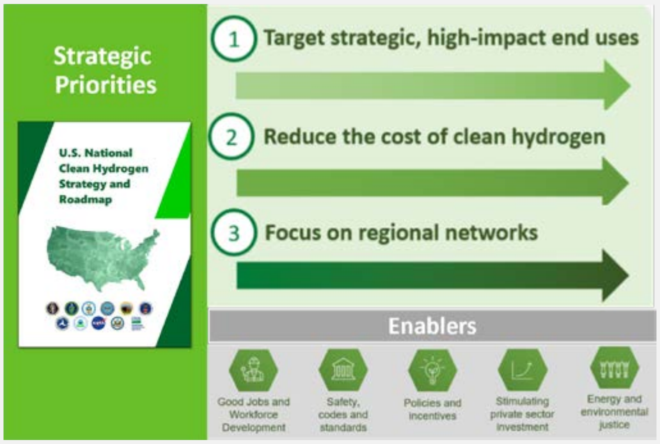
5 Fuel Cell Technologies

5.1 Overview

Goals and Objectives

The overarching goal of the **Fuel Cell Technologies** subprogram is to develop fuel cells that are competitive with incumbent and emerging technologies across diverse applications with emphasis on heavy-duty applications where significant reductions in both carbon emissions as well as criteria pollutant emissions can be achieved. The subprogram pursues this goal through its comprehensive portfolio of RD&D activities.

The Fuel Cell Technologies subprogram supports key strategic priorities identified in the ***U.S. National Clean Hydrogen Strategy and Roadmap***[51] to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit by using highly efficient and zero (or near-zero) emissions fuel cell technology. The subprogram directly supports the strategic priority to target high-impact end uses in transportation, power, and industrial sectors; and it coordinates closely with the other HFTO subprograms to support priorities targeting affordable fuel cell technologies and enabling regional clean hydrogen networks.



Fuel cells are a conversion technology offering exceptional efficiency and reliability in converting clean hydrogen as well as other fuels into electricity for high-impact end uses such as heavy-duty transportation, stationary power generation, and energy storage.

Specific objectives of the Fuel Cell Technologies subprogram include:

- Developing fuel cell systems with emphasis on near-term heavy-duty transportation applications that are highly durable, efficient, and low cost, while meeting application-specific constraints such as dynamic response, resiliency, packaging, and heat rejection.
- Developing new materials and components for next-generation fuel cell technologies in diverse applications for power generation and long-duration grid-scale energy storage, emphasizing innovative mid- to long-term approaches, including reversible fuel cells and

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[51] U.S. Department of Energy. *U.S. National Clean Hydrogen Strategy and Roadmap.* 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

hybrid approaches such as tri-generation that can use fuel cells to coproduce power, heat, and fuel.

Technology Description

Fuel cells efficiently convert the chemical energy of fuels such as clean hydrogen into electricity and are an important part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future. As illustrated in Figure 5.1, fuel cells can convert a wide range of fuels and feedstocks into electricity, with heat and water as additional coproducts. They can be used for a variety of applications across multiple sectors, including transportation (road and offroad vehicles, rail, marine, aviation), primary and backup stationary power (for industry, data centers, commercial/residential buildings), and long-duration energy storage for the grid. In addition, fuel cell technologies can be used for combined heat and power generation or in innovative, hybrid approaches such as in tri-generation (power, heat, and hydrogen) applications.

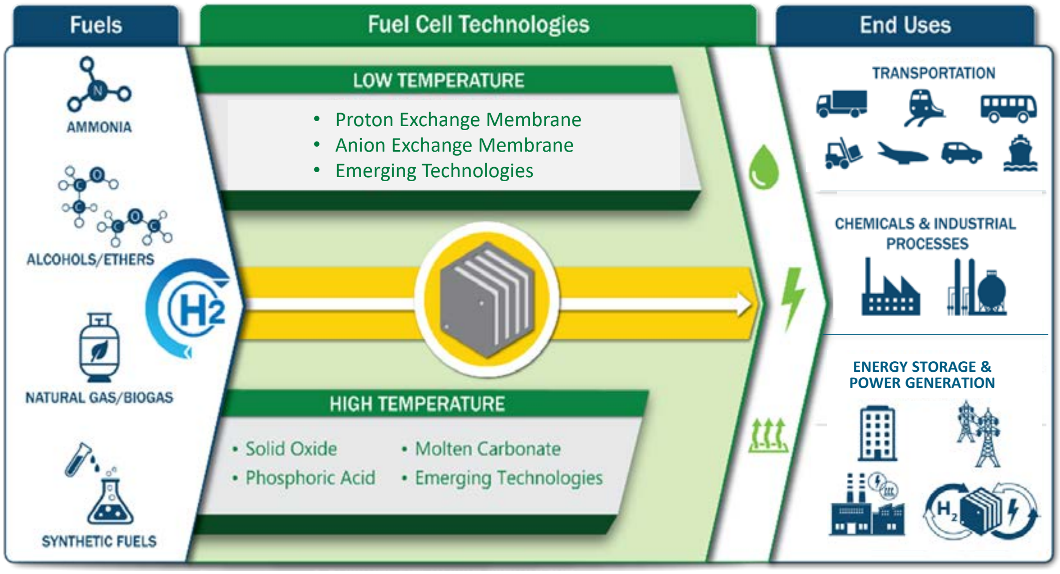


Figure 5.1. Versatility of diverse fuel cell technologies that convert clean hydrogen or other fuels into electricity, heat, and water for various high-impact end uses

A fuel cell comprises electrically conducting anode and cathode electrodes separated by an ion-conducting electrolyte or membrane. Typically, a fuel such as hydrogen is introduced at the anode, air or oxygen is fed to the cathode, and the electrolyte, through ion-exchange, facilitates the electrochemical reaction generating the electricity, heat, and water. Fuel cells are scalable, as multiple cells can be combined in a stack to generate more power. A fuel cell is usually classified by the specific type of electrolyte it employs, which determines the electrochemical reactions and required anode- and cathode-catalysts, as well the operating temperature range, fuel requirements, and other factors relevant to most suitable end uses. Table 5.1 gives examples of some common fuel cell types.

Table 5.1. Example Fuel Cell Types with Corresponding Electrolyte, Ionic Charge Carrier, and Operating Temperature Range

Fuel Cell Type	Common Electrolyte / Charge Carrier	Temperature Range
Proton Exchange Membrane	Perfluorosulfonic Acid / H^+	<120°C
Alkaline Exchange Membrane	Alkaline Polymer / OH^-	<100°C
Solid Oxide	Yttria-Stabilized Zirconia / O^{2-} Yttria-Doped Barium Zirconate/ H^+	500°–1,000°C 400°–700°C
Alkaline - Liquid	Aqueous KOH / OH^-	<100°C
Molten Carbonate	$(Li,K,Na)_2CO_3$ / CO_3^{2-}	600°–700°C
Phosphoric Acid	$H3PO_4$ / H^+	150°–200°C
Polymer Phosphoric Acid	Polymer $H3PO_4$ / H^+	150°–200°C

PEM fuel cells for diverse fuel cell vehicle and stationary applications are an important example. As illustrated in Figure 5.2, the heart of a PEM fuel cell is the MEA, which includes the electrolyte membrane, the catalyst layers, and gas diffusion layers. The anode catalyst enables hydrogen molecules to be split into protons and electrons. The polymer membrane blocks electrons while conducting the protons to the cathode. The cathode catalyst enables reduction of the oxygen with the protons, coproducing water and heat, while the electrons driven through the external circuit generate electricity. The gas diffusion layers are placed outside the catalyst layers and facilitate transport of reactants into the catalyst layer, as well as removal of product water. The catalyst layers are typically mixed with ionomer material to help facilitate proton conduction. Bipolar plates play an important role in reactant distribution, allow water to be removed from the cells, and provide electrical conductivity. All these components must be addressed to enable better cost, performance, and durability of PEM fuel cells.

