U.S. Department of ENERGY

Hydrogen with Carbon Management Multi-Year Program Plan

December 2024

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1. Overview

1.1 Introduction and Background

As part of the DOE Hydrogen Program, and aligned with the U.S. National Clean Hydrogen Strategy and Roadmap, the Hydrogen with Carbon Management Program seeks a cost-competitive decarbonized alternative to traditional fossil fuels, and provides a platform for developing the advanced energy systems of the future while reducing carbon dioxide (CO_2) and other emissions. Seeking a cost-competitive decarbonized alternative to traditional fossil fuels, the Hydrogen with Carbon Management Program provides a platform for developing the advanced energy systems of the future while reducing carbon dioxide (CO_2) and other emissions. The program will focus on the production of hydrogen through gasification, the ability to fire zero-carbon fuels in combustion turbines, reversible solid oxide fuel cells (R-SOFCs), advanced energy materials, sensors and controls, supercritical carbon dioxide (sCO_2) power cycles, and the simulations and computational tools needed to design these systems. Improvements to these technologies are also applicable to other energy systems. In addition, these improvements will enable new and existing plants to use zero-carbon fuels efficiently and safely, making them less carbon-intensive and allowing these assets to provide continued low-cost power and resilient, flexible grid services. For these reasons, the Hydrogen with Carbon Management Program aligns with the administration's priority to reduce the environmental impact of the power sector.

The Hydrogen with Carbon Management Program comprises six RDD&D programs: (1) Gasification Systems; (2) Advanced Turbines; (3) R-SOFCs; (4) Advanced Energy Materials (AEM); (5) Sensors, Controls, and Other Novel Concepts; and (6) Simulation-Based Engineering (SBE). A description of each Hydrogen with Carbon Management program is presented below.

Gasification Systems

Gasification is a process that can convert any carbon-based raw material into fuel gas, also known as synthesis gas or syngas. Gasification occurs in a gasifier, typically a high-temperature pressurized reactor where oxygen or air and steam are reacted with the feed materials, causing conversion to syngas and solid residues. Syngas contains large fractions of hydrogen and carbon monoxide (CO) and is highly useful as a gaseous fuel to fire gas turbines and as a feedstock for producing liquid fuels, ammonia, and chemicals. An advantage of gasification is the flexibility in feedstocks, with gasifiers available that can accept varied carbon-containing waste materials that would otherwise require land disposal. Gasifiers can accept solid biomass materials as fuel, and sustainably sourced biomass can realize net negative carbon footprint performance when co-gasified with other feedstocks.[1] Also, gasification allows inherent "pre-combustion" carbon capture configurations, allowing efficient decarbonization of any syngas-based process.

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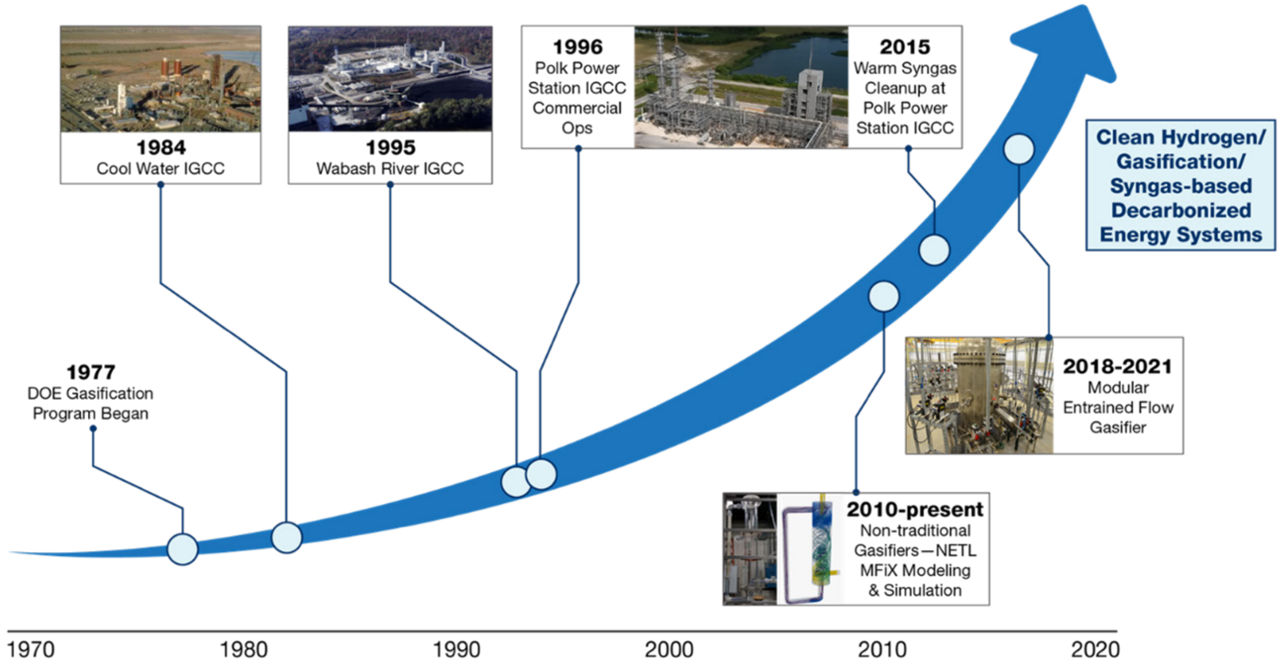
[1] https://netl.doe.gov/projects/files/ComparisonofCommercialStateofArtFossilBasedHydrogenProductionTechnologies_041222.pdf

The Gasification Systems program and its forerunners at the U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) played an important role in the development of efficient fossil fuel energy technologies in the United States. An early focus was on producing alternative gasification-based fuels (e.g., syngas or liquid fuels) in response to the energy crisis of the 1970s. Later, a need for electric power generation with superior emissions performance drove a significant program effort in large-scale integrated gasification combined cycle (IGCC) power plants. The Gasification Systems program has continued developing gasification and syngas technologies, including transport gasification, warm syngas cleanup, commercialization of high-performing gasifier refractories developed under the IGCC program, and sophisticated modeling and simulation tools (e.g., NETL's Multiphase Flow with Interphase eXchanges [MFiX] suite). These technologies are part of the larger suite of carbon management technologies aimed at accelerated achievement of sustainable, net-zero, and even net-negative carbon emissions energy production needed for economy-wide decarbonization.

Exhibit 1-1. Achievements of DOE's Gasification Program

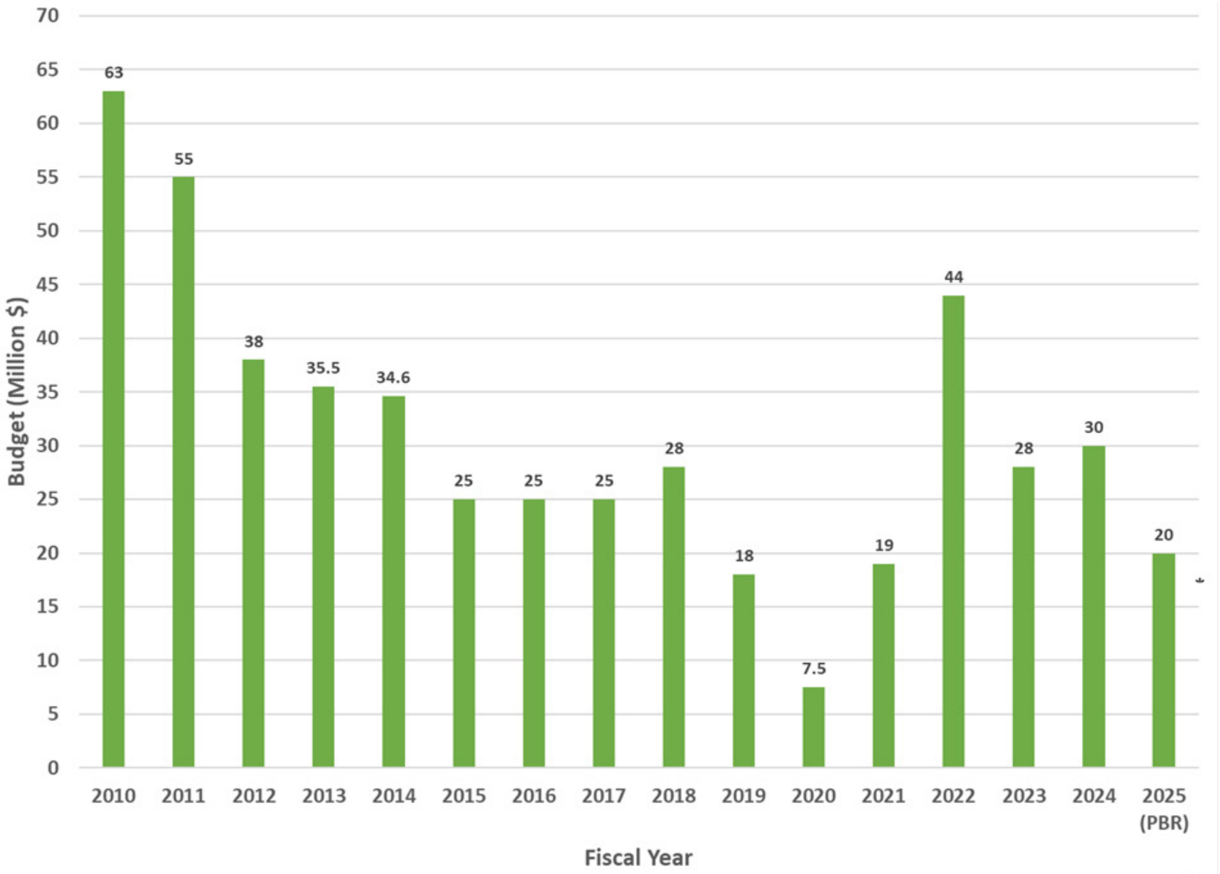


Over the course of decades, the DOE- and NETL-sponsored Research and Development (R&D) Gasification Systems program has established unique technology insights, capabilities, and expertise over a broad range of gasification and syngas technologies, ranging from novel gasifier reactors to gasifier feeding, air separation/oxygen production, syngas cleanup and syngas separations, integrated carbon capture, and systems analysis. The Gasification Systems program is poised to make significant contributions in meeting the administration's 2030, 2035, and 2050 decarbonization goals. Gasification of opportunity feedstocks (e.g., wastes, biomass, municipal solid waste, and unrecyclable waste plastics) enables deployment of clean hydrogen production—contributing to the administration's Hydrogen Shot™ with low-cost, net-zero or net-negative carbon capability in energy systems, as well as cost-effective decarbonization for U.S. industry.

This helps to accomplish ambitious administration carbon-reduction goals, leading to a complete decarbonization of the economy by 2050. Furthermore, gasification has unique advantages enabling value-added utilization of wastes (legacy waste disposal and more) to provide environmental benefits and create jobs. With continued R&D, efficient high-temperature, pressurized, oxygen-blown gasification of wastes, biomass, municipal solid waste, and unrecyclable waste plastic with carbon capture technologies can enable low-cost clean hydrogen and energy production, driving deployment and adoption of widespread net-zero technologies as required for decarbonization. Clean hydrogen production from gasification is a natural feedstock for fuels and chemicals production, aligning with the administration's Clean Fuels & Products Shot™.

Exhibit 1-2 shows DOE funding for the Gasification Systems program since 2010.

Exhibit 1-2. Gasification Systems program funding, 2010–2025



Advanced Turbines

Combustion turbines can burn a variety of liquid and gaseous fuels. This requires a firing system designed to meet emissions and operational performance needs while accounting for characteristics of specific fuel to be used, which can range from kerosene to natural gas to hydrogen. The Advanced Turbines program made a major effort to develop firing systems to fire syngas (H_2 + CO) in large-scale integrated gasification combined cycle (IGCC) power plants in the 2005-2015 timeframe. The present-day approaches to hydrogen firing in turbines were initially developed under the IGCC program, and this has led directly to the current hydrogen/

natural gas blend capabilities of gas turbines today. The Advanced Turbines program is investing in extending this capability for gas turbine combustion systems to accommodate 100 percent hydrogen and >50 percent hydrogen-natural gas fuel blends. These hydrogen-fueled turbines must operate with high efficiency while minimizing nitrogen oxide (NO_X) emissions.

