity, and integrated into complete, optimized systems. Assessments of dynamic and flexible operations are necessary to integrate and evaluate complete systems. Advanced process systems engineering, coupled with advanced materials and controls, will create a more fully integrated energy supply and delivery system. Integration of advanced fossil-based power generation with thermal, chemical, and electrical energy storage and renewable power will be developed.

Fossil Energy Approach

FE's core capabilities and aligned R&D activities will help determine which technologies to pursue and how to optimally integrate them while accounting for full life-cycle costs and market potential. FE utilizes an integrated approach that combines simulation, direct access to high-performance computing, optimization, experimental capabilities and the ability to partner with other labs and industry. The goal is enabling the rapid development, scale-up, and deployment of new technologies and processes. These are outlined in Figure 5, "Next-Gen Technologies and Processes." Some of the identified technologies are supported through existing R&D programs within FE, as consistent with budget authorizations.

NEXT-GEN TECHNOLOGIES AND PROCESSES
• **Solid Oxide Fuel Cells** – The highest efficiency technology to convert chemical energy to electrical energy. • **Pressure Gain Combustion** – A potential efficiency boost for peaking or combined cycle turbines and a method for accelerating coal or gas combustion. • **sCO_2 Power Cycles** – A high-efficiency alternative to steam power for fossil, nuclear, and concentrated solar power. • **Compound Cycles** – High efficiency and flexibility from combinations of turbine/piston/fuel cells that provide high efficiency in small systems. • **Modular Gasification** – Meeting industrial needs by aggregating standardized, low-cost modules. • **Advanced Thermal Storage** – Low-cost demand response by energy storage (not electrical). • **Direct Power Extraction** – High-efficiency, flexible coal or gas power using magneto hydrodynamics principles, but avoiding classic seeding problems via advanced cold-plasmas. • **Innovative Materials and Architectures for Heat Engines** – Exploiting new materials and manufacturing methods to boost efficiency in boiler, turbine, and reciprocating engine designs. • **Non-Thermal Chemical Conversion** – Using microwave, radiofrequency, and laser energy to control or modify traditional catalytic conversion or possibly eliminate catalysts. • **Advanced Electrical Energy Storage** – Unconventional and non-lithium battery storage technologies featuring low costs. • **Advanced Sensors and Controls** – Advanced materials and methodologies to enable process monitoring, wear/fatigue, and predictive maintenance, including real-time monitoring and fault detection.

Figure 5 – Next-Gen Technologies and Processes

FE efforts will focus on joining system components and systems into a national integrated network. To inform flexible design of such integrated systems, FE will gather fundamental component performance data, utilize hardware "in the loop" testing, create computational paradigms, expand computational optimization and modeling, examine regional markets, and generate informational data. The integrated systems conceived here would ideally feature:

- Electrical generation efficiency (i.e., exceeding 42 percent at scales from 100 kW to 350 MW);
- Accepted turndown (exceeding 50 percent) without significant impact to system efficiency;
- Dynamic response at multiple time scales (e.g., seconds, minutes, and hours);
- Emissions meeting current and anticipated regulations;
- Upgraded fossil fuel baseload plants to allow for load following;

- Advanced corrosion-resistant materials (e.g., for transmission and energy conversion); and
- Integrated sensors allowing system-wide data capture.

Real-Time Decision Science for the Subsurface

Over 80 percent of the Nation's energy needs are met by energy sources obtained from beneath the Earth's surface.[22] Because subsurface energy is a substantial portion of the Nation's energy portfolio, DOE remains committed to understanding and optimizing subsurface resources. Developments in this area will play a critical role in improving and increasing America's energy production, security, economic development, and infrastructure while enhancing environmental stewardship.

To advance DOE's subsurface priority, FE is pursuing **Real-Time Decision Science for the Subsurface.** DOE's subsurface mission ensures that information streams from novel, continuous monitoring of the subsurface can be used in real time to inform decisions to improve resource recovery, storage efficiency, and environmental performance. Such capabilities will significantly affect the efficiency and quantity of oil and natural gas production, as well as the safe and effective storage of natural gas, ethane, CO_2, hydrogen, and other products in subsurface formations.

KEY OUTCOMES

1. Expanded data mining and machine learning capabilities to evaluate oil and gas production data streams in real time.
2. Analysis tools for multiple data streams from novel distributed sensors that generate high-resolution subsurface images.
3. Advanced models of fundamental reservoir processes that enable accurate prediction of resource recovery/ storage under various production/injection scenarios.
4. Increased production per well, resulting in minimized environmental impacts.

Fossil Energy Approach

FE will improve its data analysis, predictive modeling, and real-time decision science capabilities to advance U.S. energy security and environmental stewardship over the next several decades. This initiative will build on FE's experience in leading the National Risk Assessment Partnership (NRAP) and other multi-lab partnerships, including its capabilities in integrated-assessment modeling, rapid-performance modeling, and Bayesian approaches for monitoring data streams.

[22] U.S. Energy Information Administration (EIA), *What is U.S. electricity generation by energy source?* (Washington, DC: EIA, 2017), https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

The private sector is developing commercial sensors to monitor real-time passive seismic activity, fluid pressure and temperature, rock stresses and strains, chemical and electrical changes and acoustic signals, often in distributed configurations. However, the data generated by real-time and distributed monitoring systems are voluminous, and current interpreters often have difficulty distinguishing important signals from those that could safely be ignored.

FE will work with lab and university researchers to leverage its resources and capabilities to develop new algorithms that improve real-time, signal-to-noise processing and utilize DOE's supercomputing capabilities and web services to support handling, integration, updating, and distribution of large data streams.

FE will interact frequently with oil and gas industry and carbon storage researchers to ensure relevance to current needs and to generate opportunities for field testing of promising technologies. This research envisions adaptive control (i.e., continuous decision-making and operational responses as system variables change or become better known) to reach a state in which current operations are optimally managed to increase value and reduce risk.

FE's research combines theory, field measurements, laboratory data, and numerical simulation to characterize and predict fluid flow in geologic media from the pore scale to the field scale, providing a more complete understanding of geoscience phenomena. Rapid predictive modeling capabilities developed within the NRAP risk assessment tool have utilized statistical and machine learning approaches to quantify uncertainty and assess risk in subsurface systems.

FE has built a growing suite of tools for managing, analyzing, and interpreting earth science data, including the ability to manage large, geospatially-organized data sets. FE's Energy Data eXchange (EDX®) was developed at DOE's NETL as a platform for data sharing and collaborative research. The innovative monitoring technology includes new protocols and approaches for site characterization and monitoring and advanced statistical approaches for the design and interpretation of monitoring networks. Industry partners have applied these approaches to conventional and unconventional gas production wells, geothermal test sites, and field sites for CO_2 and underground natural gas storage. FE possesses expertise with ground-based and aerial monitoring, both to detect existing wells and to monitor atmospheric conditions.

In addition, ongoing research into capabilities in applied materials science and engineering, computer science and engineering, and systems engineering and integration will strongly contribute to this effort. The development of advanced fiber optic sensors for subsurface applications, novel downhole sensors embedded in wells and nanomaterials will enhance the spatial and temporal resolution of data that can be collected from oil and gas fields.

Novel computational capabilities and facilities—such as the Joule Supercomputer and the Data Center recently built at NETL—make high-performance computing facilities, as well as machine learning and data analysis resources, available for fossil energy applications. Expertise in data analysis and decision science and the synthesis of multiple scientific, engineering, and business management disciplines will ensure the relevance of this research to commercial applications. It will make the transfer of products and research to the private sector possible.

Manufacturing High-Value Carbon Products from Domestic Coal

Given the changing dynamics for the coal industry, DOE is interested in developing and utilizing carbon materials to maximize the economic value of domestic coal, thus increasing and diversifying the Nation's energy production and applications. DOE's goal of extending the full value chain of fossil resources includes the technical challenge of **Manufacturing High-Value Carbon Products from Domestic Coal**. The objective is to identify and execute the scientific and techno-economic research required to create new coal-based manufacturing technologies.

In addition to producing heat and electricity, domestic coal can be used as a feedstock to manufacture a wide range of common products and materials, such as carbon composites for automobile and airplane parts; cement composites for construction and well-drilling applications; electrode materials for battery and energy storage devices; large-scale carbon nanomaterials production; and carbon-based optical brighteners, pigments, and dyes.

KEY OUTCOMES

1. New materials and products with revolutionary properties not previously commercialized owing to the prohibitive cost of nanomaterials.
2. New manufacturing processes for converting coal into high-value products used outside of traditional energy markets.
3. Evaluation of the costs and technical performance of coal-based materials compared to those derived from other feedstocks.
4. Characterization of the best markets for coal-based manufacturing and the barriers associated with introducing new technologies to these markets.

From a technical perspective, coal is a desirable manufacturing feedstock because it naturally contains the graphitic and aromatic carbon structures many materials require for improved strength, corrosion resistance, thermal/electrical conductivity, and enhanced optical properties. In comparison, these carbon structures are not prevalent in natural gas, biomass, or petroleum feedstocks and must be created during the manufacturing process using complex, expensive, and energy-intensive methods.

The economic value of using coal in these applications exceeds its fuel and heat value by *several orders of magnitude*; that demonstrates sustainable market potential for manufacturing materials from coal. However, due to development gaps in coal utilization technologies, there is currently not an economic case for industry to create these materials from coal.

Fossil Energy Approach

R&D efforts will focus on three thrusts that address technology gaps and economic competitiveness: *Emerging Technologies*, *Existing Technologies*, and *Systems Engineering and Analysis*.

Emerging Technologies R&D will focus on the production of carbon nanomaterials, the incorporation of coal-based nanomaterials into common composites and products, and the use of coal-based nanomaterials in both traditional manufacturing and 3D-printing processes. Efforts will address cost, supply, and commercialization issues inherent to carbon-nanomaterial markets by (1) developing chemical and physical processes for manufacturing multi-kilogram quantities (or larger) of carbon-nanomaterial samples and (2) demonstrating how these coal-based nanomaterials can be used in common products, such as optical display screens, paints/pigments/coatings, electronics, photovoltaics, and structural composites.

Existing Technologies R&D will focus primarily on the production of traditional carbon products such as carbon fiber and carbon-fiber composites, carbon electrode materials, and carbon filler materials from coal feedstocks. Product substitutability and manufacturing costs are among the most important issues to address in this area. As such, research will focus on establishing the processes for manufacturing products from coal, assessing substitutability by characterizing the performance of coal-based products, and evaluating the manufacturing costs in comparison to those of traditional products.

Systems Engineering and Analysis R&D will focus on characterizing current and future markets for coal-based carbon products. The manufacturing processes, supply chains, and manufacturing economics for emerging technologies are not well characterized, which creates uncertainty and risks for new entrants. For existing markets, coal materials will potentially displace current products, necessitating characterization of market demand, production capacity, market-entry barriers, and product substitutability. R&D efforts will include quantitative market analyses and techno-economic analyses to evaluate the risks, costs, and barriers to entry associated with commercializing new coal-based manufacturing technologies.

In addition, FE recently sponsored research focused on demonstrating how coal-based carbon nanomaterials can be used to enhance the properties of well-bore cements, fiber optic gas and temperature sensors, water remediation sorbents, and gas-selective polymer membranes. And, FE's existing core capabilities and research accomplishments are aligned with the required materials and manufacturing capability expansions.

FE's functional materials capabilities support the facilities, personnel, and expertise required to design, synthesize, characterize, and test the performance of carbon materials, catalysts, nanomaterials, electro ceramics, sensor materials, and polymers. This expertise supports research to develop low-cost processes for utilizing coal to manufacture high-performance carbon materials and to test these materials under realistic application conditions.

The functional materials capabilities include a carbon processing facility with chemical and physical processing equipment; a full complement of chemical synthesis laboratories for modifying carbon materials; vapor-phase deposition equipment for materials growth; crystallographic and electronic structure characterization tools; surface science, imaging, and analysis instrumentation; mineral processing and separation laboratories; membrane manufacturing and testing facilities and sensor manufacturing and testing facilities. In addition, FE process- and cost-engineering capabilities are used to perform detailed process-level evaluations of current and advanced energy system performance and costs as they apply to carbon materials manufacturing.[23]

Applied materials, manufacturing, and processing research has focused on reducing the costs and the time required to design, develop, and deploy the advanced materials needed for improved power system performance. Integral to these efforts is materials characterization research, which expands FE's existing strengths in experimental characterization and computational prediction of materials composition, microstructure, and performance.

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[23] U.S. Energy Information Administration (EIA), *What is U.S. electricity generation by energy source?* (Washington, DC: EIA, 2017), https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

This expanded initiative demonstrates FE's leadership in all aspects of materials characterization, establishes quantitative structure-property relationships in materials, and develops high-throughput computational models for materials development. The initiative will advance coal-derived carbon materials technologies, as depicted in Figure 6. This work aligns with FE's overarching goals and strategic objectives, further outlined in the next section, by helping promote American energy dominance and increase the access to and affordability of reliable energy.

