U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Hydrogen and Fuel Cell
Technologies Office

Multi-Year Program Plan

Disclaimer

Letter from the Director

It is my great privilege to present to you the U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office's (HFTO's) new ***Multi-Year Program Plan (MYPP)***. This important document, which is an update of prior MYPPs, identifies detailed targets and plans for fulfilling HFTO's mission—*to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy*.

The release of the *MYPP* couldn't come at a better time—a critical moment of unprecedented interest in clean hydrogen, with surging industry investments, expanding commitments, and ever-higher targets for clean hydrogen. And it comes at a time of growing awareness of hydrogen's role as an essential part of a portfolio of solutions needed for a sustainable future—a role that has evolved significantly since HFTO's last *MYPP*. Since then, DOE's **H2@Scale initiative** has laid out a broad, systemic vision for the use of clean hydrogen across multiple sectors. This vision continues to expand and inform strategic planning—for example, with important opportunities for hydrogen identified in DOE's ***Industrial Decarbonization Roadmap*** and the ***U.S. Transportation Decarbonization Blueprint***. The **Hydrogen Shot** has set a bold goal to drive down costs and open up new markets; and the ***U.S. National Clean Hydrogen Strategy and Roadmap*** has coalesced the vision for clean hydrogen into a national strategy for action, further reinforcing hydrogen's role as a versatile and essential tool for achieving a net-zero emissions economy, especially in our most difficult-to-decarbonize sectors.

While the progress in clean hydrogen today is encouraging, it is also clear that more is needed—and the actions taken must be well-planned, deliberate, carefully executed with measurable outcomes, and they must come without delay. The *MYPP* takes an important step beyond the foundations laid out in the *U.S. National Clean Hydrogen Strategy and Roadmap*, providing a blueprint for HFTO's work in support of our national goals. It is a grounding document, based on tangible steps and measurable milestones, but in some ways, it is also the most exciting of our planning documents, because it translates the vision and strategy for clean hydrogen into very real steps to complete the journey. As you read through the *MYPP*, with all its rigorous detail, I encourage you to remember the big picture—that success in these technical areas will bring us closer to realizing the enormous potential of clean hydrogen and achieving the national goal of 50 million metric tons of clean hydrogen by 2050.

The *MYPP* is inspired by the vision and devotion of the entire HFTO team, and it reflects the unparalleled expertise and experience of our technical leaders, program managers, and supporting staff. I would like to send a very special thanks to the HFTO team responsible for the latest *MYPP*, led by our chief scientist, Eric Miller, and our deputy director, Nichole Fitzgerald, with extensive technical input from our subprogram teams, led by Dave Peterson, Ned Stetson, Dimitrios Papageorgopoulos, Jesse Adams, and Neha Rustagi, and with expert writing and editing support from Joe Stanford. The entire HFTO team is also grateful for the invaluable information gained from our partners in industry, the national labs, and the broader research

community—and too many others to name. I would also like to thank the National Renewable Energy Laboratory communications team for their work in editing, layout, and graphics.

We are thrilled for the opportunity to share the *MYPP* with you. We hope that it will be a source of energy and inspiration for you as it is for us. Its goals are bold, but the steps are clear, practical, and achievable. Of course, even the best-laid plans are subject to change, and therefore must be prepared to adjust and evolve; please consult our *MYPP* landing page for updates: www.energy.gov/eere/fuelcells/mypp.

Finally, I would like to thank the hundreds of stakeholders from industry, national labs, academia, and more whom I have had the pleasure of working with over the decades, for all their input, dedication, and collaboration to inform these pages.

Sincerely,

Dr. Sunita Satyapal
Director, Hydrogen and Fuel Cell Technologies Office
DOE Hydrogen Program Coordinator
U.S. Department of Energy

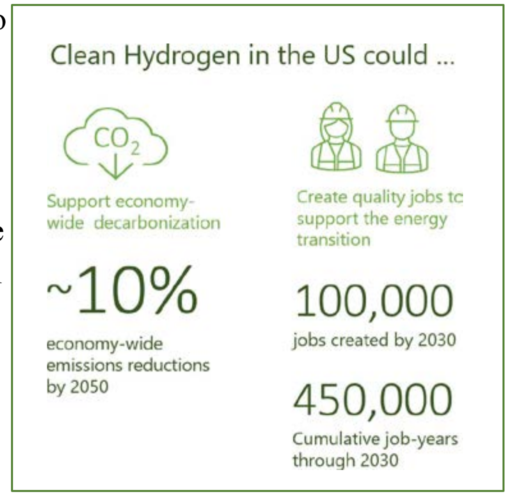
List of Acronyms

AEM	alkaline exchange membrane
BOP	balance of plant
CCUS	carbon capture, utilization, and storage
CRADA	cooperative research and development agreement
DEIA	diversity, equity, inclusion, and accessibility
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ElectroCat	Electrocatalysis Consortium
FEED	front-end engineering and design
FOA	funding opportunity announcement
GCAM	Global Change Analysis Model
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies model
HDSAM	Hydrogen Delivery Scenario Analysis Model
HFTO	Hydrogen and Fuel Cell Technologies Office
HIT	Hydrogen Interagency Task Force
H-Mat	Hydrogen Materials Compatibility Consortium
HydroGEN	HydroGEN Advanced Water Splitting Materials Consortium
HyMARC	Hydrogen Materials Advanced Research Consortium
H2NEW	Hydrogen from Next-generation Electrolyzers of Water
H2A	Hydrogen Analysis Production Model
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LHV	lower heating value

MEA	membrane electrode assembly
MYPP	Multi-Year Program Plan
M2FCT	Million Mile Fuel Cell Truck Consortium
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
O-SOEC	oxide-ion-conducting solid oxide electrolysis cell
PEC	photoelectrochemical
PEM	proton exchange membrane
PGM	platinum group metal
P-SOEC	proton-conducting solid oxide electrolysis cell
RCS	regulations, codes, and standards
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
ReEDS	Regional Energy Deployment System model
R2R	Roll-to-Roll Consortium
SCS	Safety, Codes and Standards
SDI	Systems Development and Integration
STCH	solar thermochemical
TRL	technology readiness level

Executive Summary

Clean hydrogen is a key part of a comprehensive portfolio of technologies and fuels needed to achieve our nation's climate goals and build a sustainable, secure, and equitable clean energy economy. Clean hydrogen, which has very low or zero emissions, can be produced in every part of the country and from virtually any energy resource (such as renewables, nuclear, or fossil energy with carbon capture). And it can be used in many applications: as a transportation fuel, where it can be converted to electricity in a fuel cell, with no emissions other than water vapor; as a fuel for combustion to provide high-temperature industrial heat; or as a chemical feedstock or reactant, including as a component of biofuels.



Clean hydrogen has a particularly important role to play in addressing our hardest-to-decarbonize sectors, which include key economic engines that are essential to the modern American economy and quality of life, such as heavy-duty transportation, chemical and industrial processes like steelmaking, and the production of liquid fuels and fertilizers. Clean hydrogen can also support the expansion of zero-emissions electricity by providing a means for long-duration energy storage and offering flexibility and multiple revenue streams for all types of clean power generation. The *U.S. National Clean Hydrogen Strategy and Roadmap*[1] estimates that by 2050, the use of clean hydrogen across sectors can reduce U.S. greenhouse gas (GHG) emissions approximately 10% relative to 2005[2]—a reduction greater than the GHG emissions from every truck, bus, airplane, and ship in the United States today.[3] By enabling diverse, domestic clean energy pathways across multiple sectors of the economy, clean hydrogen will also strengthen American energy independence and resilience while creating good jobs, economic growth, and export opportunities. The DOE report *Pathways to Commercial Liftoff: Clean Hydrogen*[4] estimates that by 2030, the hydrogen economy could also result in 100,000 net new direct and indirect jobs in the United States due to the build-out of new capital projects and clean hydrogen infrastructure.

While extensive progress has been achieved through decades of strategic investments in research, development, demonstration, and deployment (RDD&D)—and industry investments

[1] 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.
[2] Estimates were developed using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model: https://greet.es.anl.gov/.
[3] U.S. Environmental Protection Agency. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021*. June 2023. EPA-420-F-23-016. https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf.
[4] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/wp- content/uploads/2023/05/20230320-Liftoff-Clean-H2-vPUB-0329-update.pdf.

are growing worldwide— some significant challenges still need to be overcome to realize the enormous potential of a clean hydrogen economy. These challenges cut across the hydrogen value chain, from how hydrogen is produced, delivered, and stored to how it is used in various applications and integrated into larger energy systems. Challenges can be grouped into the following three categories:

- **Reducing cost and improving performance.** The cost of technologies for producing, delivering, and storing clean hydrogen, as well as the cost of fuel cells, must be reduced to expand existing markets and open new ones. Without substantial cost reductions, many of the opportunities for hydrogen will not be realized. The efficiency, durability, and reliability of hydrogen and fuel cell systems also need to be improved to achieve parity with incumbent technologies.
- **De-risking and scaling up technologies across the value chain.** To reduce investment risk, new hydrogen and fuel cell technologies need to be demonstrated and validated in real-world conditions. And to enable scale-up of proven technologies, more-robust domestic supply chains and improvements in manufacturing (both to reduce cost and enable scale) will be needed.
- **Barriers to large-scale adoption.** To enable large-scale adoption across multiple sectors, a number of crosscutting areas will need improvement, such as safety (e.g., improved sensors, enhanced safety practices, and knowledge dissemination), adoption of technically sound codes and standards, improved (and streamlined) permitting processes, and a well-trained workforce for the entire technology life cycle, from research through manufacturing to installation, repair, and decommissioning.

As laid out in the *U.S. National Clean Hydrogen Strategy and Roadmap*, the federal government is undertaking a holistic, whole-of-government approach to overcoming these challenges. The Hydrogen Interagency Task Force[5] coordinates activities across multiple agencies, including long-standing efforts within the U.S. Department of Energy's (DOE) Hydrogen Program. As the coordinating office of the DOE Hydrogen Program, the Hydrogen and Fuel Cell Technologies Office (HFTO) in the DOE Office of Energy Efficiency and Renewable Energy leads federal efforts in research, development, and demonstration (RD&D). HFTO works closely with other DOE offices (e.g., Fossil Energy and Carbon Management, Nuclear Energy, Electricity, Science, Loan Programs, Manufacturing and Energy Supply Chains, Clean Energy Demonstrations, Energy Justice and Equity, and the Advanced Research Projects Agency-Energy) and provides leadership in coordinating activities with other federal agencies, state agencies, regional partnerships, associations, and international counterparts worldwide.

[5] U.S. Department of Energy. "Hydrogen Interagency Task Force." https://www.hydrogen.gov.

The HFTO Mission

RD&D to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy.

HFTO's mission is to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy. Informed by input from diverse stakeholders engaged in relevant private- and public-sector hydrogen activities across multiple sectors of the economy, HFTO strategically deploys funding for RD&D activities to achieve the goals that support this mission. HFTO-funded efforts fall roughly into two broad areas:

- **Research and development** (R&D) activities, which aim to improve materials, components, and subsystems at laboratory scale. These activities address many of the underlying technical barriers to reducing the cost and improving the performance of key technologies, such as electrolyzers, fuel cells, and systems for storing, delivering, and dispensing hydrogen. Many of HFTO's R&D efforts are conducted through consortia based on teams built around national laboratories, including the HydroGEN Advanced Water Splitting Materials Consortium, which focuses on materials to improve hydrogen production through advanced water-splitting processes; the Hydrogen Materials Advanced Research Consortium, which aims to address scientific challenges in the development of viable solid-state materials for onboard hydrogen storage in vehicles; and the Million Mile Fuel Cell Truck Consortium, which focuses on improving the durability, performance, and cost of fuel cells for heavy-duty trucks.
- **Demonstration and enabling** activities, which involve integration and operation of complete systems under real-world conditions to validate performance and de-risk investment, along with deployment of commercial-scale systems to identify and help overcome nontechnological barriers. Activities focus on key strategic applications, such as demonstrations of fuel-cell-powered delivery trucks, fueling infrastructure for medium- and heavy-duty trucks, airport ground support equipment, and nuclear-to-hydrogen production. Enabling activities include comprehensive analysis, tools, and models to identify barriers and pathways to success; safety research; support for development of codes and standards; support for supply chains and improved manufacturing processes; and workforce development.

The *Multi-Year Program Plan (MYPP)* sets forth HFTO's mission, goals, and strategic approach relative to broader DOE and national clean energy priorities. The *MYPP* is aligned with the strategy and goals of the *U.S. National Clean Hydrogen Strategy and Roadmap*, and it reflects the higher-level DOE strategy and goals laid out in the *DOE Hydrogen Program Plan*.[6] Building off these foundations, the *MYPP* provides an assessment of the challenges that still must be

[6] U.S. Department of Energy. *Department of Energy Hydrogen Program Plan.* November 2020. DOE/EE-2128. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

overcome to realize large-scale adoption of clean hydrogen and a detailed, integrated plan for all RD&D and crosscutting activities conducted by HFTO, which includes:

- Assessments of the current status of key metrics (e.g., electrolyzer capital cost and efficiency).
- Technical targets related to each of those key metrics (see the inset box below for examples of HFTO's technical targets).
- Detailed plans for activities to meet those targets (see Figure ES.1 for an illustrative example of barriers, targets, and plans for electrolysis).

Over the past two decades, through strategic deployment of RD&D funding, HFTO has demonstrated success in achieving the goals and targets outlined in previous program plans. Examples include an 80% reduction in the capital cost of proton exchange membrane electrolyzer systems between 2005 and 2020; a 70% reduction in the cost of fuel cell systems for automotive applications from 2008 to 2020; and a 30% reduction in the cost of advanced compressed onboard hydrogen storage systems since 2013. HFTO funding has enabled more than 1,300 U.S. patents, roughly 30 commercial technologies, and another 65 that could be commercial in the next several years.[7] Additional information about past successes and how technologies in the HFTO portfolio have improved over time can be found in the DOE Hydrogen Program Records and accomplishment fact sheets.[8]

HFTO Key Target Examples

Targets are developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the RD&D community and inform HFTO's portfolio of activities. Examples include the following.

Clean H_2 production:

- $2/kg by 2026; $1/kg by 2031

Electrolyzer systems (low temperature):

- 2026: $250/kW, 65% efficiency, 80,000-hour durability

Electrolyzer systems (high temperature):

- 2026: $500/kW, 76% efficiency, 40,000-hour durability

H_2 dispensed for heavy-duty transportation:

- 2028: <$7/kg

Fuel cell manufacturing for heavy-duty transportation:

- 2030: 20,000 stacks/year (single manufacturing system)

Fuel cell systems for heavy-duty transportation:

- 2030: $80/kW, 25,000-hour durability

[7] Satyapal, Sunita. June 5, 2023. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/plenary1_satyapal_2023_o.pdf.
[8] HFTO. "Hydrogen and Fuel Cell Technologies Office Accomplishments and Progress." https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-accomplishments-and-progress.

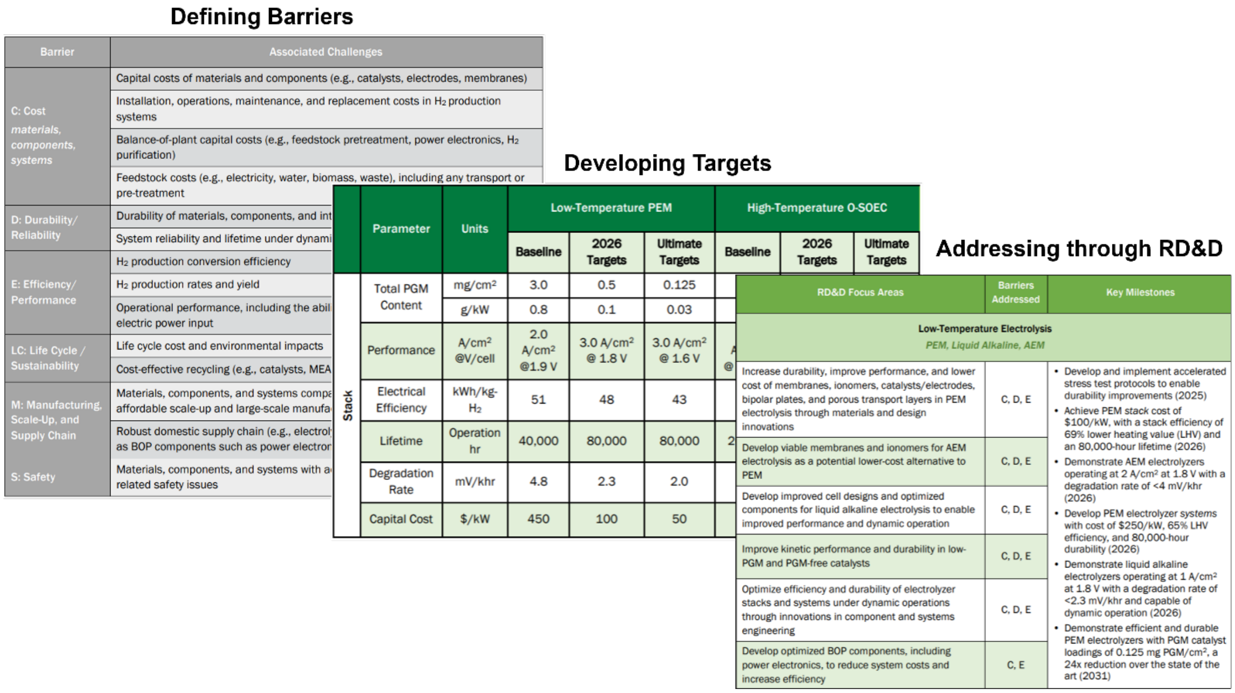


Figure ES.1. The *MYPP* defines barriers, develops targets, and lays out plans for meeting those targets. Shown here is an example of barriers, targets, and plans for electrolysis.

Building on these successes, HFTO presents plans for RD&D activities in the *MYPP* based on near-, mid-, and longer-term priorities within each of its subprograms, which are listed below:

- **Hydrogen Technologies** comprises two coordinated and closely related focus areas, both of which span materials-, component-, and system-level RD&D. *Hydrogen Production* focuses on enabling affordable production of hydrogen from diverse renewable domestic resources; *Hydrogen Infrastructure* focuses on enabling affordable and accessible delivery and storage infrastructure options.
- **Fuel Cell Technologies** focuses on the materials-, component-, and system-level RD&D for different fuel cell technologies and applications to enable highly efficient conversion of clean hydrogen for end uses such as transportation and backup-power generation using fuel cells.
- **Systems Development and Integration** focuses on the development and integration of complete hydrogen systems to enable first-of-a-kind demonstrations of integrated energy systems deploying clean hydrogen and fuel cell technologies in key hard-to-decarbonize sectors including transportation, chemical and industrial processes, and energy storage and power generation.
- **Systems Analysis** encompasses crosscutting topics, including data, modeling, and analysis that guides RD&D, and it identifies priority markets for clean hydrogen technologies with impacts assessments.

- **Safety, Codes and Standards** encompasses crosscutting topics, including RD&D that informs safe design and operation of clean hydrogen technologies while addressing regulatory and permitting challenges.

Within these subprograms, the *MYPP* illustrates specific pathways that HFTO has developed to achieve its targets, including detailed analysis of the key factors in each technical area and how HFTO-funded efforts can address those factors. For example, Figure ES.2 shows at a high level the key drivers of fuel cell system cost (donut graphic on upper right), then shows a "waterfall" diagram that illustrates cost reductions that can be achieved across four different areas (manufacturing and scale, power density and platinum group metals, stack and balance-of-plant components, and durability). (See Figure 1.8 for details.) The *MYPP* provides waterfall charts for additional technical topics such as electrolyzer capital cost, hydrogen storage system cost, and others.