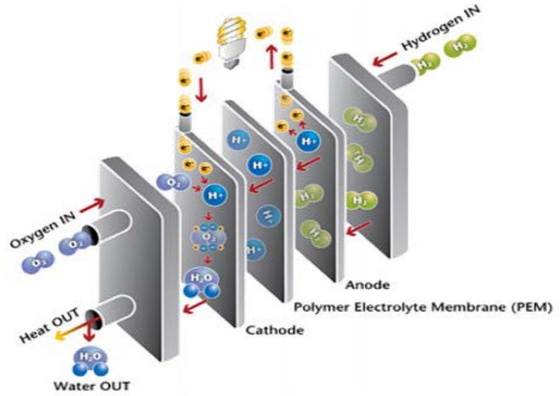


Figure 5.2. Basic operation of a PEM fuel cell, important to near-term high-impact end uses. Additional cells are stacked for more power in a fuel cell system.

Fuel cells offer several benefits over incumbent technologies in many vehicles and power applications, including high efficiency in the direct conversion from chemical to electrical energy. In fuel cells, power and energy are decoupled and can be tuned independently, which means that for a fixed fuel cell stack, more hydrogen allows higher energy capacity without changing the fuel cell size or power. Fuel cells are easily scalable, as individual cells can be stacked to yield the desired power range, and thus address the power needs for multiple applications, supporting the economies of scale required to bring down cost.

Hydrogen fuel cells are an attractive technology to power zero-emission medium- and heavy-duty vehicles, including road vehicles such as trucks and buses. Advantages over incumbent technologies such as diesel engines include higher efficiency, reduced emissions, higher torque, and no noise pollution. Additionally, to complement battery electric vehicles, hydrogen fuel cell vehicles can alleviate dependence on critical minerals (e.g., lithium), and offer fast fueling and adequate fuel storage for applications demanding longer range. Fuel cells also offer high reliability, resiliency, and efficiencies for distributed power and long-duration storage applications, with efficiencies of over 80% possible when fuel cells are used in combined heat and power applications. Also, one potential advantage of fuel cells in the form of reversible or hybrid systems is the flexibility to deploy produced hydrogen for other applications, such as transportation fuel or industrial use, potentially at higher value than grid electricity.

5.2 Strategic Priorities

As shown in Figure 5.3, the Fuel Cell Technologies subprogram's strategy incorporates near-, mid-, and longer-term focus areas, aligned with national clean hydrogen priorities and consistent with the overall HFTO strategic framework described in the Introduction. The near-term priority, aligned with highest-impact opportunities identified in the *U.S. National Clean Hydrogen Strategy and Roadmap***,** is to develop PEM fuel cells for use in commercial fleets of heavy-duty, zero-emission vehicles. In the mid- to longer term, the technology advances developed through heavy-duty PEM fuel cell RD&D efforts, in concert with ongoing research and development of other fuel cell technologies (including reversible fuel cells), are expected to offer transferrable benefits for diverse medium- to heavy-duty transportation applications (such as marine, rail, and aviation), as well as stationary power generation and energy storage applications (such as primary power, backup power, and combined heat and power).

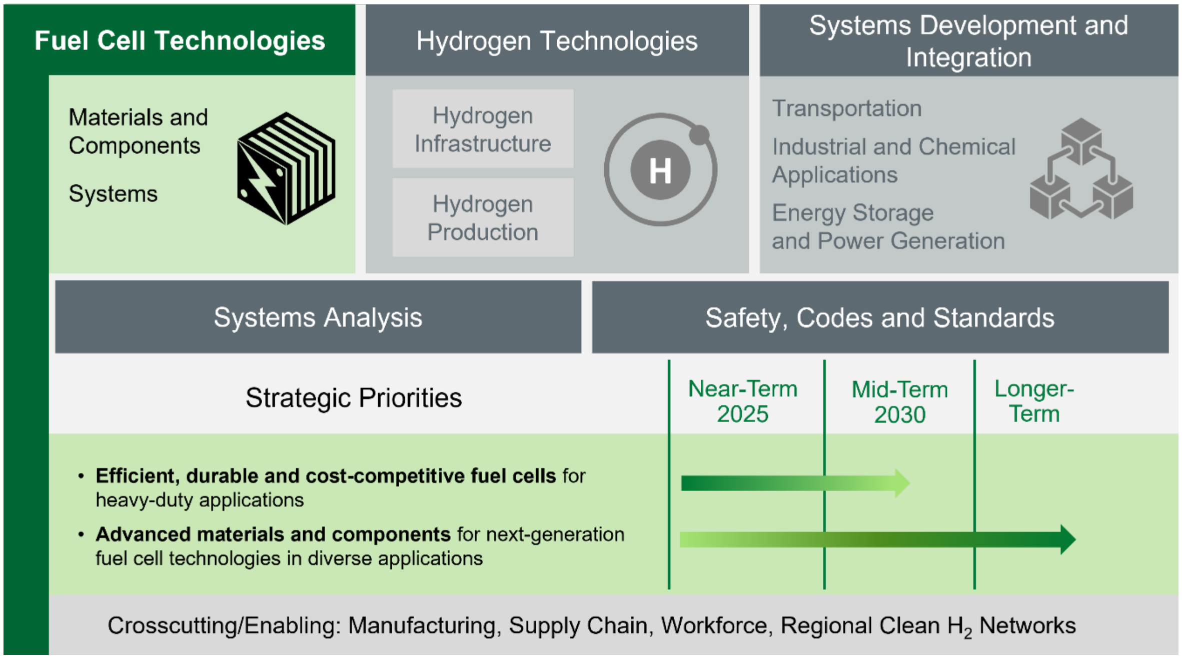


Figure 5.3. Strategic priorities guiding Fuel Cell Technologies RD&D

Near- to Mid-Term Priorities

The subprogram's near- to mid-term priorities are to improve the durability and efficiency, reduce the cost, and enable scalable manufacturing of fuel cell technologies, with primary emphasis on medium- to heavy-duty transportation applications using direct hydrogen-fueled PEM fuel cells. The aim is to achieve these improvements while meeting application needs and constraints such as transient response, duty cycles, and other parameters that will vary depending on end use and operating conditions. As described in following sections, the subprogram's PEM fuel cell RD&D addresses the materials, component, system, manufacturing, and supply chain challenges to accelerate the commercial liftoff of zero-emission heavy-duty vehicles. While the focus is primarily on the hard-to-decarbonize heavy-duty applications with limited alternatives (e.g., long haul, heavy-duty trucks, and other vehicles requiring long driving ranges, fast fueling, and/or high payloads), the near-term RD&D in this focus will also enable emerging opportunities in transportation applications such as buses, rail, aviation, marine, and offroad (mining and construction), as well as stationary power and energy storage applications.

Mid- to Long-Term Priorities

The subprogram's longer-term RD&D priorities include higher risk but potentially higher impact approaches that can leap-frog the current fuel cell technologies that are expected to be commercial in the near term for heavy-duty transportation. This includes developing new materials, components, and concepts for next-generation fuel cell technologies for applications including distributed power, long-duration grid-scale energy storage, and polygeneration, as well as additional transportation applications. Specific technology pathways for diverse mid- to longer-term applications include fuel cells with PGM-free catalysts; anion exchange membrane fuel cells; bipolar membrane fuel cells; direct liquid-fueled fuel cells; intermediate temperature fuel cells; and reversible fuel cells especially targeted toward grid-scale energy storage.