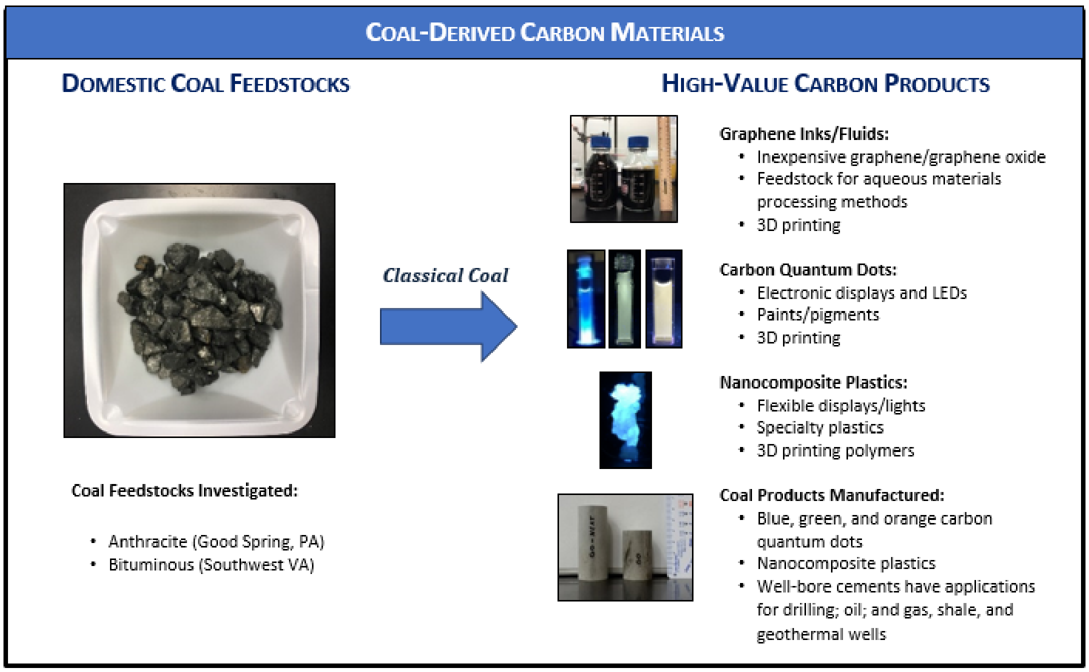


Figure 6 – Overview of the Coal-Derived Carbon Materials Created/Improved through Fossil Energy Research

V. Goals and Objectives

This FE Roadmap lays out **Strategic Goals, Objectives**, and time-defined **Performance Measures**. The Performance Measures presented under each objective have been developed to complement the Administration's updated Government Performance and Results Act Endpoint Targets as presented in the Department's Fiscal Year 2019 Congressional Budget Request.

FE Roadmap Goals

This roadmap is aligned with the Administration's America First Energy Plan and DOE priorities. It is designed to help FE accomplish its mission to discover and develop advanced fossil energy technologies and to ensure American energy dominance. This mission also includes creating American jobs, supporting a resilient infrastructure, maintaining environmental stewardship, enhancing America's economy, and ensuring America's access to and use of safe, secure, reliable and affordable fossil energy resources and strategic reserves.

FE is responsible for Federal R&D efforts to improve the performance of existing coal-fueled generation, develop advanced fossil energy systems spanning the entire fossil energy value chain, advance the prudent development of domestic oil and natural gas resources, and create new non-fuel, high-value products from coal. R&D investments are also developing technologies capable of upgrading domestic coals as combustion fuels, and economically extracting REEs from coal and coal by-products.

FE is uniquely positioned in the Department to help enable an environmentally and economically sustainable mineral resource recovery industry in the United States that will support growth in the manufacturing industry while protecting the environment. For the past 24 years, Congress has included language in the FE R&D appropriation to address the R&D challenges associated with the extraction, processing, use, and disposal of mineral substances without objectionable social and environmental costs. Work on critical minerals, including REEs, can also support the recovery of minerals from legacy mine sites and improve environmental methods. FE R&D could advance the technological and intellectual infrastructure necessary in mineral processing and extractive metallurgy through its close collaboration with industry, national laboratories and academic institutions.

In addition, FE reviews applications for exports of natural gas and manages the Nation's Strategic Petroleum Reserve and other strategic reserves, which are key emergency response tools available to protect the Nation from energy supply disruptions.

FE possesses the core technical capabilities and administrative authorities to advance and promote the transformational technologies necessary to shape, secure, and fully utilize fossil energy resources in the United States, while expanding market opportunities globally. FE serves as a nexus of innovation by uniting the private sector, DOE National Laboratories, academia, and other stakeholders to meet the vast energy challenges of today and tomorrow.

Strategic Goals

The FE Roadmap ties most closely with FE Strategic Goals 1 and 2:

FE Strategic Goal 1: Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources

> FE will focus on advanced technology R&D that will enable the continued use of all fossil energy resources by improving the safety, efficiency, and cost-effectiveness of production, transportation, and conversion of coal, oil, and natural gas, as well as by enhancing environmental stewardship. To do this, FE will create strategic partnerships to develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future; develop technologies to maximize the value from fossil energy resources, including their production and use; engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship; and create smart infrastructure technologies for fossil energy.

FE Strategic Goal 2: Enhance U.S. economic and energy security through prudent policy, advanced technology, and the use of strategic reserves

> The competitiveness of coal can be strengthened with technology solutions to allow the existing coal fleet to operate more efficiently, with lower emissions and extended unit life. The overall performance of the coal fleet can be improved by making cost-effective modifications to existing coal power plants. For example, FE will pursue public/private partnerships to develop smart controls that: (1) predict and improve power plant operational status; (2) maximize efficiency; (3) minimize emissions; and (4) maintain cybersecurity. To prevent premature retirements, FE will also pursue interagency collaboration on regulatory reform, in part by defining clear pathways to address state and Federal regulatory challenges to technology deployment. DOE will inform relevant stakeholders regarding operational requirements and financial and life-cycle assessment tools to accelerate adoption of advanced technology in the marketplace.

These goals provide a more specific focus for the enduring technical challenges outlined in the previous section. Accordingly, meeting these near-term Strategic Goals will enable the Nation to:

1. Develop the coal plants of the future by advancing small-scale modular coal plants of the future which are highly efficient and flexible, with near-zero emissions.

2. Modernize the existing coal-fired fleet by improving its performance, reliability, and efficiency.
3. Reduce the cost and risk of CCUS to enable wider commercial deployment.
4. Expand the use of big data by leveraging artificial intelligence to optimize coal plant performance, CO_2 sequestration, and the recovery of oil and gas resources with real-time analysis informed by machine learning.
5. Address the energy-water nexus by improving our efficient use of scarce water resources.
6. Advance REEs, critical materials, and coal products technologies by improving REEs separation and recovery technologies and processes to manufacture valuable products from coal, in order to address current global market and process economics.

Objectives

Strategic Goals 1 and 2 guide FE's research and technology development mission. Within the framework for achieving the Strategic Goals, five objectives have been developed to inform near-term FE investment in advances in science and technology.

GOAL 1	DEVELOP SECURE AND AFFORDABLE FOSSIL ENERGY TECHNOLOGIES TO REALIZE THE FULL VALUE OF DOMESTIC ENERGY RESOURCES
OBJECTIVE	
1.1	Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future
1.2	Develop technologies to maximize the value from fossil energy resources, including their production and use
1.3	Engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship
1.4	Create smart infrastructure technologies for fossil energy
GOAL 2	ENHANCE U.S. ECONOMIC AND ENERGY SECURITY THROUGH PRUDENT POLICY, ADVANCED TECHNOLOGY, AND THE USE OF STRATEGIC RESERVES
OBJECTIVE	
2.2	Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation

Table 1 – Hierarchy of Strategic Goals 1 and 2, and R&D-Related Objectives

Objective 1.1

Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future

The existing U.S. coal fleet is shutting down or retiring at unprecedented rates, with no new coal generation being built to replace this existing power generation. This current rate of retirement threatens the stability and reliability of the Nation's grid system.

Without continued Government investments in early-stage R&D to advance the next generation of coal-fueled power generation technology, coal production and consumption will continue to decline, potentially compromising high-paying jobs in both the coal production and coal-fired power generation sectors. Developing and deploying advanced coal-power technologies will ensure the competitiveness of the United States in the global fossil energy market.

Objective 1.2

Develop technologies to maximize the value from fossil energy resources, including their production and use

Fossil fuels themselves can be used for purposes other than energy or power generation. In fact, fossil fuels can be strategically important as chemical feedstocks. Developing novel approaches to economically use coal, hydrocarbon liquids, or natural gas in ways that are currently unused or underutilized can create new markets, improve the economic value of these resources, and help maintain or expand the jobs base.

Objective 1.3

Engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship

Despite being the source of all fossil energy resources, the subsurface is vastly underutilized. Current technology recovers only a fraction of the hydrocarbons that exist in place, even from conventional formations. For unconventional formations, recovery of oil and gas is often less than 10 percent. In addition, the subsurface has a significant unrealized potential for storage of hydrocarbons, heat, energy, or other products associated with fossil energy production. Technology R&D to improve the ability to measure, monitor, and control critical properties of the subsurface—such as pressure, stress, and fluid properties—is necessary to better understand and forecast the behavior of unconventional hydrocarbon recovery, well integrity, and seal integrity. Well integrity research will minimize the loss of valuable products and the impact to the environment. That research will help ensure the safe, underground storage of natural gas and the effective management of water usage.

Objective 1.4

Create smart infrastructure technologies for fossil energy

Energy transmission, storage, and distribution (TS&D) infrastructure links subsurface fossil energy resources, the industries that convert them into energy products, and the consumers that utilize these products. A safe and reliable energy infrastructure is necessary for future economic growth and energy security. Changes in the energy sector are already placing new requirements on America's TS&D infrastructure. Contributing factors include the rise of natural gas and renewable energy sources, increases in domestic oil and gas production, and reductions in domestic gasoline usage. Natural gas and electrical grid infrastructure have not kept pace with growing demands for natural-gas-based power generation, modern demands for electrical power, and shifts toward variable and distributed power generation.

Thousands of miles of pipelines transport oil, natural gas, CO_2, and many other fossil fuel products, commodities, or by-products each day. In particular, the use of natural gas is likely to increase as a heating source for homes and businesses, as a petrochemical feedstock, and as a strategic resource for electricity.

Natural gas infrastructure must continue to efficiently and cost-effectively support the production and delivery of natural gas—even as the system expands and becomes more complex—without affecting safety, reliability, and security. Achieving this will require a level of infrastructure capability and functionality that does not exist today. Fossil fuel infrastructure can become more efficient and cost-effective with novel materials, sensors, and intelligent tools that automatically monitor, control, and optimize the entire system.

Objective 2.2

Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation

The average age of the current coal fleet is 40 to 50 years old, and plants are retiring at unprecedented rates. Further, the average efficiency of the U.S. coal fleet is 30 percent (net higher-heating value basis), while older coal power plants are significantly less efficient. Coal-fired generation provides critical baseload generation to the U.S. energy system, and this rate of retirement threatens the stability, reliability, and resiliency of the Nation's grid system. Improving the existing coal-fired fleet, as well as the natural gas transmission and distribution infrastructure, will improve overall efficiency and reduce emissions. That improvement will help units comply with requirements, decrease fuel costs, and defer premature retirements.

VI. Technology Development Pathway

FE's research often identifies and validates promising concepts at laboratory scale at the earliest stage of discovery. Successful technologies are then tested in relevant environments; those that promise improved performance and reduced cost continue along the development process to ready them for eventual market acceptance. As promising technologies mature, technical uncertainty decreases, while scale and confidence in their ability to achieve performance targets increases. At later stages of technology maturity, public investment diminishes and private sector investment increases as it continues from development to market (See Figure 7).

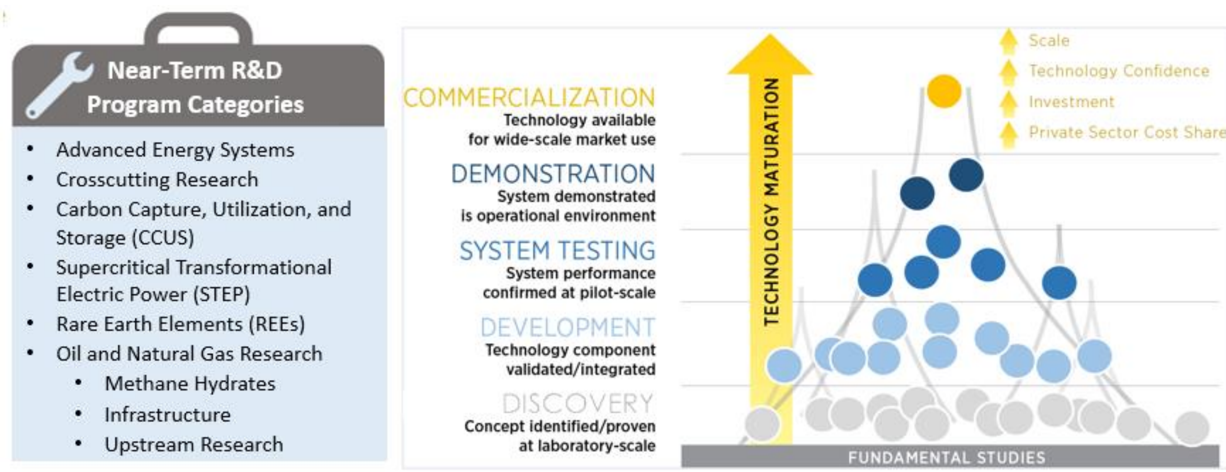


Figure 7 – Fossil Energy's Technology Development Pathway

To meet future energy challenges, coal-based power technology requires developing a portfolio of next-generation and transformational pulverized coal power plant technologies. FE will pursue early-stage R&D on advanced energy systems that enable plant readiness, including advanced combustion systems, materials, and turbines. These and other technologies can significantly improve efficiencies, enabling future energy conversion systems to meet increasingly stringent economic and environmental constraints. Higher-efficiency systems reduce costs and environmental impacts across the entire fossil energy life cycle because fewer inputs are needed to achieve the same energy output.