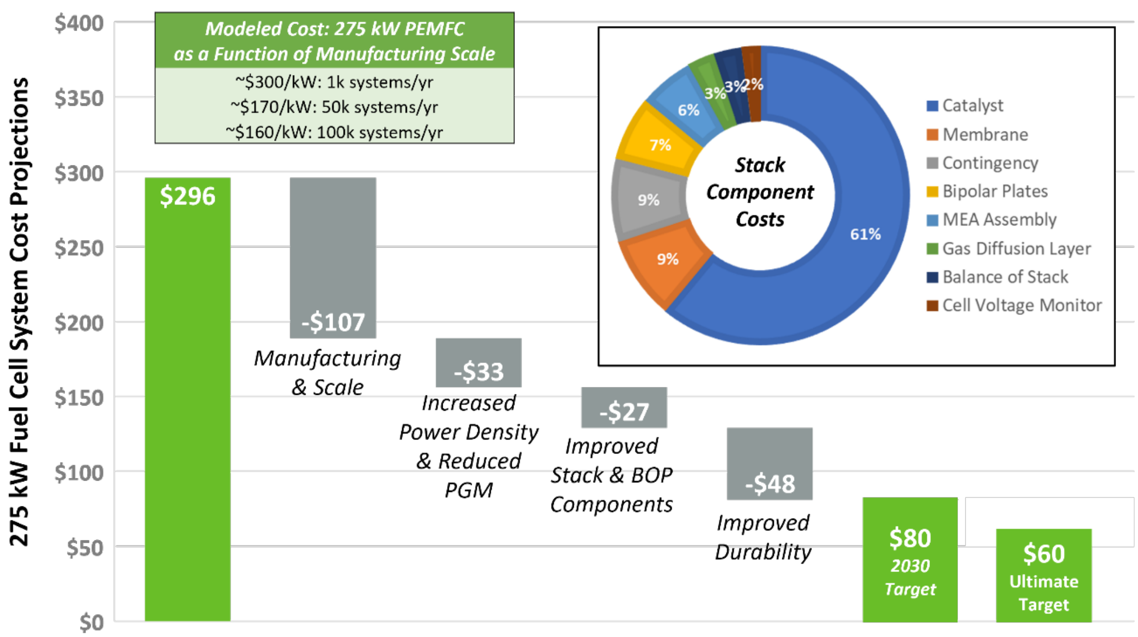


Figure ES.2. Example of "waterfall" chart showing pathways to meeting HFTO cost-reduction targets

Detailed activities and plans within the subprograms are also summarized each year in the President's Congressional Budget Request, and HFTO uses annual appropriations to fund RD&D consistent with the overall strategy. The strategic priorities for each of the subprograms as well as crosscutting and enabling activities are summarized in Figure ES.3. HFTO's RD&D portfolio, which is aligned with these priorities, relies on clearly defined metrics and targets that have been established as necessary for achieving strategic objectives. These objectives will need to be met to realize the promise of clean hydrogen and its role in a sustainable, resilient, and equitable future.

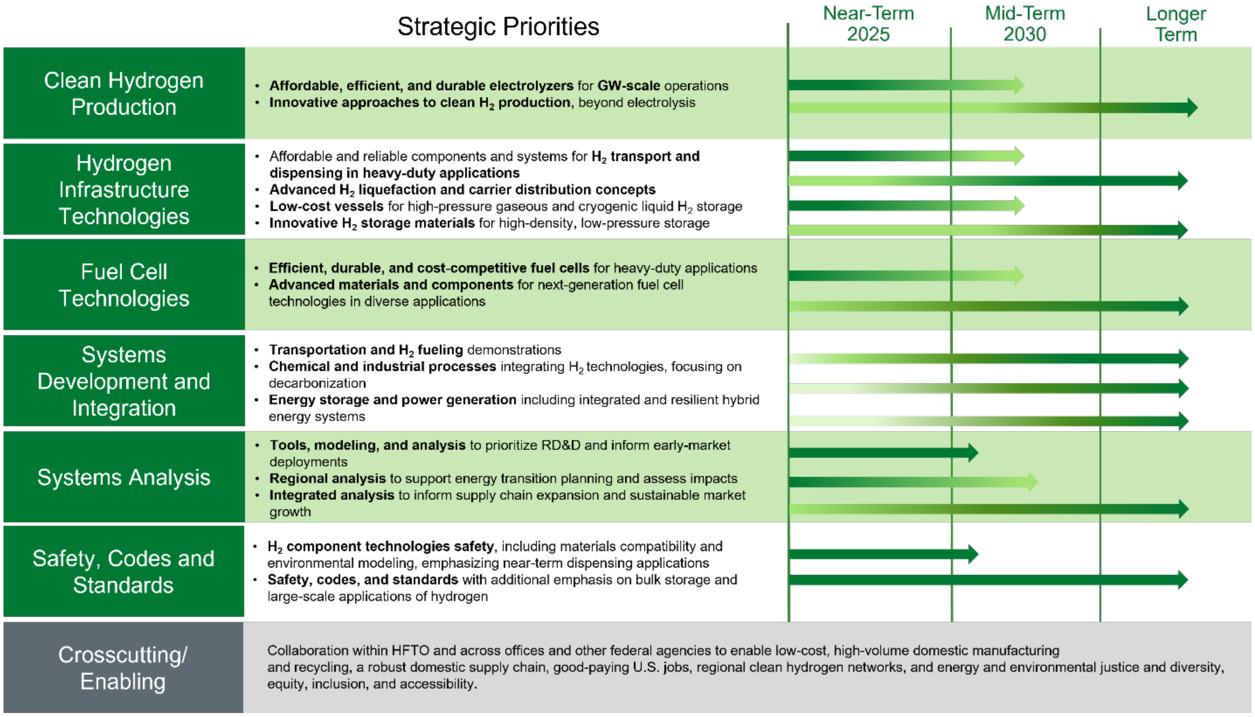


Figure ES.3. Strategic RD&D priorities in HFTO's portfolio, illustrating the multipronged approach—which includes near- to mid-term and longer-term priorities across most focus areas.

Chapters in the *MYPP* are organized by HFTO subprogram. Each chapter details the challenges and opportunities related to the above strategic priorities, including specific metrics and targets, where appropriate, and explains how the HFTO subprograms are systematically tackling the challenges through coordinated RD&D efforts.

Table of Contents

1 Introduction

1.1 Overview

The Hydrogen and Fuel Cell Technologies Office (HFTO) in the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) leads federal research, development, and demonstration (RD&D) activities to enable the commercial viability of hydrogen and fuel cell technologies.

The ***Multi-Year Program Plan* (*MYPP*)** sets forth HFTO's mission, goals, and strategic approach relative to DOE's broader clean energy priorities. It identifies the challenges that must be overcome to realize the full potential of clean hydrogen and fuel cells and explains how HFTO's activities will help overcome those challenges. The *MYPP* details how each subprogram within HFTO supports the office's overall strategic and performance goals, and it serves as an operational guide to help HFTO manage and coordinate activities, as well as a resource to help communicate its mission and goals to stakeholders and the public.

The *MYPP* reflects the key role HFTO plays in DOE's overarching Hydrogen Program. In addition to coordinating activities across multiple offices in the Hydrogen Program over the past two decades, HFTO also leads RD&D efforts in the production of hydrogen from renewable resources and in the storage, delivery, and utilization of clean hydrogen from diverse domestic resources. The *MYPP* lays out the detailed RD&D strategies for HFTO and is consistent with the overarching *DOE Hydrogen Program Plan*[9] as well as legislative requirements (see Chapter 1.4 for further discussion of the DOE Hydrogen Program). The *MYPP* synthesizes details from previous plans and provides context for HFTO's activities in hydrogen and fuel cells for Fiscal Year 2024 and the next several years.

This document provides a plan for the HFTO RD&D portfolio, specifically addressing objectives and targets for clean hydrogen and fuel cell technologies, which align closely with national clean energy priorities.

[9] U.S. Department of Energy. *Department of Energy Hydrogen Program Plan*. November 2020. DOE/EE-2128. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

1.2 Role and Benefits of Clean Hydrogen

Clean hydrogen is a key part of a comprehensive portfolio of technologies and fuels needed to achieve our nation's climate goals and build a sustainable, secure, and equitable clean energy economy. Clean hydrogen, which has very low or zero emissions, can be produced in every part of the country and from virtually any energy resource (such as renewables, nuclear, or fossil energy with carbon capture). Hydrogen is the most abundant element in the universe; however, it is rarely found in its elemental form on Earth. It must be extracted from a hydrogen-containing feedstock (e.g., water, biomass, fossil fuels, or waste materials) using an energy source (e.g., renewables, nuclear, or fossil energy). Most of the hydrogen used today is produced from natural gas (without carbon capture, utilization, and storage [CCUS]) through a process known as steam methane reforming, resulting in substantial carbon emissions. However, there are many possible pathways for producing clean hydrogen with very low or zero emissions—for example, using renewable or nuclear power to split water, or through steam methane reforming with carbon capture.

Once hydrogen is produced, it can be used to store, move, and deliver low- or no-carbon energy to where it is needed. Hydrogen can be stored as a liquid or gas, or stored within a chemical compound, and it can release stored energy through highly efficient electrochemical processes in fuel cells, or via traditional combustion methods in engines, furnaces, or gas turbines. It can also be used as a critical feedstock and reactant in important chemical and industrial processes.

Clean hydrogen has a particularly important role to play in addressing our hardest-to-decarbonize sectors, which include key economic engines that are essential to the modern American economy and quality of life, such as heavy-duty transportation and chemical and industrial processes like ammonia production (e.g., for fertilizer), steelmaking, and production of liquid fuels (including low-emissions biofuels, which will play an important role in decarbonizing the transportation sector).[10] Clean hydrogen can also support the expansion of zero-emissions electricity by providing a means for long-duration energy storage and by offering flexibility and multiple revenue streams for all types of clean power generation.

The *U.S. National Clean Hydrogen Strategy and Roadmap*[11] estimates that by 2050, the use of clean hydrogen across sectors can reduce U.S. greenhouse gas (GHG) emissions approximately 10% relative to 2005,[12] or roughly 650 million metric tons per year—a reduction greater than the

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[10] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.

[11] 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.

[12] Emission savings estimated in the *U.S. National Clean Hydrogen Strategy and Roadmap* are based on ranges of hydrogen production carbon intensities, accounting for hydrogen fossil and clean electrolysis pathways, as well as hydrogen demands across transportation, industry, and grid energy storages. Estimates were developed using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model: https://greet.es.anl.gov/.

annual GHG emissions from every truck, bus, airplane, and ship in the United States today.[13] By enabling diverse, domestic clean energy pathways across multiple sectors of the economy, clean hydrogen will also strengthen American energy independence and resilience while creating good jobs, economic growth, and export opportunities. The DOE report *Pathways to Commercial Liftoff: Clean Hydrogen*[14] estimates that by 2030, the hydrogen economy could also result in 100,000 net new direct and indirect jobs in the United States due to the build-out of new capital projects and clean hydrogen infrastructure.

As shown in Figure 1.1, which illustrates the H2@Scale™ vision launched in 2016 by DOE and its national laboratories, clean hydrogen can be produced from diverse domestic resources and used across almost all sectors of the economy.[15] Hydrogen production can be centralized or decentralized, grid-connected or off-grid—offering scalability, versatility, and resiliency. Clean hydrogen provides multiple options across sectors and can complement today's conventional grid and natural gas infrastructure. Because hydrogen can be stored, transported, and used in locations or applications where electrification may be challenging, it can play an especially valuable role in complementing "electrons to electrons" pathways such as the electric grid to batteries.

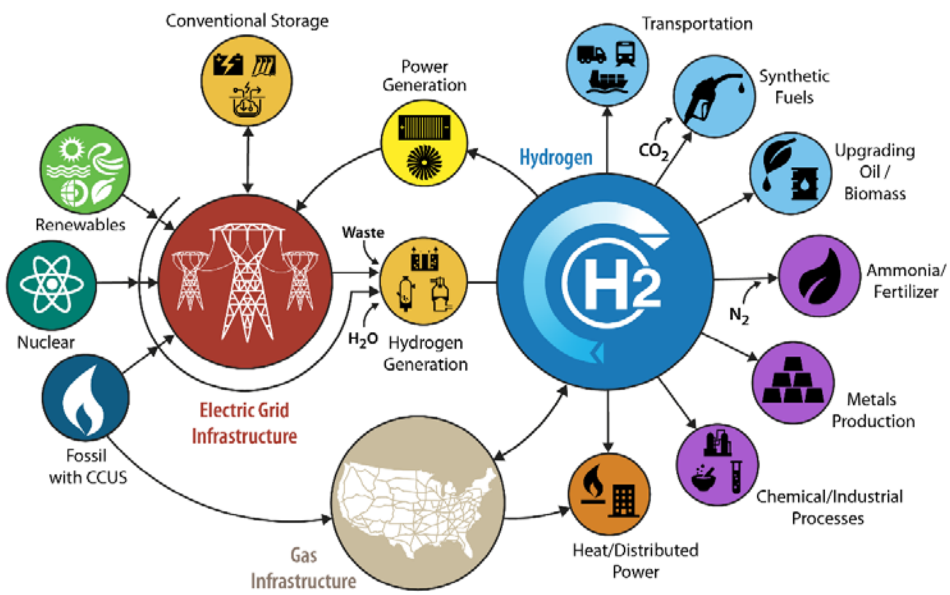

Figure 1.1. DOE's H2@Scale initiative seeks to enable resource integration and decarbonization across sectors using clean hydrogen, which can be produced from several domestic resources and used in a wide range of applications.

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13 U.S. Environmental Protection Agency. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021.* June 2023. EPA-420-F-23-016. https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf.
14 U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen.* March 2023. https://liftoff.energy.gov/wp-https://liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Clean-H2-vPUB-0329-update.pdf.
15 U.S. Department of Energy. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.

Figure 1.2 illustrates the wide range of specific applications where the use of hydrogen is either growing or has the potential for significant future demand. These diverse applications highlight the scale of the commercial potential for hydrogen and related technologies, as well as their decarbonization potential.

	Industrial feedstocks	Transportation	Power generation & energy storage	Buildings and hydrogen blending
Existing demands at limited current scales	• Oil refining • Ammonia • Methanol • Other (e.g. food, chemicals)	• Forklifts and other material-handling equipment • Buses • Light-duty vehicles	• Distributed generation: primary and backup power • Renewable grid integration with storage and other ancillary services	• Low-percentage hydrogen blending in limited regions
Emerging demands and potential new opportunities	• Steel and cement manufacturing • Industrial heat • Bio/synthetic fuels and products using hydrogen	• Hydrogen / biofuels using hydrogen for medium- and heavy-duty applications: o Trucks o Rail o Maritime o Aviation (e.g., sustainable aviation fuels) o Off-road equipment (mining, construction, agriculture)	• Long-duration energy storage • Hydrogen low NOx combustion • Direct/reversible fuel cells • Nuclear/hydrogen hybrids • Fossil/waste/biomass hydrogen hybrids with CCUS	• Mid- to high-percentage hydrogen blending in certain regions with limited alternatives • Building or district heating, including fuel cells and combined heat and power, for hard-to-electrify or limited options

Figure 1.2. Existing and emerging demands for hydrogen

Approximately 10 million metric tons (MMT) of hydrogen are currently produced in the United States each year, with about 100 MMT produced globally,[16] mostly from natural gas using conventional reforming processes that emit CO_2 at rates of around 10 kg of CO_2 per 1 kg of hydrogen produced.[17] This hydrogen is primarily used for oil refining and ammonia and methanol production. Replacing this unabated fossil-based hydrogen with *clean* hydrogen in these current uses offers significant near-term decarbonization potential. And using clean hydrogen in new applications like sustainable aviation fuels, steel manufacturing, and long-duration energy storage provides substantial additional decarbonization opportunities across many industries.

The *U.S. National Clean Hydrogen Strategy and Roadmap* identifies opportunities for increasing clean hydrogen production in the United States from a small fraction of current hydrogen production to ***10 MMT per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050*** (Figure 1.3). These goals are based on demand scenarios assuming cost competitiveness for

[16] International Energy Agency. "Global Hydrogen Review 2022." International Energy Agency, Paris, France, 2022. iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.

[17] National Energy Technology Laboratory. *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*. December 2023. https://netl.doe.gov/projects/files/HydrogenShotTechnologyAssessmentThermalConversionApproaches_120523.pdf

hydrogen use in specific sectors. The *U.S. National Clean Hydrogen Strategy and Roadmap* estimates that by 2050, the use of clean hydrogen across sectors can reduce U.S. GHG emissions approximately 10% relative to 2005.[18]

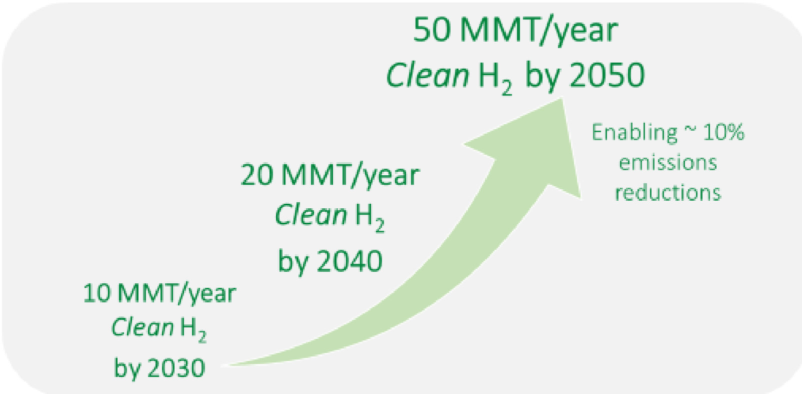

Figure 1.3. The opportunity for clean hydrogen in the United States

1.3 Challenges to Realizing Widespread Adoption of Hydrogen and Fuel Cells

Extensive technical progress has been achieved through decades of strategic investments in research, development, demonstration, and deployment (RDD&D). And this progress has laid the groundwork for rapid worldwide growth in industry investments, expanding commitments by governments and industry stakeholders to ramp up clean hydrogen production, and for the development of government and industry roadmaps for clean hydrogen across the world.[19] However, some significant challenges still need to be overcome to fully realize the enormous potential of a clean hydrogen economy. These challenges cut across the hydrogen value chain, from how hydrogen is produced, delivered, and stored to how it is used in various applications and integrated into larger energy systems. The primary challenges can be grouped into the following three categories:

- **Reducing cost and improving performance.** The cost of technologies for producing, delivering, and storing clean hydrogen, as well as the cost of fuel cells, must be reduced to expand existing markets and open new ones. The efficiency, durability, and reliability of hydrogen and fuel cell systems also need to be improved to achieve parity with incumbent technologies.
- **De-risking and scaling up technologies across the value chain.** To reduce investment risk, new hydrogen and fuel cell technologies need to be demonstrated and validated in

[18] U.S. Environmental Protection Agency. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021.* June 2023. EPA-420-F-23-016. https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf.
[19] Examples include the Hydrogen Council's *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition*, 2017. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf.

real-world conditions. And to enable scale-up of proven technologies, more-robust domestic supply chains and improvements in manufacturing (both to reduce cost and enable scale) will be needed.

- **Barriers to large-scale adoption.** To enable large-scale adoption across multiple sectors, improvements will be needed in a number of crosscutting areas, such as safety (e.g., improved sensors, enhanced safety practices, and knowledge dissemination), adoption of technically sound codes and standards, improved (and streamlined) permitting processes, and a well-trained workforce for the entire technology life cycle, from research through manufacturing to installation, repair, and decommissioning.

1.4 Alignment with National Priorities and Other Federal Activities

HFTO's strategy and plans are closely aligned with the overarching national clean hydrogen strategy as well as with priorities and activities within DOE and across multiple federal agencies. As laid out in the *U.S. National Clean Hydrogen Strategy and Roadmap*, the federal government is undertaking a holistic, whole-of-government approach to overcoming the challenges facing clean hydrogen. The Hydrogen Interagency Task Force[20] (HIT) coordinates activities across multiple agencies, including long-standing efforts within DOE's Hydrogen Program,[21] as guided by the *DOE Hydrogen Program Plan*.

***U.S. National Clean Hydrogen Strategy and Roadmap* Vision**
Affordable clean hydrogen for a net-zero-carbon future and a sustainable, resilient, and equitable economy

The *U.S. National Clean Hydrogen Strategy and Roadmap*—which was required by the Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law[22]—was published in June 2023 and provides a living strategy to enable the vision for clean hydrogen. It examines the status of the hydrogen industry and the challenges facing clean hydrogen production, transport, storage, and use in the United States today. And it provides an assessment of the opportunity for hydrogen to contribute to national decarbonization goals across sectors over the next 30 years. Both the *U.S. National Clean Hydrogen Strategy and Roadmap* and the *MYPP* are guided by input from diverse stakeholders engaged in relevant private and public sector hydrogen activities. The national vision for clean hydrogen, along with key strategic priorities, are illustrated in Figure 1.4, and the three key strategies are described below.