These technologies are all at an early stage of RD&D but have the potential to dramatically improve the competitiveness of fuel cell technologies by lowering cost, reducing dependence on critical minerals such as platinum, and improving efficiency. Current RD&D efforts for these next-generation technologies focus on smaller-scale exploratory activities in materials and component development; over time, these will grow to encompass major subprogram efforts as the technologies evolve.

Examples of next-generation fuel cell concepts include:

- ***PEM fuel cells containing PGM-free catalysts*** allow for significant cost reduction, as the PGM catalyst is projected to be the most critical PEM fuel cell stack cost component. The development of high-performing and durable PGM-free catalysts also alleviates reliance on foreign imports for PGM materials.
- ***Anion-exchange membrane fuel cells*** present the opportunity to achieve the high power-density of PEM fuel cells with alkaline conditions that are less harsh for many materials, and therefore offer possible compatibility with less expensive catalyst and bipolar plate materials.
- ***Bipolar membrane fuel cells*** offer the potential for integrating the high hydrogen-electrode kinetics in acid systems with the advantages of anion-exchange membrane fuel cells. Bipolar membranes also provide potential for self-humidifying membranes that can operate under drier conditions.
- ***Direct liquid-fueled fuel cells*** operate by electrochemically converting liquid fuels (e.g., methanol, ammonia, dimethyl ether) directly to electricity, thereby alleviating hydrogen delivery and storage challenges and offering fuel flexibility for a range of applications (e.g., maritime, rail, data centers).
- ***Intermediate temperature fuel cells*** operate in the 150–500°C temperature range, which is above the operating temperatures of PEM fuel cells but below those of solid oxide and molten carbonate fuel cells, offering the potential advantages of high-efficiency, low-cost materials, fuel flexibility, and effective heat rejection.
- ***Reversible fuel cells*** function under both fuel cell and electrolysis modes and offer a promising technology to provide long-term energy storage, grid leveling and stabilization

services, with the flexibility to deploy hydrogen for other applications. Unitized reversible fuel cells, which use the same stack in either fuel cell or electrolyzer mode, offer a pathway to lower cost and system simplification.

- ***Fuel cells and hybrid concepts for polygeneration,*** including cogeneration (combined heat and power), present the opportunity to utilize diverse feedstocks to generate multiple value streams. In tri-generation, power, heat, and hydrogen are produced with low emissions and high efficiency.

5.3 RD&D Targets

Target-Setting

The Fuel Cell Technologies subprogram's RD&D strategy is driven by application-specific targets that reflect the performance, durability, cost, and scale needed to compete with existing and other emerging technologies. The targets are developed holistically based on the ultimate life cycle cost of using fuel cell systems in comparison with other technology options. They are guided by analysis and fuel cell system modeling, including cost analysis and evaluation of system designs and operating approaches. Publicly available and industry-vetted manufacturing cost estimates are incorporated in the analysis to accurately gauge the status and future potential of the technology.

As an example, specifically relevant to its near-term priorities, the subprogram has developed interim and ultimate cost targets to enable market-competitiveness of hydrogen fuel cells for heavy-duty hydrogen trucks. Recognizing that both technology advances and economies of scale are needed, the subprogram's RD&D addresses the materials, component, system, manufacturing, scale-up, and supply chain challenges for meeting these targets. Figure 5.4 shows these targets, along with examples of specific cost reductions achievable through economies of scale and the technology development needed to achieve them. Detailed cost-breakdown analysis, such as the breakdown for stack component costs for current PEM fuel cell (PEMFC) technologies shown in the figure, is critical to the prioritization of RD&D efforts.

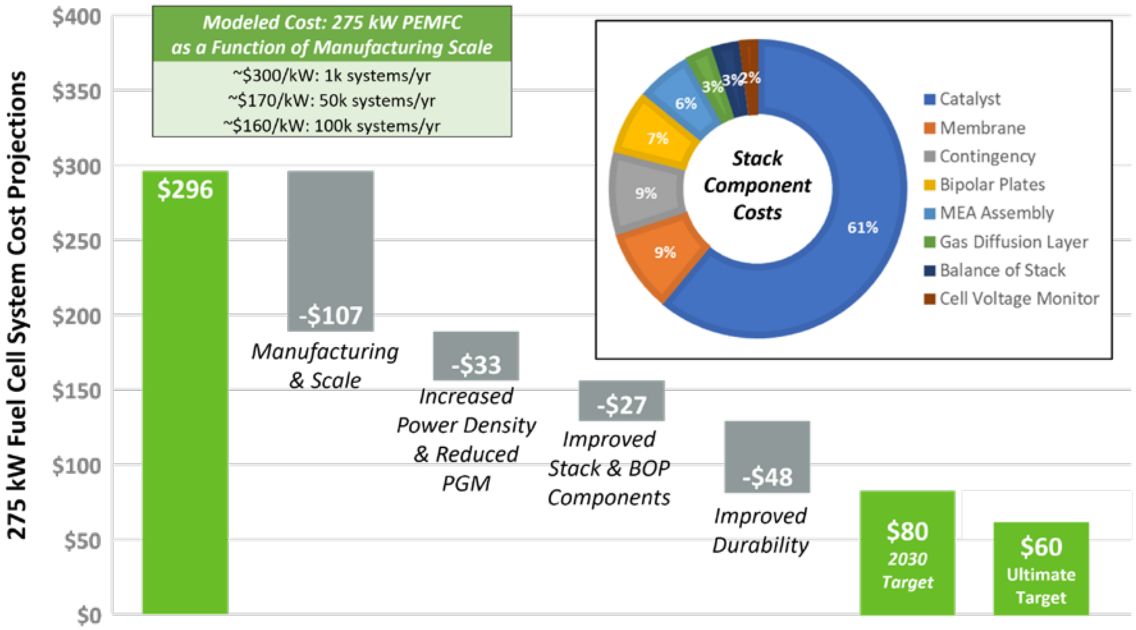
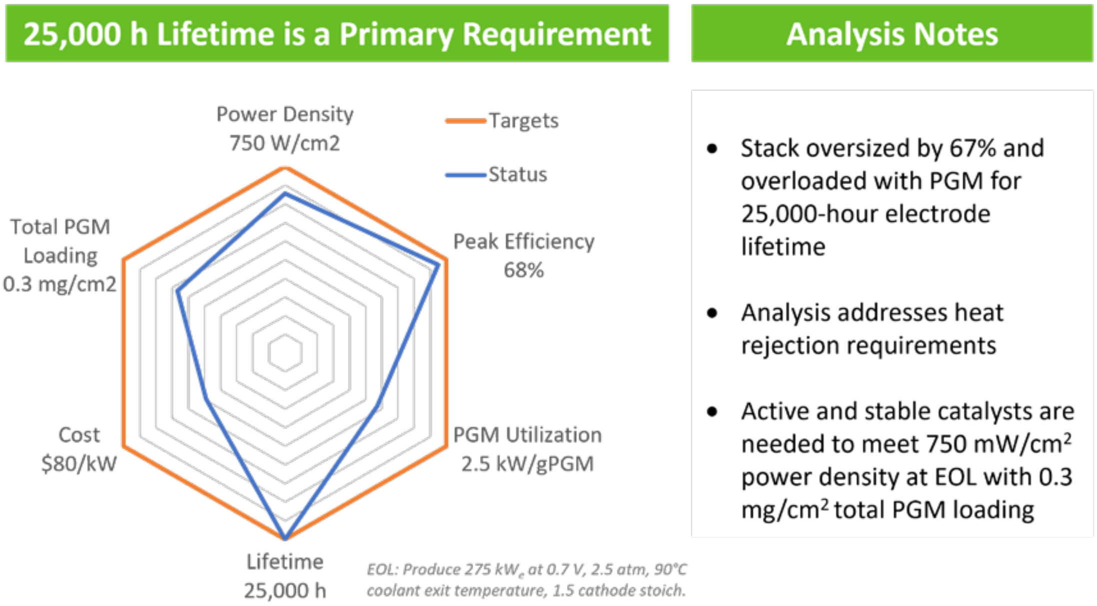


Figure 5.4. A pathway to achieve the 2030 and ultimate cost targets for a heavy-duty fuel cell vehicle system, specifically showing how RD&D can help achieve the target (based on recent analysis)

The waterfall chart in Figure 5.4 shows how addressing specific challenges can contribute to overall cost reductions, providing guidance in conceptualizing the relative magnitude of these challenges. For example, since the catalyst is the most significant cost component in the fuel cell stack, reducing or eliminating the costly PGM catalyst could result in significant cost savings with reduced reliance on sensitive supply chains, providing the fuel cell system performance is not severely impacted.