In the past, coal plants were typically operated to provide baseload power, meaning high efficiency was needed just at full load. Next-generation coal power technology will require flexible operation with high efficiency over all conditions. Specifically, designs for new competitive coal units will need to be flexible, have short startup times (<2 hours), have high turndown (5:1), and be less expensive to build.

Research leading to flexible, resilient fossil energy generation will accommodate greater supplies of intermittent renewable power without compromising plant efficiency or reliability or incurring high costs. Resilient systems will rapidly recover from component failures and resist both physical and cyber disruptions. Opportunities to incorporate advanced sensor and control systems are expected to enable greater flexibility.

Increasing the pace of innovation is essential for realizing a more immediate impact from emerging technologies. Conventional development demands that new ideas be progressively tested at larger scales, sometimes requiring years before wide deployment. In contrast, aggregating smaller, optimized "modules" could enable rapid prototyping and accelerate scale-up and market adoption.

Such a modularization strategy that involves component standardization may help reduce plant component costs (especially for industrial applications) and provide better quality control. Innovative designs incorporating large-scale system optimization and advanced computational approaches can help scale up integrated systems and reduce project cycle time. Modules could be deployed as single, self-standing units for industrial applications, for small utilities such as co-ops and for military installations, or they could be integrated into larger plant configurations. Use of modularity in combination with advanced engineering design techniques, such as parametric design, provides for reductions in construction costs, improved build quality, and reduction in project cycle time. Advantages of modularization include relatively small physical footprints, reduced capital investment, ability to be sited in locations not possible for larger plants, provisions for incremental power additions, as well as the capability of performing load-following to meet the evolving demands of the power grid, and with higher efficiency rates.

Within this document, FE's R&D is organized into six program categories, consistent with current categories for funds appropriated to FE for near-term R&D: (1) Advanced Energy Systems; (2) Crosscutting Research; (3) CCUS; (4) Supercritical Transformational Electric Power (STEP); (5) REEs; and (6) Oil and Natural Gas Research. Each R&D program category portfolio encompasses a series of related technologies.

The information in Table 2 below briefly describes each program and the activities supported by each of its contributing technology programs. The *FE R&D Portfolio Summary* also illustrates how each of FE's R&D programs and activities align with the goals, objectives, and performance measures of this roadmap. The performance goals and strategies in this roadmap are subject to future Congressional appropriations.

Message from Mark Maddox, Senior Policy Advisor to the Secretary of Energy

"The Office of Fossil Energy's strategic vision is deeply rooted in making the R&D investments necessary to achieve our goals and objectives that will move the needle toward near-zero emissions and support the Nation's energy demand."

– Mark Maddox

GOAL	OBJECTIVE	PERFORMANCE MEASURES *(Note: Green check marks denote direct alignment with performance measure; shaded green field denotes alignment with objective and goal but no specific performance measure)*	Advanced Energy Systems	Crosscutting Research	Carbon Capture, Utilization, and Storage	Supercritical Transformational Electric Power	Rare Earth Elements	Oil and Natural Gas Research
1. Develop secure and affordable fossil energy technologies to realize the full value of domestic energy resources	1.1 Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future	• By the end of Fiscal Year (FY) 2023, advance at least two engineering studies of advanced high-efficiency, low-emissions (HELE) coal fired systems that have flexible operating capacity to meet baseload and load following requirements needed for the evolving grid.	✓	✓				
		• By the end of FY 2023, improve the average modeled efficiency (heat rate) of an advanced or new coal plant by 5 percent from the 2017 baseline of 38 percent (i.e., to 40 percent).	✓	✓		✓		
		• By CY 2030, R&D technologies are available to support a new coal-fired power plant with CO_2 capture with a cost of electricity at least 30 percent lower than a supercritical PC plant with CO_2 capture, or approximately $30 per tonne of CO_2 captured. *(This is the endpoint target of the Cost of Energy and CO_2 Capture from Advanced Power Systems GPRA Goal)*			✓			
	1.2 Develop technologies to maximize the value from fossil energy resources, including their production and use	• By the end of CY 2020, develop separation technologies at the pilot-scale capable of producing 10 pounds per day of commercial-grade rare earth oxides from coal waste products.					✓	

GOAL	OBJECTIVE	PERFORMANCE MEASURES	Advanced Energy Systems	Crosscutting Research	Carbon Capture, Utilization, and Storage	Supercritical Transformational Electric Power	Rare Earth Elements	Oil and Natural Gas Research
	1.3 Engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship	• By the end of FY 2022, develop basin-specific technologies for unconventional resources, including emerging plays; and pursue and build upon unconventional oil and gas big data analytics and high-performance computing capabilities to improve modeled recovery of shale oil and gas by 20 percent, from current baseline of 10 percent to 12 percent recovery efficiency.						✓
		• By the end of FY 2022, complete a methane hydrate stratigraphic test well on the Arctic North Slope.						✓
	1.4 Create smart infrastructure technologies for fossil energy	• By the end of FY 2022, identify at least one potential alloy for a multi-purpose pipe capable of transporting natural gas, hydrogen, and CO_2.						✓
		• By the end of FY 2022, develop technologies that will reduce modeled fugitive methane emissions from natural gas transmission and distribution infrastructure by 50 percent to a level of 13.4 million metric tons (MMT) CO_2 from the current level of 26.7 MMT CO_2, as identified in the EPA's Greenhouse Gas Inventory.						✓
2. Enhance U.S. economic and energy security through prudent policy, advanced technology, and the use of strategic reserves	2.2 Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation	• By the end of FY 2022, improve the average modeled efficiency (heat rate) of a typical plant in the existing fleet by 5 percent from the 2017 baseline of 31 percent (i.e., to 32.5 percent).	✓	✓	✓	✓		
		• By CY 2030, for retrofitting an existing coal-fired power plant with CO_2 capture, ensure capture technologies are available to reduce the cost of capture by 30 percent (actual cost of capture varies for each unit). (Baseline: NETL Cost and Performance Baseline Series; 2012 Capture Technology).	✓	✓	✓	✓		

Table 2 – Overview of R&D Performance Measures to Applicable Goals and Objectives, by Program

The technologies advanced within the FE R&D portfolio span the entire fossil energy value chain, from exploration and production to final disposition, and are aligned to address FE's strategic goals and objectives. Figure 8 depicts the interface of FE's research programs and the sectors in which they contribute to improving the performance and efficiency of the Nation's fossil energy infrastructure.

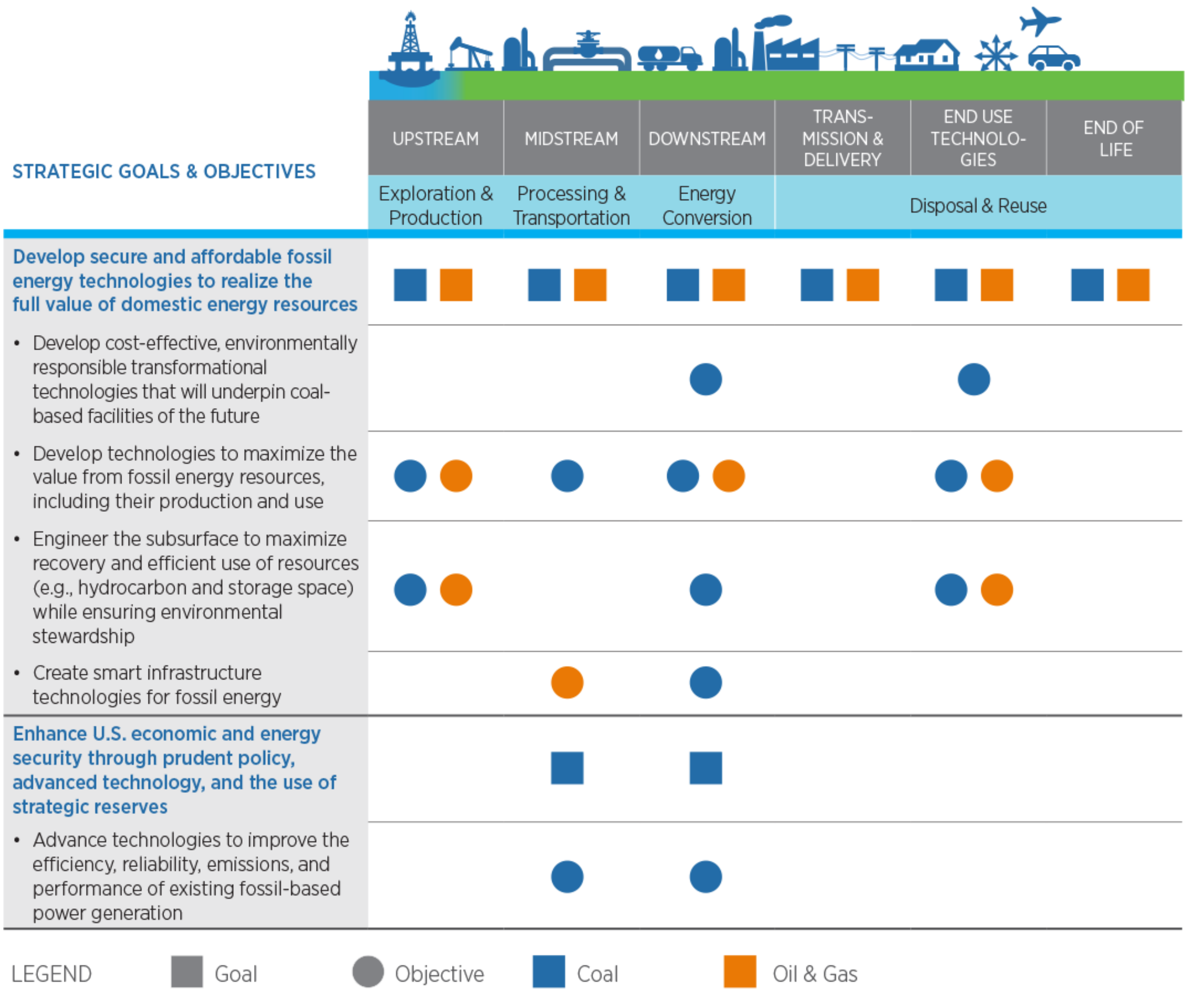


Figure 8 – FE Research Investments Span the Fossil Energy Value Chain

FE R&D Portfolio Summary

Advanced Energy Systems

The Advanced Energy Systems program portfolio develops innovative technologies with near-zero emissions. Key efforts are directed at reducing plant capital and operating costs, improving fuel-conversion efficiencies, increasing plant availability, and achieving ultra-low emissions of pollutants. Technology programs in this portfolio include Power Generation Efficiency (formerly Transformative Power Generation), Advanced Gasification Systems, Coal and Coal-Biomass to Liquids, Advanced Turbines, Solid Oxide Fuel Cells (SOFC), and Advanced Coal Processing (formerly Coal Beneficiation). This program also includes pilot-scale R&D for congressionally directed Transformational Coal projects that improve coal-powered systems' performance, efficiency, emission reduction, and cost of electricity.

Power Generation Efficiency – This technology program is focused on enhancing the performance of new and existing plant-combustion technologies and extending the life of the existing power plant fleet. This is done through new component and material technologies that improve heat rate and reliability; transformational technologies such as pressure gain combustion, oxy-combustion, and chemical looping combustion; and novel and enabling concepts such as the next-generation modular coal-fired power plants that will provide stable power generation with operational flexibility and high efficiency.

Advanced Gasification Systems – This technology program develops small-scale, revolutionary modular designs for converting diverse types of coal into clean synthesis gas to enable the low-cost production of electricity, high-value chemicals, hydrogen, transportation fuels, and other useful products to suit market needs.