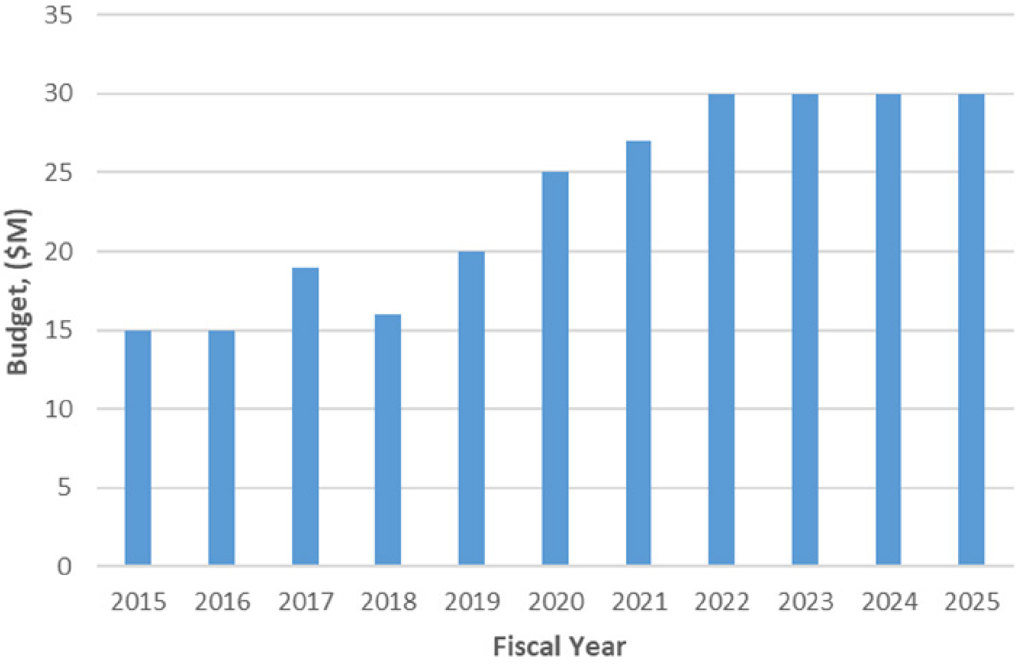
The Advanced Turbines program supports the following four key technology areas that advance clean, low-cost power production while providing options for CO_2 mitigation:

1. Advanced combustion turbines
2. Pressure gain combustion (PGC)
3. Modular turbine-based hybrid heat engines
4. The University Turbine Systems Research (UTSR) Program.

The program also invests in the application of advanced manufacturing and machine learning/artificial intelligence to attain higher efficiency goals.

Achieving the goal of a fully decarbonized power sector by 2035 requires an "all-in" approach to supplement existing lower-carbon intensity gas turbine technology. Prior technology development investments by DOE (see Exhibit 1-3), in collaboration with industry partners, have enabled the acceleration of efficiency gains that reduced carbon emissions intensity by approximately 10 percent. This was achieved through a focus on efficiency improvements that today are in commercial operation, with efficiencies approaching 65 percent in natural gas-fired combined cycle power plants (approximately 60 percent 10 years ago). Such advancements also support accelerated decommissioning of carbon-intensive energy production from coal, responsible for approximately 955 million metric tons of CO_2 per year (EPA, 2023).

Exhibit 1-3. Advanced Turbines program funding, 2015–2025



A complementary zero-carbon path for energy production would eliminate carbon from the fuel system entirely, employing fuels such as hydrogen or ammonia. However, technology challenges prevent implementation of new applications or retrofits into the installed gas turbine fleet. Ensuring such compatibility is critical since industrial gas turbines have expected lifetimes of decades, with units installed over the last decade expected to operate to 2050 and beyond. Such an approach would not reduce the necessity to continue advancements in improving efficiency (both through the gas turbine via higher firing temperatures as well as advanced thermodynamic cycles) since carbon-free fuels may require additional investments to bring them to cost parity; thus, improvements in efficiency reduce the overall fuel use in support of reduced operational costs. A fully decarbonized power sector is possible with continued investment, and the challenging timeline necessitates that all paths to eliminate carbon emissions are developed to ensure a robust implementation strategy.

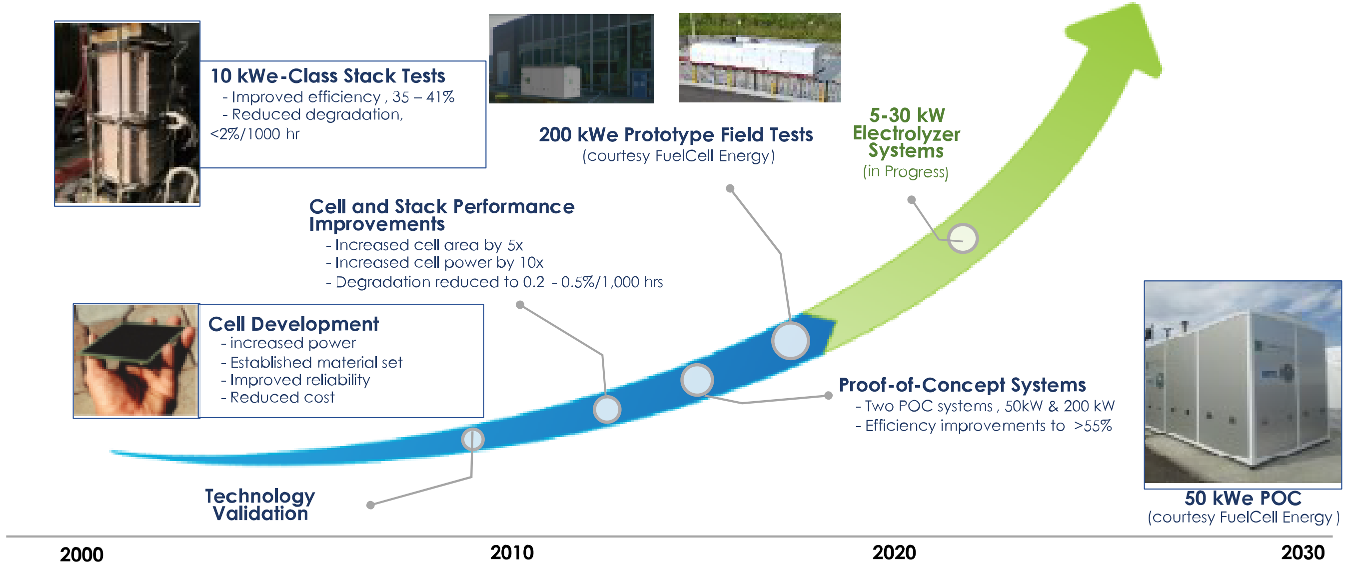
Reversible Solid Oxide Fuel Cells

R-SOFCs use natural gas and up to 100 percent hydrogen to produce electricity, water, and CO_2 when operating in a fuel cell mode. Solid oxide fuel cells (SOFCs) can be configured to operate in reverse as an electrolyzer using power and water as inputs to produce hydrogen, with oxygen as a byproduct. This electrolyzer mode turns the SOFC into a solid oxide electrolyzer cell (SOEC), which functions as an SOFC in reverse and optimizes the use of this system to reduce overall costs. The CO_2 produced from the process with natural gas as a fuel in a fuel cell mode can then be captured for storage or use in other applications. R-SOFCs can both store and produce energy in a single system and can contribute to clean energy generation/storage when paired with a renewable fuel such as hydrogen (SOFC mode) or renewable electricity (SOEC mode). Hydrogen created from R-SOFCs is a promising fuel source and can be stored for future use when renewable energy sources are unavailable. When the grid demands power, the R-SOFC consumes the stored hydrogen to produce electricity. R-SOFCs allow for a continuous stream of clean energy into the grid.

The Department of Energy, through NETL, initiated the Solid-State Energy Conversion Alliance (SECA) in 1999 to develop low-cost, environmentally friendly SOFC technology to produce electricity with an emphasis on distributed generation applications. Since its inception in 1999, the SOFC program (now referred to as the R-SOFC program) under SECA has made progress toward commercialization of SOFC systems for electricity production; stack cost has been reduced by a factor of 10, stack size has increased by a factor of 25, and the rate at which cells degrade has fallen by a factor of 10. Exhibit 1-4 shows the evolution of SOFC technology over two decades, culminating in the testing of a 200-kilowatt (kW) integrated SOFC system field test circa 2020.

While progress has been made in these areas, the R-SOFC program must address additional technical and cost issues before there is widespread acceptance of SOFC technology for commercial use. Driven by industry feedback and systems analysis, the R-SOFC program is aggressively pursuing R&D to address the remaining technical hurdles, with particular emphasis on cell performance, stack reliability, system durability and endurance, as well as overall R-SOFC system cost reduction.

Exhibit 1-4. Evolution of SOFC technology

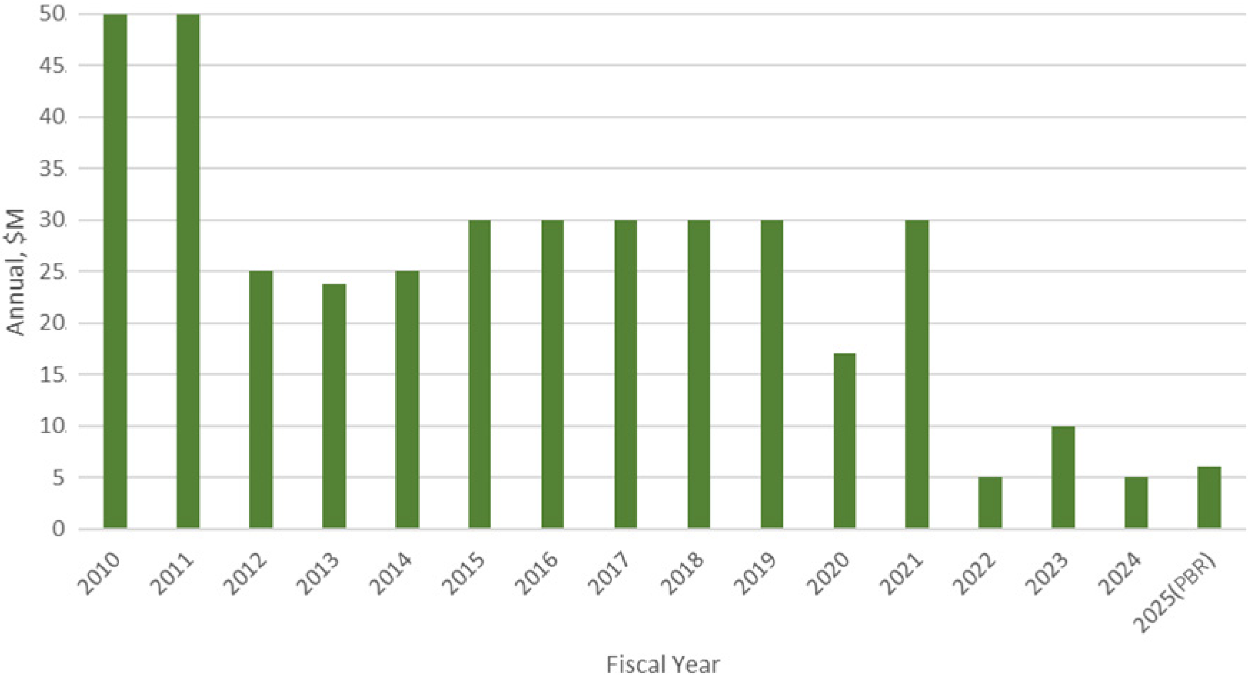


In 2021, the SOFC program shifted its emphasis from electricity production to hydrogen production through high-temperature electrolysis and was renamed the R-SOFC program. High-temperature SOEC systems offer a potentially attractive option for producing hydrogen because of their high efficiency. The SOEC technology is based upon essentially reversing the operation of SOFCs. Instead of using hydrocarbon fuels and air to electrochemically produce electricity, an SOEC system is supplied with electricity and water to produce hydrogen. The hydrogen can then be used in SOFC mode to produce electricity. The integration of a reversible SOFC/SOEC unit with a renewable energy source and hydrogen storage makes a completely green onsite system for distributed power generation possible.

The R-SOFC program is currently funding projects to develop cell materials for SOECs and 5- to 10-kW R-SOFC systems.

Exhibit 1-5 shows DOE funding for the R-SOFC (and SOFC) program since its inception.