It is important to emphasize that application-specific requirements on fuel cell performance and durability along with needs based on manufacturing scale and supply chains must be maintained in conjunction with the cost-reduction strategies. Spider charts such as the one illustrated in Figure 5.5 highlight that several subtargets must be addressed simultaneously to achieve cost-competitive fuel cell options for the specific example of heavy-duty applications. The spider chart, along with the waterfall chart, shows the types of related improvements that need to be made simultaneously through comprehensive RD&D to achieve subprogram targets. The subprogram updates these charts annually for presentation at the DOE Hydrogen Program's Annual Merit Review and Peer Evaluation Meeting.



EOL: Produce 275 kW_e at 0.7 V, 2.5 atm, 90°C coolant exit temperature, 1.5 cathode stoich.

- Stack oversized by 67% and overloaded with PGM for 25,000-hour electrode lifetime
- Analysis addresses heat rejection requirements
- Active and stable catalysts are needed to meet 750 mW/cm^2 power density at EOL with 0.3 mg/cm^2 total PGM loading

Figure 5.5. Illustrative spider chart for fuel cell system status versus targets. The line indicates the status as a fraction of the targets, from recent analysis assuming a stack oversized and overloaded with PGM meeting the 25,000-hour lifetime.

End-Use Specific Targets

The Fuel Cell Technologies subprogram has set market-driven targets specific to diverse end-use applications to enable commercial viability, including heavy-duty transportation applications (e.g., long-haul trucks), stationary power, and reversible fuel cells for energy storage applications. Some specific targets in these applications are highlighted below.

Fuel Cells for Long-Haul Trucks

Targets developed by the subprogram for long-haul fuel cell trucks—including a 2030 target of \$80/kW and ultimate system cost target of \$60/kW for high-volume production, while meeting 25,000 hours of durability (ultimate target 30,000 hours)[52]—guide RD&D priorities addressing fuel cell system cost, performance, and durability needed for cost-competitiveness and market liftoff. Lifetime fuel costs for heavy-duty vehicles are also important, making high fuel efficiency at the primary operating conditions critical. The subprogram has set peak efficiency targets of 68% in 2030 and 72% ultimate.

The RD&D priorities also address opportunities to bridge the gap between technology development and deployment by pursuing manufacturing advances to achieve economies of scale, in addition to facilitating the reuse and recycling of fuel cell materials and components to address end-of-life and critical supply chain challenges (including the dependence on PGM supply chains).

Fuel Cell Technologies:
Interim 2030 Targets Examples

Fuel Cells for Long-Haul Trucks

- \$80/kW fuel cell system
- 25,000-hour durability
- 68% fuel cell peak efficiency
- 0.3 mg/cm^2 PGM loading

Heavy-Duty Fuel Cell Manufacturing Capacity

- 20,000 stacks/year (single manufacturing system)
- 370,000 m^2/year membranes
- 2,400 MEAs/hour
- 2,400 bipolar plates/hour
- 1,300 kg PGM catalysts/year

Fuel Cells for Stationary Power

- \$1,000/kW fuel cell system cost
- 80,000-hour durability

Reversible Fuel Cells for Energy Storage

- \$1,800/kW system cost
- 60% round-trip efficiency
- 40,000-hour durability

Heavy-Duty Fuel Cell Manufacturing Capacity

To facilitate scaled manufacturing technologies and processes—as directed by Clean Hydrogen Manufacturing and Recycling provisions (Energy Policy Act sections 815[a] and 815[b])— the subprogram has established capacity targets for heavy-duty fuel cell component and stack production. This includes a target of 20,000 stacks per year in a single manufacturing system by 2030 to enable market lift-off. The needed production volumes will require a reliable supply of components, automation of the cell and stack assembly, and manufacturing capabilities not seen in the field to date.

Fuel Cells for Stationary Power Applications

RD&D advancements are needed to make fuel cells commercially competitive in the wide range of stationary power markets. While some technical challenges are specific to each type of fuel cell, reducing capital costs, extending durability, improving efficiency, and improving fuel

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[52] System cost is projected at a manufacturing volume of 100,000 systems per year. For purposes of measuring progress in fuel cell durability, a 10% voltage degradation at rated power will be used to benchmark end-of-life.

processing for fuel-flexibility are general challenges that apply across all types of stationary fuel cells. A long-term target for stationary power system lifetime has been set at 130,000 hours, reflecting requirements for data centers, where primary power systems must operate 24/7 for 365 days per year. Diverse fuel cell technologies and a range of fuels can be used for stationary applications, depending on application-specific requirements. Targets are technology neutral and make no assumption about the type of fuel cell technology. While achievement of some of the individual targets has already been demonstrated for specific fuel cell technologies, concurrent achievement of all targets remains a challenge. Eventually, the fuel cell system overall will still need to be market competitive; for example, for distributed power generation, fuel cells need to be able to demonstrate a competitive levelized cost of electricity. Fuel flexibility is also of importance, as it enables the use of bioderived fuels (biogas, landfill gas) and can also further enable tri-generation applications where power, heat, and hydrogen are produced from the same plant.

Reversible Fuel Cells for Energy Storage Applications

Energy storage with reversible fuel cell systems is a promising technology to provide long-term energy storage, grid-leveling and stabilization services, and to enable greater adoption of intermittent renewable energy sources. Unitized reversible fuel cells, which use the same stack in either fuel cell or electrolyzer mode, can be used in energy storage applications since they can create hydrogen on demand for storage and convert it back to electricity when needed. Compared with separate fuel cell and electrolyzer systems coupled for such a function, reversible cells offer a smaller footprint with system simplifications that could provide significant cost savings. Beyond grid-scale energy storage, there are other potential applications for reversible fuel cell systems including backup power, satellites, and aircraft. Challenges include optimizing performance and durability under both modes of operation. Achieving high stack and system round-trip efficiencies is critical. Both high-temperature (e.g., solid oxide) and low-temperature (e.g., PEM) technologies are of interest, with high-temperature reversible fuel cells offering higher round-trip efficiency and low-temperature reversible fuel cells offering better operational flexibility. With the aim of achieving a competitive levelized cost of storage, the subprogram has set ultimate reversible fuel cell targets for a system round-trip efficiency of 70%, a system cost of $1,300/kW, and a durability of 80,000 hours.

Interim and Ultimate Targets

In all application areas, the subprogram has developed both interim targets for early market adoption and ultimate targets for competitive, widespread commercial viability for specific technology parameters, reflecting improvements needed in the current baseline values for achieving cost-competitiveness and commercial liftoff. Table 5.2 shows examples of both interim and ultimate targets relative to current baselines for fuel cells in the three end-use areas, illustrating a timeline for near-term RD&D in pathways with the potential to achieve commercial liftoff.