Hydrogen – Hydrogen is emerging as a low-carbon fuel option for transportation, electricity generation, and manufacturing applications because it could decarbonize these large sectors of the economy. FE is well-positioned to accelerate this transition by developing technology solutions that enable the production of hydrogen from fossil fuels with zero, or even negative, carbon emissions. Research is currently underway on technologies that can produce hydrogen from coal-derived synthesis gas and build and operate a zero-emissions, high-efficiency co-production power plant that produces hydrogen and electricity from coal. For example, Coal FIRST plants will convert coal, biomass, and waste plastics to generate clean and affordable carbon-neutral electricity and hydrogen.

In addition, based on experience with Natural Gas Infrastructure, FE is in a natural position to conduct R&D initiatives that would lead to more efficient and cost effective technologies for transporting hydrogen between generation facilities and end use locations, in support of a larger effort focused on increasing opportunities for the commercialization of hydrogen as a low-carbon energy source. Similarly, FE has the potential to leverage ongoing work and current infrastructure to improve the economics of hydrogen production from natural gas steam methane reforming (SMR) with CCUS. R&D is underway to develop infrastructure and improve other transportation means to ensure low-cost and low-carbon hydrogen to meet growing demands.

Coal and Coal Biomass to Liquids – This technology program pursues improvements in technology capable of producing high-value liquid fuels and chemicals from domestic coal—with or without biomass as a co-feedstock—at costs comparable to equivalent products derived from petroleum feedstocks. This research leverages indirect conversion technologies under development within the Gasification Systems technology program and may pursue direct conversion by adding hydrogen to coal at elevated temperatures and pressures or by using a hybrid approach such as pyrolysis.

Advanced Turbines – This technology program develops innovative turbomachinery components and high-temperature materials for both combustion and steam turbines, as well as turbomachinery for sCO_2 power cycles. With a focus on improved aerodynamics, heat transfer, and turbine combustion efficiency, these advances will enable highly efficient, low-cost power cycles for application in steam and sCO_2 cycles for coal combustion, advanced coal gasification power systems, and natural gas combined cycle power systems.

Solid Oxide Fuel Cells – This technology program focuses on enabling ultra-efficient, low-cost electricity for the near-term deployment of distributed generation/modular power systems, and the longer-term deployment of utility-scale power systems. SOFCs can be fueled by natural gas or coal-derived syngas, offer the highest energy conversion efficiency of any advanced fossil fuel power-generation technology, are intrinsically amenable to carbon capture, and have minimal water requirements.

Advanced Coal Processing – This technology program—which began in FY 2018—is focused on both enhancing the value of coal as a feedstock and developing new high-value products derived from coal. Planned research includes testing laboratory- and pilot-scale technologies that produce upgraded coal feedstocks and additional revenue-producing products (e.g., carbon fiber, battery and electrode materials, 3D-printing materials, and carbon nanomaterials). This work will also revisit and expand existing coal property databases to assist research efforts and inform potential consumers in both domestic and global markets.

Objective 1.1: Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future

- By the end of FY 2023, advance at least two engineering studies of advanced high-efficiency, low-emissions (HELE) coal fired systems that have flexible operating capacity to meet baseload and load following requirements needed for the evolving grid.
- By the end of FY 2023, improve the average modeled efficiency (heat rate) of an advanced or new coal plant by 5 percent from the 2017 baseline of 38 percent (i.e., to 40 percent).

Objective 2.2: Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation

- By the end of FY 2022, improve the average modeled efficiency (heat rate) of a typical plant in the existing fleet by 5 percent from the 2017 baseline of 31 percent (i.e., to 32.5 percent).

Crosscutting Research

The Crosscutting Research program portfolio develops technologies that are applicable to a broad range of coal-based processes, including power plants. R&D is targeted to increase availability, efficiency, and plant dispatch; reduce operating and maintenance costs; conceive new materials; and reduce water consumption.

Technology programs in this portfolio include Modeling, Simulation, and Analysis; Water Management; Advanced Sensors and Controls and Other Novel Concepts and Advanced Energy Materials. The portfolio also sponsors university capacity building and student training by sponsoring academic research on topics that catalyze innovation and progress toward the FE mission.

Modeling, Simulation, and Analysis – This technology program is developing and applying advanced computational tools at multiple scales, including:

1. Prediction of the behavior of materials in extreme and high-temperature environments.
2. Device-scale simulation of complex multiphase flow reactors.
3. Process-scale optimization and dynamic operations of integrated fossil energy technologies.
4. Grid- and market-scale assessments of advanced technologies.

Research efforts combine theory, computational modeling, advanced optimization, experiments, and industrial input to optimize existing plant operation and enable new fossil fuel power generation systems.

Water Management – This technology program is aimed at reducing cooling water requirements and improving power plant conceptual designs to reduce the amount of water required for other plant processes. New water treatment technologies under investigation, ones which economically derive clean water from alternative sources, will allow greater recycling of water within energy extraction and conversion, as well as carbon storage processes. Data modeling and analysis is being aimed at regional water availability. New sensors designed specifically to measure water parameters will allow for more accurate control and monitoring of water flows throughout its use.

Advanced Sensors and Controls and Other Novel Concepts – This technology program advances optimization, monitoring, and management of fossil energy systems that increase their efficiency and availability, reduce costs, and in some cases, fundamentally enable their operation. Advanced sensor manufacturing research is being conducted to determine the feasibility of constructing embedded sensors into such devices as turbine blades, boiler walls, piping, and tubing, thereby enabling prediction of component failure and anticipatory maintenance to reduce plant downtime. Research on controls focuses on artificial and distributed intelligence for process control, automation, and fault detection. Improved process control allows for more efficient operation during challenging transient conditions, and increased plant dispatching and revenue—all with tighter cybersecurity and environmental control.

Cybersecurity – One of the top priorities of DOE is to make the Nation's electric power grid and oil and natural gas infrastructure resilient to cyber threats. Because our energy infrastructure is increasingly interconnected with a range of new technologies, FE is developing ways to improve the security and reliability of fossil energy systems. This work complements the activities of other DOE offices, including the Office of Cybersecurity, Energy Security, and Emergency Response (CESER). FE's crosscutting program pursues projects that address fossil energy's cybersecurity needs, ranging from cyber threat gap analyses, automated situational awareness technologies, data integration tools, and Blockchain technologies to harden potential targets. Other areas of interest include R&D on new components, configurations and sensor technologies combined with artificial intelligence for real-time operational monitoring and early fault prediction for the safe transport of natural gas in commerce, and infrastructure and technology to enhance and ensure the resilience and reliability of information systems, control networks and cybersecurity.

Advanced Energy Materials – This technology program develops new and cost-effective structural and functional materials needed for fossil energy system applications in extreme operating environments. Research is focused on developing next-generation materials, reducing cost, and accelerating time to market. Advanced manufacturing methods and computational materials modeling are also being pursued as enabling technologies to reduce operations and maintenance costs of both existing coal-fired plants and new fossil energy infrastructure.

Carbon Capture, Utilization, and Storage

FE invests in the improvement of environmental control technology with a focus on reducing environmental impacts and forced outages, to improve coal's competitiveness. The CCUS program portfolio develops CO_2 capture technologies for new and existing power plants and industrial sources that utilize coal and natural gas.

Research on new carbon capture approaches and opportunities to integrate capture with energy conversion are expected to substantially reduce costs. In particular, FE will invest in the development of novel technologies to drive down the price of CCUS and enable economical use of CO_2 in a broader set of markets, even at low oil prices. Science and technology needs include: (1) advances in computational/combinatorial material discovery; (2) advanced process design and development; and (3) device and system optimization using experimentally validated models.

The CCUS program develops processes to convert CO_2 to valuable products and commodities, and it develops methods for permanent geologic storage of captured CO_2. This program also includes pilot-scale R&D for congressionally directed Transformational Coal projects that improve coal-powered systems' performance, efficiency, emission reduction, and cost of electricity.

Ensuring continued environmental stewardship will require knowledge and control of pollutant formation mechanisms in new situations and improvement of pollutant removal processes for greater flexibility.

Carbon Capture – This program is focused on early-stage research that encompasses both post-combustion and pre-combustion CO_2 capture for new and existing fossil-fueled power plants, with an emphasis on reducing the energy load required to separate and compress CO_2 and lowering capital, operation and maintenance costs of the capture and compression equipment. Capture technologies include novel solvents, membranes, sorbents, and cryogenic process, as well as advanced computer simulations to accelerate the rate of materials discovery and optimize process development and integration.

Carbon Utilization – This program is focused on early-stage R&D to enable manufacturing cost-competitive products using captured CO_2 for existing and new markets. Areas of research include the investigation of catalytic conversion and other cost-effective technologies aimed at utilizing captured CO_2, or CO_2 directly from flue gas or mixed gas streams as feedstock for valuable products and commodities such as chemicals, polymers, fuels, or building materials.

Carbon Storage – This program is focused on developing technologies for the safe and permanent storage of captured CO_2 in subsurface reservoirs spanning a variety of onshore and offshore geologic settings. Innovative technologies such as simulation models and tools, high-performance computing, transformational sensors, and intelligent monitoring systems for real-time decision making will improve storage efficiency and associated storage at decreased risk and reduced overall cost, which is critical to enabling efficient management of the Nation's resources. Advances in data analytics will enhance capabilities in subsurface fluid migration imaging, reservoir management, and risk assessment and management. Those advances will improve the certainty of secure containment and help optimize storage.

Objective 1.1: Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future

- By CY 2030, R&D technologies are available to support a new coal-fired power plant with CO_2 capture with a cost of electricity at least 30 percent lower than a supercritical PC plant with CO_2 capture, or approximately $30/tonne of CO_2 captured. *(This is the endpoint target of the Cost of Energy and CO_2 Capture from Advanced Power Systems GPRA Goal)*

Objective 2.2: Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation

- By CY 2030, for retrofitting an existing coal-fired power plant with CO_2 capture, ensure capture technologies are available to reduce the cost of capture by 30 percent (actual cost of capture varies for each unit). (Baseline: NETL Cost and Performance Baseline Series; 2012 Capture Technology).

Supercritical Transformational Electric Power

The STEP program is focused on the development of the 10 MWe indirect-fired sCO_2 facility to demonstrate the operability of the cycle and to evaluate system and component performance and capabilities at the pilot scale. It is part of a DOE-wide initiative that includes the Offices of Fossil Energy, Nuclear Energy, and Energy Efficiency and Renewable Energy. This technology offers cycle operability at high-temperature (≥700 °C) with potential for a thermodynamic cycle efficiency greater than 50 percent. The sCO_2 power cycle has broad applicability across the spectrum of DOE-supported power plant research, including fossil, nuclear, waste heat, and concentrated solar power energy systems.

To achieve these ends, the program is focused on R&D advancements in four key areas: (1) turbomachinery; (2) recuperators; (3) advanced concepts for direct-fired cycles and (4) systems integration and optimization. The technologies and components within each of these key areas will complement each other, advancing the overall development and implementation of the supercritical CO_2 power cycles.

These sCO_2 power cycles are part of a broader portfolio of new fossil fuel energy-conversion systems integrated with CCUS that may be capable of producing competitively priced electricity. The sCO_2 power cycle will have significant benefits for fossil-fueled heat sources with regard to topping and bottoming power conversion cycles, including waste heat recovery.

Objective 1.1: Develop cost-effective, environmentally responsible transformational technologies that will underpin coal-based facilities of the future

- By the end of FY 2023, improve the average modeled efficiency (heat rate) of an advanced or new coal plant by 5 percent from the 2017 baseline of 38 percent (i.e., to 40 percent).

Objective 2.2: Advance technologies to improve the efficiency, reliability, emissions, and performance of existing fossil-based power generation

- By the end of FY 2022, improve the average modeled efficiency (heat rate) of a typical plant in the existing fleet by 5 percent from the 2017 baseline of 31 percent (i.e., to 32.5 percent).

Rare Earth Elements

DOE has identified the diversification of critical materials and REEs supply chains as important to addressing material shortages and encourage action to facilitate extraction, processing, and manufacturing here in the United States. Since the 1980s, China has been the dominant supplier of REEs and strategic materials for global markets. Therefore, a secure, reliable, and sustainable domestic supply of these strategic resources is an important contributor to national security, essential to the continued health of the Nation's economy.

FE has an R&D program aimed at producing a domestic supply of critical materials from the Nation's abundant coal resources and associated byproducts from legacy and current mining operations. Many of the technologies being developed can also be used to separate critical minerals from other mining materials and byproducts. Tapping into these resources has the potential to stimulate the economy with new industries and increase energy security.

FE is working to expand the Nation's REEs reserve base by developing economic pathways to an affordable and secure supply of separated rare earth feedstocks for critical industrial, military, and defense applications. Shifting the sourcing of these materials from imports to resources in coal country can create new economic opportunities in U.S. coal-producing regions and improve the U.S. balance of trade.

Specifically, this technology program investigates the technical and economic feasibility of producing REEs from U.S. coal and coal by-products—driving down the cost and time required for the next generation of coal production and providing new jobs for the fossil fuel industry. Achieving an economic pathway for REEs production from coal and coal by-products requires (1) finding the highest REEs contents (assays) available in these materials; (2) characterizing these materials from the standpoint of economic REEs extraction and (3) developing plant designs to achieve the extraction. The program addresses the need for transformational early-stage R&D in the areas of mineralogy, pressure leaching, continuous ion chromatography, and hydrometallurgy to improve the economics of REEs production from coal and coal by-products.