Exhibit 1-5. R-SOFC (and SOFC) program funding, 2010–2025



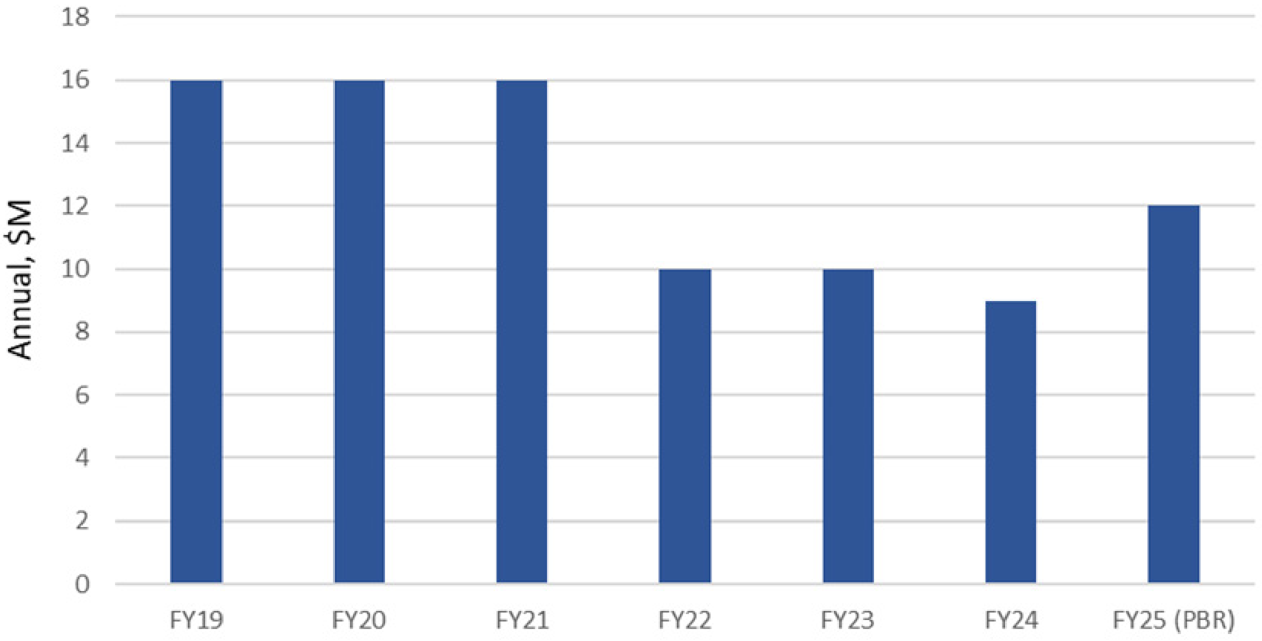
Advanced Energy Materials

The Advanced Energy Materials (AEM) program primarily focuses on creating cost-effective structural and functional materials that enable components and equipment to perform in advanced energy systems' high-temperature, high-pressure, corrosive environments. Materials of recent interest are ceramic matrix composites for turbine applications. The program also emphasizes advanced manufacturing methods for high-performance materials and computational materials modeling as enabling technologies. In addition, the program evaluates the impact of hydrogen on materials to develop models critical to understanding hydrogen-related impacts to develop new hydrogen-resistant materials.

The AEM program has an exceptional history and record of accomplishments within DOE's Office of Fossil Energy and Carbon Management (FECM). It was formerly under the Crosscutting program, and under that program and now going forward as the AEM program, it has developed novel materials that aim to reduce the cost and time needed to develop and commercialize fossil energy applications in extreme operating environments.

The funding history of the AEM program is shown in Exhibit 1-6.

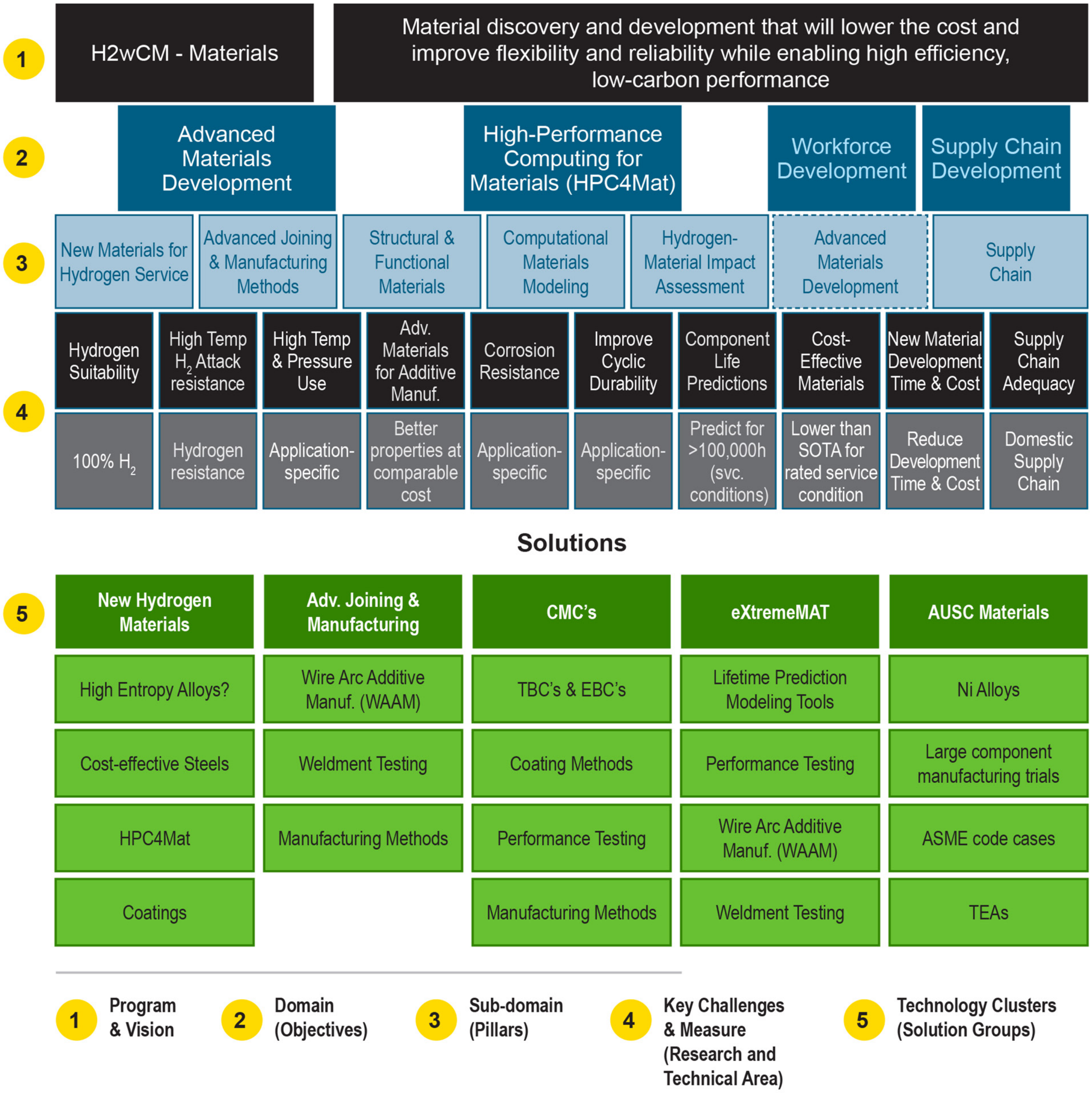
Exhibit 1-6. Advanced Energy Materials program funding, 2019–2025



With a focus through the early 2000s on continuing to deploy coal power plants and supercritical CO2, the research led to enhancements to the coal-powered fleet (e.g., improved serviceable welds), improved plant efficiency, lowered emissions, and new ways to address the challenges of load-following.

Today, the focus is decarbonizing power production across all energy sectors and developing and utilizing materials capable of performing in hydrogen environments. The AEM program's vision, objectives, challenges, and solutions are shown in Exhibit 1-7. Research has led to the development of patentable, cost-effective steels, Ni-superalloys, and novel high-entropy alloys and coatings (e.g., Nb-X-Y alloys). Notable accomplishments and advancements include the development of a mechanistic model that can simulate 10 years of material damage through simulation of high temperature mechanical stresses such as creep in approximately five hours, incorporation into models of complex stress states representative of real service conditions and incorporation of microstructural evolution (coarsening) during service in predictive models. This physics-based simulation of creep mechanisms was validated with creep testing durations up to 10,000 hours for specific materials.

Exhibit 1-7. AEM program vision, objectives, technology challenges, and solutions



1 H2wCM - Materials

Material discovery and development that will lower the cost and improve flexibility and reliability while enabling high efficiency, low-carbon performance

2
- Advanced Materials Development
- High-Performance Computing for Materials (HPC4Mat)
- Workforce Development
- Supply Chain Development

3
- New Materials for Hydrogen Service
- Advanced Joining & Manufacturing Methods
- Structural & Functional Materials
- Computational Materials Modeling
- Hydrogen-Material Impact Assessment
- Advanced Materials Development
- Supply Chain

4

Hydrogen Suitability	High Temp H_2 Attack resistance	High Temp & Pressure Use	Adv. Materials for Additive Manuf.	Corrosion Resistance	Improve Cyclic Durability	Component Life Predictions	Cost-Effective Materials	New Material Development Time & Cost	Supply Chain Adequacy
100% H_2	Hydrogen resistance	Application-specific	Better properties at comparable cost	Application-specific	Application-specific	Predict for >100,000h (svc. conditions)	Lower than SOTA for rated service condition	Reduce Development Time & Cost	Domestic Supply Chain

Solutions

5

New Hydrogen Materials	Adv. Joining & Manufacturing	CMC's	eXtremeMAT	AUSC Materials
High Entropy Alloys?	Wire Arc Additive Manuf. (WAAM)	TBC's & EBC's	Lifetime Prediction Modeling Tools	Ni Alloys
Cost-effective Steels	Weldment Testing	Coating Methods	Performance Testing	Large component manufacturing trials
HPC4Mat	Manufacturing Methods	Performance Testing	Wire Arc Additive Manuf. (WAAM)	ASME code cases
Coatings		Manufacturing Methods	Weldment Testing	TEAs

1 **Program & Vision**
2 **Domain (Objectives)**
3 **Sub-domain (Pillars)**
4 **Key Challenges & Measure (Research and Technical Area)**
5 **Technology Clusters (Solution Groups)**

Note: CMCs = Ceramic matrix Composites
TBCs = Thermal Barrier Coatings
EBCs = Environmental Barrier Coatings
TEAs = Techno Economic Analyses

Sensors, Controls, and Other Novel Concepts

Sensors are crucial to the safe and efficient operation of power system technologies. Improvements in chemical and physical sensing technologies can lead to improvements in the overall performance of power generation or in carbon capture, utilization, and storage systems. However, due to the strong requirement for reliability in power generation, it is difficult for new sensor technologies to be adopted for existing power generation applications without a strong benefit, either in the cost of the sensor or in its accuracy and stability. The National Energy Technology Laboratory's Sensors, Controls, and Other Novel Concepts program goal is to drive advancements in instrumentation, sensors, and control technology to enhance reliability, availability, and cost reduction for integrated energy and carbon management systems.

Since 2015, the program has supported the development of novel sensors critical to implementing and optimizing current and new advanced fossil fuel-based power generation systems, including new classes of sensors capable of monitoring key parameters (temperature, pressure, and gases) while operating in harsh environments. Recent successes include but are not limited to:

1. The development, optimization, and testing of a deployable miniaturized laser-induced breakdown spectroscopy (LIBS) system for subterranean chemical sensing that resulted in a patent and an R&D 100 Award.
2. Developing a Raman gas analyzer (RGA) system that enables rapid (one-second), simultaneous gas detection.
3. The development of an optical fiber sensing system leveraged from the R&D 100 Award-winning technology suite called Transformer Watchman, enabling the measurement of temperature, several dissolved gases, and acoustic signals for arc fault detection in aging transformers.
4. Testing visible light communications (Li-Fi) systems and sensors for use as a secure, wireless alternative to RF communications that successfully transmitted data wirelessly over a distance of 100 meters.

To achieve the national targets of a net-zero electric grid by 2035 and a decarbonized economy by 2050, the Sensors, Controls, and Other Novel Concepts program is conducting R&D for technologies that enable complex, integrated FECM-relevant applications for optimal process performance, reliability, and environmental integrity. Program goals include enabling real-time measurement in extremely harsh environments using novel technologies; advancing the accuracy of artificial and distributed intelligence systems for process control, automation, and fault detection; developing next-generation sensing technologies using quantum sensing and machine learning approaches; and developing novel/emerging technologies to support future Hydrogen with Carbon Management applications essential for energy security and efficiency, including the Hydrogen Shot and the Long Duration Storage ShotTM. New sensor and control technologies are also being researched to further improve control to withstand the high-temperature and corrosive environments of advanced coal plants and gasifiers and to protect plant equipment from cyber threats by ensuring sensor data, control system, and supply chain security through the use of cutting-edge automated awareness cyber technologies.

Exhibit 1-8 shows the technology development timeline for the Sensors, Controls, and Other Novel Concepts program, from 2015 to the present.