Table 5.2. Examples Showing Pathways from Baseline Technology Parameters toward Ultimate Targets

End Use	2023 Status	2030 Target	Ultimate Target
Heavy-Duty Transportation	• Cost \$170/kW • Durability >10,000 h • Peak efficiency 64% • PGM loading >0.4 mg/cm^2	• Cost \$80/kW • Durability 25,000 h • Peak efficiency 68% • PGM loading ≤0.3 mg/cm^2	• Cost \$60/kW • Durability 30,000 h • Peak efficiency 72% • PGM loading ≤0.25 mg/cm^2
Distributed Stationary Power	• Cost \$1,200–2,500/kW • Durability 40,000–80,000 h • Efficiency 40%–60%	• Cost \$1,000/kW • Durability 80,000 h • Efficiency 65%	• Cost \$750/kW • Durability 130,000 h • Efficiency >65%
Reversible Fuel Cells	• System round-trip efficiency ~37% • Cost NA • Levelized cost of storage \$1.10/kWh • Durability ~10,000 h	• System round-trip efficiency 60% • Cost \$1,800/kW • Levelized cost of storage \$0.10/kWh • Durability 40,000 h	• System round-trip efficiency 70% • Cost <\$1,300/kW • Levelized cost of storage \$0.05/kWh • Durability 80,000 h

The technology baselines and targets are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

For the latest, most up-to-date information on technical targets and the status of the technologies covered by HFTO, see:
www.energy.gov/eere/fuelcells/mypp

5.4 Addressing Challenges

The Fuel Cell Technologies subprogram has a balanced and integrated RD&D approach addressing challenges to meeting the application-driven targets formulated to facilitate fuel cell competitiveness. As illustrated in Figure 5.6, the critical overarching challenges are being addressed at the *Materials and Components* and *Systems and Manufacturing* levels.

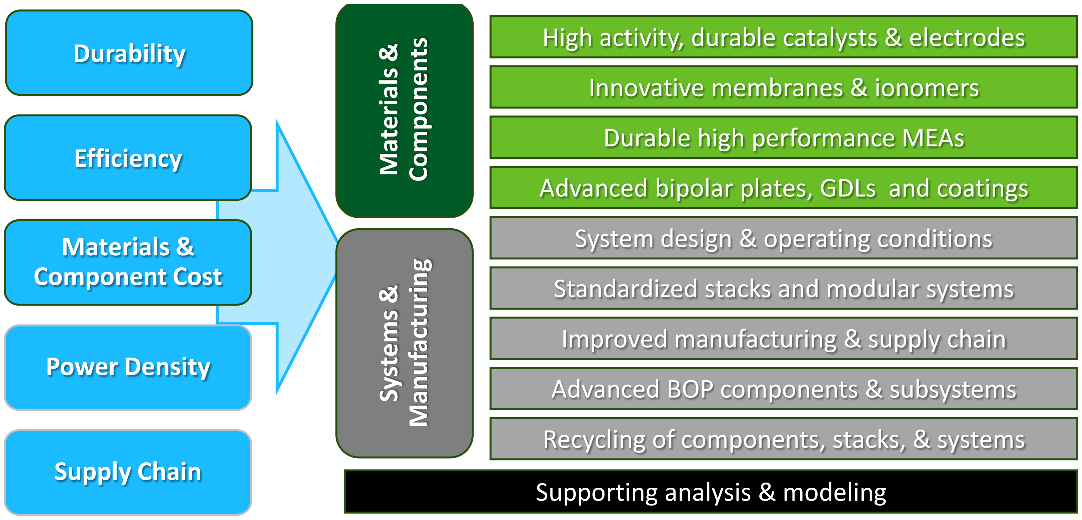

Figure 5.6. Comprehensive RD&D addressing fuel cell materials and components, as well as systems and manufacturing

Materials and Components

Subprogram RD&D addresses materials and components challenges at the cell level for both current and next-generation fuel cell technologies. The key challenges are to identify and develop optimized materials and components that can reduce fuel cell cost while improving durability, power density, and environmental sustainability. Examples include:

- **Catalysts**, including catalyst supports, are a key factor determining fuel cell performance and efficiency, as well as the largest single contributor to the cost of PEM fuel cell stacks, specifically based on costly and supply-chain-sensitive PGM materials used. The oxygen reduction reaction is the primary challenge for catalysts in PEM fuel cells and requires a significant amount of platinum-based catalyst on the fuel cell cathode. Catalyst degradation is a major factor limiting durability in all fuel cell technologies. It also contributes to cost, as catalyst degradation introduces the need for higher catalyst loadings.
- **Membranes and ionomers** are critical fuel cell components that can limit performance and durability, especially under high-power conditions with high temperature and low relative humidity. Membranes need to suppress gas crossover to maintain high fuel cell efficiency and performance. Membrane degradation is caused by mechanical stresses from swelling and shrinking with varying humidity, and by chemical decomposition, which can be accelerated by metal contaminants. The environmental sustainability of polymer membrane materials, such as perfluorosulfonic acid, is a potential concern.
- **MEAs** require strategic integration of membranes, catalysts, ionomers, and electrodes, accounting for component interactions, to optimize fuel cell stack performance (both

efficiency and power density), robustness, and durability. All of these traits are crucial to providing a competitive total cost of ownership for fuel cell applications. It is also critical to understand how fuel cell operating conditions impact the performance and degradation of the different interacting components.

- **Bipolar plates** play an important role in fuel cell performance through reactant distribution and water management and can add significant cost to the fuel cell stack. Metallic and carbon-based (carbon composites and flexible graphite) bipolar plates are both potential options for transportation fuel cells. Metallic plates made thin to increase power density are susceptible to corrosion. Carbon-based alternatives have lower mechanical strength, leading to thicker plates—and thus, potentially lower stack power density and high manufacturing costs.
- **Gas diffusion layers** play an important part in determining stack performance by transporting reactants to, and water away from, the catalyst layers. Gas diffusion layers typically consist of carbon fibers and carbon blacks with a hydrophobic coating. The hydrophobicity of gas diffusion layers tends to degrade over the operational life of the fuel cell, which may become problematic for the very long lifetimes of heavy-duty applications.

Systems and Manufacturing

Subprogram RD&D also addresses systems and manufacturing challenges in fuel cell technologies. To enable commercially viable systems across applications, advancements are required for fuel cell stacks, BOP components, systems design and integration, and manufacturing technologies and processes. The optimization of performance, efficiency, durability, and cost for the different fuel cell technologies across diverse applications requires addressing challenges such as:

- Development of durable and affordable stack designs optimized for power density and efficiency to meet application-specific requirements, including air-, fuel-, water-, and thermal-management considerations.
- Improvements in BOP component performance (e.g., in compressors/expanders, power electronics, etc.) to decrease parasitic power losses and improvements to BOP component durability for increased system reliability and decreased maintenance costs.
- For stationary power applications, development of a single cleanup and fuel processing system capable of purifying and converting multiple fuels to enable fuel flexibility.
- Development of innovative system designs and operation strategies that optimize performance while mitigating system degradation.
- Development of fuel cell systems that meet application-specific packaging requirements with demonstrated durability and robustness including under dynamic load following, start/stop operation, vibration/shock (for mobile applications), and ambient conditions.

- Development of modular, scalable fuel cell systems with standardized stacks and BOP components, designed with manufacturability and recyclability in mind, that could enable significant cost reductions and potential for scale-up.