[20] U.S. Department of Energy. "Hydrogen Interagency Task Force." https://www.hydrogen.energy.gov/interagency.
[21] U.S. Department of Energy. "Hydrogen Program." https://www.hydrogen.energy.gov/.
[22] Infrastructure Investment and Jobs Act. Public Law 117–58. 2021. Section 40314, (42 U.S.C. 16161c). https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

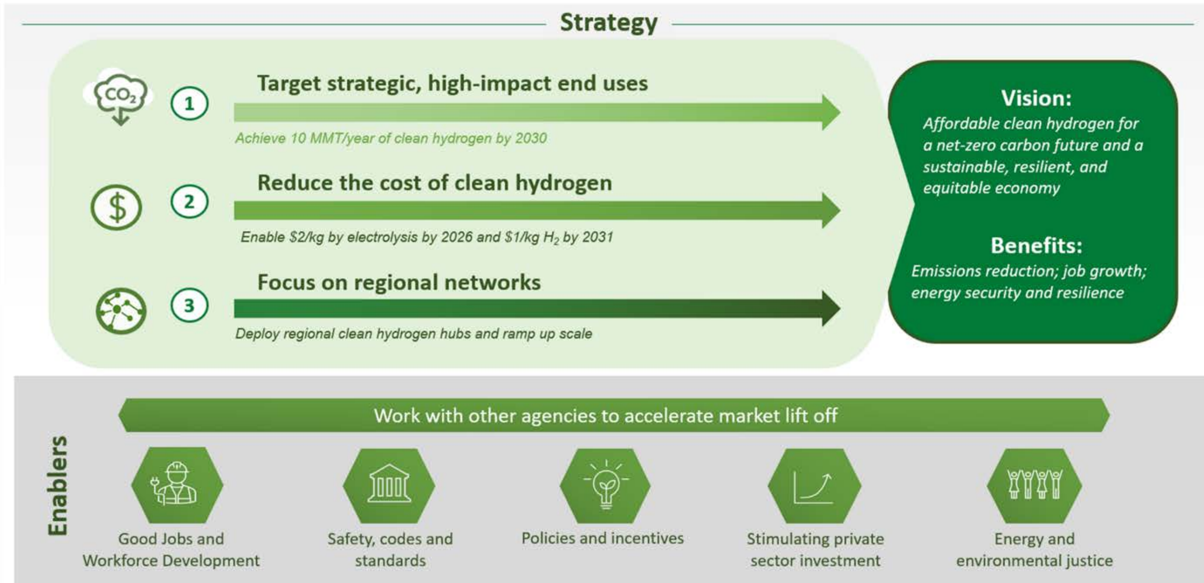

Figure 1.4. The national strategy for clean hydrogen is aligned with DOE and HFTO missions.

1. **Target strategic, high-impact end uses**: The use of clean hydrogen will be focused strategically to provide maximum benefits, particularly in sectors that are hard to decarbonize.
2. **Reduce the cost of clean hydrogen**: The United States can dramatically lower the delivered cost of clean hydrogen by developing sustainable and supply-resilient pathways including water electrolysis; thermal conversion with CCUS; and advanced or hybrid production pathways.
3. **Focus on regional networks**: Scale can be achieved strategically by focusing on regional networks—ramping up hydrogen production and end-use in close proximity to drive down transport and infrastructure costs and create holistic ecosystems that provide local benefits.

Launched in August 2023, the HIT is a collaboration among U.S. federal agencies to further advance a whole-of-government approach to executing the national clean hydrogen strategy, including development of a robust market supported by domestic supply chains and sustainable jobs. HIT members work to coordinate federal adoption of hydrogen and fuel cell technologies to support national commercialization and industry growth. Activities are conducted under staff-level working groups, which include Supply and Demand at Scale; Infrastructure, Siting, and Permitting; and Analysis and Global Competitiveness, along with other crosscutting teams. Interagency coordination will continue to expand to implement the national strategy, and agencies may be added to the HIT as the clean hydrogen economy develops over time.

As the coordinating office of the DOE Hydrogen Program, HFTO works closely with other DOE offices (e.g., Fossil Energy and Carbon Management, Nuclear Energy, Electricity, Science, Loan Programs, Manufacturing and Energy Supply Chains, Clean Energy Demonstrations, Energy

Justice and Equity, and the Advanced Research Projects Agency-Energy) and provides leadership in coordinating activities with other federal agencies, state agencies, regional partnerships, associations, and international counterparts worldwide. HFTO's plans and those of all other DOE offices are conducted under the overarching guidance of the *DOE Hydrogen Program Plan***,** which was updated in 2020 and presents an agency-wide strategic plan for all DOE offices engaged in hydrogen-related activities.

HFTO's activities in clean hydrogen production are also coordinated under the Hydrogen Shot,[23] the first of DOE's Energy Earthshots™, which was launched in June 2021 with an ambitious goal to reduce the cost to producing clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). The Energy Earthshots initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions.

The *MYPP* also aligns with other important strategy documents such as DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* and *Industrial Decarbonization Roadmap*,[24] as well as the *U.S. National Blueprint for Transportation Decarbonization*,[25] which was jointly issued by DOE, the U.S. Department of Transportation, the U.S. Environmental Protection Agency, and the U.S. Department of Housing and Urban Development. The *MYPP* also addresses fundamental research priorities, such as those identified in the DOE report *Foundational Science for Carbon-Neutral Hydrogen Technologies*.[26]

Figure 1.5. Important strategic documents underlying the HFTO RD&D strategy

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[23] Office of Energy Efficiency and Renewable Energy. "Hydrogen Shot." https://www.energy.gov/eere/fuelcells/hydrogen-shot.
[24] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. September 2022. https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[25] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.
[26] U.S. Department of Energy. *Foundational Science for Carbon Neutral Hydrogen Technologies*. October 2021. https://www.energy.gov/policy/articles/foundational-science-carbon-neutral-hydrogen-technologies.

1.5 HFTO RD&D Framework

The HFTO Mission

RD&D to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy.

HFTO's mission is to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy. HFTO strategically deploys funding for RD&D activities to achieve the goals that support this mission. HFTO-funded efforts fall roughly into two broad areas:

- **Research and development** activities, which aim to improve materials, components, and subsystems at laboratory scale. These activities address many of the underlying technical barriers to reducing the cost and improving the performance of key technologies, such as electrolyzers, fuel cells, and systems for storing, delivering, and dispensing hydrogen. Many of HFTO's research and development efforts are conducted through consortia based on teams built around national laboratories, such as the HydroGEN Advanced Water Splitting Materials Consortium, which focuses on materials to improve hydrogen production through advanced water-splitting processes; the Hydrogen Materials Advanced Research Consortium (HyMARC), which aims to address scientific challenges in the development of viable solid-state materials for storage of hydrogen on board vehicles; and the Million Mile Fuel Cell Truck Consortium, which focuses on improving the durability, performance, and cost of fuel cells for heavy-duty trucks.
- **Demonstration and enabling** activities, which involve integration and operation of complete systems under real-world conditions to validate performance and de-risk investment, along with activities to support the deployment of commercial-scale systems and identify and help overcome nontechnological barriers. Activities focus on key strategic applications, such as demonstrations of fuel-cell-powered delivery trucks, fueling infrastructure for medium- and heavy-duty trucks, airport ground support equipment, and nuclear-to-hydrogen production. Additional enabling activities include comprehensive analysis, tools, and models to identify barriers and pathways to success; safety research; support for development of codes and standards; workforce development activities; and support for supply chains and improved manufacturing processes.

As the guiding document for HFTO's activities, the *MYPP* provides an assessment of the challenges that still must be overcome to realize large-scale adoption of clean hydrogen and a detailed, integrated plan for all RD&D and crosscutting activities conducted by HFTO. For each technical area within HFTO, the *MYPP* includes the following:

- Assessment of the current status of key metrics (e.g., electrolyzer capital cost and efficiency).

- Technical targets related to each of those key metrics (See Chapter 1.6 for a deeper discussion of HFTO's technical targets).
- Detailed plan for activities to meet those targets.

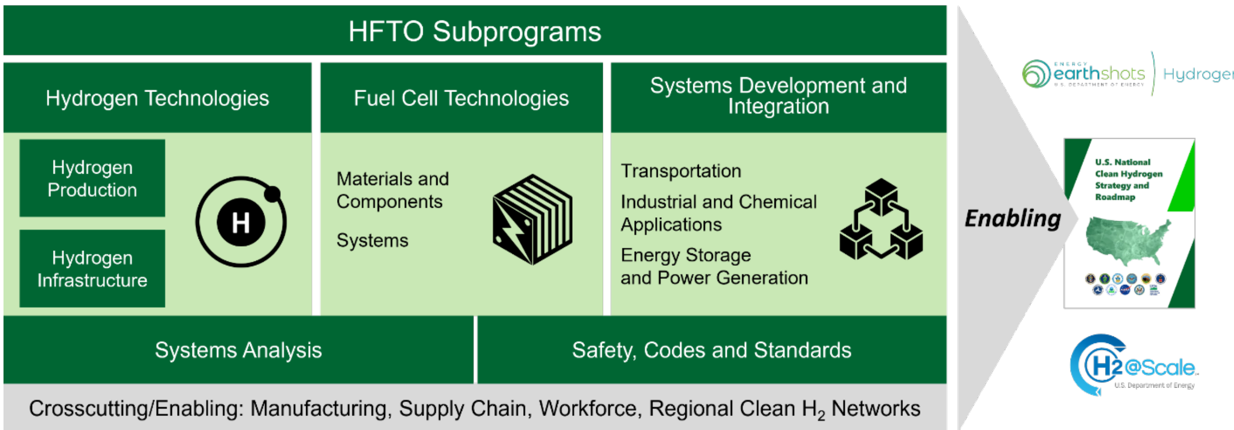

Figure 1.6. HFTO subprogram structure supporting national clean hydrogen priorities

HFTO has established the RD&D framework of subprograms illustrated in Figure 1.6 and described below:

- **Hydrogen Technologies** comprises two coordinated and closely related focus areas, both of which span materials-, component-, and system-level RD&D:
  - *Hydrogen Production* focuses on enabling affordable production of hydrogen from diverse renewable domestic resources.
  - *Hydrogen Infrastructure* focuses on enabling affordable and accessible delivery and storage infrastructure options.
- **Fuel Cell Technologies** focuses on the materials-, component-, and system-level RD&D for different fuel cell technologies and applications to enable highly efficient conversion of clean hydrogen for end uses such as transportation and backup-power generation using fuel cells.
- **Systems Development and Integration** focuses on the development and integration of complete hydrogen systems to enable first-of-a-kind demonstrations of integrated energy systems deploying clean hydrogen and fuel cell technologies in key hard-to-decarbonize sectors—including transportation, chemical and industrial processes, and energy storage and power generation.
- **Systems Analysis** encompasses crosscutting topics including data, modeling, and analysis that guides RD&D, and identifies priority markets for clean hydrogen technologies with impacts assessments.

- **Safety, Codes and Standards** encompasses crosscutting topics, including RD&D that informs safe design and operation of clean hydrogen technologies, while addressing regulatory and permitting challenges.

Overall cost reductions, including technology manufacturability and scale-up, are common crosscutting topics covered across the subprograms, as well as in collaboration with other DOE offices and federal agencies. Other crosscutting topics include workforce development; addressing DEIA; and ensuring well-paying U.S. jobs.

For each of these subprograms, the *MYPP* documents HFTO's plans for RD&D activities based on near-, mid-, and longer-term priorities:

- **Near- to mid-term priorities** are to enable cost reductions and demonstrate advances, including component and systems development and integration, leading to fully integrated systems.
- **Mid- to longer-term priorities** are early-stage materials and component research to enable innovation and leapfrog current approaches to meet ultimate targets.

HFTO has developed a multipronged, target-driven strategic approach to achieve its mission and support national priorities in clean hydrogen. This approach is illustrated in Figure 1.7, which shows specific priorities for each subprogram area—with darker shades indicating the time periods when a greater level of effort is planned. The subprogram priorities, along with supporting RD&D efforts, are described in detail in the corresponding subprogram chapters of the *MYPP*. Details for each of the subprograms are also summarized each year in the President's Congressional Budget Request, and HFTO uses annual appropriations to fund RD&D consistent with the overall strategy.

	Strategic Priorities
Clean Hydrogen Production	• **Affordable, efficient, and durable electrolyzers** for **GW-scale** operations • **Innovative approaches to clean H_2 production**, beyond electrolysis
Hydrogen Infrastructure Technologies	• Affordable and reliable components and systems for **H_2 transport and dispensing in heavy-duty applications** • **Advanced H_2 liquefaction and carrier distribution concepts** • **Low-cost vessels** for high-pressure gaseous and cryogenic liquid H_2 storage • **Innovative H_2 storage materials** for high-density, low-pressure storage
Fuel Cell Technologies	• **Efficient, durable, and cost-competitive fuel cells** for heavy-duty applications • **Advanced materials and components** for next-generation fuel cell technologies in diverse applications
Systems Development and Integration	• **Transportation and H_2 fueling** demonstrations • **Chemical and industrial processes** integrating H_2 technologies, focusing on decarbonization • **Energy storage and power generation** including integrated and resilient hybrid energy systems
Systems Analysis	• **Tools, modeling, and analysis** to prioritize RD&D and inform early-market deployments • **Regional analysis** to support energy transition planning and assess impacts • **Integrated analysis** to inform supply chain expansion and sustainable market growth
Safety, Codes and Standards	• **H_2 component technologies safety**, including materials compatibility and environmental modeling, emphasizing near-term dispensing applications • **Safety, codes, and standards** with additional emphasis on bulk storage and large-scale applications of hydrogen
Crosscutting/ Enabling	Collaboration within HFTO and across offices and other federal agencies to enable low-cost, high-volume domestic manufacturing and recycling, a robust domestic supply chain, good-paying U.S. jobs, regional clean hydrogen networks, and energy and environmental justice and diversity, equity, inclusion, and accessibility.

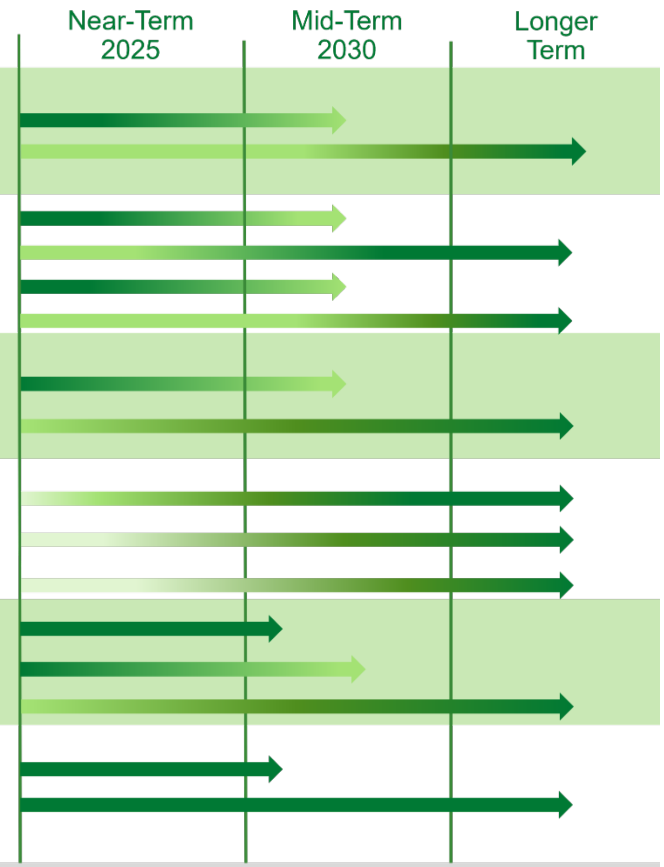

Figure 1.7. Strategic RD&D priorities in HFTO's portfolio, illustrating the multipronged approach—which includes near- to mid-term and longer-term priorities across most focus areas.

1.6 Target-Driven Approach

To effectively achieve outcomes aligned with its mission, HFTO defines and refines near- and longer-term goals with specific targets based on what is required for clean hydrogen and fuel cells to be cost-competitive across sectors. These targets are developed through techno-economic analysis and with extensive input from industry and other relevant stakeholders. Importantly, they are closely correlated with milestones in the *U.S. National Clean Hydrogen Strategy and Roadmap* shown in Table 1.1.

HFTO Key Target Examples

Targets are developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the RD&D community and inform HFTO's portfolio of activities. Examples include the following.

Clean H_2 production:

- $2/kg by 2026; $1/kg by 2031

Electrolyzer systems (low temperature):

- 2026: $250/kW, 65% efficiency, 80,000-hour durability

Electrolyzer systems (high temperature):

- 2026: $500/kW, 76% efficiency, 40,000-hour durability

H_2 dispensed for heavy-duty transportation:

- 2028: <$7/kg

Fuel cell manufacturing for heavy-duty transportation:

- 2030: 20,000 stacks/year (single manufacturing system)

Fuel cell systems for heavy-duty transportation:

- 2030: $80/kW, 25,000-hour durability

The key priority underlying HFTO's targets is to achieve affordability at scale, in addition to improving—or at least not compromising—technological performance and reliability. Each of the subprograms addresses high-level cost targets through RD&D guided by detailed technical targets developed at the materials-, component-, and integrated systems level.

For each subprogram, the *MYPP* illustrates specific pathways HFTO has identified to achieve its targets—including detailed analysis of the key factors affecting targets in each technical area and how HFTO-funded efforts can address those factors. For example, Figure 1.8 shows at a high level the key drivers of fuel cell system cost (*donut* graphic on upper right), then shows a "waterfall" diagram that illustrates cost reductions that can be achieved across four different areas (manufacturing and scale, power density and platinum group metals [PGM], stack and balance of plant [BOP] components, and durability). The *MYPP* provides waterfall charts for additional technical topics such as electrolyzer capital cost, hydrogen storage system cost, and others.

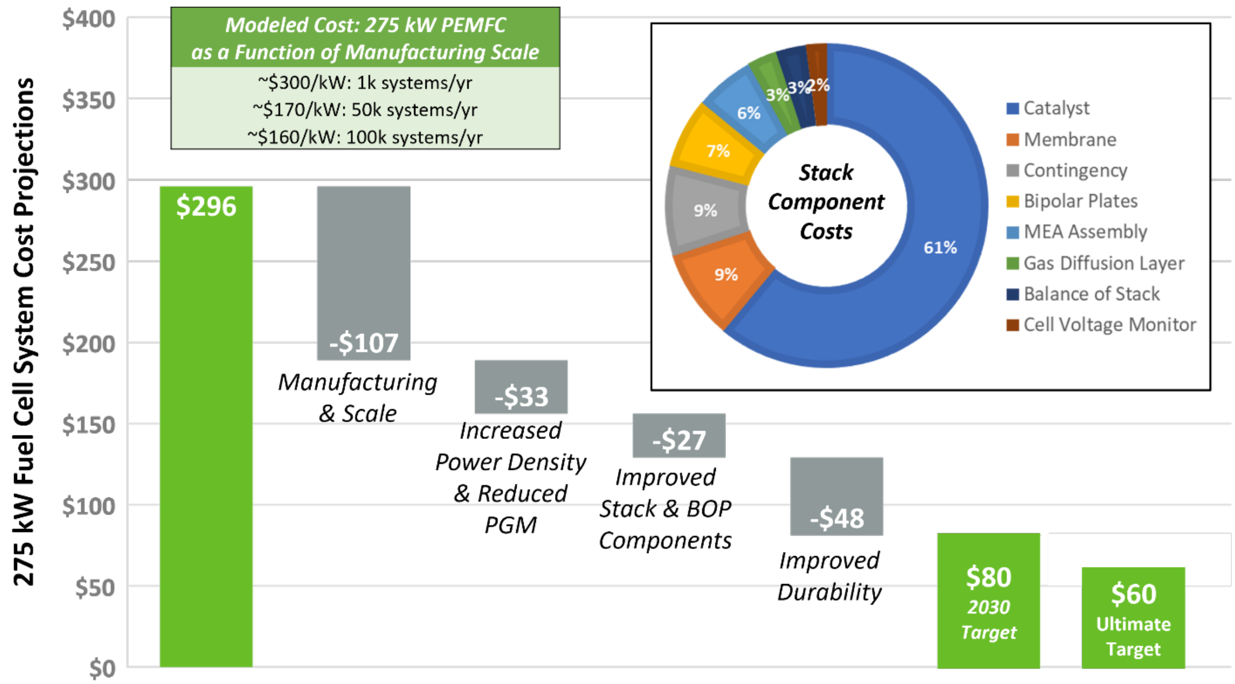

Figure 1.8. Example of “waterfall” chart showing pathways to meeting HFTO cost-reduction targets

Table 1.1 Examples of Key Milestones, Status and Targets

Includes key milestones adapted from the U.S. National Clean Hydrogen Strategy and Roadmap