Objective 1.2: Develop technologies to maximize the value from fossil energy resources, including their production and use

- By the end of CY 2020, develop separation technologies at the pilot-scale capable of producing 10 pounds per day of commercial-grade rare earth oxides from coal waste products.

Oil and Natural Gas Research

The Oil and Natural Gas Research program portfolio is developing technologies to maximize ultimate recovery and operational efficiency from existing conventional and unconventional oil and natural gas sources, as well as emerging fossil energy sources. The prudent development of these natural resources is essential to ensuring the Nation's continued energy resilience and security. The program portfolio includes methane hydrates, natural gas infrastructure, and unconventional oil and gas.

Methane Hydrates – This technology program is advancing the scientific understanding of methane hydrate resources as they occur in nature. It is also developing complex drilling and coring technologies to confirm the scale and nature of this potentially recoverable resource. Research is focused on conducting field tests, fundamental science, numerical simulations, and resource characterization through periodic, well-planned, scientific drilling programs supported by sustained expertise at the National Laboratories and in academia. The research helps to safely and efficiently discover, characterize, and recover methane from these hydrates.

Natural Gas Infrastructure – This technology program aims to improve the integrity and operational reliability, minimize the emissions, and enhance the efficiency of natural gas delivery in the United States. Research addresses five key areas: (1) External Leak Detection and Rate Quantification Technologies/Methodologies; (2) Pipeline Inspection and Repair Technologies; (3) Improved Compressor System Operational Performance and "Next-Generation" Compressors; (4) Smart Sensors for Pipeline Operations and (5) Advanced Materials.

Upstream Oil and Gas (OG) – Upstream OG technology is focused on ensuring a reliable, affordable, and secure domestic supply of oil and natural gas that can be developed and produced in a manner that maximizes recovery efficiency while minimizing environmental impact. Despite significant growth in production of unconventional oil and gas (UOG) resources during the "shale revolution," the mechanisms controlling recovery efficiency in these reservoirs remain poorly understood.

FE is focused on increasing the recovery factor in Upstream OG reservoirs. Recovery factors (the ratio of produced resource to total in-place resource) are typically quite low—approximately 20 percent in gas-rich shale reservoirs and less than 10 percent in liquid-rich plays. Increasing the per well recovery factors of UOG plays will reduce the development impacts by reducing the number of wells required to economically exploit the resource. Even in onshore and offshore conventional oil reservoirs, more than half of the oil typically remains. The long-term maximization of ultimate recovery from this significant domestic energy resource can benefit from advanced scientific understanding of the thermodynamic, petrophysical, chemical, and geomechanical processes controlling the producing behavior of UOG reservoirs and the relationship between these processes and well stimulation practices. Given current estimates of UOG resources, the benefits of advanced technology that allows greater resource recovery from fewer wells could be substantial, with significant economic benefits.

Research is aimed at (1) improving understanding of unconventional resources; (2) increasing recovery of conventional and unconventional OG resources; and (3) mitigating impacts associated with OG recovery. Given the large volumes of produced water associated with oil and gas operations, efforts to reduce and treat such produced water will be a key focus.

Objective 1.3: Engineer the subsurface to maximize recovery and efficient use of resources (e.g., hydrocarbon and storage space) while ensuring environmental stewardship

- By the end of FY 2022, develop basin-specific technologies for unconventional resources including emerging plays and pursue and build upon unconventional oil and gas big data analytics and high performance computing capabilities, to improve modeled recovery of shale oil and gas by 20 percent, from 10 percent (current baseline) to 12 percent recovery efficiency.
- By the end of FY 2022, complete a methane hydrate stratigraphic well test on the Arctic North Slope.

Objective 1.4: Create smart infrastructure technologies for fossil energy

- By the end of FY 2022, identify at least one potential alloy for a multi-purpose pipe capable of transporting natural gas, hydrogen, and CO_2.
- By the end of FY 2022, develop technologies that will reduce modeled fugitive methane emissions from natural gas transmission and distribution infrastructure by 50 percent to a level of 13.4 MMT CO_2 from the current level of 26.7 MMT CO_2, as identified in the EPA's Greenhouse Gas Inventory.

The performance measures identified for each goal are summarized on the technology timelines indicated in Figures 9–17. The collection of performance measures shows how strategic goals are achieved in the near term and demonstrate the collective contributions of multiple programs to achieving the overall goals. The performance measures that are achieved by 2030 are foundational to continued technical innovations described in the section "Technology Landscape." The bridge between these two periods of technical achievements is the continued maintenance and extension of competencies, discussed in the next section, **Supporting Infrastructure (2030)**. Investments beyond FY 2021 are subject to the future year budgetary prerogatives of the President. Additionally, later stage items identified in the technology timelines below could be in partnership with industry and could be financed in part, or in full, by non-Federal interests.

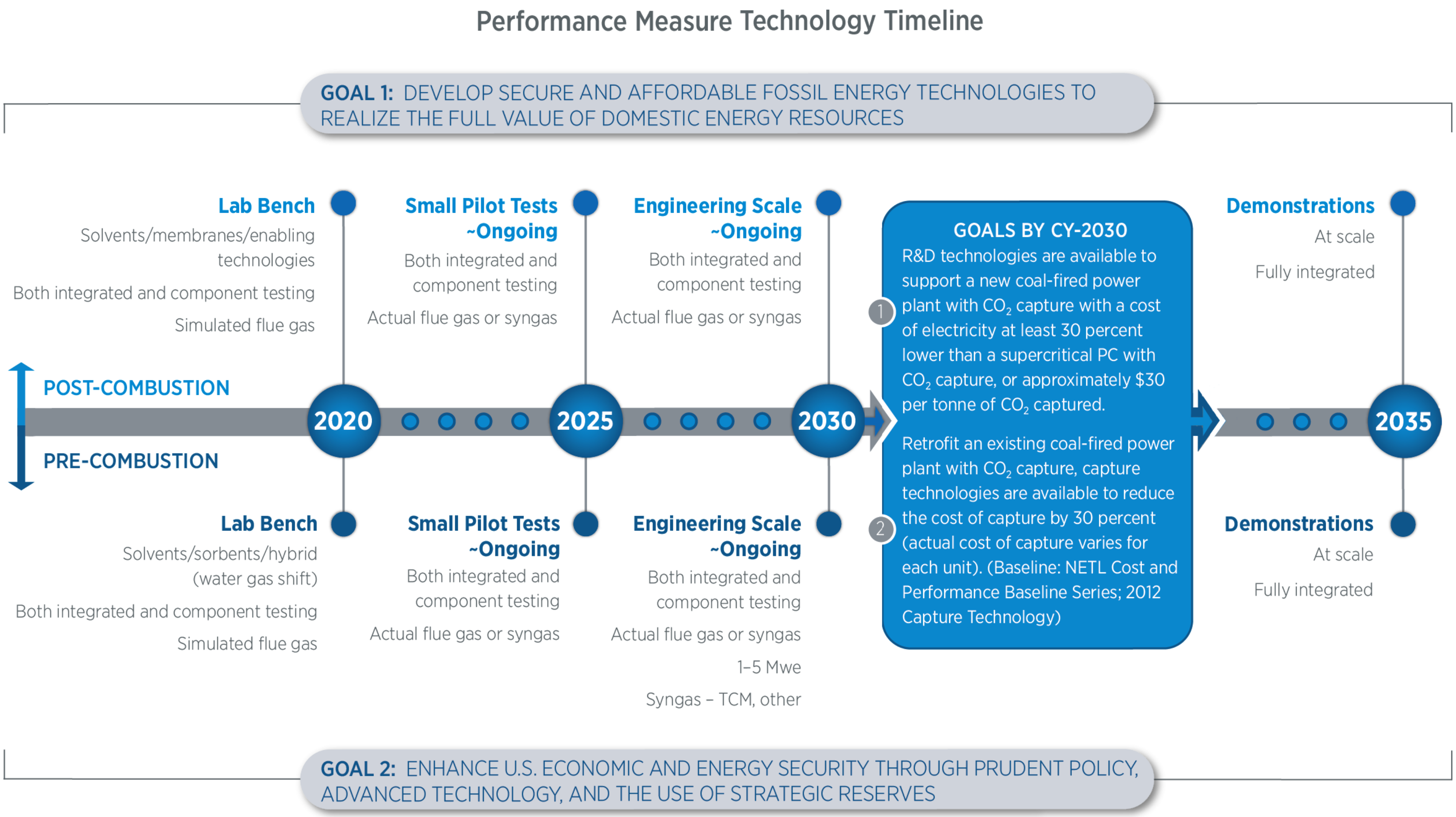


Figure 9 – Goal 1 and Goal 2: Contributive Performance Measures Timeline for Carbon Capture Program (FE Objectives 1.1 and 2.2)

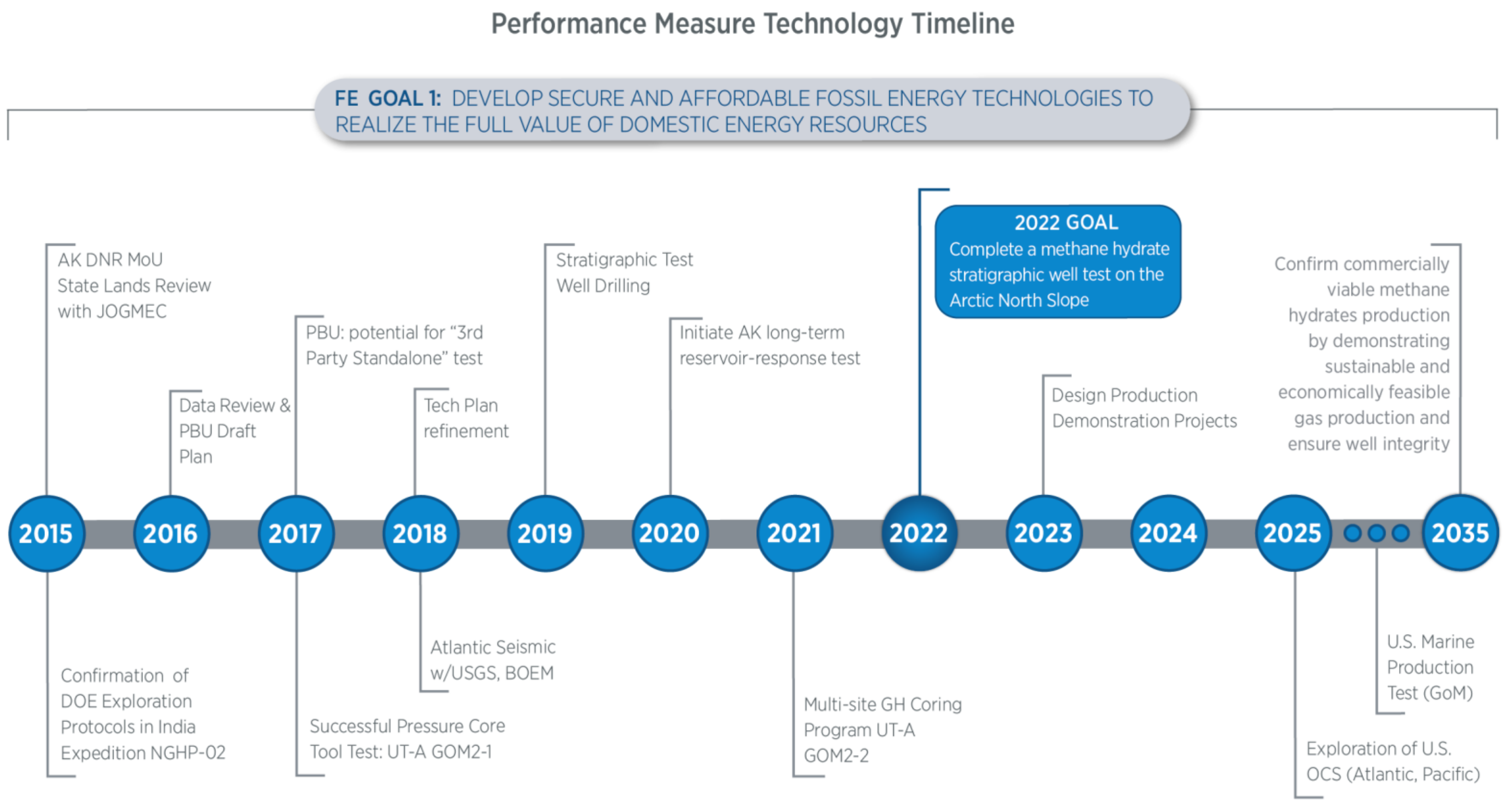


Figure 10 – Goal 1: Contributive Performance Measures Timeline for the Oil and Gas Program (Methane Hydrates) (FE Objective 1.3)