Advanced manufacturing applicable to fuel cell technologies is essential to strengthen the supply chain and meet economies of scale, especially at lower production volumes, to lower fuel cell costs for all end uses. Subprogram RD&D addresses challenges that industry either does not have the technical capability to undertake or is too far from market realization to merit sufficient industry focus and critical mass. An example is the development of low-cost, scalable manufacturing processes to bring innovative, lab-demonstrated materials and components to the market. This includes the development of best practices for material and component handling, roll-to-roll manufacturing techniques, inline diagnostics and quality control/assurance methods, and reduction of manufacturing defects to ensure high-throughput production of membranes, electrodes, and MEAs. The subprogram RD&D also addresses challenges in the development of efficient approaches to recycling/upcycling of critical materials, including PGMs, in support of a transition to a circular economy.

Comprehensive Approach

To address the challenges across fuel cell technologies and end uses, the Fuel Cell Technologies subprogram supports a portfolio of RD&D projects implemented through funding mechanisms described in the Program Implementation section. To accelerate progress, the subprogram has established RD&D consortia, which leverage the world-class capabilities, expertise, and research activities of core national laboratories and foster collaborations among the labs, industry, and universities. Currently, the subprogram supports three consortia and plans for additional support of others.[53]

- **Million Mile Fuel Cell Truck Consortium (M2FCT)** focuses on achieving an MEA target by 2025 that combines efficiency, durability, and cost in a single goal: 2.5 kW/g_{PGM} specific power (1.07 A/cm^2 current density) at 0.7 V after a 25,000 hour-equivalent accelerated durability test. The unique M2FCT capabilities include advanced experimental techniques and characterization tools, as well as modeling and machine learning approaches; capabilities include accelerated stress testing to address fuel cell lifetime.
- **Electrocatalysis Consortium (ElectroCat)** focuses on PGM-free catalyst and electrode RD&D for both fuel cells and electrolyzers, employing advanced high-performance computing, unique synthesis and characterization tools, and high-throughput combinatorial approaches in the development, processing, component integration, and qualification of PGM-free MEAs.

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[53] Additional information on HFTO's consortia approach to RD&D can be found in this report's Program Implementation chapter.

- **Roll-to-Roll Consortium (R2R)** focuses on advancing efficient, high-throughput, and high-quality manufacturing methods to accelerate domestic manufacturing and reduce the capital cost of clean hydrogen technologies, specifically regarding high-volume production of MEA components for PEM fuel cells and electrolyzers. The consortium works directly with industry via CRADA and FOA support, and it addresses scale-up of manufacturing technologies for catalysts and ionomers, coating and drying for membranes and electrodes, quality tool development, and artificial intelligence/machine learning tool development for process modeling and control. R2R is a collaboration between the Advanced Materials and Manufacturing Technologies Office and HFTO and coordinates with M2FCT, as well as H2NEW, to ensure appropriate materials and test methods are used.

Fuel Cell Technologies Consortia Examples

M2FCT focuses on RD&D to improve fuel cell durability, performance, and cost to better position fuel cells as a viable option in the long-haul trucking market and other heavy-duty applications: M2FCT Consortium

ElectroCat focuses on accelerating the R&D of catalysts made without platinum group metals for use in fuel cells and electrolyzers: ElectroCat Consortium

R2R focuses on MEA manufacturing technology advancements to reduce costs for fuel cells and electrolyzers.

- **Recovery and Recycling Consortium:** To address end-of-life and critical supply chain challenges for PEM fuel cells, the subprogram will also pursue activities to sustainably and efficiently recover and recycle critical materials for PEM-based systems, with crosscutting application to PEM-based electrolyzers. Plans include establishing a Recovery and Recycling Consortium that will include industry, academia, national labs, and other key stakeholders. Subprogram activities will address critical barriers for recovery and recycling related to PEM systems, components, and materials, including activities in analysis, component recycling, and reuse of the systems, illustrated in Figure 5.7.

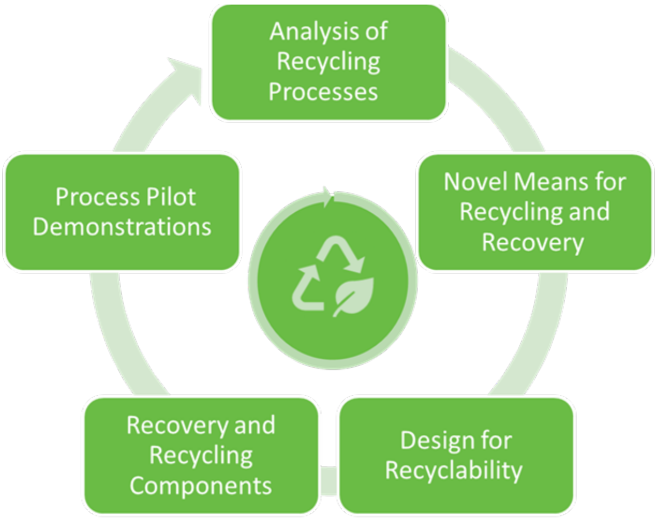

Figure 5.7. The holistic approach to address RD&D for recycling PEM fuel cells

To maximize resources, the Fuel Cell Technologies subprogram works closely with the other HFTO subprograms and with other DOE offices, and it also collaborates with diverse stakeholders from industry, academia, and the national labs in implementing approaches to accelerate the commercialization of cutting-edge lab-demonstrated fuel cell materials and components. These innovations can reduce costs and improve the durability of fuel cells, creating a strong competitive edge for technology developers in an emerging industry. One important example is the L'Innovator™ ("Lab Innovator") program,[54] developed to enable a robust domestic fuel cells industry by assembling bundles of unique, state-of-the-art national lab intellectual property and facilitating their development by a commercialization partner.

5.5 RD&D Focus Areas

Technical and economic barriers common to the challenges being addressed in the Fuel Cell Technologies subprogram include *Cost, Durability/Reliability, Efficiency/Performance, Life Cycle/Sustainability, Manufacturing/Scale-Up,* and *Safety*. These barriers are summarized in Table 5.3 with some specific examples of associated fuel cell technologies challenges in materials, components, or systems.

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[54] U.S. Department of Energy. "DOE's L'Innovator Pioneers a New Model for Jumpstarting Commercialization of Cutting-Edge Fuel Cell Technologies." February 23, 2024. https://www.energy.gov/eere/fuelcells/articles/does-linnovator-pioneers-new-model-jumpstarting-commercialization-cutting.

Table 5.3. Fuel Cell Technology Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost ***materials, components, systems***	Capital costs of stack materials and components (e.g., membranes, MEAs, PGM catalysts, gas diffusion layers, and bipolar plates)
	Capital costs of system BOP components (e.g., air-, water-, fuel-, and thermal-management components; power electronics)
	Operations, maintenance, and replacement costs of fuel cell stacks and systems
	Standardized/modular designs needed to achieve economies of scale for multiple applications
D: Durability/ Reliability	Durability of materials, components, and integrated systems
	System reliability and robustness under dynamic and harsh operating conditions (e.g., start/stop, dynamic load, thermal cycles, shock, and vibration for transportation applications, as well as mode cycling for reversible fuel cells)
	Impurity tolerance (e.g., air impurities, fuel contaminants, and saline contaminants)
E: Efficiency/ Performance	Fuel cell stack fuel-conversion efficiency and BOP component operational efficiency
	Power density (to achieve high power within size/weight constraints)
	Performance needs under realistic operating conditions (e.g., high power to haul loads up inclines, sustained power under cold/hot conditions, and quick dynamic response)
	Round-trip efficiency in reversible fuel cells
LC: Life Cycle/ Sustainability	Life cycle environmental impacts
	Material resource availability (e.g., critical minerals and the potential reliance on precious metals) and supply chain
	Materials environmental sustainability (membranes and ionomers)
	Recovery and recycling of fuel cell components, including PGMs and membranes
M: Manufacturing, Scale-Up, and Supply Chain	Manufacturing materials, components, and systems using automation and high-volume processes
	Ensuring environmental justice in manufacturing, including specialized workforce development, and reducing environmental impacts
	Developing and expanding domestic supply chains, standardization, and manufacturing processes

S: Safety	Materials, components, and systems with adequate consideration given to all safety issues
	Safety regulations and standards
	Education/training of users

The Fuel Cell Technologies subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 5.3. Tables 5.4 through 5.6 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for fuel cells in different end uses, along with examples of key targeted milestones. These RD&D focus areas are aligned with the subprogram's near-, mid-, and longer-term priorities. Based on project results, along with continued analysis and stakeholder engagement, the RD&D portfolio is assessed on a regular basis and is refined to maximize impact.