	Examples of Key Milestones and Status (2023)	2024–2028	2029–2036
Production	• **Three first-of-a-kind demos** of electrolyzers with renewables and nuclear • **\$5 to \$7/kg** for clean H_2 from electrolysis • **~55 kWh/kg** efficiency, **~40,000-hour** (projected operation), ~\$1,500 to \$2,500 installed cost	• **Ten or more** demos with renewables, nuclear, and waste/fossil with CCUS • **\$2/kg clean H_2** from electrolysis at scale by 2026[a] • **51 kWh/kg** efficiency, **80,000-hour** life, and **\$250/kW** uninstalled cost for PEM electrolyzers	• **10 MMT** per year by 2030 or more of clean H_2 produced in the United States • **\$1/kg** clean H_2 production from diverse resources at scale[a] • **46 kWh/kg** efficiency; **80,000-hour** life; **\$100/kW** uninstalled cost for PEM electrolyzers
Infrastructure, Manufacturing, and Supply Chains	• **\$12 to 16/kg** H_2 (modeled cost including delivery and dispensing at fueling stations with electrolytic hydrogen)[b] • Initiated **four** carbon fiber R&D projects for cost reduction • Announced new awards to enable **10 GW electrolyzer manufacturing capacity** in the United States • Announced new awards to enable **14 GW fuel cell manufacturing capacity** in the United States • Announced **Recovery and Recycling Consortium** with industry, labs, and academia to address end-of-life for electrolyzers, fuel cells, and components	• **\$7/kg** H_2 cost at scale (modeled cost including production, delivery, and dispensing at fueling stations) • **50%** cost reduction of carbon fiber for H_2 storage vessels (vs. 2020) • **3 GW or more** electrolyzer manufacturing capacity (in operation) in the United States • **GW-scale** fuel cell and supply chain component manufacturing plants in operation in the United States • **>50%** of membrane/ionomer material recovery and **>95%** of PGMs recovery from fuel cell MEA from pathways identified through recycling and upcycling	• **\$4/kg** H_2 cost at scale (modeled cost including production, delivery, and dispensing at fueling stations) • Demonstrate carbon fiber cost reduction to meet \$9/kWh H_2 storage • **>10 GW/year** electrolyzer manufacturing capacity in operation in the United States to meet national targets • **>14 GW/year** fuel cell manufacturing capacity in operation in the United States to meet heavy-duty fuel cell demand (e.g., 15% of trucks) • **>70%** of membrane/ionomer material recovery and **99%** of PGMs from MEA pathways identified through recycling and upcycling
End Use	• **\$170/kW** heavy-duty truck fuel cell cost vs. \$200/kW baseline • Initiated **three SuperTruck projects** for medium- and heavy-duty trucks • Announced selection of **seven Regional Clean Hydrogen Hubs** (\$7 billion) • Announced funding opportunity for best practices on community benefit agreements	• **\$140/kW** heavy-duty truck fuel cell cost (modeled at 50,000 units/year manufacturing) • **Three** H_2 fuel cell Super Truck projects completed to demonstrate viability • **Four or more** Regional Clean Hydrogen Hubs using diverse resources and for multiple strategic end uses • **Four** template community benefit agreements	• **\$80/kW** heavy-duty truck fuel cell cost at high volumes while also meeting durability and performance • Follow-on truck and station demos in operation to meet market needs • **10 MMT** per year or more of clean H_2 used in strategic markets at scale aligned with the National Hydrogen Strategy goal

[a] *Modeled cost at scale to meet Hydrogen Shot goal.*

[b] *Cost of \$7–\$11/kg for delivery and dispensing in early markets (based on modeled scenarios) and \$5/kg for clean H_2 production. Source: Bracci, Justin, Mariya Koleva, and Mark Chung. 2024. Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-88818. https://www.nrel.gov/docs/fy24osti/88818.pdf.*

CCUS: carbon capture, utilization, and storage; MEA: membrane electrode assembly; PEM: proton exchange membrane; PGM: platinum group metal

1.7 Impacts from Prior Investments

While Chapter 1.6 outlines aggressive targets for the future, it is important to recognize that HFTO has a proven track record of successfully driving down costs and addressing technical challenges through strategic deployment of RD&D funding. For example, HFTO-funded RD&D has resulted in reductions of over 90% in the adjusted uninstalled capital cost of proton exchange membrane (PEM) electrolyzers, as shown in Figure 1.9.[27] These cost reductions have been enabled by innovations developed through DOE-supported projects conducted in partnership with several manufacturers of PEM electrolyzers. The primary focus of this work has been on advances in PEM electrolyzer stacks—both in advancements to the underlying technology and in manufacturing innovations.

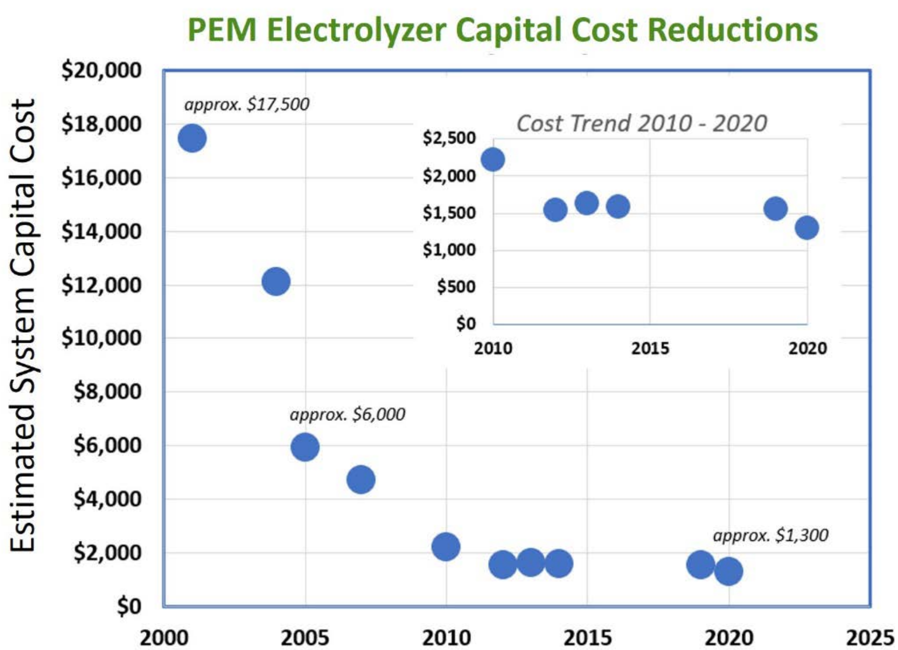

Figure 1.9. Historical reductions in the capital cost of PEM electrolyzers enabled by HFTO investments

The significant reductions in cost closely parallel HFTO funding for RD&D. Note that the data shown through 2020 represents the evolution and scale-up of relatively small electrolyzer systems (<1 MW); more recent advances in stack and system scale-up offer opportunities for further cost reduction, especially for larger multi-megawatt (MW) to gigawatt (GW) systems.

HFTO investments have had a similar impact on reducing costs for fuel cells used in transportation applications. Figure 1.10 shows the 70% reduction in fuel cell system cost for light

[27] Randolph, Katie, James Vickers, David Peterson, McKenzie Hubert, and Eric Miller. June 11, 2022. "Historical Cost Reduction of PEM Electrolyzers." DOE Hydrogen Program Record # 22002. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/22002-historical-cost-reduction-pem-electrolyzers.pdf?Status=Master. Note that the period from 2010 to 2018 (shown in the figure insert) shows only modest cost reductions, reflecting a period of limited/zero HFTO funding in electrolyzer RD&D.

duty vehicles from 2008 to 2020, achieved through RD&D focused on improvements in high-power performance along with reductions in platinum catalyst loading.[28]

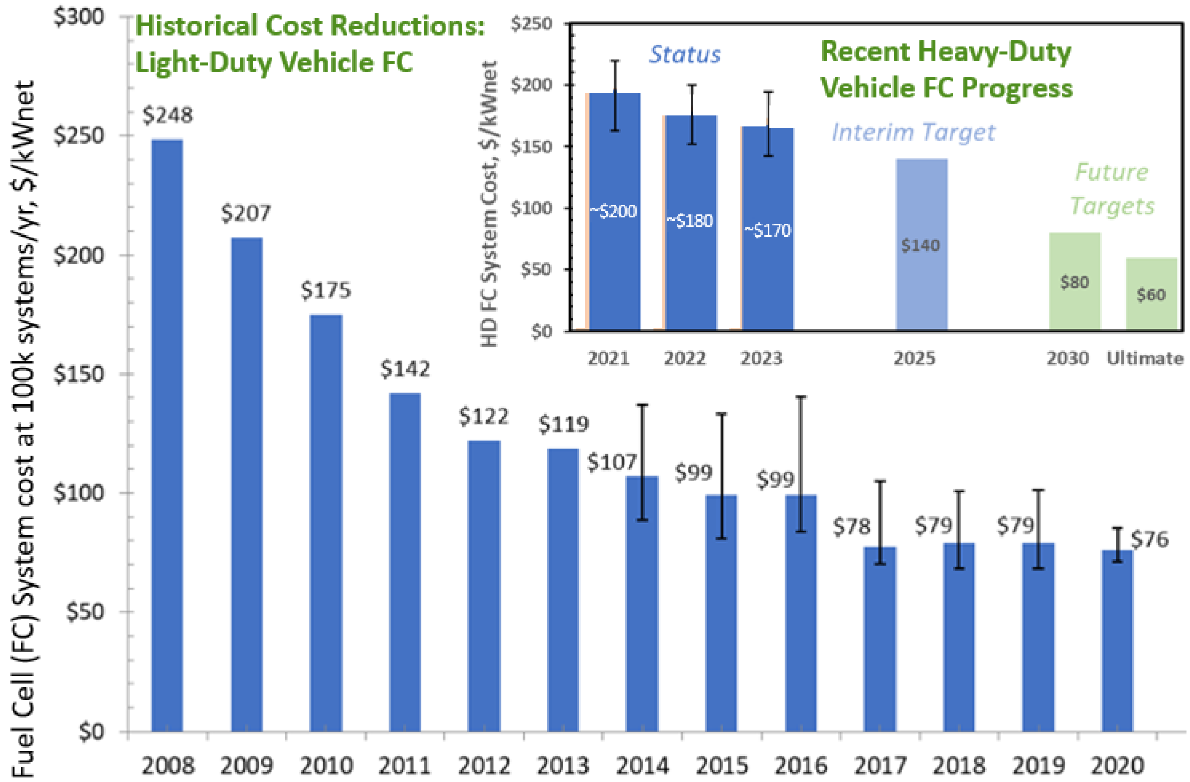

Figure 1.10. Historical reductions in fuel cell system costs enabled by HFTO investments

While past work focused on fuel cell cost reduction for light-duty vehicles, recent efforts prioritize fuel cell targets to meet the duty cycle, cost, and durability requirements for heavy- and medium-duty trucks. The Figure 1.10 inset includes the modeled fuel cell system cost status for heavy-duty vehicles based on recent analysis, compared with the interim target (2025) for a manufacturing volume of 50,000 systems per year, as well as a future 2030 target (for an $80/kW system) and ultimate target (for a $60/kW system) based on manufacturing volumes of 100,000 systems per year.

Complementing the milestones in Table 1.1, additional examples of recent accomplishments enabled by HFTO funding include:[29]

[28] Kleen, Gregory, and Elliot Padgett. January 7, 2021. "Durability-Adjusted Fuel Cell System Cost." DOE Hydrogen Program Record # 21001. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/21001-durability-adjusted-fcs-cost.pdf. The uncertainty bars in the charts reflect system costs with 90% confidence based on a Monte Carlo distribution.

[29] Office of Energy Efficiency and Renewable Energy. July 2023. "Progress in Hydrogen and Fuel Cells." DOE/EE-2743. https://www.energy.gov/eere/fuelcells/articles/progress-hydrogen-and-fuel-cells.

- Improved the performance of specific PGM-free catalysts for fuel cells by approximately 60% over the 2021 baseline.
- Achieved over 10,000 hours of high-temperature electrolyzer testing.
- Demonstrated 1.25 MW electrolysis integrated with nuclear power for H_2 production.
- Commissioned a first-of-a-kind test facility for high-throughput hydrogen fueling; and demonstrating a 10 kg/min average H_2 fueling rate for heavy-duty applications.
- Demonstrated greater than 1.5 MW of H_2 fuel cells for data center resilience.
- Reduced the cost of advanced onboard compressed-hydrogen storage systems by 30% since 2013.
- Achieved a 40% footprint reduction in liquid H_2 fueling stations vs. current code (2016).
- Achieved a 50% increase in seal and metal durability in H_2 service vs. the 2018 baseline.
- Demonstrated H_2 flow meters with 5% or better accuracy for flows up to 20 kg/min.
- Developed an American Society of Mechanical Engineers Code Case that extends H_2 storage vessels design life by up to 300%.
- Demonstrated 1 ton/week iron reduction with H_2, with a pathway to 5,000 ton/day.
- Demonstrated fuel cell delivery trucks in a disadvantaged community.

HFTO RD&D has achieved many prior year goals and targets; many of these successes are tracked in the Hydrogen Program Records.[30] Additional detailed examples of historical progress to date are included in individual subprogram chapters of this document.

1.8 *MYPP* Structure

The *MYPP* outlines remaining technical challenges that must be systematically addressed through further targeted RD&D funding to ensure continued progress toward national clean hydrogen goals. Chapter 2 provides an explanation of HFTO program implementation, with the remainder of the document providing a detailed description of HFTO's comprehensive portfolio of RD&D and enabling activities, organized by chapters focused on each of the subprograms. Each chapter includes specific technology focus areas in the subprograms' near- and longer-term strategic approach, highlighting specific challenges, risk mitigation strategies, and examples of relevant techno-economic targets and milestones. Additional references and links to important supplemental information are provided, including technology-specific target listings and status updates.

[30] U.S. Department of Energy. "Hydrogen Program: Program Records." https://www.hydrogen.energy.gov/library/program-records.

2 Program Implementation

2.1 Overview

HFTO implements programmatic activities in support of nationally established priorities for clean energy and environmental justice, such as those articulated in the ***U.S. National Clean Hydrogen Strategy and Roadmap***.[31] HFTO program implementation comprises of RD&D activities managed across its subprograms as well as stakeholder engagement and collaborative activities with diverse government, community, industry, academic, and national laboratory stakeholders. HFTO adheres to the guiding principles illustrated in Figure 2.1 established for all federal agencies, with a specific focus on RD&D and enabling activities in the production, transport, delivery, storage, and end-use of clean hydrogen. Program implementation stemming from specific congressional authorizations, and adhering to these guiding principles, is described below.

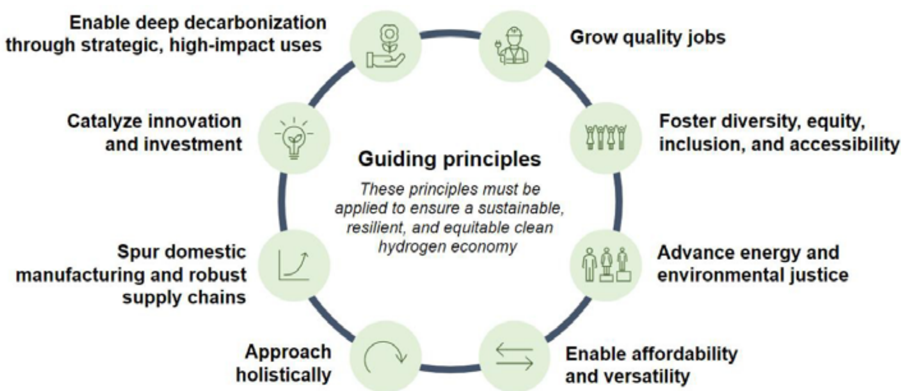

Figure 2.1. Eight guiding principles for the development of clean hydrogen production, transport, delivery, storage, and use

2.2 Congressional Authorization

Various statutory authorities have enabled DOE to establish a robust RD&D program in hydrogen and fuel cells technologies, including: the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990; the Energy Policy Act of 2005; the Energy Independence and Security Act of 2007; and U.S. Code (42 U.S. Code § 16154). These authorizing statutes, policies, and annual appropriations provide the basis for much of the work discussed in the *MYPP*. In 2021, the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law (BIL) was signed into law, authorizing funds for clean hydrogen RD&D and providing specific amendments to the Energy Policy Act of 2005. In 2022, the

[31] 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.

Inflation Reduction Act was signed into law (Public Law 117-169), providing additional policies and incentives for hydrogen including a production tax credit to further boost a U.S. market for clean hydrogen.

2.3 Program Management

Stakeholder Input

To maintain alignment with the priorities of key stakeholders—including industry, end users, academia, the investment community, and other government agencies—HFTO actively solicits input to inform its programmatic activities across its subprograms. Among the primary channels for this input are requests for information and workshops conducted by DOE to help establish high-level program direction and to develop and update technology-specific RD&D plans. These workshops convene a wide range of stakeholders and provide an open forum for discussion of the status of the technologies and the challenges facing their development and deployment. Results from these stakeholder input activities feed into the development of HFTO strategies and funding plans, including in developing rigorous targets and milestones for all RD&D pathways.

Funding Mechanisms

HFTO's activities are funded using various competitive mechanisms, including funding opportunity announcements (FOAs), through which industry, university, national laboratory, and other private-sector projects are selected. HFTO also issues separate lab calls to make selections for national laboratory projects; uses cooperative research and development agreements (CRADAs) to encourage partnerships between the private sector and national labs for joint development; and creates strategic partnership projects, through which industry can contract company-specific tasks to be conducted at national labs.

Project Management

HFTO's comprehensive RD&D portfolio comprises projects that are competitively selected under the various funding mechanisms. A rigorous selection process ensures projects are selected based on technical feasibility, high-impact potential, innovation, and the likelihood of making progress toward HFTO technical targets. Each project proposal is reviewed by independent experts. The proposals are evaluated based on a specific set of criteria and how well the proposal helps the HFTO to address the challenges, targets, and goals. A federal panel considers the independent experts' review comments when selecting projects for award negotiations.

Once a project is selected, funding award recipients submit a plan detailing their approach to reaching project objectives and overcoming technical challenges. Each project plan incorporates go/no-go decisions to help project managers decide whether the project should continue into the next budget period. These go/no-go decisions define performance-based milestones and quantitative metrics at the subprogram, task area, and project level.

HFTO regularly assesses progress, approaches, and priorities by monitoring portfolio performance. An Annual Merit Review and Peer Evaluation of the DOE Hydrogen Program portfolio and HFTO projects allows external experts to evaluate project objectives, approach, success, and relevance. These performance assessment activities provide avenues for input from other government agencies, industry representatives, academia, other stakeholders, and independent subject matter experts on program effectiveness and progress toward the Hydrogen Program's mission and goals.

2.4 RD&D Consortium Model

Activities across government, industry, and academia are working in concert with HFTO to advance the clean hydrogen and fuel cell technologies described in the *MYPP*. As a key enabler of such collaboration, HFTO has pioneered a consortium model comprising national laboratory core teams that make available their world-class resources and expertise to universities and industry through consultations as well as collaborative projects awarded through FOAs and CRADAs, as illustrated in Figure 2.2. Each consortium has a specific technical focus area, with comprehensive RD&D efforts within the core lab team and with the collaborative projects.

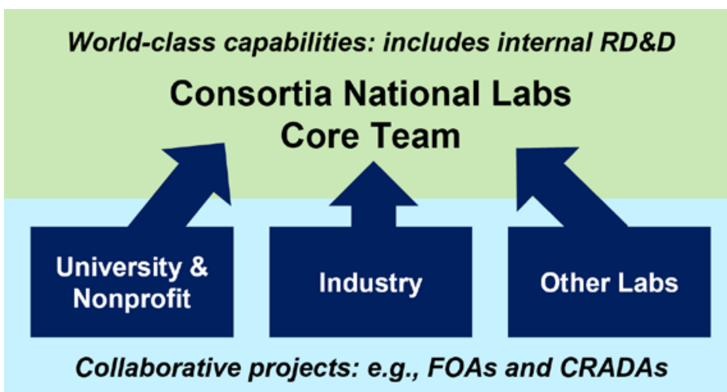

Figure 2.2. HFTO consortia model approach to research collaborations

HFTO Consortia Advancing RD&D in Hydrogen and Fuel Cell Technologies

Million Mile Fuel Cell Truck (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

Hydrogen from Next-generation Electrolyzers of Water (H2NEW) conducts RD&D to achieve large-scale, affordable electrolysis powered by clean electricity, supporting large industry deployment by enabling more durable, efficient, and low-cost electrolyzers: H2NEW Consortium

HyBlend addresses technical barriers to blending hydrogen in natural gas pipelines through materials compatibility RD&D and analysis that informs development of publicly accessible assessment tools on blending: HyBlend Consortium

Hydrogen Materials Compatibility Consortium (H-Mat) focuses on crosscutting R&D on hydrogen materials compatibility to improve the reliability and reduce the costs of materials, and to inform relevant codes and standards: H-Mat Consortium

Hydrogen Materials Advanced Research Consortium (HyMARC) addresses unsolved scientific challenges in the development of viable solid-state materials for onboard storage of H_2 that could lead to more reliable and economic hydrogen fuel cell vehicles: HyMARC Consortium

HydroGEN Advanced Water Splitting Materials (HydroGEN) focuses on innovative R&D on advanced water-splitting materials, primarily for photoelectrochemical, solar thermochemical, and advanced electrolytic hydrogen production pathways: HydroGEN Consortium

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

Roll-to-Roll Consortium (R2R) focuses on membrane electrode assembly manufacturing technology advancements to reduce costs for fuel cells and electrolyzers.