Exhibit 1-8. Sensors and Controls technology development timeline

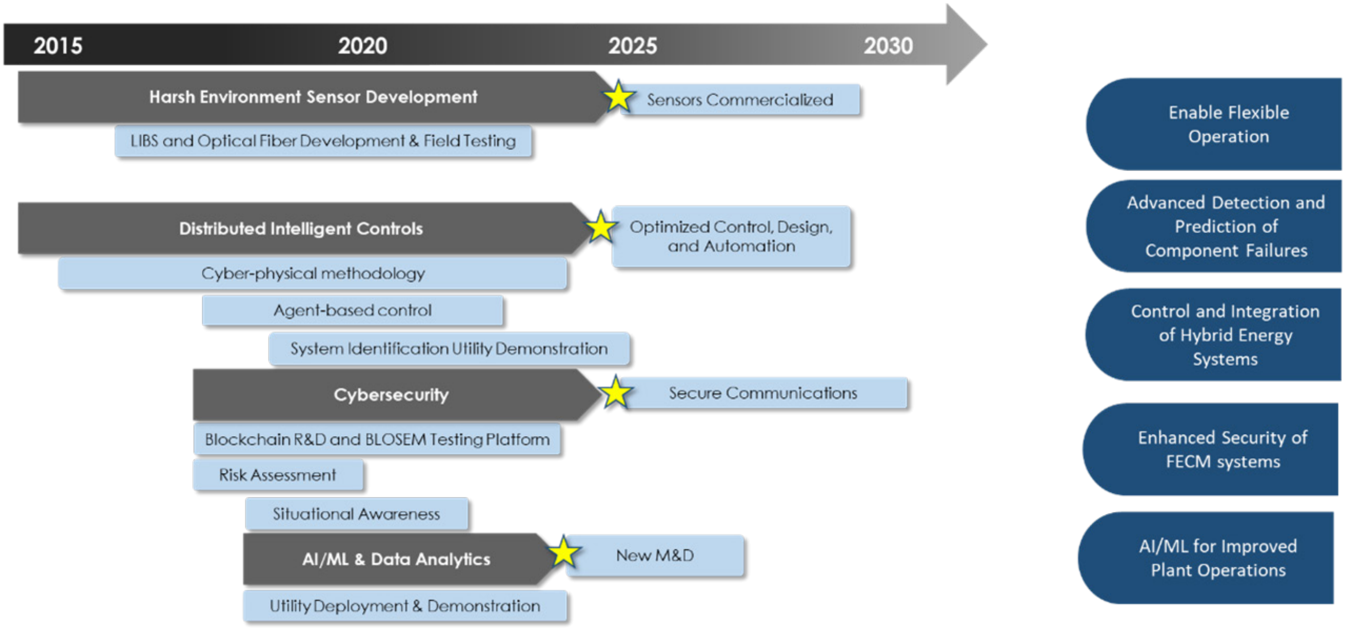
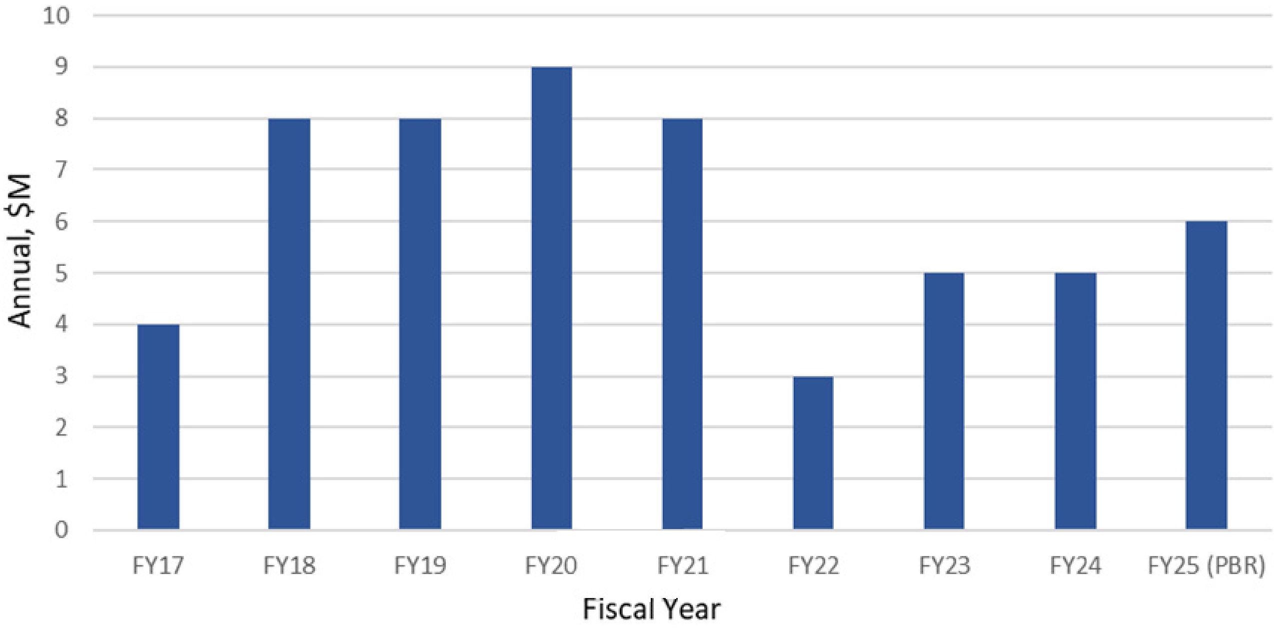


Exhibit 1-9 shows recent DOE funding for the Sensors, Controls, and Other Novel Concepts program.

Exhibit 1-9. Sensors, Controls, and Other Novel Concepts program funding, 2017–2025



Simulation-Based Engineering

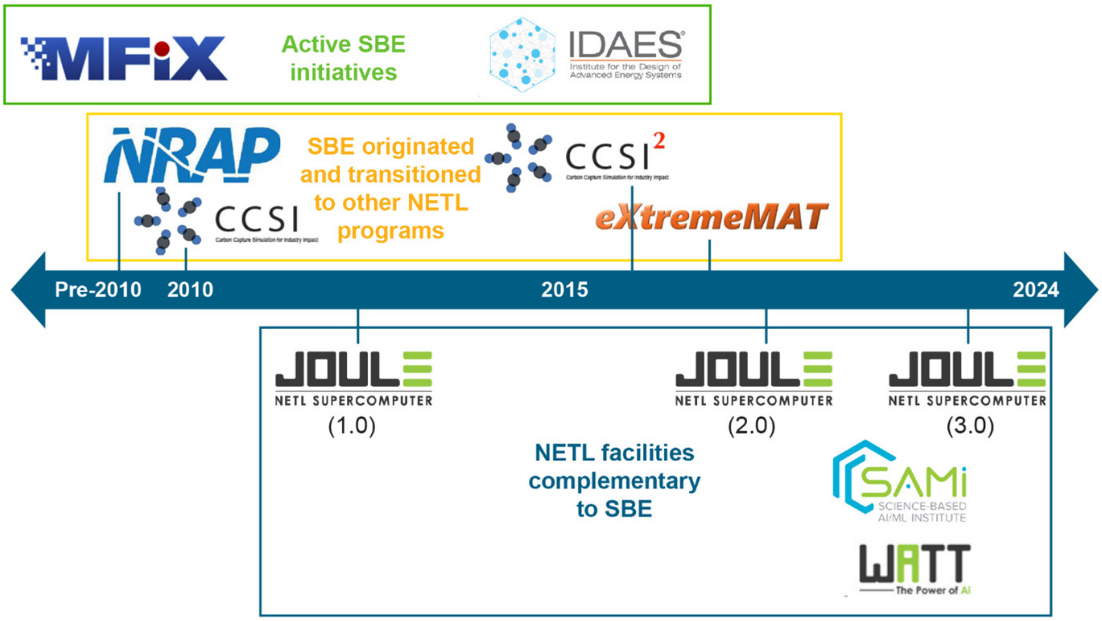
NETL's Simulation-Based Engineering (SBE) program guides a multidisciplinary approach comprising software development, computational power, data repositories, experimental facilities, and unique partnerships to support research into timely and accurate solutions for sustainable energy and carbon management systems. Analysis and visualization tools are manipulated to gain scientific insights into complex, uncertain, high-dimensional, and high-volume datasets. The information generated is then collected, processed, and used to inform research combining theory, computational modeling, advanced optimization, physical experiments, and industrial input with a focus on advanced process simulation, multiphase flow science, and computational materials design.

The SBE subprogram leverages the in-house capabilities of NETL's Research Innovation Center (RIC) for the development, validation and application of flagship, open-source software codes, including Multiphase Flow with Interphase Exchanges (MFiX) and the Institute for the Design of Advanced Energy Systems (IDAES). These computational modeling platforms are truly crosscutting efforts that support not only Hydrogen with Carbon Management, but also most of FECM's programs and as several other DOE programs.

DOE-FECM has developed and successfully applied SBE tools to overcome challenges to FECM technologies. Model development and refinement have been achieved through in-house research and partnerships to utilize nationwide expertise.

The extensive computational resources available to NETL ensure timely solutions to the complex problems associated with advancing power sector technologies toward deep decarbonization and sustainable energy (Exhibit 1-10). NETL's Joule 3.0 supercomputer is one of the world's fastest and most energy-efficient, intended to help energy researchers discover new materials, optimize designs, and better predict operational characteristics. Speed-up is also achieved through research in modern graphical processing unit (GPU) computing, and the development and application of reduced-order models when appropriate. Furthermore, the latest advances in artificial intelligence and machine learning are utilized in the SBE portfolio wherever applicable to optimize performance.

Exhibit 1-10. History of SBE tools developed for FECM applications



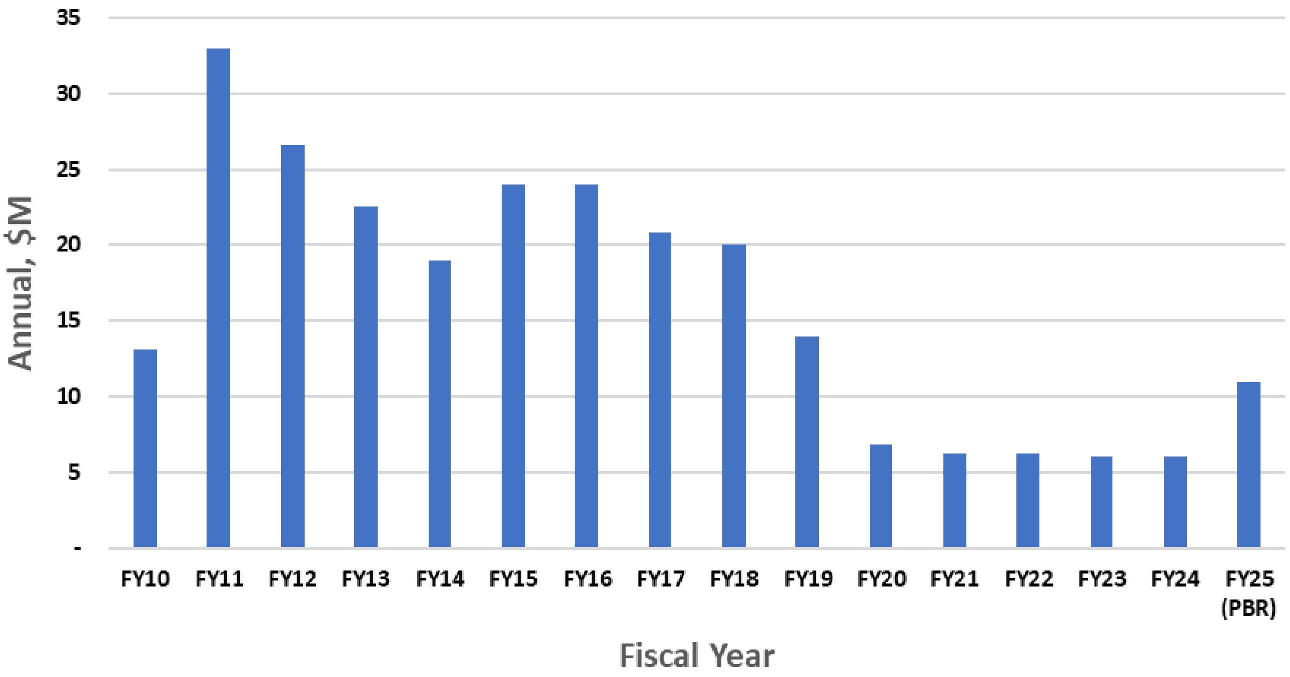
The SBE program develops innovative physics- and chemistry-based models and computational tools at multiple scales (i.e., atomistic, device, process, grid, and market) to help achieve DOE's Strategic Vision through targeted research, development, and deployment efforts. These include integrated energy systems and advanced ultra-supercritical operation; gasification of sustainably sourced carbon-based feedstocks; and hydrogen storage and combustion technologies to support the Hydrogen with Carbon Management infrastructure and DOE's Hydrogen Shot, Long Duration Storage Shot, and Carbon Negative ShotTM goals. SBE also supports technologies for carbon capture (both point source capture and carbon dioxide removal [CDR]), utilization, transport and storage to support both industrial and domestic carbon management goals.

NETL's SBE program enables multiphase flow science (through MFiX) and advanced process simulation (IDAES) through research to support the DOE net-zero greenhouse gas (GHG) emissions goals. With each platform, NETL leads a consortium of partners at other national laboratories and universities via fieldwork proposals and extramural research projects for continual code improvement and the development of additional capabilities.

The MFiX software suite has more than 8,000 registered users and is a leading platform for gasification process simulation using computational fluid dynamics (CFD) code. Model development and refinement are achieved through in-house research combined with external partnerships to harness cutting-edge CFD expertise across the country. IDAES has provided enhanced capabilities to support FECM and industry R&D, technology development, scale-up, and commercialization to enable the ongoing energy transition; provided new techniques for multi-scale optimization and uncertainty quantification to enable optimization of new technologies within the context of the broader energy ecosystem (grid, markets, supply chains); and demonstrated applications to optimize, evaluate, and fully quantify the value of low-carbon integrated energy systems making electricity and hydrogen.

Exhibit 1-11 shows DOE funding for the SBE program since 2010.

Exhibit 1-11. SBE program funding, 2010–2025



1.2 Alignment with DOE and FECM Plans

Like most developed countries around the world, the United States has committed to goals of a carbon-free electric grid by 2035 and a net-zero carbon economy by 2050. The U.S. energy portfolio and U.S. economy currently depend heavily on fossil fuels and other sources of GHG emissions, spanning sectors like power generation, industry, heat, and transportation fuels.