Near- to Mid-Term

The subprogram's near-term strategic priorities in electrolysis cover heavy- to medium-duty transportation applications such as trucks, buses, maritime, rail, offroad, and aviation, as well as primary and backup power for stationary applications. Specific RD&D focus areas addressing barriers and challenges are described in Table 5.4.

Table 5.4. Fuel Cell Technologies RD&D Addressing Near- to Mid-Term Strategic Priorities

RD&D Focus Areas	Barriers Addressed	Key Milestones
Heavy-Duty Transportation		
Coordinate RD&D efforts with the Million Mile Fuel Cell Truck consortium and industry/university projects to achieve fuel cell truck cost, durability, and efficiency targets	C, D, E	• Develop and disseminate accelerated stress testing protocols for catalysts, membranes, and MEA durability, to enable rapid assessment of up to 25,000 hours operation for heavy-duty truck applications (2024) • Demonstrate MEAs with 2.5 kW/g_{PGM} at 0.7 V after accelerated durability test equivalent to 25,000 hours (2025) • Reduce heavy-duty fuel cell system cost to $140/kW (50,000 systems/year) (2025)
Develop extremely durable, high mass-activity low-PGM catalysts to enable competitive fuel cell lifetime, efficiency, and cost	C, D, E,	
Improve the performance and durability of membranes and ionomers under hot (up to 120°C) and dry conditions to improve heat rejection, power density, and efficiency	C, D, E, LC	
Develop low-cost, environmentally sustainable membranes, suitable for heavy-duty applications, that improve efficiency by suppressing gas crossover and improve durability by reducing chemical and mechanical degradation	C, D, E, LC	

Optimize electrode layer performance to improve efficiency and durability for heavy-duty applications	D, E	• Develop bipolar plates with area specific resistance of <0.01 ohm cm^2 and cathode corrosion of <1 µA/m^2 at a cost of $5/kW (2030) • Demonstrate standardized fuel cell stacks for heavy-duty applications with a durability of 25,000 hours at a projected cost of $40/kW (2030) • Demonstrate air compression systems for heavy-duty vehicles with a turndown ratio of 20 at a cost of $12/kW (2030) • Develop direct-hydrogen fuel cell systems at a projected cost of $80/kW (at 100,000 systems per year) and 25,000-hour durability (2030) • Demonstrate heavy-duty fuel cell manufacturing capacity of 20,000 stacks per year in a single manufacturing system (2030) • Demonstrate MEA manufacturing rates of 2,400 MEAs/hour (2030) • Demonstrate bipolar plate manufacturing rates of 2,400 bipolar plates/hour (2030) • Develop membrane manufacturing processes capable of meeting a production rate of 370,000 m^2 per year (2030) • Develop gas diffusion layer manufacturing processes capable of meeting a production rate of 650,000 m^2 per year (2030) • Develop sustainable process to recover >50% of membrane/ionomer materials and >95% of PGMs from fuel
Assess fuel cell truck component, stack, and system durability through the development of accelerated stress testing protocols	D	
Develop strategies to mitigate degradation of MEAs through materials integration and operating conditions	D	
Integrate materials and components to demonstrate MEA efficiency, power density and durability compatible with the operating conditions, lifetime requirements, and drive cycles of trucks	C, D, E, LC, M	
Develop innovative, low-cost bipolar plates with improved mechanical properties and manufacturability, high corrosion resistance, and minimal degradation	C, D, M	
Improve the microstructure, hydrophobic properties, stability, and manufacturability of gas diffusion layers to improve stack performance and water management	C, D, M	
Develop low-cost, easy-to-manufacture, and resilient BOP components, including thermal management and power electronics	C, D, M	
Develop low-cost air management systems suitable for heavy-duty truck applications, with improved reliability, reduced input power, extended durability, and high turndown ratios	C, D, E	
Develop standardized low-cost stacks and BOP components	C, M	
Demonstrate modular, scalable fuel cell systems with standardized stacks and BOP components	C, M	
Pursue and optimize MEA material and a component manufacturing process that is low-cost and scalable, and design for recyclability	C, M, LC	
Assess technical and cost status of current and advanced (2025, 2030) fuel cell truck systems for a range of production volumes	C, M, LC	
Compare and assess alternative system designs and operation strategies to inform optimization of performance, efficiency, durability, and cost for heavy-duty truck applications	C, D, E	

Develop high-throughput stack and component manufacturing approaches to strengthen the domestic supply chain and enable capacity expansion	C, M	cell MEAs for recycling/upcycling (2029) • Annually update the cost estimate for fuel cell systems for heavy-duty trucks
Develop and implement recovery and recycling of critical materials, including PGMs and polymers	LC	
Near-Term Other Applications ***(e.g., Medium-Duty Trucks, Buses, Maritime, Rail, Off-Road, Aviation, Primary and Backup Power for Stationary Applications Including Data Centers and Combined Heat and Power)***		
Coordinate R&D efforts with the Million Mile Fuel Cell Truck consortium and industry/university projects to achieve cost, durability, and efficiency targets across medium- and heavy-duty applications	C, D, E, LC, M	• Demonstrate fuel cell buses with 25,000-hour fuel cell durability (2030) • Develop a 60% efficient (over the duty cycle), direct hydrogen fuel cell power system (1–10 kW) for backup power applications at a cost of $1,000/kW with 10,000 hours of durability (2027) • Develop a 60% efficient (over the duty cycle), direct hydrogen fuel cell power system (at the MW scale) for distributed power/energy storage applications at a cost of $1,000/kW with 40,000 hours of durability (2027) • Demonstrate medium-scale combined heat and power fuel cell power systems (100 kW-3MW) that can achieve over 50% electrical efficiency, 90% combined heat and power efficiency and 80,000-hour durability at a cost of $1,500/kW for operation on biogas (2027). • Develop medium-scale distributed generation fuel cell power systems (100 kW–3 MW) that achieve 65% electrical efficiency) and 80,000-hour durability at a cost of $1,000/kW (2030)
Leverage advancements in heavy-duty fuel cells to meet fuel cell cost, efficiency, and durability targets for medium-duty and stationary applications	C, D, E	
Develop environmentally sustainable electrode ionomers that enable high-power performance with high oxygen permeability, proton conductivity, and durability	D, E, LC	
Develop electrodes, MEAs and cells with improved power density and efficiency	C, E	
Design flexible and modular fuel cell components to lower costs, for use in multiple applications	C, M	
Integrate standardized, modular stacks into systems meeting heavy-duty application specific requirements (long lifetime, air impurity tolerance, shock and vibration tolerance)	D, E	
Demonstrate low-cost fuel cell systems for diverse heavy-duty applications (maritime, rail, mining) meeting application specific targets and operation requirements	C, D, E, LC, M	
Demonstrate cost-effective integrated stationary fuel cell systems for application-specific stationary power generation (e.g., data centers, combined heat and power)	C, D, E	
Develop low-cost, durable cell and stack components for stationary fuel cells	C, D	
Develop and demonstrate megawatt-scale H_2 stationary PEM fuel cells with cost, efficiency, and durability optimized for hydrogen energy-storage applications	C, D, E	

		• Demonstrate fuel cell power systems with modular designs and standardized stacks and BOP components for medium-duty vehicles, maritime, rail and offroad applications meeting application specific targets (2030)

Longer Term

The subprogram’s longer-term strategic priorities include development of advanced materials, components, and systems for next-generation fuel cells for diverse applications such as flexible fuel use, reversible operations to enable energy storage, and others. Specific RD&D focus areas addressing barriers and challenges are described in Table 5.5.