2.5 Collaboration Networks

In addition to its internal collaborative RD&D, HFTO engages in coordinated activities with diverse stakeholders involved in the development of clean hydrogen and fuel cell technologies, including other DOE offices; federal, state, and local government agencies; public-private partnerships with industry; and international partnerships. The aim of such broader collaboration is to optimize federal investments, best leverage available resources, avoid duplication, and ensure consistent messaging to stakeholders.

DOE Collaboration

While HFTO has had the lead role in coordinating hydrogen-related activities across the government for over two decades, multiple DOE offices are engaged either directly or indirectly in hydrogen-related activities, including offices under the Under Secretary for Science and Innovation like EERE, FECM, NE, OE, and SC; offices under the Under Secretary for Infrastructure like LPO, MESC, and OCED; and Secretary-level offices like ARPA-E.[32] These offices are core to the DOE Hydrogen Program, whose structure is illustrated in Figure 2.3; they collaborate regularly to evaluate technical progress, share programmatic developments, share best practices on technical management, and assess the impacts of alternative technology pathways from environmental, energy, equity, and economic standpoints.

[32] EERE: Office of Energy Efficiency and Renewable Energy; FECM: Office of Fossil Energy and Carbon Management; NE: Office of Nuclear Energy; OE: Office of Electricity; SC: Office of Science; LPO: Loan Programs Office; MESC: Office of Manufacturing and Energy Supply Chains; OCED: Office of Clean Energy Demonstrations; ARPA-E: Advanced Research Projects Agency-Energy; AE: Arctic Energy Office; EJE: Office of Energy Justice and Equity; IA: Office of International Affairs; IE: Office of Indian Energy Policy and Programs; OTT: Office of Technology Transitions.

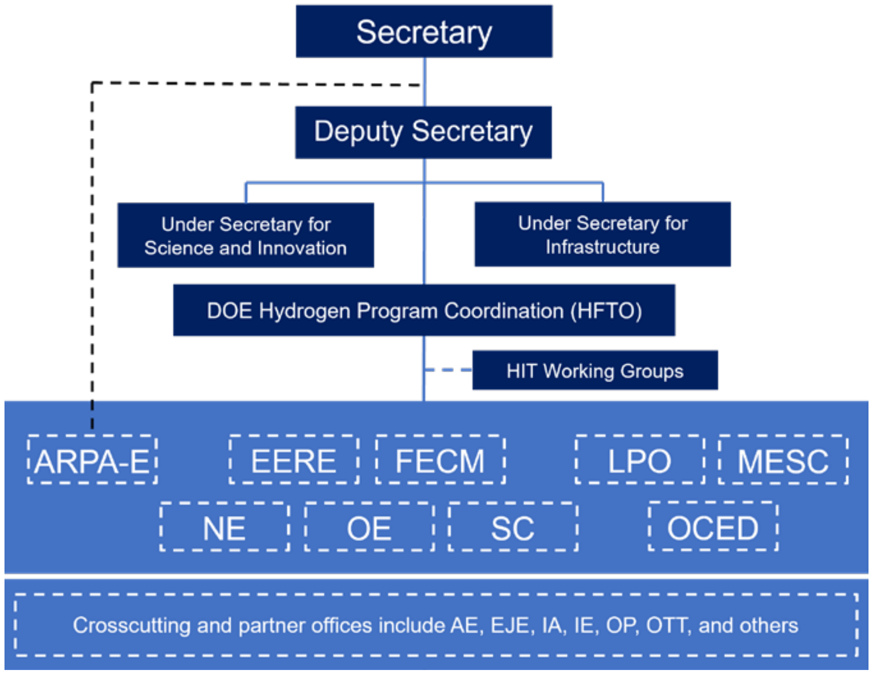

Figure 2.3. DOE Hydrogen Program organizational structure

HFTO also had a lead role in supporting the launch of the Office of Clean Energy Demonstrations (OCED) and the Regional Clean Hydrogen Hubs and continues to support OCED in execution of the $7 billion announced for seven regional clean hydrogen hubs. The *DOE Hydrogen Program Plan*[33] catalogs coordinated clean hydrogen and fuel cell activities across the DOE offices, spanning fundamental scientific research and development; applied research, development, and demonstration; and scale-up and deployment activities. The collaborative cycle of research, development, demonstration, and deployment (RDD&D) adopted by the DOE Hydrogen Program is illustrated in Figure 2.4, aimed at accelerating the technology-, manufacturing-, and commercial-readiness of affordable options for clean hydrogen production, storage, delivery, and utilization across sectors.

[33] U.S. Department of Energy. *Department of Energy Hydrogen Program Plan.* November 2020. DOE/EE-2128. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

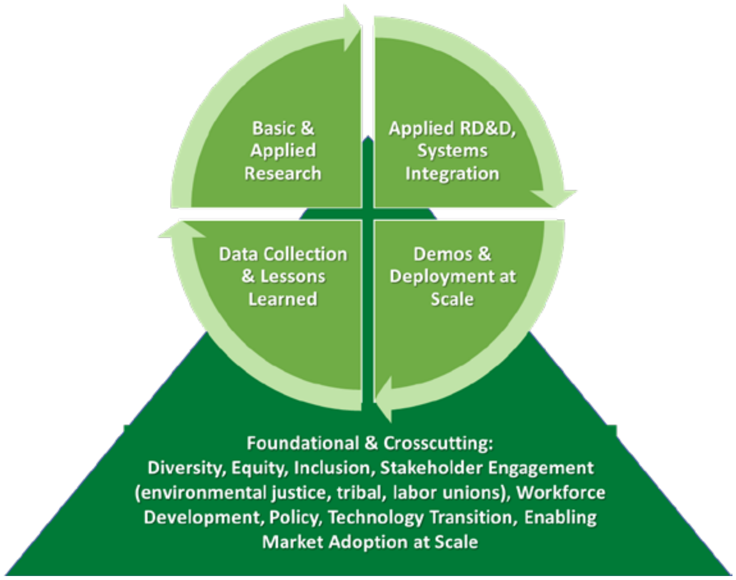

Figure 2.4. DOE's foundational and crosscutting efforts support the entire life cycle, from basic research through large-scale deployment.

DOE established the Hydrogen Joint Strategy Team (JST) with representatives from offices across the department to better coordinate the spectrum of RDD&D efforts in targeted focus areas of the *Hydrogen Program Plan*, as shown in Figure 2.5.

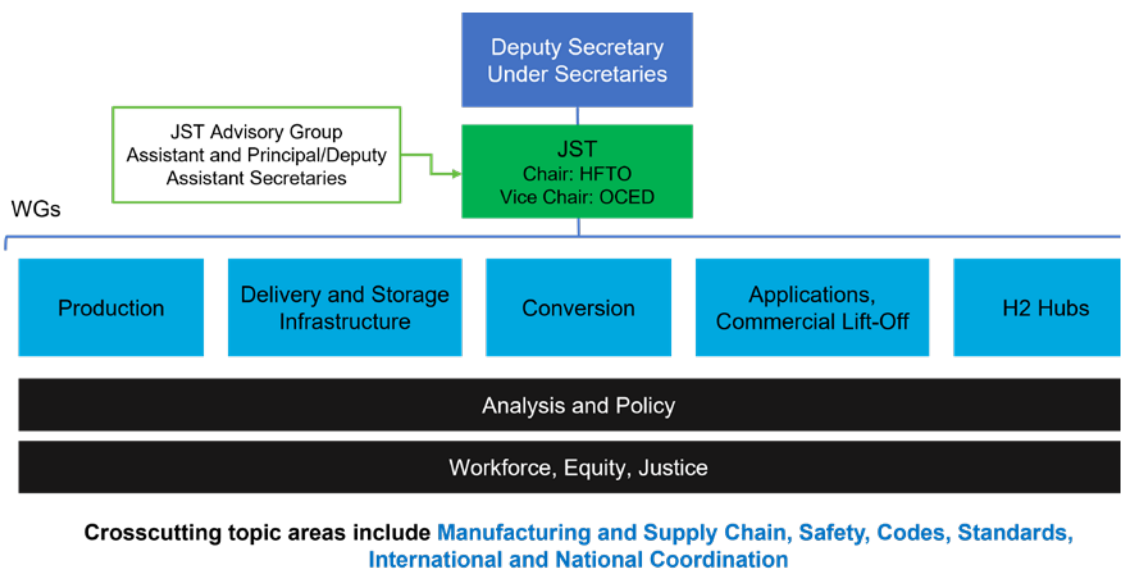

Figure 2.5. DOE Hydrogen Joint Strategy Team framework and focus areas

In addition to coordinating within DOE on the Hydrogen Program, HFTO partners with EERE offices to address decarbonization across many sectors. For example, HFTO collaborates with

EERE Sustainable Transportation pillar offices in several key areas including: sustainable aviation fuels and biobased hydrogen production with the Bioenergy Technologies Office, hydrogen internal combustion engines and the SuperTruck program with the Vehicle Technologies Office, and infrastructure and fueling corridors with the Joint Office of Energy and Transportation. In addition, modal leads across the offices coordinate on technologies for both road and offroad vehicles, rail, marine, and aviation sectors. Within the renewable energy pillar of EERE, HFTO collaborates on relevant topics such as solar thermochemical (STCH) hydrogen production and electrolysis via both onshore and offshore wind. And within EERE's buildings and industry pillar, HFTO collaborates on multiple topics including hydrogen for steel manufacturing, advanced manufacturing technologies such as carbon fiber and roll-to-roll processes, and fuel cells for buildings.

Domestic Coordination

In addition to coordinating hydrogen and fuel cells RD&D within DOE as described in the *DOE Hydrogen Program Plan*, HFTO has been leading the Hydrogen and Fuel Cell Interagency Working Group since 2005, which has provided a forum for sharing research results, technical expertise, and lessons learned about hydrogen program implementation and technology deployment, as well as coordinating related projects across federal agencies. Recently, partner agencies have elevated the Interagency Working Group to the deputy secretary level across over 10 agencies to collaborate through the HIT to accelerate progress in hydrogen technologies. The HIT builds upon the Interagency Working Group, which DOE established in response to the Energy Policy Act of 2005, which required the Secretary of Energy to coordinate across agencies on hydrogen.[34] To facilitate coordination, the HIT is structured into working groups and crosscutting teams focused on addressing a portfolio of key clean hydrogen and fuel cell priorities, as illustrated in Figure 2.6. This structure is complementary to the DOE Hydrogen Joint Strategy Team framework shown in Figure 2.5.

[34] Energy Policy Act. 42 USC 16155 (Pub. L. 109–58, title VIII, §806, Aug. 8, 2005, 119 Stat. 848).

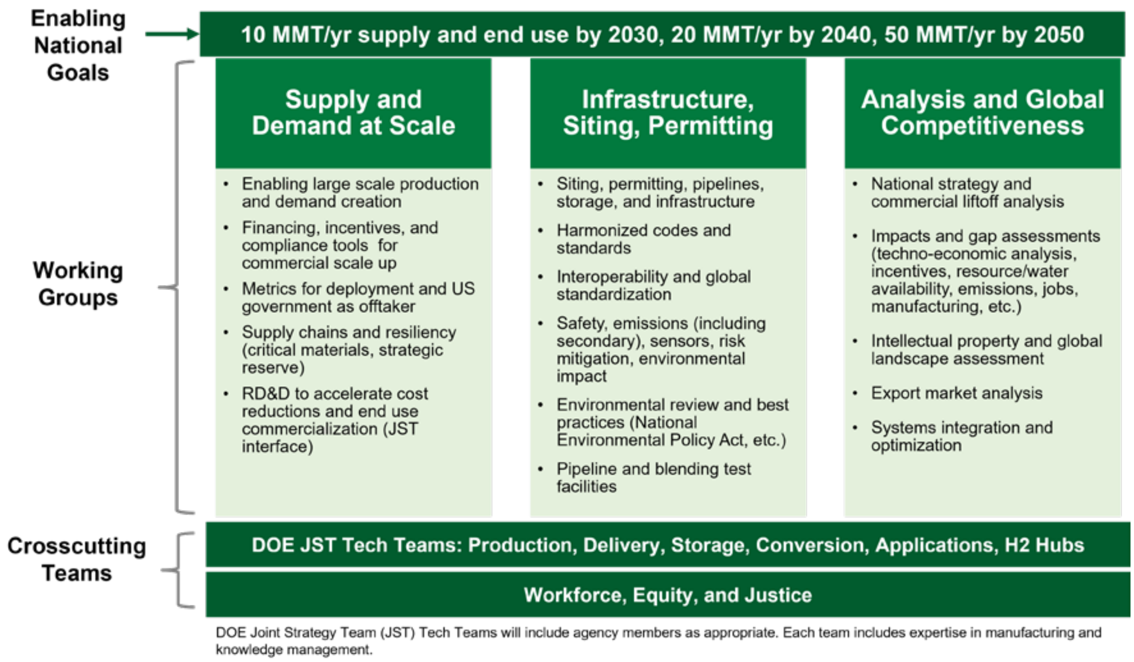

Figure 2.6. HIT working group structure and focus areas

In addition to this federal coordination, HFTO engages with several state governments and with private-sector and nonprofit stakeholders through partnerships to ensure that the RD&D efforts of government, academia, and industry are well coordinated, their diverse capabilities are well integrated, and their resources are effectively utilized. Examples of successful partnerships have included U.S. DRIVE,[35] the 21st Century Truck Partnership,[36] and the H2@Scale project consortium.[37]

International Coordination

HFTO engages in multiple international activities and partnerships to share technology lessons learned, foster collaboration, and advance mutual RD&D areas of interest at a global scale. Key examples include the Clean Energy and Hydrogen Energy Ministerials, the International Energy Agency, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Mission Innovation, and various bilateral and multilateral arrangements with countries involved in hydrogen and fuel cell activities. The Breakthrough Agenda[38] was established in 2021 at COP26 in Glasgow as a coordination framework to help unify various organizations and initiatives and avoid duplication, leverage resources, and accelerate the successful scale-up of clean hydrogen

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[35] Vehicle Technologies Office. "U.S. DRIVE." https://www.energy.gov/eere/vehicles/us-drive.
[36] Vehicle Technologies Office. "21st Century Truck Partnership." https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.
[37] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.
[38] "The Breakthrough Agenda." https://breakthroughagenda.org/.

technologies. HFTO serves as a colead, along with counterparts in the United Kingdom and India, to coordinate across international hydrogen initiatives through the Breakthrough Agenda.

2.6 Crosscutting Priorities

To achieve national clean energy goals through the advancement of clean hydrogen and fuel cell technologies, HFTO's RD&D portfolio and collaborative activities support important crosscutting priorities in diversity, equity, inclusion, and accessibility (DEIA); energy and environmental justice; workforce development; and innovations in manufacturing and supply chain development.

Diversity, Equity, Inclusion, and Accessibility and Justice40

Aligned with DOE priorities, HFTO promotes DEIA, including through stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds that are foundational to delivering on the goals in the *MYPP*. HFTO is also committed to ensuring that its technologies contribute substantively to the holistic approach of the DOE Hydrogen Program, which includes addressing energy and environmental justice and equity in support of national priorities in the Justice40 Initiative.[39]

HFTO takes several approaches to ensure DEIA and environmental justice principles are present in all aspects of program implementation, supported by modeling and analysis to understand and quantify environmental and economic effects of hydrogen and fuel cell technologies. Important activities include:

- **Community engagement*:*** HFTO demonstrates commitment to DEIA and environmental and energy justice through community engagement. Activities include listening to and increasing transparency with various impacted groups such as tribes and community members who live in disadvantaged communities.
- **Prioritizing safety and positive impacts of hydrogen technologies:** HFTO prioritizes safety and positive impacts of hydrogen technology for all. The crosscutting Safety Codes and Standards subprogram ensures that safety is paramount in all HFTO-funded activities.

Figure 2.7 illustrates the important intersection of DEIA and justice with community engagements and job creation, specifically highlighting HFTO's priorities in equity as well as energy and environmental justice.

[39] The White House. "Justice40: A Whole-of-Government Initiative." https://www.whitehouse.gov/environmentaljustice/justice40/.

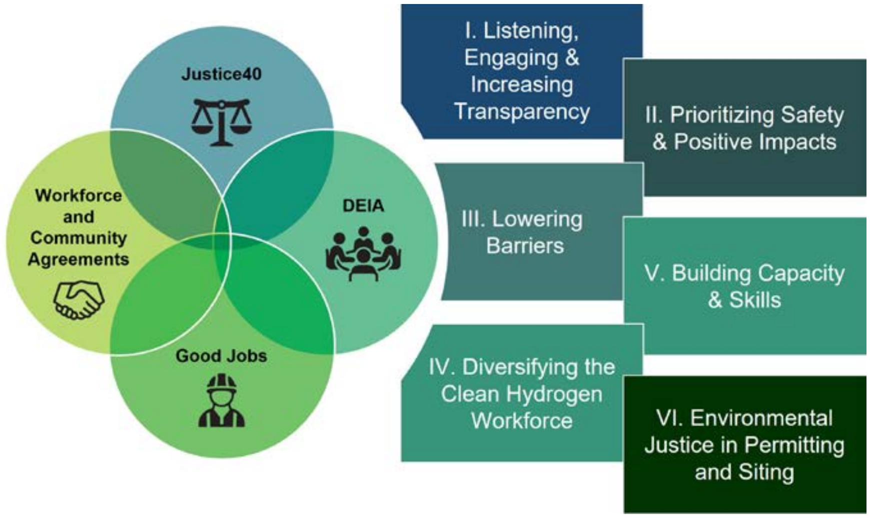


Figure 2.7. HFTO's holistic approach, prioritizing diversity, equity, environmental justice, and jobs creation, leveraging strong community engagement

HFTO continues to advance DEIA by lowering barriers to funding and designing new tools and opportunities to facilitate partnerships that will broaden access to DOE funding. Activities related to decreasing barriers include offering prizes that require less effort to apply and encourage more first-time applicants. Additionally, the office has designed and released funding opportunities specifically for minority-serving institutions and historically Black colleges and universities. HFTO continuously broadens its pool of participants by funding nontraditional, emerging, and historically underfunded investigators through such programs as the Minority Educational Institution Student Partnership Program. In addition to domestic efforts, HFTO spearheaded the launch of H2–DEIA[40] as a global platform to advance DEIA and share best practices, through IPHE and with the Hydrogen Council, a global industry partnership.

Workforce Development

A knowledgeable and well-trained workforce is essential for meeting future energy demands, and a growing hydrogen and fuel cells industry has the potential to create opportunities for individuals with a wide range of skills and training. DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* report[41] estimated that approximately 100,000 new direct and indirect jobs could be created related to the build-out of new projects and clean hydrogen infrastructure. Direct jobs relate to roles such as engineering and construction, and indirect jobs relate to manufacturing and the raw material supply chain. HFTO is advancing American energy security and economic development

[40] H2–DEIA. https://h2-deia.org/.
[41] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/clean-hydrogen/.

through the development of tools and information on the careers, education, and training opportunities available to meet the needs of a growing hydrogen and fuel cells workforce.

In support of both DEIA and workforce development priorities, HFTO is also committed to diversifying the hydrogen workforce both within the office and externally. Workforce DEIA activities include engaging with diverse audiences through STEM initiatives, prioritizing outreach efforts to reach nontraditional audiences, and providing support for faculty and students at minority-serving institutions to expand their research capacities in clean hydrogen. An example is the expansion of the H_2EDGE initiative,[42] Figure 2.8, which was designed to engage historically Black colleges and universities. With DOE support, EPRI, GTI Energy, and partner universities have created the H_2EDGE initiative (Hydrogen Education for a Decarbonized Global Economy) to develop and train a workforce for the emerging hydrogen technology industry and its end-use applications.

Figure 2.8. The H_2EDGE initiative is advancing the emerging hydrogen workforce by developing newly trained personnel and enabling the existing workforce to migrate into the hydrogen field.

Manufacturing and Supply Chain Innovations

For hydrogen to transition from niche applications to mass markets, it will be essential to develop industrial-scale techniques, processes, and facilities for manufacturing hydrogen-related technology components and systems at large volumes. A robust domestic supply chain will be needed to ensure the United States stays at the forefront of this emerging global industry. While the bulk of the investment needed to build manufacturing capacity will fall to industry—as incentivized by growing market demands—RD&D efforts will be needed to overcome technical challenges and accelerate progress.

[42] Electric Power Research Institute. "H_2EDGE: Summary of the Project." https://grided.epri.com/H2EDGE.html.