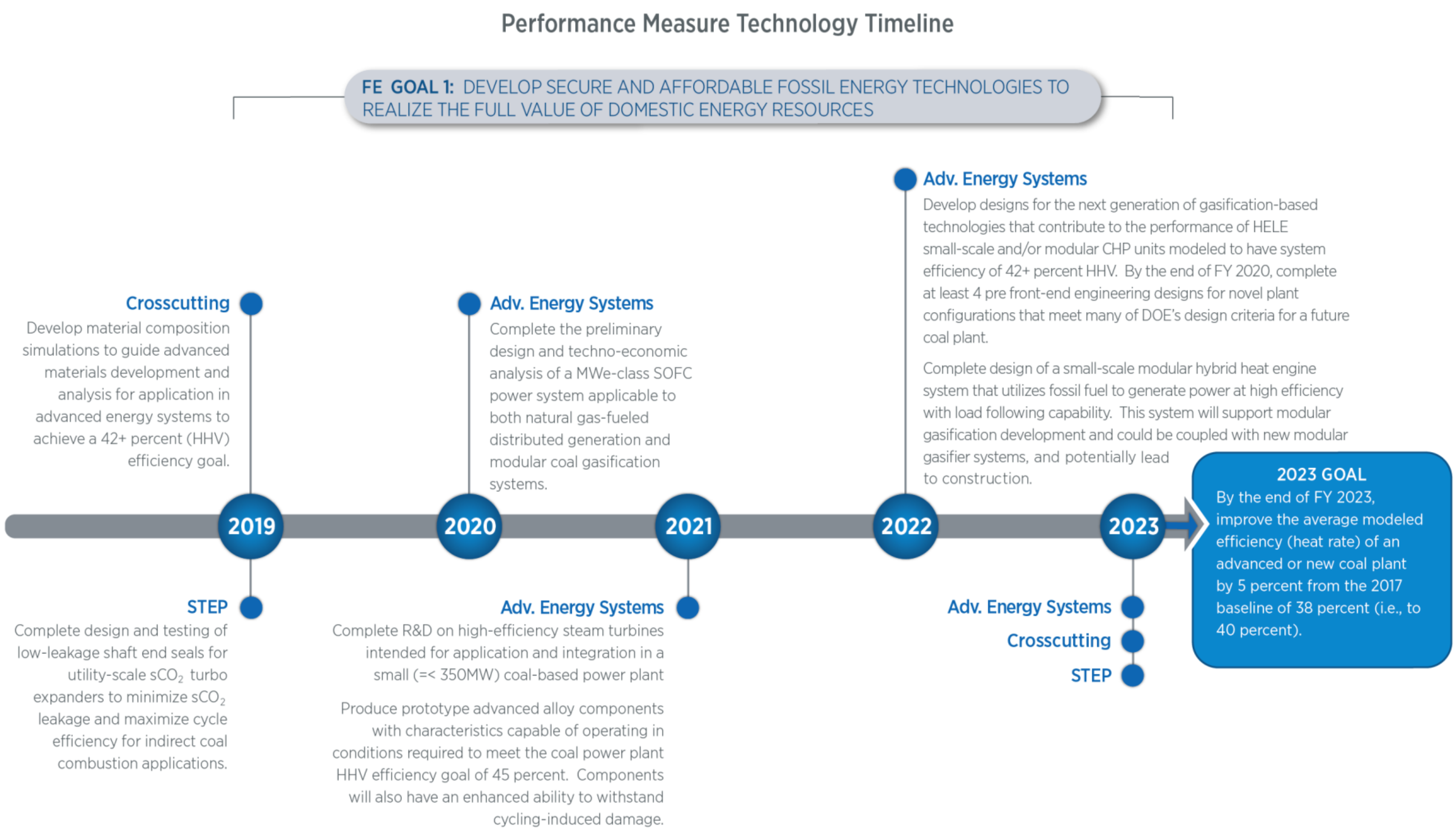


Figure 11 – Goal 1: Contributive Performance Measures Timeline for Crosscutting, STEP, and Advanced Energy Systems Programs (FE Objective 1.1)

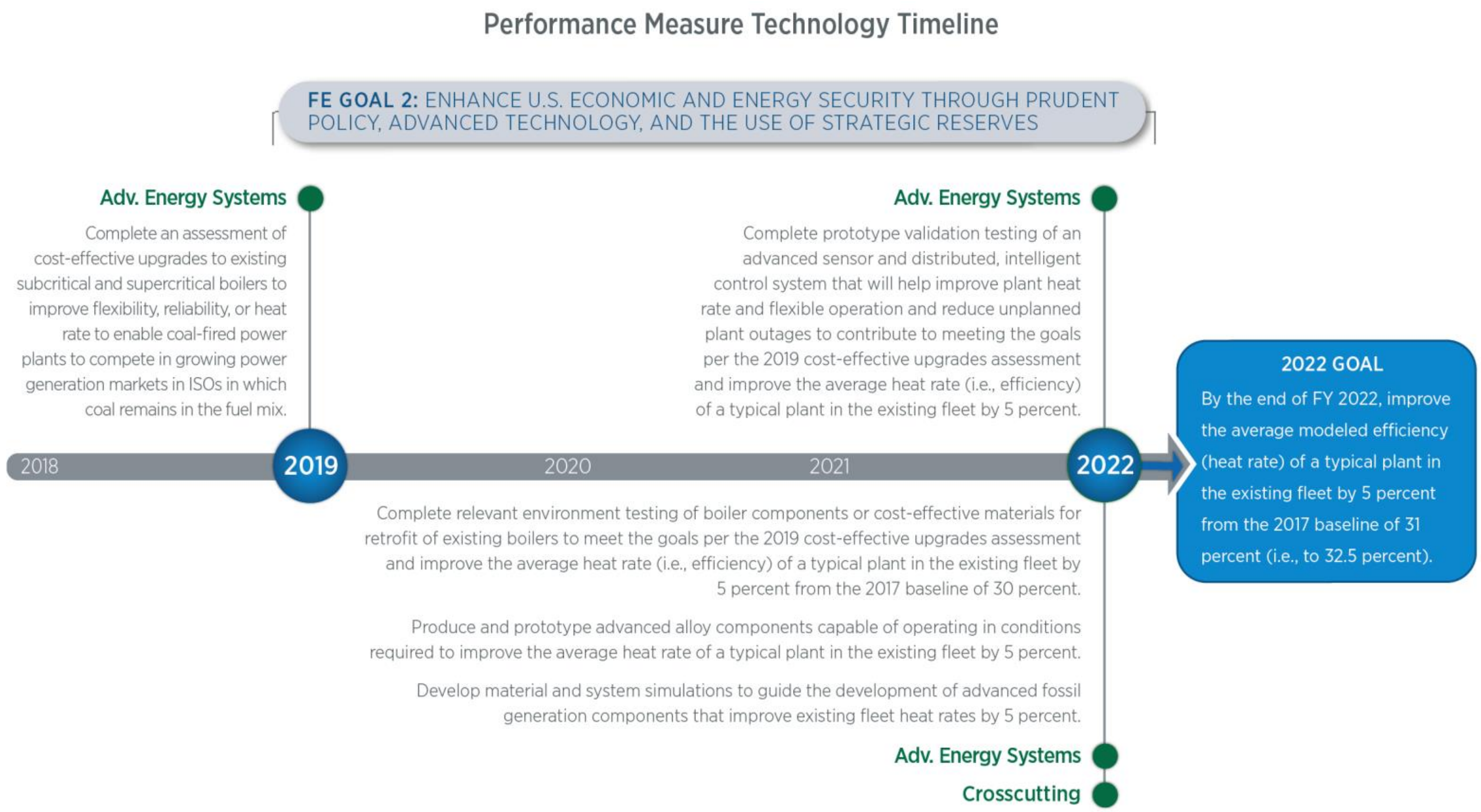


Figure 12 – Goal 2: Contributive Performance Measures Timeline for the Crosscutting and Advanced Energy Systems Programs (FE Objective 2.2)

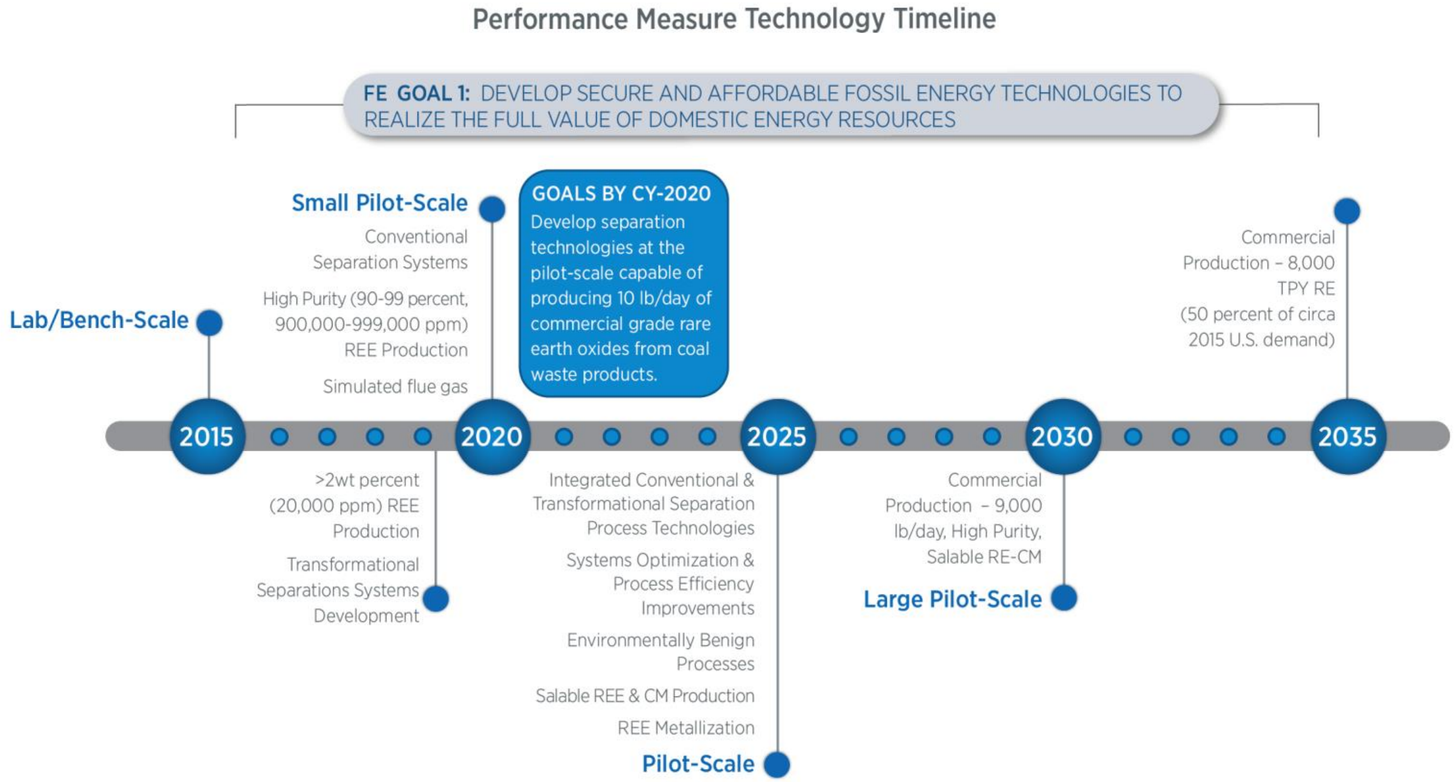


Figure 13 – Goal 1: Contributive Performance Measures Timeline for the Rare Earth Elements Program (FE Objective 1.2)