Table 5.5. Fuel Cell Technologies RD&D Addressing Longer-Term Strategic Priorities

RD&D Focus Areas	Barriers Addressed	Key Milestones
Next-Generation Fuel Cells ***(e.g., PGM-free, Anion Exchange Membrane, Bipolar Membranes, Direct Liquid-Fueled, Intermediate Temperature, Tri-Generation)***		
Develop high-performance, durable PGM-free catalysts through the ElectroCat consortium and industry/university projects to reduce stack cost and alleviate dependence on precious metal imports	C, D, LC	• Achieve PGM-free cathode MEA performance in an H_2/air fuel cell of ≥100 mA/cm^2 at 0.8 V and ≥500 mA/cm^2 at 0.675 V, with ≤10% loss in current density after accelerated testing (2025) • Develop anion exchange membrane MEAs with initial performance of 1000 mW/cm^2 under H_2/air (CO_2-free) with total PGM loading of ≤0.125 mg cm^{-2}, at temperatures ≥80°C, and pressures ≤250 kPa (2025) • Demonstrate direct liquid-fueled PEM fuel cell MEAs with maximum power >0.3 W/cm^2 at
Improve performance of thick electrode layers to enable PGM-free catalysts	C, E	
Advance long-term membrane technologies including anion exchange membranes and intermediate-temperature (150°–500°C) membranes	C, D, E, LC, M	
Develop high-performing and durable PGM-free MEAs for anion exchange membrane fuel cells with improved water transport and performance in the presence of CO_2	D, E	
Develop innovative durable intermediate-temperature (150°–500°C) fuel cells to allow for fuel flexibility and low system cost for a range of applications	C, D, E, LC, M	

Develop durable materials and components—including low-PGM catalysts, membranes and MEAs—to enable efficient electrochemical conversion of liquid fuels (e.g., ammonia, methanol, dimethyl ether, hydrogen carriers) for power generation	D, E	total catalyst loading of <3 mg_{PGM}/cm^2 (2030) • Demonstrate intermediate temperature (150°–500°C) membrane conductivity of >0.05 S/cm at operating temperature (>120°C , pH_2O < 40 kPa); and membrane durability >10,000 hours (performance degradation <1%/1,000 hours under relevant operating conditions) (2027) • Develop anion exchange membrane fuel cell PGM-free MEAs with initial performance exceeding 600 mW/cm^2 under H_2/air (2030)
Demonstrate innovative technologies including the use of fuel-flexible gas-cleanup reforming technologies for polygeneration including tri-generation (power, heat, and hydrogen)	C, D, E, LC, M	
Advanced Energy Storage Concepts ***(including Reversible Fuel Cells)***		
Develop bifunctional catalyst and electrode materials for high- and low-temperature reversible fuel cells that provide competitive performance, durability, and round-trip efficiency	C, D, E	• Conduct analysis to identify use cases where reversible fuel cells (discrete versus unitized) will be competitive energy storage solutions (2025) • Achieve low-temperature reversible fuel cell performance/round-trip electric efficiency of 55% at 0.5 A/cm^2 (fuel cell); 1 A/cm^2 (electrolyzer) (2030) • Achieve high-temperature reversible fuel cell performance/round-trip electric efficiency of 85% at 0.5 A/cm^2 (fuel cell); 1 A/cm^2 (electrolyzer) (2030) • Develop reversible fuel cells with a degradation rate of 0.25%/1,000 hours (2030) • Achieve a system round-trip efficiency of 60%, system cost of $1,800/kW, and lifetime of 40,000 hours (2030)
Optimize efficiency, performance, and durability of components, cells, and stacks for application-specific energy storage	D, E	
Develop cost-effective integrated systems—including BOP components such as power electronics—for application-specific energy storage	C	
Demonstrate unitized reversible fuel cell systems with high round-trip efficiency and lifetime, with the ability to cycle repeatedly between fuel cell and electrolyzer mode	D, E	
Design and demonstrate reversible fuel cell systems that address thermal management issues specific to high-temperature reversible fuel cells	C, D, E	
Identify use cases where reversible fuel cells will be competitive energy storage solutions	C, D, E, LC, M	

Crosscutting

In addition to the focus areas described in Tables 5.4 and 5.5, the subprogram also conducts crosscutting RD&D that is synergistic with activities in other HFTO subprograms and supports broad strategic priorities relevant to the advancement of clean hydrogen and fuel cell technologies. Examples are included in Table 5.6.

Table 5.6. Fuel Cell Technologies Crosscutting RD&D Activities

Crosscutting RD&D	Barriers Addressed	Key Milestones
Conduct assessments to benchmark projected cost and technical status of current and advanced fuel cell systems for a range of applications	C, D, E	Annually update the cost estimate for fuel cell systems for diverse applications
Identify key barriers to meeting system operating requirements, application-specific demands, and life cycle cost targets through fuel cell system analysis to guide R&D efforts.	E, LC	Annually conduct key strategic analysis to assess needs for transportation and stationary applications, including power generation and long-duration energy storage
Develop standardized fuel cell test protocols and best practices	D, E	Disseminate standardized test protocols, including accelerated stress test protocols, addressing performance and durability requirements for transportation and stationary fuel cell applications (2030)
Develop and standardize BOP components including power electronics (e.g., DC/DC converters) across technologies and applications, to help strengthen the supply chain	C	Develop BOP components addressing air, thermal, and water management for fuel cell systems contributing to meeting application-specific fuel cell system cost, performance, and durability targets (2030)
Investigate and develop high-throughput manufacturing techniques including automated component and stack assembly, quality control, conditioning, and testing protocols to advance stack- and system-level manufacturing	M	Demonstrate heavy-duty fuel cell manufacturing capacity of 20,000 stacks per year in a single manufacturing system (2030)
Develop efficient approaches to recycling/upcycling of critical materials, to reduce environmental impacts and support a “circular economy”	E	Develop sustainable process to recover >50% of membrane/ionomer materials and >95% of PGMs from fuel cell MEAs for recycling/upcycling (2029)
Develop and implement approaches to streamline technology transfer and accelerate the commercialization of cutting-edge laboratory-demonstrated materials and components	M	Expand the L’Innovator program by establishing at least three new national lab and industry partnership projects to commercialize national lab demonstrated hydrogen and fuel cell technologies (2027)

Leverage activities and work in partnership with minority-serving institutions and Tribal Nations, and engage with labor organizations for workforce development	LC	Provide training opportunities to over 50 minority-serving institution students, including from Tribal Nations, on hydrogen and fuel cell technologies (2028)
Coordinate R&D and leverage activities with other DOE offices, U.S. Government agencies, and domestic/international stakeholders for high impact and to avoid duplicated efforts	LC	Annually identify common RD&D areas of interest, coordinate stakeholder engagement activities, and compile solicitation topics on hydrogen conversion technologies
Foster DEIA as well as community engagement across diverse stakeholders to enable energy and environmental justice	LC	Conduct reviews of Community Benefits Plans and support information-sharing for RD&D projects at least annually