By developing processes and technologies specifically tailored to high-volume manufacturing, RD&D efforts can help achieve economies of scale in manufacturing. These efforts can also lead to additional technology and systems-integration improvements, resulting in even greater cost reductions. Key opportunities for crosscutting advances include development of:

- High-speed manufacturing techniques for processes such as forming, stamping, molding, sealing, joining, coating, and roll-to-roll processing.
- Best practices for material and component handling.
- Additive and automated manufacturing/assembly processes.
- Technologies for in-line diagnostics and quality control/quality assurance.
- Sensors and other technologies to reduce manufacturing defects in high-throughput production.
- Manufacturing processes and technology designs that enable efficient recycling/upcycling, especially of critical materials.

Standardized designs for systems and components are also needed to unify specifications among system and component providers, which simplifies technology development, lowers supplier costs, and can lead to more robust supply chains. HFTO coordinates closely with DOE's Manufacturing and Energy Supply Chains office as well as the Office of Policy on tax credits and other initiatives to accelerate domestic manufacturing and global competitiveness.

2.7 Conclusion

Crosscutting activities within HFTO include RD&D aimed at addressing manufacturing and supply chain challenges as well as associated Justice40 and workforce development benefits. To achieve national clean energy goals through the advancement of clean hydrogen and fuel cell technologies, HFTO supports important crosscutting priorities in DEIA; energy and environmental justice; safety; workforce development; and innovations in manufacturing and supply chain development.

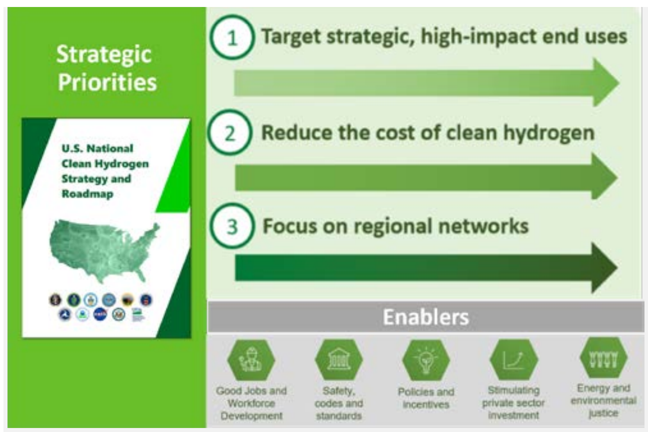
3 Hydrogen Production

3.1 Overview

Goals and Objectives

The goal of the **Hydrogen Production** subprogram is to accelerate innovation, commercialization, and large-scale adoption of efficient, low-cost, and durable clean hydrogen production technologies that are competitive with incumbent technologies and can be manufactured at scale to meet national targets. The subprogram pursues this goal by innovative RD&D to enable technology solutions for affordable clean, low-carbon intensity hydrogen production that leverage the nation's diverse clean energy resources.

The Hydrogen Production subprogram supports key strategic priorities identified by the **DOE Hydrogen Shot** and the ***U.S. National Clean Hydrogen Strategy and Roadmap***[43] to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit to the United States. The subprogram directly supports the strategic priority to reduce the cost of clean hydrogen, foundational to all the priorities; and it coordinates closely with the other HFTO subprograms to support priorities targeting strategic high-impact uses for clean hydrogen and focusing on regional networks.



Reducing the cost of clean hydrogen production is critical to achieving the full decarbonization potential of hydrogen and fuel cells.

The main objective is successful RD&D addressing key challenges to developing affordable clean hydrogen technologies that meet an interim cost target of ***$2/kg by 2026*** established by the Clean Hydrogen Electrolysis Program provisions (Energy Policy Act section 816), and the Hydrogen Shot target of ***$1/kg by 2031***.

As illustrated in Figure 3.1, the subprogram considers promising technology pathways for clean hydrogen production that leverage diverse domestic clean energy sources (such as wind, solar, hydropower, geothermal, or nuclear power) with natural resources (including water and organic material such as biomass or waste streams) as process feedstocks; the clean hydrogen, in turn, helps address national decarbonization goals across sectors, particularly in difficult-to

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[43] 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.

decarbonize end-uses in transportation, industrial, and chemical processes; and integrated systems including energy storage and power generation.

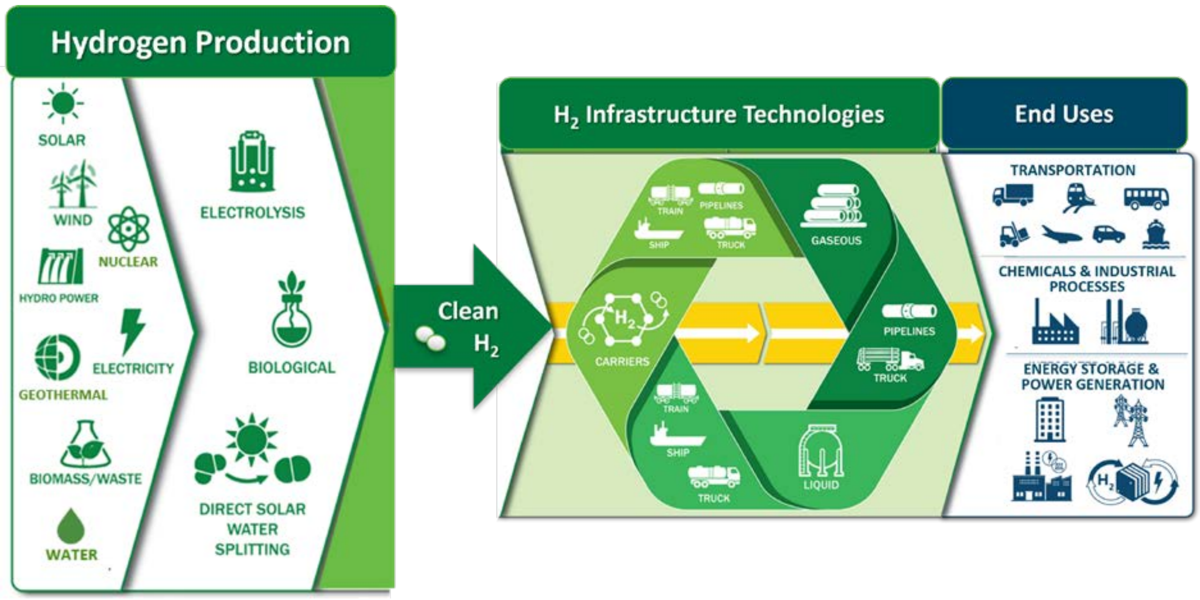


Figure 3.1. Clean hydrogen production leverages diverse clean energy options and abundant natural resources found across the United States for distribution to multiple end uses in support of national decarbonization goals.

Technology Pathways

The Hydrogen Production subprogram's RD&D efforts are focused on promising technology pathways that leverage natural clean energy resources to convert sustainable feedstocks into hydrogen with little-to-no CO_2 emissions. For reference, the vast majority of hydrogen for current markets is produced at less than $1.50/kg of hydrogen from steam methane reforming of natural gas (a process that emits about 10 tons of CO_2 for every ton of hydrogen produced). Alternative clean hydrogen production pathways will need to achieve cost parity with this incumbent approach to enable market adoption and commercial liftoff. This requires varying levels of continued technology development through RD&D across the different pathway options, as well as manufacturing innovations to enable cost savings expected with economies of scale.

The clean hydrogen production pathways addressed by the subprogram fall under the two major categories shown on the left in Figure 3.2. The ***electrolysis pathways*** are based on commercial and near-commercial technologies that split water into hydrogen and oxygen, which can be powered by low-carbon energy sources such as wind, solar, and nuclear to produce clean hydrogen in the near term, but at costs typically more than $5/kg-$H_2$ with current options.[44] The

[44] $5/kg is the baseline cost in 2020 for the launch of Hydrogen Shot in 2021. Hydrogen and Fuel Cell Technologies Office. Hydrogen Shot. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

advanced pathways go beyond electrolysis and have the potential to achieve more efficient utilization of diverse, domestic, renewable resources for affordable hydrogen production. These include photoelectrochemical (PEC) and thermochemical processes for direct solar water splitting that don't require electricity, and biological processes that can convert biomass or waste streams into hydrogen with value-add coproducts (such as purified water). The ***additional processes*** shown in the figure include conversion of natural gas into H_2 plus CO_2 (i.e., steam methane reforming processes) or solid carbon (i.e., methane pyrolysis processes); and cogasification of mixed feedstocks such as natural gas, biomass, and solid municipal wastes. For decarbonization, these processes can be coupled with carbon capture, utilization, and storage, offering in some cases the potential for net-negative CO_2 emissions (e.g., with biomass feedstocks). The hydrogen production subprogram works closely with colleagues in the DOE Office of Fossil Energy and Carbon Management to leverage lessons learned from their RD&D in these additional processes, and to explore advanced hybrid approaches combining electrochemical, thermochemical, pyrolytic, biological, and even PEC processes to optimize performance and further reduce costs in future clean hydrogen production scenarios.

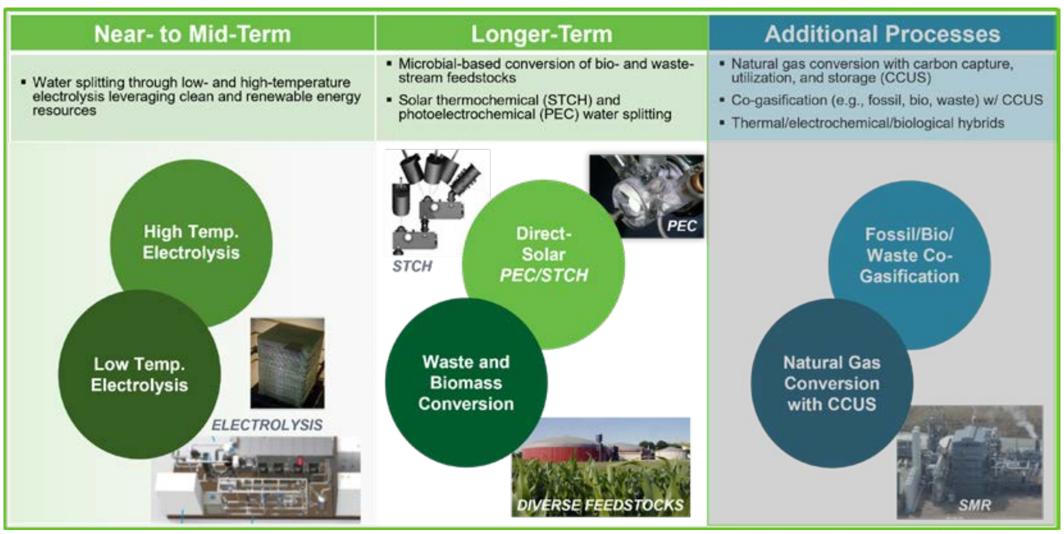


Figure 3.2. Clean hydrogen production pathways covered in the subprogram's RD&D portfolio

3.2 Strategic Priorities

The Hydrogen Production subprogram's overarching strategic framework addressing RD&D in the near-, mid-, and longer-term clean hydrogen pathways is depicted in Figure 3.3. The subprogram works in close coordination with the other HFTO subprograms in support of strategic priorities described in the Introduction.

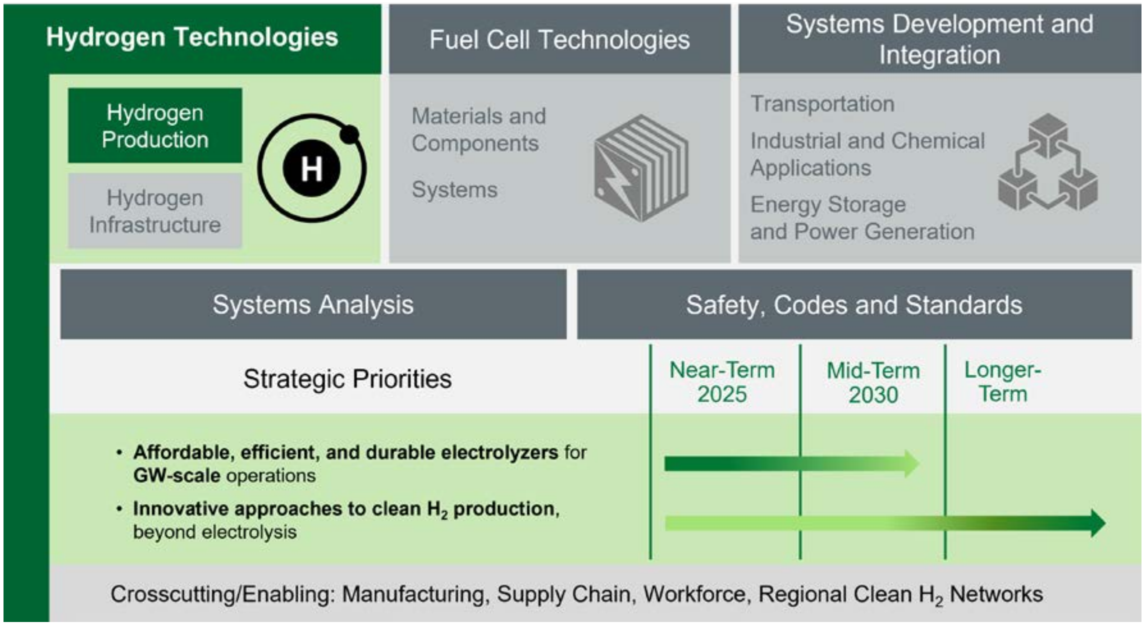


Figure 3.3. Strategic priorities guiding hydrogen production RD&D

Near-term priorities include RD&D that supports advancing the affordability, efficiency, and durability of electrolyzer technologies for deployment with renewable and/or nuclear electricity to provide low-cost, clean hydrogen for accelerated decarbonization across sectors. In addition, the subprogram will pursue innovative approaches beyond electrolysis, including those that are potentially higher risk but have high impact potential and do not rely directly on electricity. Examples include direct solar-water splitting through PEC or thermochemical processes, and microbially assisted hydrogen conversion of organic waste streams. The following sections provide additional details of the clean hydrogen production technologies being addressed by the subprogram's RD&D in support of the near- and longer-term subprogram priorities.

Near-Term: Electrolysis

Electrolyzers utilize the basic electrochemical process shown in Figure 3.4 to produce hydrogen from water using electricity. The electrically conducting cathode and anode are separated by an ion-conducting electrolyte; applied electricity drives catalytically assisted hydrogen- and oxygen-evolution half reactions at the cathode and anode, respectively, that are coupled by ion transport through the electrolyte. The net result is the splitting of water molecules fed into the system into hydrogen and oxygen gas.

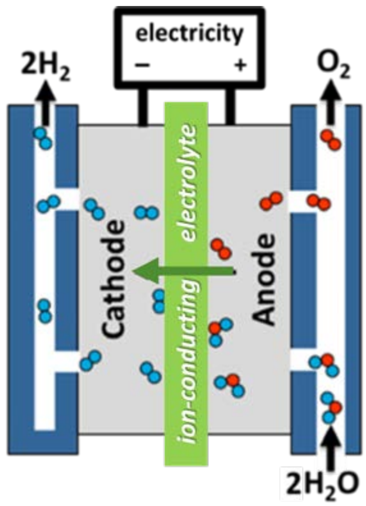


Figure 3.4. Electrolyzer cell: water and electricity in; H_2 and O_2 gases out

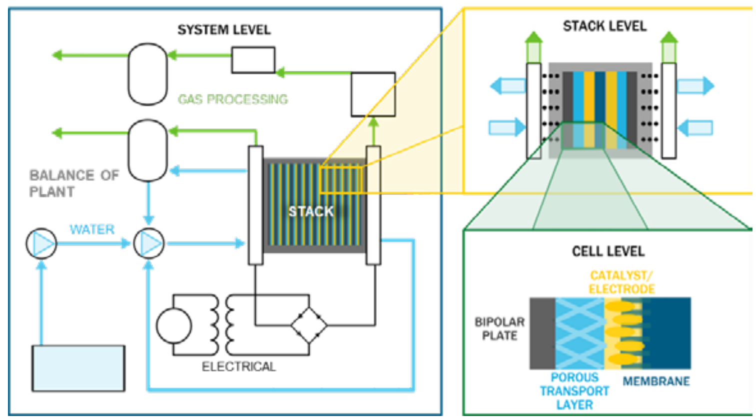


Figure 3.5. Electrolyzer systems are composed of stacks comprising multiple individual cells and balance-of-plant components

As illustrated in Figure 3.5, electrolyzer systems consist of *stacks (*groups of individual *cells)* and *BOP* equipment that manage the inputs (electricity and water) and outputs (hydrogen and oxygen) from the stack.

There are a number of electrolyzer technologies currently under development that use different ion-conducting electrolyte materials, such as liquids, solid polymer membranes, or solid ceramics. Different electrolyzer types operate over different temperature ranges and require different catalysts to promote the anode and cathode reactions; the electrode configuration is typically determined by limits and characteristics of the electrolyte material. These technologies are commonly grouped into two categories based on operating temperature:

- **Low-temperature electrolysis technologies**, which include:
  - Proton exchange membrane (PEM) electrolyzers.
  - Liquid alkaline electrolyzers.
  - Alkaline exchange membrane (AEM) electrolyzers.
- **High-temperature electrolysis technologies,** which include:
  - Oxide-ion-conducting solid oxide electrolysis cell (O-SOEC) electrolyzers.
  - Proton-conducting solid oxide electrolysis cell (P-SOEC) electrolyzers.

Each of these electrolyzer technologies presents unique advantages and challenges in terms of performance, durability, and cost when integrated with clean electricity sources, but some are at earlier stages of development, as summarized in Table 3.1. For all electrolyzer types, continued improvements in performance, lifetime, cost, and scale-up are being made through RD&D at the material, component, stack, and system levels.

Table 3.1. Summary of Electrolyzer Technologies, with Advantages and Development Status

Technology	Temp. Range	Electrolyte	Catalysts	Advantages	Challenges
Proton Exchange Membrane	~50°–80°C	polymer membrane- H^+-conducting	PGM-based (e.g., Pt, Ir)	• Commercial technology • High current density at high efficiency • Differential pressure operation • Dynamic operation capability	• Use of critical materials (e.g., Ti, Ir, Pt, PFAS) • Temperature-limited efficiency
Liquid Alkaline	~70°–90°C	aqueous solution - OH^--conducting	PGM-free (e.g., Ni based)	• Commercial technology • Low-cost materials • Proven long lifetime • Established supply chain and manufacturing processes	• Corrosive electrolyte • Dynamic operation limitations • Low performance • Differential pressure operations difficult • Temperature-limited efficiency
Oxide-Ion-Conducting Solid Oxide	~700°–850°C	ceramic membrane- O^{2-}-conducting	PGM-free	• Early-commercial technology • High electrical efficiency • Thermal energy integration, e.g., with nuclear or solar	• Need for high-temperature materials • Effective thermal integration • Cold-start and intermittent operations • Lifetime
Alkaline Exchange Membrane	~60°–80°C	polymer membrane- OH^- -conducting	PGM-free (e.g., Ni-based)	• Pilot demonstrations • Low-cost materials • Dynamic operation capability • Differential pressure operation	• Durability and performance of current membranes • Trace PGM catalysts still needed • Efficiency losses using pure water feed
Proton-Conducting Solid Oxide	~450°–600°C	ceramic membrane – H^+-conducting	PGM-free	• High electrical efficiency potential • Thermal energy integration, e.g., with nuclear or solar • Lower cost materials and operating temperature than O-SOEC	• Only demonstrated at the laboratory scale • Lifetime • Faradaic efficiency limitations • Manufacturability/scale-up

Longer-Term: Advanced Pathways

Electrolysis powered by clean electricity will be important in the near- and longer terms; however, the GW-scale electrolyzer facilities needed to meet projected clean hydrogen demands will require a significant expansion of clean electricity generation and transmission infrastructure. As part of the longer-term vision, clean hydrogen can also be produced through a variety of new and advanced pathways that require little or no electricity input and also leverage the nation's diverse renewable resources and feedstocks.

Foundational Science for Carbon-Neutral Hydrogen Technologies:
Priority Research Opportunities

- Discover and control materials and chemical processes to revolutionize electrolysis.
- Manipulate H_2 interactions to harness the full potential of hydrogen as an energy carrier.
- Elucidate the structure, evolution, and chemistry of complex interfaces for energy and atom efficiency.
- Understand and limit degradation processes to enhance the durability of hydrogen systems.

The three categories of advanced pathways under development by the Hydrogen Production subprogram include solar PEC and STCH water-splitting, and biological conversion of biomass and waste streams, as illustrated in Figure 3.6. These pathways, detailed in the figure, represent emerging longer-term options for clean hydrogen production at relatively early stages of development that are expected to have regional impacts on decarbonization as they mature.