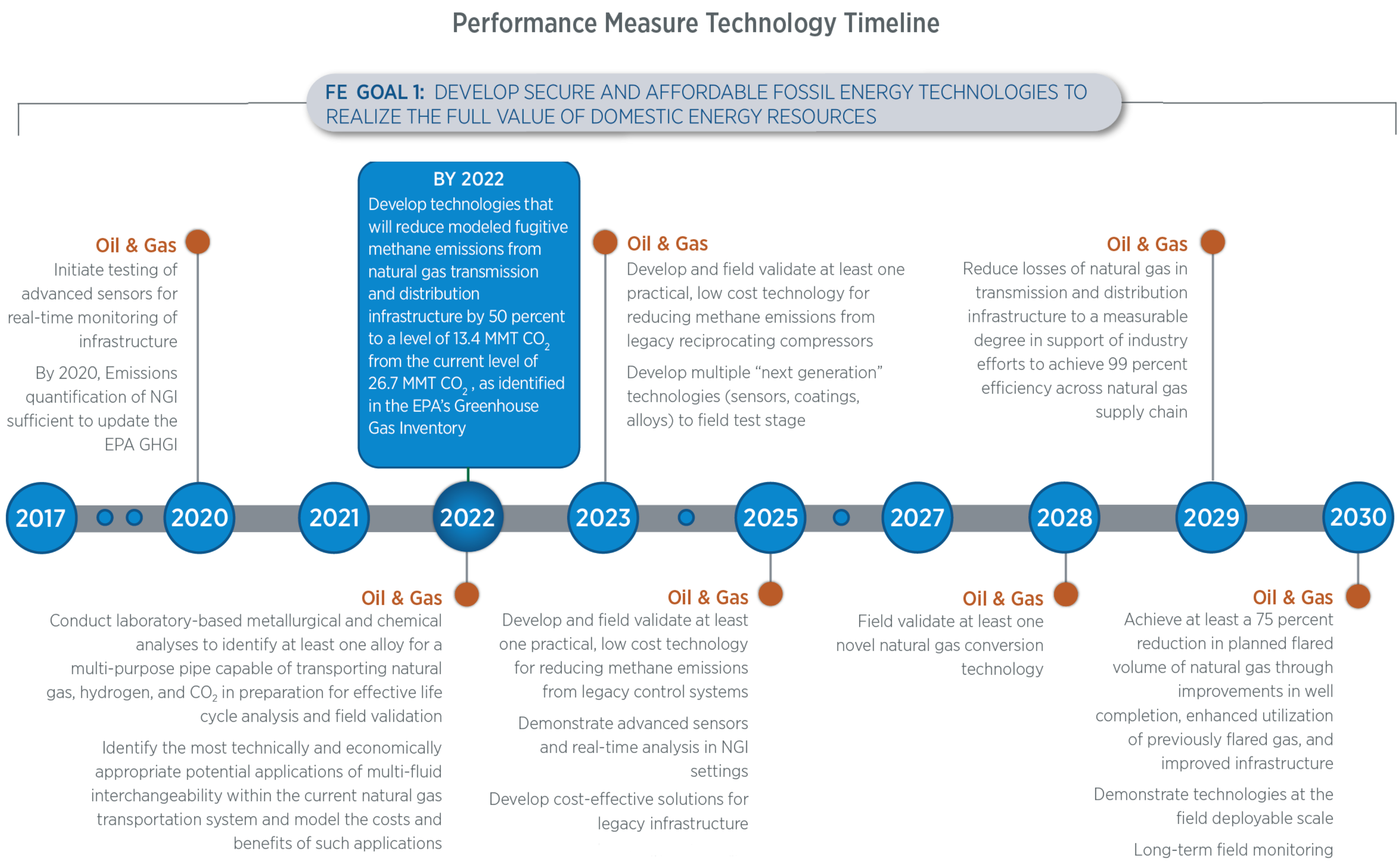


Figure 14 – Goal 1: Contributive Performance Measures Timeline for the Oil and Gas Program (Infrastructure) (FE Objective 1.4)

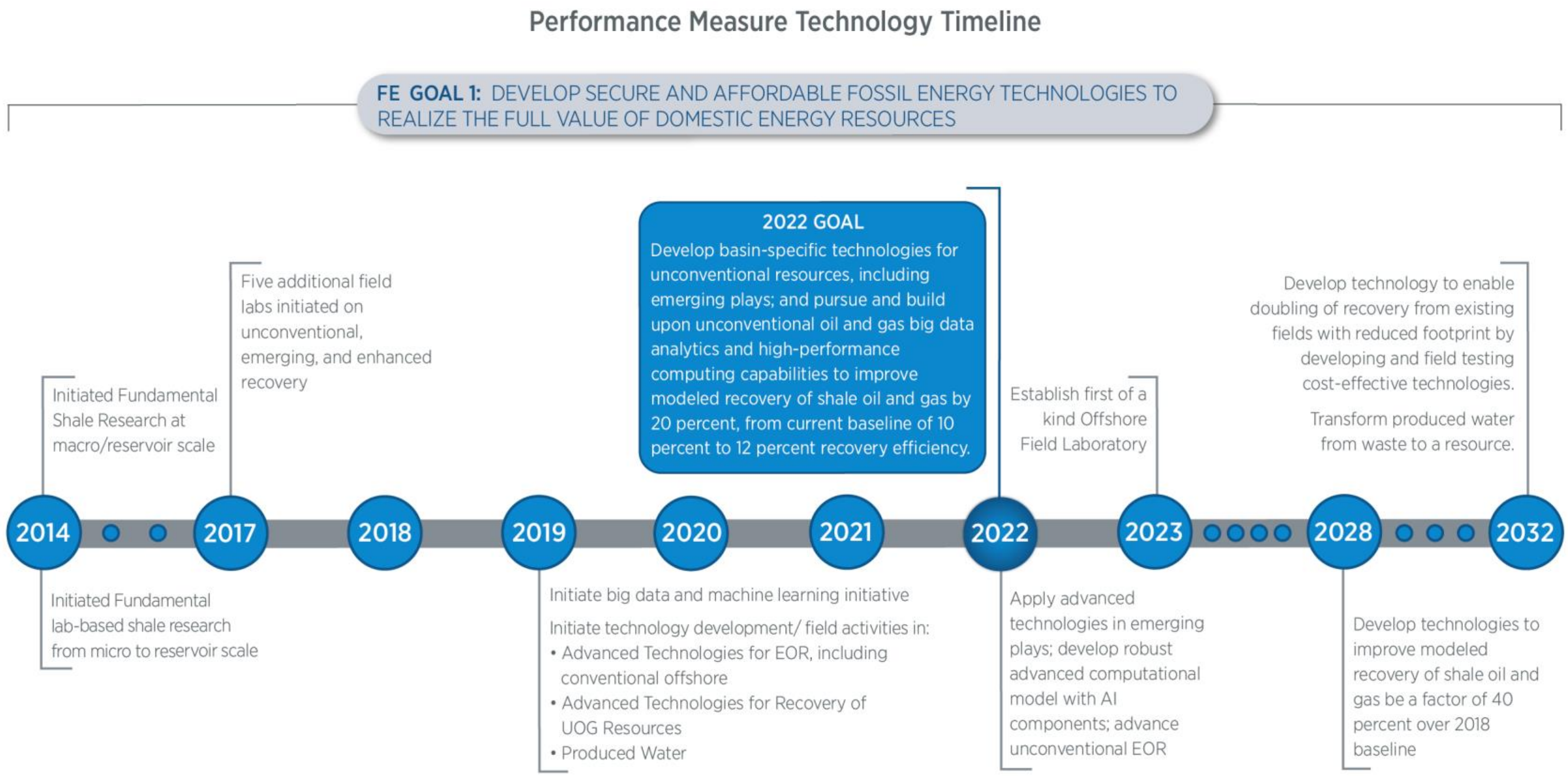


Figure 15 – Goal 1: Contributive Performance Measures Timeline for the Oil and Gas Program (Upstream Research) (FE Objective 1.3)

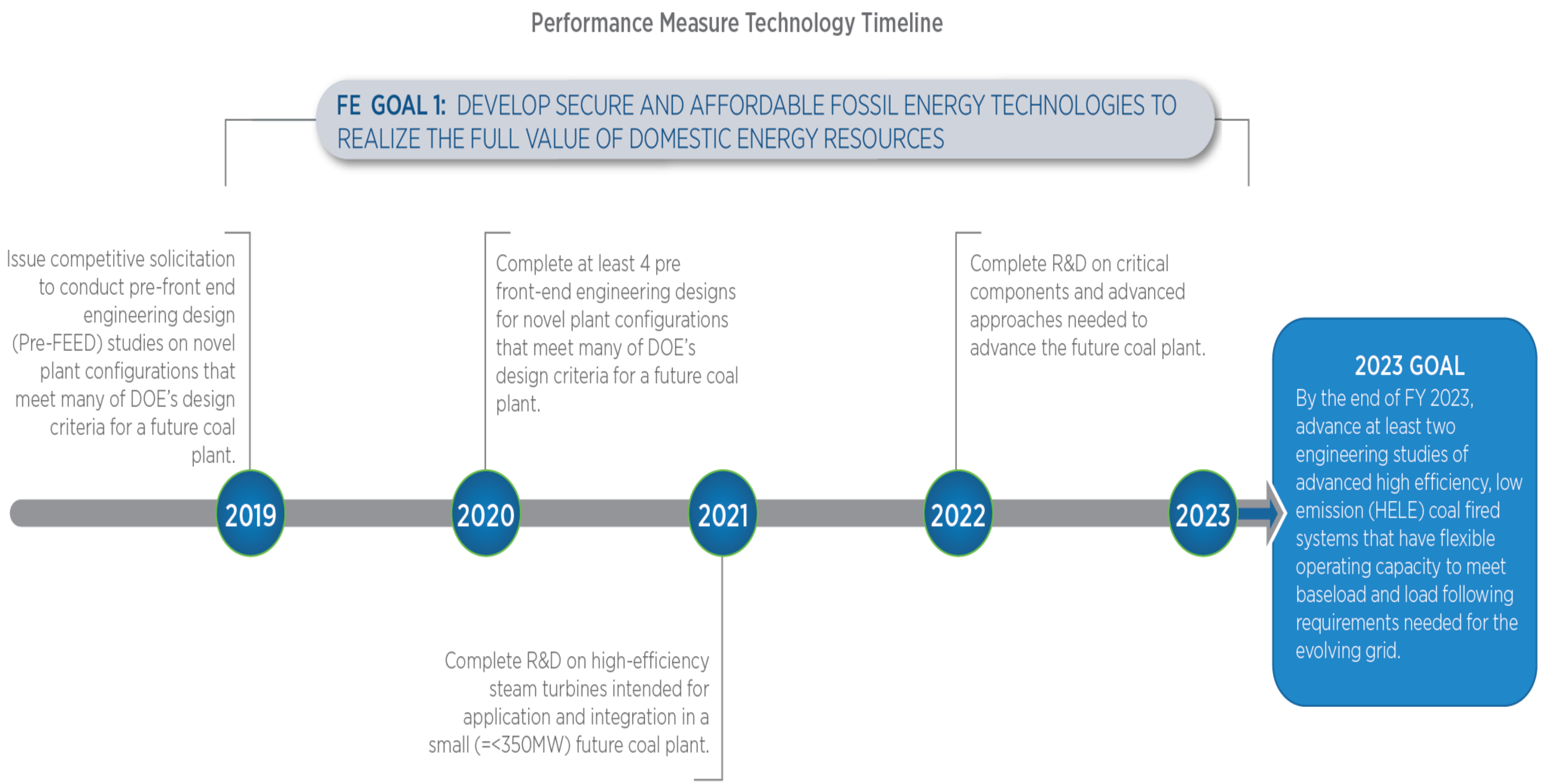
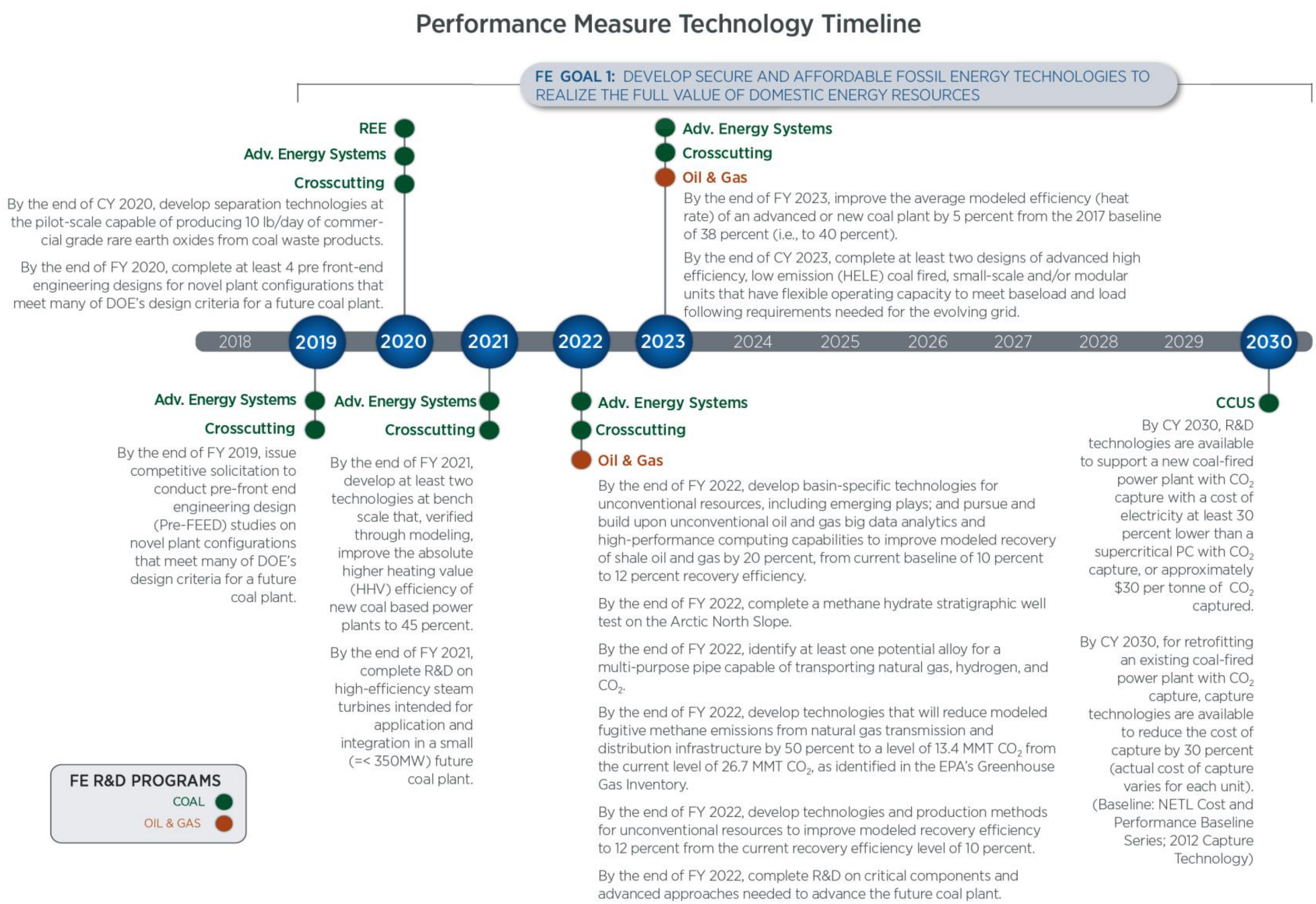