Achieving these carbon emission reductions will require DOE to make strategic decisions regarding the demonstration and ultimate deployment of technologies for carbon management to mitigate emissions from fossil fuel use and key industrial processes, with the goal of achieving net-zero GHG emissions by mid-century. DOE-FECM has prioritized its program to achieve these goals.

The Hydrogen with Carbon Management Program Plan is well aligned with the current DOE strategy, administration policies, Congressional legislation, emerging regulatory frameworks, and the perspectives of the scientific research community, as detailed below.

DOE-FECM Strategic Vision—This multi-year program plan (MYPP) is a direct outgrowth of the DOE-FECM Strategic Vision published in 2022, which highlights seven strategic research, development, and demonstration (RD&D) pathways associated with advancing carbon management. While each is distinct in its own way, these seven pathways interact and integrate with each other to fulfill DOE-FECM's contribution to decarbonization. To help achieve U.S. climate goals, DOE-FECM has a strategy to advance the deployment of commercial-scale point source carbon capture technologies with long-duration carbon storage to the power and industrial sectors in the near term. DOE-FECM's strategy is to support the large-scale conversion of CO_2 into environmentally responsible and economically valuable products, as well as the advancement of a diverse portfolio of CDR approaches that will aid in gigatonne-scale CO2 removal by 2050. Further, the DOE-FECM Strategic Vision includes a robust analysis of life cycle impacts of the various CDR approaches. For carbon storage and transport, DOE-FECM's strategy envisions making key investments in RD&D, large-scale transport and storage facilities, and regional hubs to support the rapid deployment of carbon storage. Finally, the DOE-FECM strategy envisions hydrogen research as an integral element of the DOE-wide Hydrogen Program, which includes multiple offices covering diverse feedstocks and is coordinated with DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE).

Other Government Hydrogen Initiatives—The Hydrogen with Carbon Management MYPP aligns with other recent government reports specific to advancing a hydrogen economy as part of the U.S. national decarbonization plan. The Bipartisan Infrastructure Law of 2021 (BIL) included $9.5 billion for hydrogen

deployment, including $8 billion for Regional Clean Hydrogen Hubs, $1 billion for electrolyzer development, and $500 million for electrolyzer manufacturing and recycling programs. The Office of Clean Energy Demonstrations (OCED) has a primary objective to accelerate market adoption and deployment of decarbonized energy systems by supporting at-scale clean energy demonstration projects. OCED's portfolio includes execution of the Regional Clean Hydrogen Hubs and FECM has supported the H2Hub

FOA and its associated review. The H2Hub efforts are consistent with DOE's Hydrogen Shot goal of achieving $1/kg hydrogen production cost in one decade, the first Earthshot goal announced by DOE. Each applied energy office has plans for achieving the Hydrogen Shot goal. FECM was the first office to issue "Strategies for Achieving the DOE Hydrogen Shot Goal: Thermal Conversion Approaches" on cost reduction approaches for thermal conversion pathways. A plan for meeting cost, infrastructure and demand challenges is included in the U.S. National Clean Hydrogen Strategy and Roadmap, a comprehensive national framework for facilitating large-scale production, processing, delivery, storage, and use of clean hydrogen to help meet bold decarbonization goals across virtually all sectors of the economy. This is closely paralleled by DOE's Pathways to Commercial Liftoff Report on Clean Hydrogen, which is in part enabled by the RD&D programs undertaken by this MYPP.

Other FECM Programs—The Hydrogen with Carbon Management Program is comprised of our research on Hydrogen with Carbon Management as well as other program areas that were formerly part of a separate Crosscutting R&D program. This includes the Advanced Energy Materials program, the Sensors, Controls, and Other Novel Concepts program, and the Simulation-Based Engineering program—each of which provides supporting capabilities leveraged by the other FECM programs.

1.3 Goals and Benefits

The goal of the Hydrogen with Carbon Management Program, in support of the administration's goals for a net-zero carbon emissions economy, is to develop clean hydrogen as a cost-competitive alternative to traditional carbon-based fuels and support the development of technologies to use hydrogen. The Hydrogen with Carbon Management Program will invest in the advancement and utility-scale demonstration of clean hydrogen production (e.g., through co-gasification of biomass and through R-SOFCs) and utilization technologies such as 100 percent hydrogen-fired turbines and SOFCs, supporting DOE's Hydrogen Shot target. Development and demonstration are supported by the crosscutting Advanced Energy Materials, Sensors and Controls, and Simulation-Based Engineering programs.

2. Technical Plan

2.1 Gasification Systems

2.1.1 Gasification Technology Challenges

The Gasification Systems Program supports the development of innovative designs and technologies for converting diverse types of solid feedstocks into clean syngas to enable the low-cost production of hydrogen, transportation fuels, chemicals, electricity, and other useful products. Technological challenges can be grouped under three key technology areas: Process Intensification for Syngas/Hydrogen, Air Separation Technology, and Clean Hydrogen and Negative CO_2 Emissions. The technological challenges for each key area are listed below:

Process Intensification for Syngas and Hydrogen:

- Improved Precision and Control in Reacting Systems—Syngas quality and hydrogen content vary widely for gasification processes. Meeting this challenge equates to a high extent of conversion of feedstocks and maximized hydrogen yield in syngas, with minimized methane, water vapor, and inert gases.
- High-Temperature Oxygen- or Steam-Blown, Pressurized, Entrained-Flow Gasification of Biomass-Containing Feed Streams—Biomass gasifiers are currently limited to fixed/moving bed and fluidized bed types. Enabling high efficiency entrained flow gasification of biomass feedstocks requires solving feeding and gasifier operational difficulties, and this is one focus of current FECM Gasification Program RD&D funding.
- Co-Gasification of Municipal Solid Waste (MSW), Waste Plastics, and Biomass—MSW and waste plastics are novel feedstocks for gasification. There are technical risks in the permutations of feedstock mixtures, tradeoffs of feedstock pretreatment versus gasification of lower-quality raw feedstocks, and tradeoffs of co-gasification versus separate gasification units for different feedstocks. Success will be measured by well-supported/validated process scenarios for highest-efficiency and lowest-cost clean hydrogen and decarbonized energy systems.
- Water-Gas Shift (WGS) and Hydrogen Separation for Maximizing Conversion of Syngas into Hydrogen—Current hydrogen production systems use multi-stage WGS to maximize hydrogen content in syngas and pressure swing adsorption (PSA) to separate pure hydrogen. This involves multiple shift stages, and high energy penalties of the pressure swing to extract the hydrogen. Success metrics in this area will be shift and hydrogen separation technologies at higher efficiencies and lower costs.
- Development of Cost-effective, Modular Gasification Systems Appropriate for Biomass and Waste Feedstock Gasification Conversions—Current technology tends to large unit size for economies of scale. Success in this area equates with cost competitiveness of gasification systems at modular scale defined as 5–50 megawatt-electric (MWe) equivalent.

Air Separation Technology:

- Cost-Effective Modular Oxygen Production at the Approximate Scale of 10–50 Tons/Day (TPD)—Large cryogenic air separation plants produce oxygen at relatively low unit costs, taking advantage of economies of scale for this type of plant. For a 2,300 TPD plant, onsite oxygen production cost was estimated at $33/tonne (2018 basis).[2] However, for a modular scale of production (less than 60 TPD), traditional cryogenic methods become impracticable or more expensive. Commercially available PSA and vacuum PSA oxygen generators tend to be the most cost-effective at smaller scales yet are considerably more expensive than the large cryogenic units on a unit basis ($100–$500/tonne is typical for 95 percent oxygen production using these methods).[3] Developmental air separation/oxygen production technologies target low unit costs of cryogenic methods even on a small scale, but they must overcome issues such as technical risks of membranes/sorbents costs, operability and maintainability concerns, and regeneration energy penalties.
- Maximize Membrane Life for Membrane-Based Air Separation Systems, Improve the Durability of System Components, and Increase Manufacturing Yield—Many of the developmental air separation technologies are based on high-performing oxygen separation membranes and are considerably more sophisticated than conventional polymer gas separation membranes. They face challenges of high fabrication and materials costs, manufacturing difficulties, and operational durability concerns.
- Cost-Effective Oxygen Carriers to Provide In-Situ Oxygen Production in Gasifiers—Oxygen carrier-based oxygen production is not a commercially available technology. Bench-scale results indicate excellent potential for low-cost production, but technical risks/barriers of carrier cyclability, carrier oxygen capacity, and scale-up to commercially relevant reactor size must be overcome.

Clean Hydrogen and Negative CO_2 Emissions:

- Low Biomass Energy Density—Significant fractions of sustainable biomass are needed in the feedstock mix for decarbonized gasification systems; given the current limitations of biomass feeding in high-efficiency conventional gasification systems (typically 10–30 percent), a risk is entailed in increasing proportions further.
- Feedstock Water Content—Intent to use high fractions of biomass in clean hydrogen and negative CO_2 emissions systems introduces the inherent risk of poor feedstock quality (low thermal content, often from high water content) without feedstock pretreatment, entailing extra cost and energy penalty.
- Feedstock Collection and Preparation—Any transportation and retreatment/preparation will incur additional costs and energy penalties.
- Seasonal and Regional Feedstock Availability—Many contemplated biomass resources are only seasonably available, and stockpiling to ensure steady supply is risky in terms of costs from the large amount of seasonal storage needed for load leveling.
- In Situ Oxygen Production and Gas Separations for Reduced Cost of CO_2 Capture—In situ methods of oxygen generation and gas separations could significantly improve fundamentals of process energy demands and consolidate process unit operations for cost savings, but technical risks are high.

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[2] https://cosia.ca/sites/default/files/attachments/22164-%20Oxygen%20Generation%20Technologies%20Review%20-%20Rev0.pdf.

[3] https://adgastech.com/products/industrial-gas-generators/oxygen-generators/.

2.1.2 Gasification Technology Status

Co-gasification of MSW, waste plastics, and biomass is a technically challenging problem. The current technology portfolio includes several innovative gasification reactor concepts:

- A process-intensified two-stage bubbling fluidized bed gasifier that integrates a membrane separator and pre-combustion CO_2 capture system with syngas recycling.
- A process-intensified gasification system for modular hydrogen production from biomass using catalytic membrane reactors based on carbon molecular sieve hollow fiber membrane technology.
- In situ measurement of MSW, waste plastics, and biomass gasifier feedstocks in near real-time to provide immediate and time-sensitive fuel data that gasifier operators can use in a feedback or feedforward control scheme to maximize performance.
- A rotary kiln gasifier for hydrogen production that has been validated by testing results to understand the complex reactions occurring when gasifying these mixed feedstocks.
- Chemical looping gasification using solid oxygen carriers to supply oxygen, thereby eliminating a separate air separation unit.
- Microwave-based gasification uses microwave energy to supply energy to the gasification reactions, allowing selective heating and a more favorable syngas composition (higher hydrogen).

Various methods of hydrogen separation have been commercialized or proposed, including liquid phase absorption using a range of solvents (e.g., Selexol, methyldiethanolamine [MDEA]), sorbent adsorption, membrane separation, and cryogenic (or sub-ambient) cooling. Research on hydrogen separation has mainly focused on hydrogen membrane development to produce a low-pressure hydrogen stream and CO_2 adsorption to produce a purer hydrogen stream at pressure. Combinations of membrane and sorbent methods, potentially along with PSA, may allow for higher recoveries of high-purity hydrogen and a pure CO_2 stream.

The Gasification Program continues a non-restrictive strategy of fostering technology advancement in any of the air separation technology areas, from cryogenic to innovative concepts. These include formulations and configurations of membranes enabling higher efficiency, advantageous operating conditions, or reduced costs; solid oxygen carriers in a looping configuration to provide in situ oxygen production in gasifiers; and innovative concepts, including magnetic field-based air liquefaction.

In situations where the feedstock resource is not large, but with economic or other reasons for implementing a gasification process (e.g., waste remediation), smaller, more modular gasification systems can take advantage of economies of higher volume manufacturing of these gasification systems. The size, configuration, flexibility, and other aspect of modular gasifiers require further R&D for their development and commercialization.

Reaction intensification, innovative fabrication of reactor components, advanced materials and manufacturing methods, and increasingly sophisticated modeling and simulation techniques will underpin the development of modular technology for using coal more efficiently and creating more valuable end products from coal wastes, MSW, waste plastics, and biomass feedstocks.

Ultimately, high-pressure, oxygen-blown entrained flow gasification systems with improvements to accept large fractions of biomass feed may best allow lower-cost hydrogen production.

2.1.3 Gasification Milestones

Mature Technical Readiness Levels (TRLs) of Technologies for Integrated and Optimized Clean Hydrogen Production Systems

This milestone requires R&D to mature novel technologies capable of producing clean hydrogen with net-negative emissions through co-gasification of blended biomass and wastes, including MSW and non-recyclable waste plastics, to enable remediation and reduction of legacy pollution. Success will be based on optimized hydrogen production efficiency and cost reductions.

TRLs of technologies and clean hydrogen production systems are targeted (ending at TRL 6–7), which set the stage for industrial collaborations and near-commercial-scale pilots. Metrics for success are generally defined in terms of increasing system efficiency and ultimately clean hydrogen cost competitiveness.