The fundamental scientific research relevant to the advanced pathways in areas such as energy transfer, catalysis, separations, and degradation mechanisms specifically address Priority Research Opportunities identified by the DOE Office of Basic Energy Science's report on *Foundational Science for Carbon-Neutral Hydrogen Technologies.*[45] Importantly, the foundational understanding and lessons learned from such research is also transferable to the advancement of other hydrogen production, storage, and delivery technologies (including electrolyzers), as well as other clean energy technologies such as clean synthetic fuels and products.

[45] U.S. Department of Energy. *Foundational Science for Carbon Neutral Hydrogen Technologies*. October 2021. https://www.energy.gov/policy/articles/foundational-science-carbon-neutral-hydrogen-technologies.

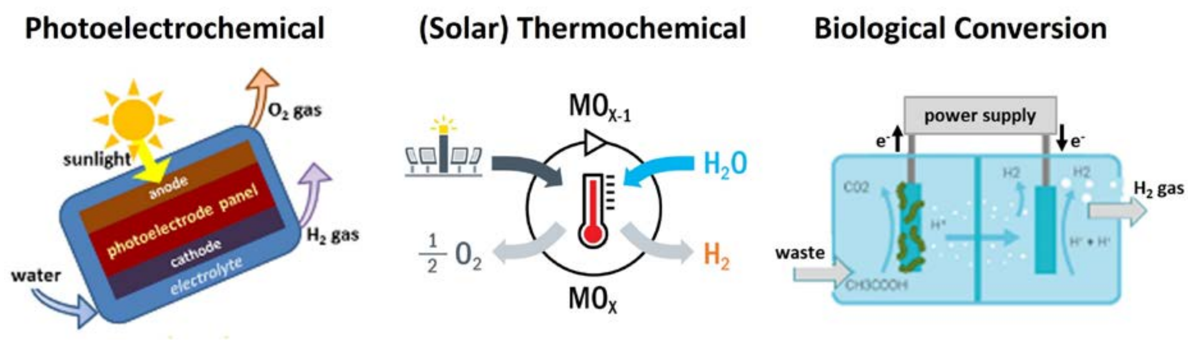


Figure 3.6. Categories of advanced pathways for clean hydrogen production

The three main categories of advanced pathways for clean hydrogen production under development by the Hydrogen Production subprogram and illustrated in Figure 3.6 include:

- **PEC:** Solar PEC hydrogen production is a low-temperature process that bypasses the need for electricity and instead directly uses sunlight to split water into hydrogen and oxygen. It is based on semiconductor photoelectrodes and/or photocatalysts that offer theoretical potentials for solar-to-hydrogen efficiency as high as 30% under optimized circumstances. PEC hydrogen production has been demonstrated extensively at the laboratory scale, leveraging diverse semiconductor materials systems and catalysts, with early scale-up efforts underway.
- **STCH:** Direct STCH hydrogen production is another promising technology with the potential to achieve high theoretical solar-to-hydrogen conversion efficiencies. STCH processes can be divided into two broad categories: (1) *direct cycles*, which use concentrated solar thermal energy (at temperatures typically >1000ºC) to drive a two-step metal oxide reduction/oxidation reaction to split water; and (2) *hybrid cycles*, which use lower-temperature thermochemical reduction (<800ºC, more compatible with inputs from concentrated solar or nuclear power) coupled with a secondary electrochemical step. All cycles represent a closed loop that consumes only water and produces hydrogen and oxygen. Various STCH cycles have been demonstrated at the laboratory scale, with limited small-scale reactor demonstrations.
- **Biological Conversion:** Biological conversion processes take advantage of the ability of microorganisms to consume and digest biomass and waste streams while releasing hydrogen. In direct hydrogen fermentation, the microbes produce the hydrogen themselves. Microbial electrolysis cells are devices that harness the energy and protons produced by microbes breaking down organic matter combined with an additional small electric current to produce hydrogen. Both fermentation and microbial electrolysis systems have the potential to produce clean hydrogen from biomass or waste streams; however, integrated hybrid systems integrating both processes could be more promising

by producing a higher mass yield of hydrogen per unit of feedstock. Both fermentation and microbial electrolysis cells as well as hybrid systems have been demonstrated at the laboratory scale, with scale-up efforts underway.

In addition to the advanced pathway technologies covered in these categories, there are unique opportunities to explore ***hybrid approaches*** that couple electrochemical, photochemical, thermochemical, and/or biological processes to enhance the efficiency and durability of affordable clean hydrogen production from diverse domestic resources. Examples include the cogasification with CCUS of biomass with waste streams and/or natural gas; and the thermal and electrochemical polygeneration of hydrogen, heat, electricity and/or concentrated CO_2 using diverse fuels such as natural gas or biogas. The Hydrogen Production subprogram works closely with other DOE offices (including Fossil Energy and Carbon Management and Basic Energy Sciences, as well as the Solar Energy Technologies and Bioenergy Technologies Offices in EERE) in exploration of advanced clean hydrogen production pathways leveraging such hybrid approaches, some of which have the potential to produce carbon negative hydrogen.

3.3 RD&D Targets

Setting Targets

The Hydrogen Production subprogram's holistic approach to RD&D includes the development of techno-economic targets for clean hydrogen production addressing costs, conversion efficiency, performance, durability, and scale. Targets for the diverse production pathways are informed by comprehensive modeling and analysis by respective experts in their fields and are vetted by stakeholder engagement with industry and the national labs. Rigorous target-setting is a critical part of the subprogram's objective to identify and pursue pathways to affordable clean hydrogen that address the *U.S. National Clean Hydrogen Strategy and Roadmap* strategic priorities and meet the aggressive but achievable Hydrogen Shot cost goal. For each of the production pathways, sets of targets developed by the subprogram provide an invaluable tool for quantifying the most critical RD&D challenges and needs at the materials, components, device, and system levels. The targets take into account capital costs associated with materials and supply chains, feedstock costs tied to hydrogen conversion efficiencies, operations and maintenance costs related to durability, and costs related to manufacturing economies of scale.

In the target-setting process, key cost drivers are identified for each clean hydrogen production pathway; some are specifically tied to technology development needs in performance and durability, and others are tied to innovations addressing manufacturing and scale-up. The subprogram's RD&D, guided by targets, is focused on the key cost drivers that can enable meeting the overarching cost goal. An example of the importance of this target-based approach is illustrated in Figure 3.7 for PEM electrolysis, where the baseline installed system capital cost is consistent with recent status. For example, real-world data from DOE's Regional Clean Hydrogen Hub applications reported by applicants reveal an average estimated total installed electrolyzer cost of ~$1,900/kW for projects that currently plan to use PEM electrolyzers. The weighted average estimated cost was ~$2,100/kW across applicant projects (average size of 350 MW).[46]

Rigorous analysis has shown how the capital costs associated with the electrolyzer stack and with BOP components significantly contribute to the levelized cost of clean hydrogen. The analysis also developed detailed cost breakdowns of specific stack and BOP components, identifying key cost drivers such as the catalysts in the stack and power supplies in the components that will need to be addressed both through manufacturing innovations and technology improvements. The process allows for quantitative assessments of cost-reduction scenarios capable of meeting the overarching clean hydrogen production cost targets.

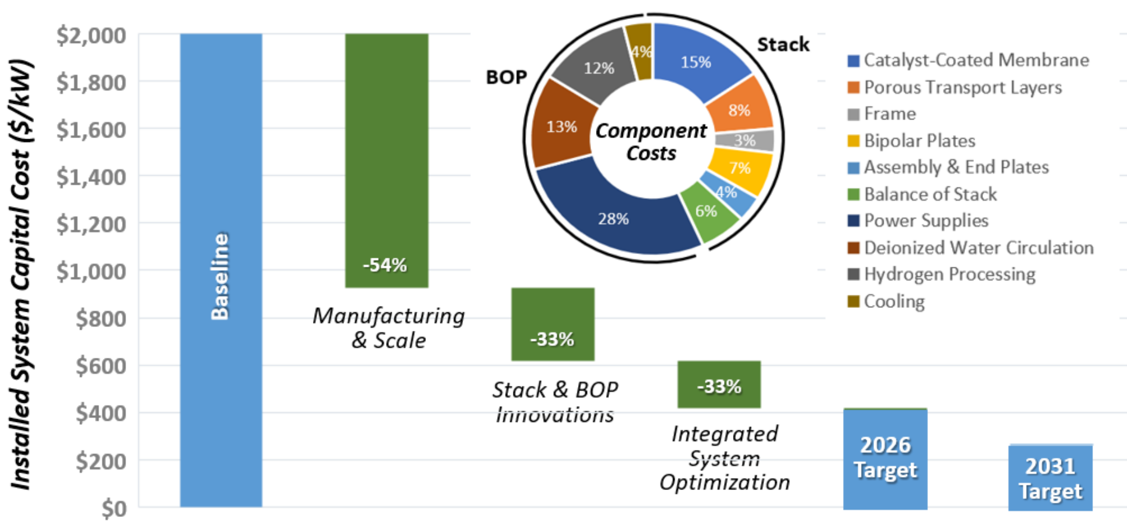


Figure 3.7. Reducing electrolyzer capital costs will require innovating the electrolyzer stack and BOP components and also reaching economies of scale.

For the advanced pathways, the target-setting process relies on the development of conceptual models of large-scale deployment facilities in conjunction with boundary-level techno-economic analysis identifying key cost drivers. Figure 3.8 shows an example for PEC hydrogen production based on the conceptual design for a Type-4 system. The system consists of a multijunction semiconductor photoelectrode, similar to a solar cell, incorporated into a water-splitting reactor that is integrated into a solar trough device to concentrate sunlight. The projected baseline for the estimated levelized cost of hydrogen production uses assumptions for system conversion efficiency, durability, and component-level costs based on laboratory-scale demonstrations of a Type-4 system. Boundary-level analysis has developed scenarios for meeting the Hydrogen

[46] Gilbert, Andrew, Michael Penev, Katelyn O'Dell, Campbell Howe, and Chris Wu. February 22, 2024. "Summary of Electrolyzer Cost Data Synthesized from Applications to the DOE Clean Hydrogen Hubs Program." DOE Hydrogen Program Record # 24002. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24002-summary-electrolyzer-cost-data.pdf.

Shot's $1/kg-$H_2$ cost goal based on targeted improvements over the projected baseline in conversion efficiency, durability, component cost, and system optimization, as illustrated in the figure. Such targets take into account the physics-based potential and limits of the PEC process as well as engineering-based system design and optimization conventions.

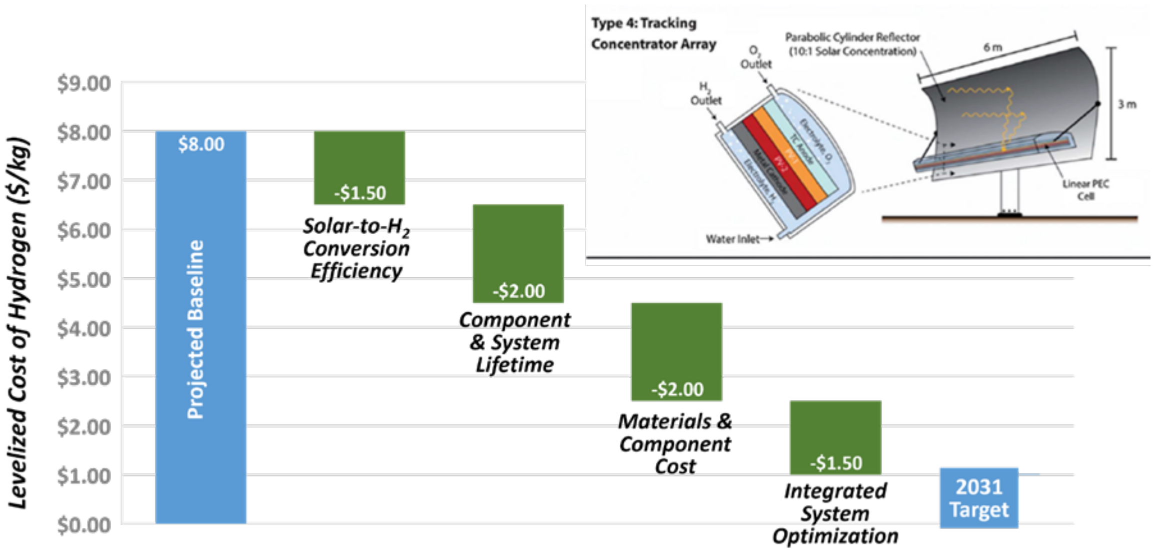


Figure 3.8. Boundary-level analysis of a conceptual Type-4 PEC system (i.e., photoelectrode-based with nominal solar concentration and tracking), illustrating a cost-reduction pathway to meeting the Hydrogen Shot goal

Interim and Ultimate Targets

The Hydrogen Production subprogram prioritizes RD&D that addresses key technology-specific cost drivers for each of the clean hydrogen production pathways, identified through analysis and stakeholder engagement; and progress is regularly assessed with respect to interim and ultimate targets established by the subprogram. RD&D priorities are adjusted to address important gaps identified through this assessment. For the electrolysis pathways, the interim targets for clean hydrogen production specifically address scenarios for meeting the 2026 cost goal of $2/kg-$H_2$; while ultimate targets address meeting the Hydrogen Shot goal of $1/kg by 2031.

Hydrogen Production Interim Target Examples

- **Clean H_2 production by 2026:** $2/kg
- **Electrolyzer systems (low-temperature) by 2026:** $250/kW, 65% efficiency, 80,000-hour durability
- **Electrolyzer systems (high-temperature) by 2026:** $500/kW, 76% efficiency, 40,000-hour durability
- **Direct solar-to-hydrogen conversion by 2025:** >10% conversion efficiency for >500 hours
- **Integrated fermentation-MEC reactor by 2025:** 35 L H_2/L/day continuous production with wastes

Table 3.2 illustrates an example of targets developed specifically for low-temperature PEM electrolyzers and high-temperature oxide ion-conducting solid oxide electrolyzers, including both interim targets for meeting the 2026 cost goal and ultimate targets meeting the Hydrogen Shot goal. Note that although the targets provide important quantitative guidelines for RD&D, there could be multiple scenarios for meeting cost goals through tradeoffs among the parameters. As one important example, reducing PGM catalyst content in PEM electrolyzers can address cost and supply chain issues associated with these materials; but performance and durability targets still need to be met with the reduced PGM loading, posing an important RD&D challenge.

The performance targets, such as electrical conversion efficiency, are particularly important given the impact of electricity costs on the levelized cost of clean hydrogen production. Maintaining high conversion efficiency is a critical consideration in minimizing electricity usage. In addition to the technical parameters in Table 3.2, additional parameters related to the coupling of electrolyzers with clean energy become critical, including the electricity costs as well as capacity factors and dynamic responses relative to intermittent renewable power generation. The interim and ultimate targets in the table were established based on availability of clean electricity at \$0.03/kWh and \$0.02/kWh, respectively, and rely on expected progress in technologies such as wind, solar, and nuclear power generation.

Table 3.2. Examples Showing Pathways from Baseline Technology Parameters toward Ultimate Targets in Low- and High-Temperature Electrolyzer Technologies

	Parameter	Units	Low-Temperature PEM			High-Temperature O-SOEC		
			Baseline	2026 Targets	Ultimate Targets	Baseline	2026 Targets	Ultimate Targets
Stack	Total PGM Content	mg/cm^2	3.0	0.5	0.125	-	-	-
		g/kW	0.8	0.1	0.03	-	-	-
	Performance	A/cm^2 @V/cell	2.0 A/cm^2 @1.9 V	3.0 A/cm^2 @ 1.8 V	3.0 A/cm^2 @ 1.6 V	0.6 A/cm^2 @ 1.28 V	1.2 A/cm^2 @ 1.28 V	2.0 A/cm^2 @ 1.28 V
	Electrical Efficiency	kWh/kg-H_2	51	48	43	34	34	34
	Lifetime	Operation hr	40,000	80,000	80,000	20,000	40,000	80,000
	Degradation Rate	mV/khr	4.8	2.3	2.0	6.4	3.2	1.6
	Capital Cost	\$/kW	450	100	50	300	125	50

System	Energy Efficiency	kWh/kg-H_2	55	51	46	47	44	42
	Uninstalled Capital Cost	$/kW	1,000	250	150	2,500	500	200

For all the clean hydrogen production pathways, the subprogram has developed ultimate targets for different technology-specific parameters that reflect improvements needed in the current baseline values for achieving cost-competitiveness and commercial liftoff. The baseline 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

3.4 Addressing Challenges

The subprogram's comprehensive RD&D portfolio addresses key challenges identified for all the clean hydrogen production pathways, including the different low- and high-temperature electrolyzer technologies as well as the advanced pathways. All the pathways, to varying degrees, face materials-, component-, device-, and system-level challenges that fall in broad categories of *capital, installation, and operating costs; durability and reliability; efficiency and performance; life cycle sustainability; manufacturing and scale-up;* and *safety.* Under these broad categories, there are unique sets of challenges at the materials, components, device, and systems level specific to each of the electrolysis and advanced pathway technologies.

Electrolysis Pathways

The overarching challenge in the electrolysis pathways is achieving GW-scales of deployments and operations in electrolyzer systems that meet performance, durability, and cost requirements when coupled with clean energy generation sources. Some technology-specific challenges include:

- **PEM Electrolysis:** Stack challenges need to be addressed related to materials and components that are costly and/or supply-chain sensitive, as well as manufacturing and scale-up; system challenges include optimization of BOP integration, decreasing installation, and other soft costs, and continued improvement of dynamic response and intermittent operations. Specific examples include:
  - *Optimized Membrane Systems,* comprising multiple elements such as membrane polymers, reinforcements, radical scavengers, and gas recombination catalysts, that

are amenable to high-volume manufacturing processes such as roll-to-roll fabrication.

- *Improved Electrodes* maintaining performance and durability with reduced PGM catalyst loading, fabricated with high-throughput processes; with particular focus on anodes with reduced iridium loading.
- *Improved Porous Transport Layers* fabricated with scalable, high-volume compatible, precision manufacturing techniques; optimized for electrical conductivity, heat management, mechanical support, and management of water and evolved hydrogen and oxygen gases including at interfaces.
- *Advanced Catalysts, Ionomers, and Membranes* for next generation electrolyzers, with particular focus in areas of high-performance oxygen evolution reaction catalysts with minimal or no PGM content, and non-perfluorosulfonic acid membranes and ionomers.

- **Liquid Alkaline Electrolysis:** Stack challenges need to be addressed related to safe operations at increased current density and under pressurized conditions; system challenges include improving performance and durability under dynamic and intermittent operations through stack and BOP innovations. Specific examples include:
  - *Advanced Cells* compatible with scalable manufacturing processes, including electrodes and support structures with high surface areas, high catalytic activity, and high conductivity to improve performance; optimized for reverse-current tolerance and intermittent operations.
  - *Improved Interfaces* (e.g., catalyst/substrate, catalyst/electrolyte, and separator/electrolyte) through material development and interface engineering, mitigating degradation and minimizing voltage losses, including during intermittent operations.
  - *Improved Separators*, including tailored structures (e.g., porosity, thickness) and composite membranes optimized for chemical, mechanical, and thermal properties.
- **O-SOEC Electrolysis:** Stack challenges include improving the durability of materials and interfaces under high temperatures with thermal cycling, and scalability of cell architectures; system challenges relate to overall thermal management and improved performance and durability under dynamic and intermittent operations through stack and BOP innovations. Specific examples include:
  - *Advanced Engineered Materials and Interfaces* compatible with scalable synthesis and manufacturing processes, addressing degradation mechanisms such as thermal stresses under temperature cycling, Ni coarsening and Cr poisoning.
  - *Improved Thermal Processing* of cells and stacks to lower manufacturing costs, including decreasing the number of high-temperature firing steps, decreasing the

required heat treatment temperatures and firing times, and using novel, quicker sintering approaches.

  - *Improved Interconnects* including affordable interconnect materials fabricated using high-throughput, low-cost manufacturing techniques.

- **AEM Electrolysis:** Challenges relate to the need for stable alkaline membranes, ionomers, catalysts, and electrodes providing long life, including under dynamic operations; efficient operations with pure water feed without a supporting electrolyte; and water management. Specific examples include:
  - *Advanced AEM Membranes* that enable high electrolyzer efficiency with enhanced durability at expected stack operating temperatures above 60°C, including improved mechanical stability addressing degradation due to swelling from water uptake and edge failures.
  - *PGM-Free Catalysts* that replace the trace-PGM catalysts in current AEM electrolyzers while maintaining efficiency and durability, including a focus on integration into electrodes.
- **P-SOEC Electrolysis:** Challenges relate to the need for proton-conducting solid oxide materials and components with increased faradaic efficiencies and durability at operating conditions below 600°C with improved mechanical properties; and low-cost scalable synthesis and manufacturing processes. Specific examples include:
  - *Improved Cell Component Materials,* including the proton-conducting electrolyte, with improved mechanical properties, and with a necessary combination of performance, efficiency, and durability over a targeted range of electrolyzer operating temperatures and steam concentration.