Figure 16 – Goal 1: Contributive Performance Measures Timeline for the Advanced Energy Systems Program (FE Objective 1.1)



* The simultaneous integration of multiple advanced technologies is vital to achieving Strategic Plan Performance Measures

Figure 17 – Goal 1: Performance Measures Technology Timeline

VII. Supporting Infrastructure (2030)

Overview

Infrastructure investments are targeted to maintain, sustain, and recapitalize the facilities that are critical to achieving the goals of near-term R&D programs, as well as to enhancing those capabilities critical to meeting enduring technical challenges. Capital investments are identified, planned, and prioritized to enhance technical capabilities, meet specific programmatic mission requirements, upgrade and maintain critical infrastructure, and meet mandated sustainability goals. The primary program benefit, type, and magnitude of investment, as well as the purpose of the investment, are the principal factors that determine the type of funding used. Additionally, facilities and infrastructure projects less than $20 million are typically funded using infrastructure funding, while projects larger than $20 million require line-item appropriations.

Capital planning begins with an assessment of existing core capabilities and FE mission needs, and project requirements are developed with consideration of overall mission, programmatic needs, condition assessments, energy audit findings, deferred maintenance, and factors impacting site development. Project recommendations are evaluated by an Investment Review Board for final selection and implementation.

Infrastructure Strategic Objectives

An infrastructure investment strategy has been developed to meet four primary objectives:

Objective 1

Includes projects targeted to maintain and enhance mission-critical core capabilities. These projects ensure that essential core capabilities focused on near-term R&D goals are sustained into the future.

Objective 2

Includes major infrastructure projects needed to ensure future mission readiness for enduring technical challenges. These involve complete renovations of existing facilities or construction of new facilities.

Objective 3

Includes projects targeted to maintain critical infrastructure to ensure mission readiness and manage the growth in deferred maintenance.

Objective 4

Includes projects targeted to maintain or enhance mission-critical IT infrastructure.

Infrastructure Project Timeline

Projects are targeted to maintain and enhance mission-critical core capabilities and are aligned with enduring technical challenges. These projects ensure that essential core capabilities are sustained into the future.

1–5 Years: *Investments in the 1–5-year time frame are targeted to achieve two primary goals: (1) maintain and strengthen critical core capability to ensure FE continues to meet the DOE mission through near-term research and development and (2) bolster capability essential for FE to meet the DOE mission through 2030.*

6–10 Years: *The major initiatives planned in this time frame will ensure DOE's mission readiness through 2030 and beyond to meet enduring technical challenges. The focus of FE's investment plan during the 6–10-year timeframe will expand some of these capabilities, but the primary focus will be on a strategic upgrade of R&D laboratories to ensure future mission readiness. These renovations will include upgrades to building ventilation and controls and alarm infrastructure to meet sustainability goals for DOE buildings, thus reducing the laboratories' emissions, energy usage, and operation and maintenance costs.*

Major Infrastructure Projects

Major infrastructure projects will be aligned with the enduring technical challenges identified in the **Technology Landscape** section and support maturation of existing core capabilities. In most cases, the major infrastructure projects will crosscut several enduring technical challenges and core capabilities within FE. Each major project will be prioritized in a multi-year project plan.

Core capabilities are leveraged to support near-term R&D projects. They will be matured over time to address enduring technical challenges. Investments will be prioritized to ensure applicability to both near-term R&D and enduring technical challenges.

Core Capability: Applied Materials Science and Engineering

The FE capability in Applied Materials Science and Engineering is focused on the development of advanced structural materials and functional materials that are essential to developing the next generation of efficient, sustainable fossil-fueled power generation and fossil-based resource recovery. New heat- and corrosion-resistant alloys are not only critical to achieving FE's enduring missions, but they are also broadly applicable to other energy sources, including geothermal energy, nuclear energy, and industrial waste heat recovery. Functional materials are critical for two initiatives that will develop new sensor technologies needed to improve the efficiencies of advanced power systems and subsurface sensing, and to produce and recover high-value products from fossil fuel resources. Infrastructure investments in this area will ensure future mission readiness, improve operational safety of laboratories, and proved access to the range of conditions necessary to meet FE's enduring missions into the future.

Core Capability: Chemical Engineering

As a technology gap exists for addressing cycle integration and controls issues for these advanced cycles, FE plans to expand its testing capability by using cyber-physical systems testing to identify cycle integration issues and develop control strategies to facilitate advanced cycle development. FE and NETL possess unique facilities for advanced energy systems development with optical accessibility for validation of simulations. New concepts such as oxy-fuel, sCO_2, and other advanced concepts may require additional infrastructure development as cycle temperatures and pressures increase and more emphasis is placed on advanced cycles. To achieve high efficiency, future power cycles will be highly integrated. Facilities will leverage existing core capabilities and expertise, while improving operational safety. Investments to advance test capabilities for developing future low-emission power systems will be considered, as means of improving cycle efficiencies.

Core Capability: Decision Science and Analysis and Systems Engineering and Integration

FE has substantial capabilities in Decision Science and Analysis and Systems Engineering and Integration. FE's NETL is recognized for pioneering work to integrate high-fidelity, advanced simulation capabilities into systems engineering software to enable development of advanced cycles. The 1–5-year vision for NETL is to grow the Decision Science and Analysis and the Systems Engineering and Integration capabilities, and to better integrate these capabilities and to more fully assess technology options to meet the FE mission. Investments to help identify and accelerate the commercial development of advanced FE power concepts will be considered.

Core Capability: Environmental Subsurface Science

FE has significant capabilities for supporting DOE's mission elements in the environmental subsurface arena. These include state-of-the-art capabilities for energy resource characterization and assessment; energy database development, characterization, and modeling of subsurface permeability and flows; and assessment of water quality. Investments will ensure that capabilities in these areas continue to fully meet DOE's mission. In addition, new capabilities will enable trace metal and isotope ratio analyses, and should provide key information to support both the environmental subsurface and materials development mission spaces.

R&D Computing Environment

R&D computing is defined as computing that supports scientific discovery of the laboratory mission, including institutional computing and clusters, scientific workstations and servers, collaboration and storage services, networking, special-purpose computing for data collection and analysis, and scientific software licenses not captured in other places. NETL is home to JOULE, a high-performance computing platform designed specifically to address the needs of materials science, chemistry, and fluid dynamics research. Supercomputing gives FE and industry partners an innovation advantage, enabling the development of globally competitive technologies and a sustainable and affordable energy portfolio for the Nation. Congress approved funding to refresh the current JOULE supercomputer, employing a 3-year lease option beginning in FY 2018. The new system provides an eight-fold increase in performance to ensure readiness to meet the FE mission over the period from 2018 – 2020.

The demand for computing infrastructure within the R&D portfolio continues to increase. Meeting the R&D computing needs while satisfying Government-wide directives for data center consolidation and efficiency requires a unified infrastructure to support multiple mission components and will require a modern data center. Improving the network connectivity among all sites in support of scientific computing is a critical component of maintaining mission readiness.

Technology Transfer (Commercialization)

Transitioning to commercialization is a part of an integrated R&D program that contributes to DOE's strategic goal of ensuring America's access to—and use of—secure, affordable, and reliable fossil energy resources and strategic reserves. Technology transfer to a commercialization partner is the logical extension of the R&D activities performed and implemented by FE. The advanced fossil energy technologies that are developed are more commercially attractive if they have been tested at full scale in an integrated facility before they are ready for full commercialization, and DOE support can help reduce the risks inherent in these first-of-a-kind projects. In this way, FE and its broad array of partners—from industry as well as from academic institutions—can develop commercially viable technologies.

Technical and financial challenges associated with the deployment of new "high-risk" fossil energy technologies must be overcome for them to succeed in the marketplace. Technology transfer at high technology readiness levels reduces technical, economic, and environmental risks and uncertainties for new technologies and provides the large-scale experience needed to validate pilot or smaller-scale tests at the most cost-effective scale.

Partnerships and Stakeholder Engagement

Partnership activities enable FE to expertly deliver on its core mission. FE utilizes a comprehensive suite of contractual vehicles, including NETL's inherent authority as a Government-owned, Government-operated laboratory, to pursue technology development through intramural and extramural associations and to accelerate transition of those technologies into commercial markets. Successful mission delivery requires effective partnerships.

FE's partnership strategies are founded upon—among other things—DOE's 10-Year plans for the Science and Energy National Laboratories, DOE's Strategic Plan, FE program plans, NETL infrastructure plans and site plans, and FE competency development plans. These technical visioning tools serve as an overarching framework within which partnership strategies are designed—strategies that ensure mission readiness by maintaining infrastructure, retaining intellectual capital, and pursuing strategic alliances.

FE pursues partnerships to deliver the most effective technical development portfolio relative to identified needs of supported agencies and programs. FE utilizes a variety of classically defined Strategic Partnership Projects and augments them with financial assistance agreements to (1) access universities; (2) pursue public-private partnerships; and (3) engage Federal agencies, programs, and national laboratories.

FE partnerships deliver competency in exchange for resources (funds in or in-kind) and deliver resources in exchange for competency (funds out). Often, when FE partners to deliver competency (funds in), NETL submits proposals (solicited and unsolicited) to non-DOE Federal agencies (e.g., the U.S. Department of the Interior) and non-Federal organizations (domestic and foreign, public and private) for work that aligns with DOE's and FE's research priorities and partnership strategies. Where appropriate, FE engages industrial, academic, and government partners to participate in the proposals.

FE conducts multidisciplinary research in some technical domains that are not economically viable, or which exceed the competency of traditional developers. FE's collaborations with external organizations have solidified NETL's reputation as a technical resource, both within and outside government.

To ensure that FE remains the Nation's authority on fossil energy and related technologies, and to promote the commercialization of these technologies in international markets, FE works in partnership and shares information with domestic and foreign governments, industry, and research organizations through a variety of research agreements. While some of these arrangements include R&D work conducted in FE laboratories and partner facilities, all agreements include the exchange of information between the partners and may also include the provision of training seminars for the partner's stakeholders. These actions have proven highly effective in strengthening FE's value, thereby leveraging American energy solutions for global markets.

VIII. Conclusion

The FE Roadmap connects near-term R&D goals and the enduring technical challenges facing the Nation. These technical objectives were articulated in the context of near- and long-term policy goals, current technical and economic realities, and the transformation of the domestic energy economy over the past decade.

FE supports near-term research and technology development efforts that: (1) advance the coal plants of the future by advancing small-scale modular coal plants of the future, which are highly efficient and flexible with near-zero emissions; (2) modernize the existing coal fleet by improving the performance, reliability, and efficiency of the existing coal-fired fleet; (3) reduce the cost and risk of CCUS to enable wider deployment; (4) expand the use of big data by leveraging artificial intelligence to optimize the recovery of oil and gas resources with real-time analysis informed by machine learning; (5) address the energy-water nexus by improving our efficient use of scarce water resources; and (6) advance REEs, critical materials, and coal products technologies by improving REEs separation and recovery technologies and processes to manufacture valuable products from coal, to address current global market and process economics.

Technology development roadmaps aligned with existing budgets were used to describe interim technical progress in the context of overarching program milestones. FE will continue to maintain disciplined focus on enduring technical challenges that will face the Nation for decades. These challenges include HELE Power Generation; Fossil Energy Integration, Optimization, and Resiliency; Real-Time Decision Science for the Subsurface; and Manufacturing High-Value Carbon Products from Domestic Coal. The infrastructure investments necessary to maintain, sustain, and recapitalize facilities supporting the competencies required to address near-term research goals and to meet enduring technical challenges are identified within this roadmap.

This comprehensive roadmap outlines courses of action that hold the potential to result in a more prosperous, secure, and reliable domestic system of energy production, transfer, delivery, and end use. Adaptation of this roadmap will accelerate American leadership within the global energy economy, support preservation of economic freedom and expansion of prosperity, and preserve this country's stature as the global leader at the intersection of technology innovation and commerce.