Advance TRLs of Oxygen Production Technologies

This requires advancing the TRL of emerging oxygen production technologies from air separation to facilitate interest from the commercial sector and attract technology transfer partners. Lower-cost oxygen is a key enabling technology for gasification to leverage pre-combustion carbon capture and produce clean hydrogen to meet the Hydrogen Shot initiative's goal. Accomplishing this milestone will improve the viability and economics of net-zero carbon gasification systems.

For example, NETL's perovskite oxygen carrier and oxygen reactor technology development:

- TRL 4 in 2024.
- TRL 6 (small pilot in operation) in 2029.
- Full-scale demo in 2030.

Develop Novel Microwave Technologies for Gasification Processes

This requires new microwave technologies for feed-flexible gasification of wastes and biomass for efficient, hydrogen-selective gasification and a microwave-based technology for efficient syngas cleanup, converting organic impurities in syngas that might survive the primary gasification process.

Microwave-based gasification can be considered a process intensification technology for gasification itself, with preliminary results suggesting advantages in energy efficiency and hydrogen selectivity. NETL's gasification reactor with microwave heating of the catalyst for versatile mixed feedstock gasification, a path forward to commercialization, may involve:

- Preliminary bench-scale testing of microwave-enhanced gasification (TRL 3). (In progress)
- Systems analysis and techno-economic analysis (TEA) updates of microwave-enhanced gasification. (ongoing)
- Benchtop microwave reactor (10 kg/day) design and testing. (2024–2026)
- Pre-pilot reactor (100 kg/day) design and testing. (2027–2029)
- Near-commercial pilot with industrial collaboration. (2030–2035)

Enhanced Blended Gasification Feedstock Pretreatment Processes

This requires investigating, developing, and advancing the TRL of various novel pretreatment techniques for blended feedstocks such as biomass, mixed wastes, MSW, and unrecyclable waste plastics). Blended feedstocks that include biomass are important for future gasification systems to produce power, hydrogen, and ammonia with net-zero emissions. However, blended feedstock-based systems are severely limited in scope due to two key issues: reliably feeding blended materials with different characteristics into the gasification process and accessing, shipping, and storing the feedstock materials in a low- or zero-carbon-intensity method. Successful completion of this milestone, addressing these two key issues, should be completed by 2030.

2.2 Advanced Turbines

2.2.1 Technology Challenges

Several challenges must be addressed along the pathway to 67 percent (lower heating value [LHV]) combined cycle efficiency using high hydrogen content fuels. This goal could be accomplished using lean premixed hydrogen combustion systems, ammonia combustion systems, or even transformative PGC systems. Since hydrogen production itself might have carbon emissions, the recently released Clean Hydrogen Production Standard (DOE, 2023) provides guidance on target life cycle CO_2 emissions associated with hydrogen production. To survive the high temperatures required for 67 percent efficiency operation, the turbine hot gas path will require sophisticated cooling technologies that can be incorporated into advanced materials using advanced manufacturing methods. Future turbine applications in the power and industrial sectors may also require systems specifically developed for higher-temperature waste heat recovery using modular hybrid heat engines and/or supercritical CO_2 (sCO_2) bottoming cycles. Further, direct sCO_2 cycles, which utilize oxy-fired turbines with a substantial CO_2 recirculation stream for temperature control, are a potential power generation technology for achieving high carbon capture levels at high efficiency and low cost. All these elements have their own technological challenges, which are being addressed by ongoing projects within the Advanced Turbines program.

Hydrogen combustion challenges:

- Low volumetric energy density.
- Low mass density.
- High flame temperature—leading to potentially high NO_x emissions.
- High flame speed—Flashback risk.
- Dry low NO_x combustion technologies.
- Combustion instabilities.
- Fuel flexibility to accommodate markets and availability (hydrogen, natural gas, ammonia).

Ammonia combustion challenges:

- High ignition temperature (difficult to initiate combustion).
- Narrow flammability limits.
- Slow reaction speed.
- Low flame speed.
- NO_x emissions (exacerbated by fuel-bound nitrogen content).
- Fuel flexibility to accommodate markets and availability (hydrogen, natural gas, ammonia).

PGC challenges:

- Fuel injection.
- Fuel and air mixing.
- Backflow prevention.
- Detonation initiation.
- Maintaining wave direction and pressure gain.
- NO_X emissions.
- Unsteady heat transfer and cooling flow challenges (combustor and turbine).
- Material fatigue life uncertainties.

Advanced hot gas path component challenges:

- Development of advanced materials (i.e., single crystal alloys, ceramic matrix composites, environmental barrier coatings, etc.).
- De-risking additively manufactured components.
- Development of cooling technologies for advanced materials/manufacturing.
- Heat transfer and materials consideration of increased water content in hydrogen combustion exhaust.

Modular hybrid heat engines and/or sCO_2 power cycle challenges:

- Development of piping and components using new high-temperature materials.
- Systems engineering and control of sophisticated cycle configurations.
- Design and operation of turbomachinery.
- Need for low-cost heat exchangers for waste heat recovery and recuperation.
- Optimizing operation and control in environments with variable ambient conditions.
- Direct sCO_2 oxy-combustors, turbines, and compressors.

2.2.2 Technology Status

The results of prior research have shown that 100% hydrogen turbines are an achievable goal, but more effort is needed to overcome the technical challenges at large scales to achieve full commercialization of the technology. Several original equipment manufacturers (OEMs) have made significant progress in reaching high levels of hydrogen usage in their commercial turbine models through primary funding from DOE, especially through the Advanced Turbines program's IGCC efforts from the early 2010s. In general, high hydrogen usage is currently available, but at lower efficiencies due to either steam injection or selective catalytic reduction (SCR) technologies to reduce NO_x emissions. The development of dry low NO_x combustors is needed to maintain both efficiency and low NO_x emissions of gas turbines operating on high hydrogen fuel. The Advanced Turbines program has been instrumental in enabling the research that has managed to achieve key benchmarks. Through continued research efforts, it is anticipated that the majority of turbines produced by the leading OEMs will achieve 100 percent hydrogen combustion capability by 2030, resulting from both DOE- and non-DOE-funded research initiatives. Nearly all large-scale turbine OEMs have expressed plans to release a 100 percent hydrogen engine by 2030–2035.

PGC is seen to have great potential as a means of achieving higher efficiency in gas turbine power systems, potentially reaching 4 percent–6 percent improvement for simple cycle systems and 2 percent–4 percent improvement in combined cycle systems. PGC provides an alternative pathway to the ultra-high efficiency target that bypasses the material limitations currently faced by technology developers. Advanced materials and cooling schemes coupled with PGC provides the potential for ultra-high-efficiency combustion turbines. NETL systems studies show a potential of 75 percent combined cycle efficiency in an advanced turbomachine with a rotating detonation combustor (RDC) system (Uysal, 2021).

Over the years, the Advanced Turbines program has invested in hot gas path component R&D to enable higher turbine inlet temperatures. These components utilize advanced materials/coatings, such as ceramic matrix composites, with environmental barrier coatings and additively manufactured components with sophisticated cooling geometries. Some of these technologies/concepts enable state-of-the-art H-Class[4] natural gas combined cycle (NGCC) turbines to reach world record efficiency marks exceeding 63 percent LHV, and the most recent record efficiency of 64.18 percent was achieved in May 2024 by Siemens Energy. These technologies, along with the knowledge gained through decades of DOE investment through the Advanced Turbines program, will be critical for enabling hydrogen-fired combined cycle gas turbines to reach 67 percent. Gas turbine efficiency improvements are still needed to make the best use of decarbonized fuels like hydrogen or ammonia.

For novel cycles applicable to advanced turbines, DOE has several active projects that aim to advance the TRL of both the direct and indirect variants of sCO_2 cycles. Supercritical carbon dioxide power cycles have the potential for high efficiency (more efficient than a standard Rankine Cycle and more efficient than a

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[4] H-Class/H-Frame: Letter grades are attached to all turbines based on the turbine inlet temperature (which is also related to the turbine's size/gross power output). Definitions from different manufacturers vary. Using GE turbines as an example, an H-Class turbine will typically have a turbine inlet temperature (TIT) of more than 2,600°F (1426°C) and a pressure ratio of at least 21. This corresponds to a simple cycle power output of about 300 megawatts (MW) per machine. The most common classes of turbines used in power applications are F-Class and H-Class (for political/marketing reasons, there are no G-Class engines). The class of turbine will usually be given as a part of its model number (e.g., GE 7F or Siemens SGT6-8000H). Aero and aero-derivative engines are not a part of this system.

typical NGCC plant with 90 percent carbon capture installed), built-in CO_2 removal without requirin expensive capture technologies (for the direct-fired system), and high energy density/compactness. Pursuing these benefits, DOE continues to support R&D efforts into both the direct and indirect variants of the sCO_2 power cycle. Specific projects have advanced these power cycles in areas such as combustion modeling and testing, optimization of the cycle configurations through system studies, development and testing of materials compatible with the conditions of the cycle, and the development related to key components, including turbomachinery/seals, recuperators, and combustors.

2.2.3 Milestones

Hydrogen and Ammonia in Power and Industrial Applications

- Develop gas turbines with 100 percent ammonia and/or hydrogen combustion capabilities through either modification of existing technologies or development of new technologies. (2027)
- Enable 100 percent hydrogen and ammonia turbines to have comparable NO_X emissions (mass per unit power output basis). (2031)
- Achieve full commercialization for hydrogen and ammonia turbines. (2035)

Improve Advanced Combustion Turbine Performance at High (2,900˚F+) Temperatures[5]

- Develop novel materials and thermal barrier coatings to withstand higher temperature combustion in new turbines. (2030)
- Develop improved hot gas path cooling architectures to protect first-stage blades from higher combustion temperatures. (2030)
- Develop advanced manufacturing methods for various turbine components. (2030)

Improve the Performance and Cost of sCO_2 Power Cycles

- Develop new greenfield facilities and components for sCO_2 power cycles. (2029)
- Facilitate the construction of a full, large-scale commercial facility (TRL 9). (2035)

Accelerate the Deployment of RDCs in Gas Turbine Applications

- Develop computational tools for predicting RDC performance, especially with hydrogen and other fuels. (2027)
- Demonstrate the performance of a bench-scale RDC system integrated with a gas turbine engine (with hydrogen fuel). (2028)
- Facilitate the construction of an RDC-integrated gas turbine pilot facility. (2033)

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[5] Note this is a long-term goal that will continue beyond the scope of this MYPP. Dates are estimates.

2.3 Reversible Solid Oxide Fuel Cells

2.3.1 Technology Challenges

The R-SOFC program seeks to address the following technology challenges:

- Further reducing cell fabrication and system costs to meet commercial targets established in previous R-SOFC program technological pathway studies.
- Further reducing SOFC and SOEC stack degradation rates to meet commercial targets established in previous R-SOFC program technological pathway studies.
- Understanding and optimizing the lifetime degradation rate for solid oxide cell (SOC) systems operating reversibly in both SOFC and SOEC modes instead of strictly one mode or the other.
- Developing SOC quality assessment methods for increasing quality control and reducing costs of SOC stack fabrication and assembly.
- Acquiring fabricating and operational experience on SOFC and R-SOFC systems above 250 kW to validate cost assessments on scaling up R-SOFC technology.
- Defining market parameters and the necessary resulting R-SOFC system operating conditions for commercially viable integration of R-SOFC systems into the modern dynamic grid to take advantage of the R-SOFC's capability for power production and energy storage/hydrogen production.
- Acquiring fabricating and operational experience on integrated prototype R-SOFC field tests.

Resolving the above technology challenges will result in the maturation of SOFC and SOEC technologies to TRLs greater than 7. This will facilitate commercialization of R-SOFC technology and support DOE-FECM's goal of clean hydrogen costs of $1/kg within one decade (1-1-1).

2.3.2 Technology Status

SOFCs are electrochemical devices that convert the chemical energy of a fuel and oxidant directly into electrical energy. Since SOFCs produce electricity through an electrochemical reaction and not through a combustion process, they are theoretically much more efficient and environmentally benign than conventional electric power generation processes. Their inherent characteristics make them uniquely suitable to address the environmental, climate change, and water concerns associated with fossil fuel-based electric power generation.

The R-SOFC program is also developing synergistic SOEC technology. Electrolysis is a process that splits hydrogen from water using an electric current. SOEC systems offer a potentially attractive option for producing hydrogen because of high efficiency and system flexibility. In addition to the development of standalone SOEC systems, developers are exploring the potential to use both the SOEC and SOFC in a single hybrid device to produce electricity during times of high demand (high value) and to produce hydrogen during times of off-peak demand (low cost). The hydrogen produced during off-peak demand could, for example, later be used in electricity generation or used in the production of higher-value fuels and chemicals. This makes the SOEC system a key component in enabling the wider adaptation of intermittent renewable power sources such as wind and solar.

The R-SOFC program maintains a portfolio of R&D projects that address the technical issues facing the commercialization of SOFC and R-SOFC technologies and pilot-scale testing projects intended to validate the solutions to those issues. To successfully complete the maturation of the SOFC technology from its present state to the point of commercial readiness, the program's efforts are channeled through three key technologies, each of which has its respective research focus.

The R-SOFC program R&D efforts apply to three key technology areas for SOFCs and SOECs: Cell Development, Core Technology, and Systems Development.

Cell Development

Research is focused on the cell-related technologies critical to the commercialization of SOFC/R-SOFC technology. The components of the SOFC/R-SOFC—the anode, cathode, and electrolyte—are the primary research emphasis of this key technology. The electrochemical performance, durability, and reliability of R-SOFCs are key determinants in establishing the technical and economic viability of SOFC power and SOEC hydrogen systems. Thus, the R-SOFC program maintains a diversified portfolio of cell development projects that are focused on improving electrochemical performance and cell power density, reducing long-term degradation, developing more robust cells, and reducing costs. Additional research projects include the evaluation of contaminants, advanced materials, materials characterization, advanced manufacturing, and failure analysis. Program participants include academia, national laboratories, small businesses, NETL's RIC, and other R&D organizations. The portfolio maintains a mix of near-, mid-, and long-term R&D projects at the bench- and laboratory-scale and coordinates with synergistic activities focused on solid oxide electrolysis cells with the H2NEW Consortium run by the Hydrogen and Fuel Cell Technologies Office in the Office of Energy Efficiency and Renewable Energy.

Core Technology

The R-SOFC program conducts applied R&D on technologies—exclusive of the cell components—that improve the cost, performance, robustness, reliability, and endurance of SOFC/R-SOFC stack or balance-of-plant (BOP) technology. Projects in the core technology portfolio focus on interconnects and seals; identify and mitigate stack-related degradation; develop computational tools and models; and conduct laboratory- and bench-scale testing to improve the reliability, robustness, endurance, and cost of stacks and BOP components, respectively. Program participants include academia, national laboratories, small businesses, NETL-RIC, and other R&D organizations.

Systems Development

The R-SOFC program also maintains a portfolio of projects that focus on the RD&D of SOFC/R-SOFC power and hydrogen systems. Project participants (industry teams) are independently developing unique and proprietary SOFC technology suitable for either syngas-, hydrogen-, or natural gas-fueled applications.

The industry teams are responsible for the design and manufacture of the fuel cells, integration of cells hardware development, manufacturing process development, commercialization of the technology, and market penetration. These developers also focus on the scale-up of cells and stacks for aggregation into fuel cell modules and the validation of technology. This key technology also supports laboratory-scale stack tests, proof-of-concept systems, and pilot-scale tests. The multi-industry team approach not only provides technology diversification but also offers insurance against business environment risk, reducing program dependency on a single developer. The industry teams have the opportunity to determine relevant R&D topics based on their design-specific experience and needs and are held to a common set of performance and cost metrics.

Also within the systems development area is a portfolio of projects focused on innovative concepts. These projects conduct bench-scale R&D on innovative SOFC/R-SOFC stack technologies that have the potential to significantly decrease the cost of SOFC power and SOEC hydrogen systems by leveraging advancements in lower-cost materials, advanced manufacturing methods, and/or alternative architectures. These efforts also include small pilot-scale studies on the operation of R-SOFC stacks to develop control systems to optimize reversible operation and to determine lifetime operational regimes to extend the life of the stacks. Projects are also underway to investigate the operability of SOFCs in hybrid system configurations for improved efficiency, including work on system control approaches to avoid harmful dynamic operating modes to reduce SOC degradation mechanisms that reduce its useful life.

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

2.3.3 Milestones

SOFC Small-Scale Demonstrations

- Conduct field-testing of a 25–50-kW SOFC system on both hydrogen and natural gas at small-scale commercial installation. (2025)
- Testing of R-SOFC systems at greater than 5-kW scale to demonstrate small-scale (up to 50 kW) R-SOFC systems for hydrogen production. (2026)
- Demonstrate 200–400-kW SOFC and/or R-SOFC systems to produce hydrogen and electricity using natural gas/hydrogen blends up to 100 percent hydrogen. (2028)

SOFC R&D for Degradation at Start-Up of SOEC Operation and Enabling Technology for Dynamic Operation of SOEC/SOFC Systems

- Identify enabling technologies for enhancing energy conversion efficiency with increased operation stability and flexibility. (2023–2028)

SOFC BOP R&D for SOFC Systems Operating on Hydrogen-Natural Gas Fuel Mixtures

- Demonstrate surface modification through such techniques as ALD to protect the BOP materials. (2026)

2.4 Advanced Energy Materials

2.4.1 Technology Challenges

The technology challenges being addressed by the crosscutting AEM program include:

- Hydrogen embrittlement of alloys and hydrogen compatibility.
- High-temperature hydrogen attack resistance in steels used in hydrogen production from carbonaceous sources.
- Materials performance in high-temperature, high-pressure, and corrosive hydrogen environments.
- Impact of hydrogen on components produced by advanced materials for additive manufacturing.
- Lack of facilities for testing materials and components under realistic hydrogen environments.
- Corrosion resistance.
- Improve cyclic durability.
- Component life prediction of components in hydrogen environments.
- Development of cost-effective, high-performing materials for hydrogen service.
- New material development time and cost.
- Development of domestic supply chain adequacy for materials and components used in hydrogen production and utilization.

2.4.2 Technology Status

The Advanced Energy Materials (AEM) program drives to characterize, produce, and certify advanced alloys and high-performance materials. Materials capable of the production and utilization of hydrogen from carbonaceous sources with carbon management are key to realizing dispatchable, reliable, high-efficiency, decarbonized power generation. In addition, the program aims to encourage change and stimulate innovation in the high- performance materials value chain to spur U.S. competitiveness and enable meeting 2050 goals. Materials of interest include those that enable components and equipment to perform on hydrogen in the high-temperature, high-pressure, and corrosive environments of advanced hydrogen energy systems, with specific emphasis on durability, availability, and cost.

The program is also focused on developing ceramic matrix composites and compatible environmental barrier coatings to enable 70 percent efficient and 100 percent hydrogen-fired turbines. Ceramic matrix composites allow for higher operating temperatures compared to conventional superalloy used in turbines, and thereby, ceramic matrix composites can accommodate higher temperatures associated with 100 percent hydrogen combustion and offer the possibility of increasing turbine efficiency. Ceramic matrix composites are reinforced with long fibers and are commonly manufactured by infiltration. Leveraging smart fabrication methods is key in the development and deployment of ceramic matrix composites.

The eXtremeMAT project addresses the materials of construction challenges by harnessing the unparalleled computational and experimental materials science expertise and capabilities of the NETL-led DOE national laboratory consortium into an integrated team aimed at improving heat-resistant alloys for the use of hydrogen. Models developed there for component lifetime prediction are critical to managing a flexible fleet of generators that enable high penetration of renewables into the grid.

DOE-FECM supports the High-Performance Computing for Materials (HPC4Mtls) Program as part of DOE's High-Performance Computing for Energy Innovation initiative. HPC4Mtls accelerates industry discovery, design, and development of materials in energy technologies by enabling access to computational capabilities and expertise in the DOE laboratories. Furthermore, R&D covering materials compatibility in hydrogen environments is synergistic with efforts in HFTO's H-Mat consortium.

2.4.3 Milestones

Evaluate the Impact of Hydrogen

- Establish a data repository of materials performance in high-temperature hydrogen service that provides information on degradation mechanisms and is of importance to materials selection. (2025)
- Develop mechanistic models that are critical to understanding hydrogen-related impacts, such as hydrogen embrittlement, high-temperature hydrogen attack, and creep in hydrogen. (2026)
- Advance data-driven computational tools for predicting the performance of materials subjected to high-temperature hydrogen and long service life. Tools to assist in certification, selection, and monitoring the in-service integrity of alloys and materials in hydrogen service. (2026)
- Generate and disseminate information that enhances confidence in the production and utilization of hydrogen. (2026)

Affordable, Durable Alloys and Materials to Resist Hydrogen

- Improve hydrogen resistance of alloys and components by utilizing advanced manufacturing methods. (2025)
- Support robust domestic hydrogen materials supply chain by providing U.S. materials and manufacturing options for worldwide utilization of materials for hydrogen production. (2025)
- Develop materials that reduce costs and improve reliability, availability, and maintainability. Enhance the safety of materials, components, and systems for hydrogen service. (2026)

Materials for Hydrogen Turbines

- Develop physics-based predictive life models for ceramic matrix composites and environmental barrier coating systems. (2025)
- Support innovative manufacturing of lower-cost and more durable ceramic matrix composites. (2026)
- Develop cost-effective and high-performance environmental barrier coating systems to protect silicon carbide (SiC) ceramic matrix composites from hydrogen combustion environments. (2026)
- Develop a robust domestic ceramic matrix composites and environmental barrier coatings supply chain to support 100 percent hydrogen-fired gas turbines. (2028)
- Develop facilities for testing of ceramic matrix composites and environmental barrier coatings in realistic gas turbine conditions.

Supply Chain Development Support

- Assist U.S. industry in advancing the new materials needed for hydrogen turbines and enhance the reliability of materials for hydrogen service. Enhance the competitiveness of U.S. materials and manufacturing options and diversify supply chains for materials for hydrogen turbines and hydrogen service. Milestones will be developed in future updates of this MYPP.

2.5 Sensors, Controls, and Other Novel Concepts

2.5.1 Technology Challenges

The Sensors, Controls, and Other Novel Concepts program seeks to address the technological challenges that can be categorized into three key research areas:

Harsh Environment Sensors

Extreme environments, often observed in carbon management technologies, ranging from hydrogen fuel production to power generation, can make temperature or concentration measurements difficult or even impossible over extended operating periods. The conditions in gasifiers for hydrogen production from waste plastics and biomass, as wells as inside SOFCs and gas turbines, are all in harsh environments. Gasifiers have high temperatures and oxidizing conditions in some locations but also have pockets of reducing gases, ash, slag, acid species, and other chemically aggressive conditions that shorten the life of most sensors. SOFCs operate at slightly lower temperatures (600˚–800˚C) but have both oxidizing and reducing (high hydrogen) flows. Chemical looping—an advanced process for producing heat with integrated CO_2 separation—has operating temperatures that can exceed 1,000˚C while circulating large quantities of abrasive oxygen carrier particles. Hydrogen gas weakens materials like carbon steel via hydrogen embrittlement, and pollutants like sulfur and chlorine are corrosive. The ability to monitor performance in gasifier systems is important, especially for new fuel sources like MSW, plastics, biomass, or coal wastes, which have high variability in composition. It is necessary to monitor the environmental integrity of these systems in addition to tracking maintenance needs in order to optimize low operating expenses. Given the challenges of monitoring and maintaining the environmental integrity and system security of integrated energy and carbon management systems, advanced sensors are required for high-temperature, harsh environmental conditions in which other measurement technologies are incapable of functioning.

Advanced Controls and Cyber-Physical Systems

The fundamental challenge of controls research is to optimize processes under static and dynamic operating conditions. While finding and maintaining optimal operating conditions is beneficial at a steady state, many systems must also perform significant load changes. For example, R-SOFCs may produce hydrogen when excess renewable power is available but can produce power when cheap renewable power is unavailable. Because cells and stacks are sensitive to extreme temperature gradients or rapid changes in load, these cycles require advanced control strategies to protect the cell stack from damage or excess degradation. R&D on control systems to ensure reliability of fuel cells and electrolyzers experiencing large fluctuations in load will be done in coordination with DOE's HFTO, including leveraging of the ARIES hydrogen testing equipment and infrastructure at the National Renewable Energy Laboratory (NREL).

Furthermore, as SOFC systems are not yet produced at a full commercial scale, they remain expensive. Therefore, pilot systems for SOFC and SOEC will be high-risk endeavors, underscoring the importance of developing preliminary control strategies before the pilot plant becomes operational. Hybrid power systems —such as fuel cell-turbine hybrids, chemical looping systems, sCO_2 power systems, and systems with integrated energy storage—present challenges for the development of both control strategies for optimal operation and dynamic control to maintain system stability. The optimal control of the system during dynamic events will depend on what is being optimized, such as efficiency or operating cost. However, such control typically involves closely following an optimal path of operating states. Controls research may improve the speed of following the optimal path between states, how closely it is followed, and the stability of operation once the desired state is reached. Systems' strongly coupled components exhibiting nonlinear behavior are generally more challenging to control optimally. The integration of hydrogen with carbon management systems and hybrid power systems necessitates advanced control methods to achieve an optimal balance between operational performance and reliability while managing the complex interactions inherent in hybrid systems, which often include renewable generation, energy storage, carbon management, and other elements.

Emerging Technologies

Emerging technologies in this field face several challenges. Key issues include cost effectiveness, wherein emerging sensor technologies often start with expensive production costs but must be made affordable for widespread use. Data management constitutes another key hurdle; sensors produce a lot of data and keeping this data secure and private is crucial. Developing efficient data management and analytics solutions to extract meaningful information from sensor data and protecting sensor data from unauthorized access is a significant challenge. Rapid technological advancements in new sensing technologies, such as quantum sensors or sensors based on emerging materials, also present challenges in terms of understanding, harnessing, optimizing their capabilities, and industry acceptance.

Novel concepts complemented with quantum technologies, such as artificial intelligence and machine learning, will prove essential to a secure, clean energy future.

2.5.2 Technology Status

The Sensors, Controls, and Other Novel Concepts program is conducting R&D for technologies that will provide pivotal insights into optimizing the performance, reliability, and availability of integrated energy and carbon management systems. The program invests in technologies that develop, test, and mature novel sensors and control technologies that are operable in next-generation energy systems, including hybrid plants incorporating components such as hydrogen-powered turbines and fuel cells, renewables, and energy storage applications. These sensors enable responsiveness to varying conditions in real time, maintaining high efficiencies and reducing emissions.

Harsh Environment Sensors

Advanced manufacturing techniques under investigation offer the potential to enable the design and rapid, cost-effective reproduction and wide distribution of new and novel sensors that can be embedded into several plant components. In combination with traditional manufacturing that improves performance and operational range, these efforts amplify the ability to monitor key components, transmit data to a distributed network in real-time, and assist in improving plant efficiency, reliability, and availability. The development of distributed optical fiber sensors poses a significant research challenge. Currently, silica optical fibers exhibit limited durability in high-temperature process environments, especially when exposed to hydrogen or water vapor. This limitation can be addressed by employing sapphire fibers; however, commercial sapphire fibers lack a durable and cost-effective optical cladding, which is essential for confining light as an optical fiber when in contact with other materials. Additionally, optical fibers, while flexible, cannot be sharply bent like metal wire without breaking. Therefore, they require greater care during installation and handling in sensor applications.

- **High-Temperature Environments—**Gasifiers, reformers, electrolyzers, and other process equipment under the Hydrogen with Carbon Management space all operate at temperatures well above 600˚C, which is a challenge for developing in situ sensing of these environments.
- **Real-Time Measurements, Diagnostics, and Inspection**—The ability to make measurements to diagnose issues and to facilitate preventative and predictive maintenance to maintain reliable operation and keep operating expenses low is an important goal for this program.
- **Optical Fiber, Wireless, Imaging, Robotics**—The ability to guarantee accurate transmission of plant-critical data securely within the plant while asserting data integrity..
- **Materials Development, Packaging, Prototyping**—The ability to make the sensing equipment small enough to be transported easily around the field or rugged enough to withstand harsh outdoor plant environments. Low cost is also critically important.
- **Testing in relevant environments—**Lab testing and development needs to be performed with the knowledge of the end application, requiring sensor testing using the conditions that the sensor would experience in the field.

Advanced Controls and Cyber-Physical Systems

Research in Advanced Controls and Cyber-Physical Systems (CPS) is developing systems with fast dynamics for non-steady-state operation and incorporating controls capable of handling systems that are inherently nonlinear using real-time data. Using a dynamic process of highly integrated sensors allows for increased control of the plant and is more robust than the current slate of linear model predictive control algorithms. Research is also exploring sensor placement to improve performance, management, and cost of the entire control system, as well as to further optimize cognitive capabilities.

The development of new hybrid technologies within aggressive time constraints requires a novel technology development paradigm. A cyber-physical approach must be employed to create a conceptual design for a hybrid system that incorporates hydrogen production and utilization, thermal management, and carbon management at a scale that could be feasibly adopted in distributed power markets with economic viability. Specific areas of interest in this area of the program include:

- Controls strategies for advanced energy systems and hybrids.
- PID-MPC (proportional, integral, and derivative-model predictive controller), agent-based controls.
- Online system identification, potentially including artificial intelligence/machine learning approaches.
- Condition-based maintenance.

Novel/emerging technologies are being developed to support energy applications that will prove essential to a clean energy future. These activities start with next-generation technologies such as quantum sensors, move toward technology maturation and then transition to the marketplace. For example, quantum sensors, quantum optics, and quantum sensing methodologies have the potential to realize unprecedented performance in advanced sensing instrumentation, with at least an order of magnitude noise reduction as compared to classical counterparts within acceptable cost budgets. Quantum sensing also has the potential for inherent cybersecurity through entangled pair generation via Bell state measurements.

2.5.3 Milestones

- Accurately measure harsh process environment conditions to facilitate optimized performance; improve component health monitoring and prediction; faster response times; and safe, environmentally responsible operation of hydrogen/carbon management applications.
  - Demonstrate compact RGA at a real-world facility. (2025)
  - Demonstrate optical fiber hydrogen sensing technology under harsh gasification conditions at a real-world facility. (2028)
- Design and enable efficient, safe, and flexible operation of new or retrofit integrated energy systems with carbon management to enhance grid stability.
  - Successful deployment of cyber-physical systems in direct air capture (DAC) test center. (2026)
  - Demonstrate hybrid carbon capture cyber-physical system. (2027)
- Develop novel/emerging technologies to support future Hydrogen with Carbon Management applications essential for energy security and efficiency.
  - Optimization of magnetohydrodynamic (MHD) code to maximize MHD power generator performance with varying levels of bio-fuel inputs. (2024)
  - Develop a machine learning model to predict the temperature-dependent gas sensing responses for FECM applications (e.g., detecting methane [CH_4], CO, and CO_2). (2025)

2.6 Simulation-Based Engineering

2.6.1 Technology Challenges

FECM is seeking improvements in all aspects of modeling, from algorithms to software engineering, to enable the discovery of new materials, optimization and troubleshooting of novel devices, and design and optimization of complex process systems. This unique expertise is needed to resolve challenges associated with greater flexibility requirements for evolving energy ecosystems, tighter coupling across temporal and spatial scales/domains, integration of future energy systems in a dynamic and evolving electricity grid environment and enabling deep decarbonization of the energy and industrial sectors.

Understanding the performance of complex flows and components used in advanced power systems and having the means to impact their design early in the development process provides significant advantages in product design. During new technology development (e.g., the development of a new sorbent adsorber/desorber reactor for CO_2 capture), empirical scale-up information is not available because the device has not yet been built at the scale required. Traditional scale-up methods do not work well for many of the components of complex power systems. Therefore, science-based models with quantified uncertainty are important tools for reducing the cost and time required to develop these components.

The SBE program guides a multidisciplinary approach comprising software development, computational power, data repositories, experimental facilities, and unique partnerships to support research into timely and accurate solutions for sustainable energy and carbon management systems. Analysis and visualization tools are manipulated to gain scientific insights into complex, uncertain, high-dimensional, and high-volume datasets. The information generated is then collected, processed, and used to inform research that combines theory, computational modeling, advanced optimization, physical experiments, and industrial input.

The extensive computational resources available to FECM through NETL ensure timely solutions to the complex problems associated with advancing power sector technologies toward deep decarbonization and sustainable energy. Speed-up is also achieved through research in modern GPU computing, as well as the implementation of reduced-order models when appropriate. Furthermore, the latest advances in artificial intelligence and machine learning are utilized in the SBE program's portfolio wherever applicable to optimize performance.

The technology challenges being addressed by the SBE program are associated with improving the efficiency and reliability of the existing fleet, designing and scaling-up next generation energy systems, designing and operating devices handling multiphase with solids and lead time, cost, and designing risk reduction for reactor development. SBE addresses:

Enhanced understanding of integrated, complex energy systems and chemical processes.

- Device, process system, and grid/market scales.
- Conceptual design.
- Steady-state design.
- Dynamic operations.
- Optimization of performance and costs.

Scientific insights into complex, uncertain, high-dimensional, and high-volume datasets.

- Design, optimization, scale-up, and troubleshooting.
- Data reconciliation, parameter estimation, and uncertainty quantification.
- Better predict operational characteristics.

Accelerated time to deploy energy technologies.

- Advanced ultra-supercritical operation.
- Gasification of sustainably sourced carbon-based feedstocks.
- Hydrogen storage and combustion technologies.
- Point source carbon capture.
- CDR.
- CO_2 utilization.
- CO_2, CH_4, and hydrogen storage and transport.

2.6.2 Technology Status

SBE continues to be a rapidly evolving field. Advances in computing power, algorithms, and modeling techniques have allowed for increasingly sophisticated simulations in many industries, including aerospace, automotive, manufacturing, and the power generation industry. The SBE program has developed and deployed unique toolsets that are being deployed to solve complex problems that cannot be otherwise understood. These tools are critical to achieving policy priorities and in modeling technologies and systems needed to manage and reduce carbon across the full life cycle. The SBE program will continue to be a research priority for FECM in support of its decarbonization goals.

The SBE program develops advanced process simulation (through IDAES) and multiphase flow science (through MFiX) research comprised of innovative physics- and chemistry-based models and computational tools at multiple scales (i.e., atomistic, device, process, grid, and market) to help achieve DOE's strategic vision through targeted RD&D efforts.

NETL's IDAES integrated platform utilizes the most advanced computational algorithms to enable the design and optimization of complex, interacting energy and process systems from individual plant components to the entire electrical grid. IDAES represents a paradigm shift as the only fully equation-oriented platform with integrated support for steady-state design, optimization, dynamic operations, data reconciliation, parameter estimation, and uncertainty quantification of complex energy and chemical processes. IDAES uniquely supports the process modeling life cycle, from conceptual design to dynamic optimization and control, by providing rigorous modeling capabilities to increase efficiency, lower costs, increase revenue, and improve the sustainability of power generation and electricity distribution, including:

- Optimization of the design and operation of complex, interacting technologies and systems.
- Supporting the process modeling life cycle.
- An extensible, open platform that empowers users to create models of novel processes.

NETL has developed the MFiX software suite, which is the world's leading open-source design software for comparing, implementing, and evaluating multiphase flow constitutive models. These tools provide an accurate, validated, and cost-effective capability to design, optimize, scale-up, and troubleshoot a diverse range of multiphase flow applications, including gasification systems, point source capture, and CDR systems. Model development and refinement is achieved through in-house research combined with external partnerships to harness cutting-edge CFD expertise across the country.

Wafer-Scale Engine (WSE) technology is a new computing architecture, like GPU in terms of data management but vastly different in scale. Since their inception, WSEs have been used primarily in the context of artificial intelligence/machine learning algorithmic programming as the data transfer volume easily invites that synergy. The SBE program is exploring the architecture in the context of scientific programming along various fronts of interest to DOE. The most difficult is that of CFD, as reactor geometry and transient calculations, along with intermittent data dumps, complicate simulation administration.

2.6.3 Milestones

IDAES is developing (1) next-generation process system engineering tools and applications for process innovation and improved efficiency of integrated energy systems and (2) new capabilities for design, control, dynamic operation, multi-criteria optimization, and multi-scale modeling.

MFiX leads the development and maintenance of strategic reactor modeling capabilities based on multiphase flow with strategic capability for the design, scale-up, and optimization of existing and advanced fossil energy reactors and provides verification, validation, and uncertainty quantification of critical, high-quality data describing complex flow physics encountered in FECM devices. Specific milestones include:

- Accelerate design and deployment of integrated power, hydrogen, and industrial processes to support broad decarbonization and emerging R&D priorities. (IDAES: 2025)
- Continuing support for the growing stakeholder community. (IDAES/MFiX: 2025/2026)
- Ongoing computational platform support to maximize DOE-FECM investment. (IDAES/MFiX: 2025/2026)
- Leverage models and simulations to accelerate the design, optimization, and/or scale-up of complex, integrated technologies and systems. (IDAES/MFiX: 2025/2026)
- Support multiphase computational efforts, including machine learning, in collaboration with industry to gain deep insight into plant operation to improve performance outcomes and reduce unexpected, forced outages. (MFiX: 2026)
- Exploration of novel methodologies to increase computational speeds and/or reduce computational energy requirements. (MFiX: 2026)
- Expand the WSE field equation application programming interface—WSE field-equation application programming interface (WFA)—to include all necessary kernels to couple to existing multiphase reacting flow CFD software. (WSE: 2026)

3. References

DOE (2021). *Hydrogen Shot*. U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

DOE (2023). *Clean Hydrogen Production Standard Guidance*. U.S. Department of Energy Hydrogen Program. https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard.

EPA (2023). *Inventory of U.S. Greenhouse Gas Emissions and Sinks*: 1990–2021. U.S. Environmental Protection Agency, EPA 430-R-23-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021.

Federal Register. (2021, January 27). *Tackling the Climate Crisis at Home and Abroad*. Retrieved from Federal Register: https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad.

IEA (2019, June). *The Future of Hydrogen: Seizing today's opportunities*. International Energy Agency. https://www.iea.org/reports/the-future-of-hydrogen.

Lawrence Livermore National Laboratory (2020). Ge*tting to Neutral: Options for Carbon Negative Emissions in California*. Livermore Lab Foundation. https://livermorelabfoundation.org/2019/12/19/getting-to-neutral.

NETL. (2021, April 21). *Gas to Carbon Fiber Crystals*. National Energy Technology Laboratories. https://www.netl.doe.gov/node/9812.

Uysal, S. C. (2021). *Comparative Study for Pressure Gain Combustion-Gas Turbine System Performance in NGCC Configurations*. (Report No. NETL/DOE-2021/2644). NETL. https://doi.org/10.2172/1888021.

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