There are also system level challenges that are common across all the electrolysis technologies. One example is the need for low-cost power electronics that are designed and optimized specifically for electrolyzer operating requirements. Also, installation and other soft costs, such as site preparation, construction, permitting, engineering, and design costs, can be a large fraction of the overall installed system costs today. Some of these costs are anticipated to decrease as experience with large-scale electrolyzer installations (>50 MW) is gained, but other aspects will require additional work to streamline the installation process and to facilitate achieving the hydrogen production cost targets.

Advanced Pathways

The advanced pathways are at a lower technology readiness level (TRL), with fundamental challenges related to materials, interfaces, and components, which need to be addressed with affordable synthesis, manufacturing, and system-level scale in mind. Pathway-specific challenges include:

- **PEC:** Materials and component challenges need to be addressed in the development of sophisticated multicomponent devices, leveraging enhancements of existing materials (e.g., semiconductors, catalysts, coatings, etc.), and/or discovery and development of new ones that are low cost and simultaneously achieve high solar-to-hydrogen conversion efficiencies, and long lifetimes. This includes the need for an effective combination of functionalized interfaces specifically optimized for light-absorption, charge transport, interfacial catalysis, and surface protection; system challenges need to be addressed in the demonstration and scale-up of promising electrode-based or particle-based PEC reactor systems, maintaining efficiency, durability, cost, and safety requirements.
- **STCH:** Materials challenges need to be addressed in the development of RedOx-based systems (i.e., reversibly reduced and oxidized) through the enhancement of existing materials and/or discovery and development of new ones. These materials need to be low cost, and have high oxygen storage capacity at appropriate reduction temperatures, optimized thermodynamics and kinetics for hydrogen evolution in steam, efficient heat-transfer properties, and resistance to extreme thermal and chemical stresses induced by cycling; system challenges relate to the integration and scale-up of promising RedOx materials in efficient reactor solar-collector and reactor designs operating at high temperatures, with potential to meet cost and safety as well as cycle efficiency and durability requirements.

- **Biological Conversion:** Challenges need to be addressed in the development of microbial-based processes (including fermentation, microbial electrolysis, and hybrid combinations) that can sustainably produce hydrogen at high rates and with high molar yield, including through bioengineering of new or optimized microorganisms adaptable to useable organic feedstocks; system challenges need to be addressed in the demonstration and scale-up of affordable reactor designs tailored to promising microbial cultures and processes, including optimization of thermal management, culture maintenance, and hydrogen collection, while maintaining safety requirements.

Advanced hybrid approaches combining electrochemical, thermochemical, pyrolytic, biological, and/or PEC processes offer the potential to optimize performance, further reduce costs, and, in some cases, lead to the production of carbon-negative hydrogen; however additional challenges related to materials compatibility, component integration, and added systems complexity would need to be addressed.

Comprehensive Approach

The Hydrogen Production subprogram takes a comprehensive approach to address materials-, component-, device-, and system-level RD&D needs for each technology pathway in the portfolio. This approach spans a range of TRLs, starting with new material development and optimization, for the advanced pathways as well as next-generation electrolyzers, and continuing through manufacturing, system integration, and recycling, particularly relevant to the later-TRL electrolyzer technologies. This is illustrated in Figure 3.9.

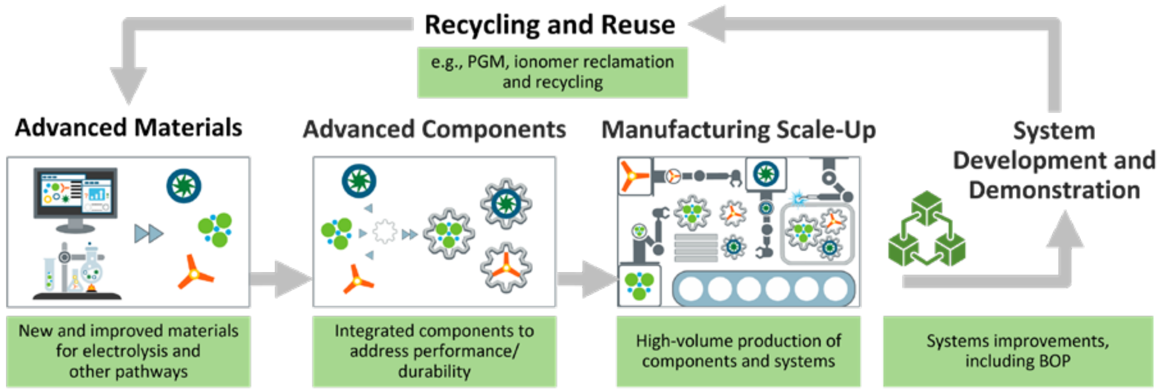


Figure 3.9. Comprehensive materials-, component-, and system-level RD&D across the near- and longer-term clean hydrogen production pathways takes into account requirements for manufacturing and scale-up as well as the systems integration and end-of-life recycling and reuse.

Implementing this approach, the Hydrogen Production subprogram supports a portfolio of RD&D projects implemented through funding mechanisms described in the Program Implementation chapter. 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 four consortia specifically relevant to electrolyzer technologies and the advanced pathways.[47]

The H2NEW consortium on electrolyzer technologies is bringing together national labs, industry, and academia to accelerate progress in multiple electrolyzer technologies by integrating advanced materials and interfaces together to create optimized, high-performing, low-cost, durable components. The ElectroCat consortium includes a focus on development of PGM-free catalysts applicable to electrolyzers and advanced pathways. The HydroGEN consortium focuses on the discovery and development of materials and components for advanced water splitting technologies, including next generation electrolysis as well as direct PEC and thermochemical methods. The R2R Consortium is advancing efficient, high-throughput, and high-quality manufacturing methods with a focus on high-volume production of membrane electrode assembly (MEA) components for PEM electrolyzers and fuel cells.

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

Together, these consortia employ state-of-the-art methodologies such as multiphysics modeling, high-throughput synthesis and characterization, and machine learning to build a pipeline for advanced materials and components to be commercially adopted in efficient, durable, and affordable next-generation clean hydrogen-producing systems.

Consortia Supporting Hydrogen Production

H2NEW conducts RD&D to achieve large-scale, affordable electrolysis powered by clean electricity, supporting large industry deployment by enabling more durable, efficient, and low-cost electrolyzers: H2NEW Consortium

HydroGEN focuses on innovative R&D on advanced water-splitting materials for innovative hydrogen production pathways such as PEC, STCH, and next-generation electrolysis: HydroGEN Consortium

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

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

Beyond its consortium collaborations, the Hydrogen Production subprogram works in close concert with the Hydrogen Infrastructure and other HFTO subprograms, as well as across other DOE offices and external agencies to advance clean hydrogen technologies. For example, the HFTO Systems Development and Integration subprogram is heavily engaged in demonstrating novel schemes to integrate electrolyzers with clean energy sources such as wind, solar, and nuclear. As examples of cross-DOE coordination, the Advanced Materials and Manufacturing Technologies Office has supported roll-to-roll manufacturing innovations relevant to electrolyzers; and the Office of Science has launched an Energy Earthshots Research Center initiative to support fundamental scientific research relevant to the Earthshots, including the Hydrogen Shot. As an example of cross-agency coordination, the National Science Foundation has supported research activities coordinated with the HydroGEN Consortium. Leveraging expertise from other HFTO subprograms, DOE offices, and agencies accelerates innovation in clean hydrogen production technologies across the spectrum of TRLs.

3.5 RD&D Focus Areas

Technical and economic barriers common to the challenges being addressed in the Hydrogen Production subprogram include: *Cost, Durability/Reliability, Efficiency/Performance, Life Cycle/Sustainability, Manufacturing/Scale-up,* and *Safety*. These barriers are summarized in Table 3.3 with some specific examples of associated challenges being addressed in the electrolysis and advanced pathways.

Table 3.3. Hydrogen Production Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost *materials, components, systems*	Capital costs of materials and components (e.g., catalysts, electrodes, membranes)
	Installation, operations, maintenance, and replacement costs in H_2 production systems
	Balance-of-plant capital costs (e.g., feedstock pretreatment, power electronics, H_2 purification)
	Feedstock costs (e.g., electricity, water, biomass, waste), including any transport or pre-treatment
D: Durability/ Reliability	Durability of materials, components, and integrated systems
	System reliability and lifetime under dynamic operating conditions
E: Efficiency/ Performance	H_2 production conversion efficiency
	H_2 production rates and yield
	Operational performance, including the ability to dynamically respond to changes in electric power input
LC: Life Cycle / Sustainability	Life cycle cost and environmental impacts
	Cost-effective recycling (e.g., catalysts, MEA)
M: Manufacturing, Scale-Up, and Supply Chain	Materials, components, and systems compatible with high-volume processes for affordable scale-up and large-scale manufacturing
	Robust domestic supply chain (e.g., electrolyzer PGM catalysts, membranes, as well as BOP components such as power electronics)
S: Safety	Materials, components, and systems with adequate consideration of all hydrogen-related safety issues

The Hydrogen Production subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 3.3. Tables 3.4 through 3.6 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for the different clean hydrogen production pathways along with examples of key targeted milestones. These RD&D focus areas are aligned with the subprogram's near-, mid-, and longer-term priorities; and 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-Term: Electrolysis

The subprogram's near-term strategic priorities in electrolysis cover low-temperature technologies including PEM, liquid alkaline, and AEM electrolyzers; as well as high- to intermediate-temperature technologies including both oxide-ion-conducting and proton-conducting solid oxide electrolyzer cells. Specific RD&D focus areas addressing barriers and challenges are described in Table 3.4.

Table 3.4. Hydrogen Production RD&D Addressing Near- to Mid-Term Strategic Priorities in Electrolysis

RD&D Focus Areas	Barriers Addressed	Key Milestones
Low-Temperature Electrolysis ***PEM, Liquid Alkaline, AEM***		
Increase durability, improve performance, and lower cost of membranes, ionomers, catalysts/electrodes, bipolar plates, and porous transport layers in PEM electrolysis through materials and design innovations	C, D, E	• Develop and implement accelerated stress test protocols to enable durability improvements (2025) • Achieve PEM *stack* cost of \$100/kW, with a stack efficiency of 69% lower heating value (LHV) and an 80,000-hour lifetime (2026) • Demonstrate AEM electrolyzers operating at 2 A/cm^2 at 1.8 V with a degradation rate of <4 mV/khr (2026) • Develop PEM electrolyzer *systems* with cost of \$250/kW, 65% LHV efficiency, and 80,000-hour durability (2026) • Demonstrate liquid alkaline electrolyzers operating at 1 A/cm^2 at 1.8 V with a degradation rate of <2.3 mV/khr and capable of dynamic operation (2026) • Demonstrate efficient and durable PEM electrolyzers with PGM catalyst loadings of 0.125 mg PGM/cm^2, a 24x reduction over the state of the art (2031)
Develop viable membranes and ionomers for AEM electrolysis as a potential lower-cost alternative to PEM	C, D, E	
Develop improved cell designs and optimized components for liquid alkaline electrolysis to enable improved performance and dynamic operation	C, D, E	
Improve kinetic performance and durability in low-PGM and PGM-free catalysts	C, D, E	
Optimize efficiency and durability of electrolyzer stacks and systems under dynamic operations through innovations in component and systems engineering	C, D, E	
Develop optimized BOP components, including power electronics, to reduce system costs and increase efficiency	C, E	
Develop low-cost, high-throughput, high-quality manufacturing techniques, including for materials, components, stacks, and systems	M	
Address electrolyzer installation and other soft costs to decrease the clean hydrogen production cost	C	
Explore novel, alternative electrolyzer cell and stack chemistries and configurations (e.g., intermediate temperature operation)	C, D, E	
Develop standardized accelerated stress testing procedures and protocols	D, E	

<table>
<tr><th colspan="3">High-Temperature Electrolysis
O-SOEC, P-SOEC</th></tr>
<tr><td>Improve understanding of degradation mechanisms to increase durability of cell and stack components in SOEC technologies</td><td>D</td><td rowspan="9">• Develop and implement accelerated stress test protocols to enable durability improvements (2025)
• Demonstrate viability of P-SOECs for enhanced durability at intermediate temperatures (<600 °C), including performance of >0.8 A/cm² at 1.3 V with >85% faradaic efficiency and degradation rate of <5 mV/khr (2025)
• Achieve stack cost of $125/kW, with 98% electrical efficiency (LHV) and 40,000-hour durability (2026)
• Develop electrolyzer systems with cost of $200/kW, 79% LHV energy efficiency, and 80,000-hour durability (2031)</td></tr>
<tr><td>Develop advanced cell and stack materials and components with improved performance and decreased degradation</td><td>D, E</td></tr>
<tr><td>Address thermal management issues in stacks and systems</td><td>D, E</td></tr>
<tr><td>Develop efficient technologies operating at reduced temperatures (<700°C) through materials and design innovations (e.g., P-SOEC)</td><td>C, D, E</td></tr>
<tr><td>Develop optimized BOP components, including power electronics, to reduce system costs and increase efficiency</td><td>C, E</td></tr>
<tr><td>Develop low-cost, high-throughput, high-quality manufacturing techniques, including for materials, components, stacks, and systems</td><td>M</td></tr>
<tr><td>Address electrolyzer installation and other soft costs to decrease the clean hydrogen production cost</td><td>C</td></tr>
<tr><td>Optimize efficiency and durability of electrolyzer stacks and systems under steady state and dynamic operations, including thermal cycling, through innovations in component and systems engineering</td><td>D, E</td></tr>
<tr><td>Develop standardized accelerated stress testing procedures and protocols</td><td>D, E</td></tr>
</table>

Longer-Term: Advanced Pathways

The subprogram's longer-term strategic priorities in the advanced pathways for hydrogen production cover PEC and thermochemical water splitting, including the direct use of sunlight as the primary energy source; biological pathways such as fermentation and microbial electrolysis; as well as hybrid approaches. Specific RD&D focus areas addressing barriers and challenges are described in Table 3.5.

Table 3.5. Hydrogen Production RD&D Addressing Longer-Term Strategic Priorities in the Advanced Pathways

RD&D Focus Areas	Barriers Addressed	Key Milestones
Advanced Water-Splitting *PEC and Thermochemical (including STCH)*		
Develop efficient, durable, and cost-effective materials (e.g., semiconductors, catalysts, and membranes) for PEC hydrogen production	C, D, E	• Develop standard metrics and characterization protocol for STCH materials to verify efficiency and durability at high temperatures (2024) • Demonstrate PEC device assembly with >200-hour durability at a solar-to-hydrogen conversion efficiency >5%, with active areas scaled to >4 cm^2 (2025) • Demonstrate effective theory-guided design of high-performing STCH materials using machine learning to predict viable and synthesizable metal oxides (2025) • Validate a PEC material system, demonstrating stable on-sun operation at ≥20% solar-to-hydrogen efficiency, with the potential to achieve H_2 cost of <$2/kg (2031) • Demonstrate on-sun operation of a high-temperature STCH cycle with the potential to achieve H_2 cost of <$2/kg (2031) • Determine further investment in PEC and STCH advanced water splitting pathways based on technology status and demonstrated potential (2031)
Develop efficient, durable, and cost-effective integrated photoelectrode or photocatalyst devices and systems for PEC hydrogen production	C, D, E	
Develop efficient, durable, and low-cost functional materials (e.g., RedOx materials) for thermochemical cycles	C, D, E	
Develop thermochemical cycles operating at reduced temperatures (<1400°C)	C, D, E	
Develop robust, scalable, and cost-effective STCH reactor components and systems	C, D, M	
Develop standardized solar-to-hydrogen conversion testing protocols for PEC and STCH H_2 production	D, E	
Explore innovative hybrid approaches to maximize efficiency and lifetime	D, E	
Biological Conversion *Fermentation, Microbial Electrolysis, and Hybrid Approaches*		
Address organic waste feedstock clean-up issues for biological processes through innovations in component and systems engineering	C	• Demonstrate an integrated fermentation-microbial electrolysis cell reactor capable of 35 L H_2/L/day continuous production utilizing waste feedstock (2025) • Verify the techno-economic feasibility of a microbial conversion system based on demonstrated technology that can achieve a cost goal of <$2/kg H_2 (2031)
Optimize for H_2 production rate and molar yield of conversion	C, E	
Optimize hybrid systems to maximize the H_2 produced per unit of feedstock, addressing integration issues such as mass flow and thermal management	C, E	

Improve feedstock loading and conversion in biological processes	E	
Improve microbial electrolysis cell lifetime and robustness to enable system resilience with real waste streams	D, E	

Crosscutting

In addition to the focus areas described in Tables 3.4 and 3.5, the subprogram also conducts crosscutting RD&D that is synergistic with activities in other HFTO subprograms and that supports broad strategic priorities relevant to the advancement of clean hydrogen and fuel cell technologies. Examples are included in Table 3.6.

Table 3.6. Hydrogen Production Crosscutting RD&D Activities

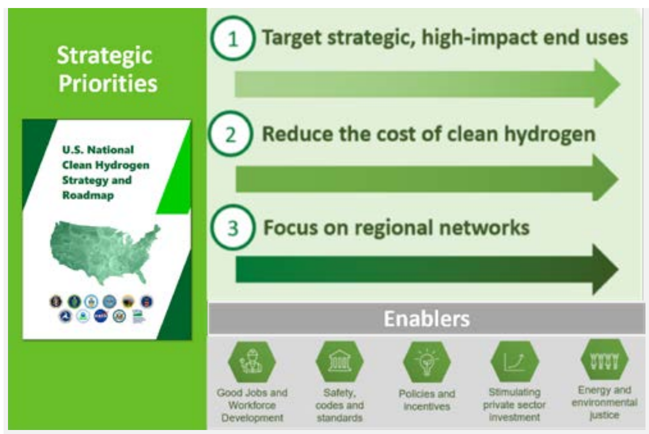
Crosscutting RD&D	Barriers Addressed	Key Milestones
Develop standardized testing and validation procedures and protocols for the different production pathways	D, E	• Ensure public access to >35 advanced water-splitting protocols and verify utilization in HFTO-funded efforts (2024) • Verify stack and system efficiencies against targets (2026) • Verify that high-volume manufacturing processes for fabricating electrolyzer components can achieve economies of scale (2027) • Validate achieving clean hydrogen production cost targets of \$2/kg-H_2 (2026) and \$1/kg-H_2 (2031)
Develop low-cost, high-throughput, high-quality manufacturing techniques, including for materials, components, stacks, and systems, leveraging synergies with fuel cell manufacturing	M	
Perform application-specific techno-economic analysis and life cycle assessments to inform RD&D priorities across all production pathways	C, LC	
Ensure adherence to rigorous safety standards and protocols	S	
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

4 Hydrogen Infrastructure

4.1 Overview

Goals and Objectives

The goal of the **Hydrogen Infrastructure** subprogram is to accelerate innovations in R&D to enable commercialization and large-scale adoption of efficient and durable clean hydrogen technologies with a focus on the storage, transmission, distribution, delivery, and dispensing of hydrogen for various delivery pathways and end uses. The Hydrogen Infrastructure subprogram works closely with the Hydrogen Production subprogram to advance the R&D needed to deploy clean hydrogen technologies. *Hydrogen infrastructure* refers to the technologies used for transmission, distribution, storage, and dispensing of hydrogen—from the point of production to the end-use application. The Hydrogen Infrastructure subprogram's RD&D primarily focuses on reducing the cost and improving the reliability of current hydrogen infrastructure options for today's end uses.



Second to the cost of clean hydrogen to the end user, the need for sufficient infrastructure has been identified as an important priority.

The Hydrogen Infrastructure subprogram supports key strategic priorities identified by the **DOE Hydrogen Shot** and the ***U.S. National Clean Hydrogen Strategy and Roadmap***[48] to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit to the United States. The subprogram directly supports the strategic priority to reduce the cost of clean hydrogen, foundational to all the priorities; and it coordinates closely with the other HFTO subprograms to support priorities targeting strategic high-impact uses for clean hydrogen and focusing on regional networks.

RD&D solutions pursued by the Hydrogen Infrastructure subprogram will take a holistic approach that considers both the hydrogen production method and end use. For example, the left and central parts of Figure 4.1 show the various types of production, delivery, and storage technologies that can be linked together into various pathways that support diverse clean hydrogen end uses. Interdependencies among the technologies and processes create unique challenges that can be addressed through RD&D. As an example, the approach chosen for hydrogen distribution (gaseous, liquid, or hydrogen carrier) affects the storage options and

[48] 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.

overall cost and efficiency of the pathway. For each end-use application, an optimized integration of production, delivery, and storage technologies throughout the entire pathway is needed to enable competitive, efficient, and clean hydrogen opportunities.

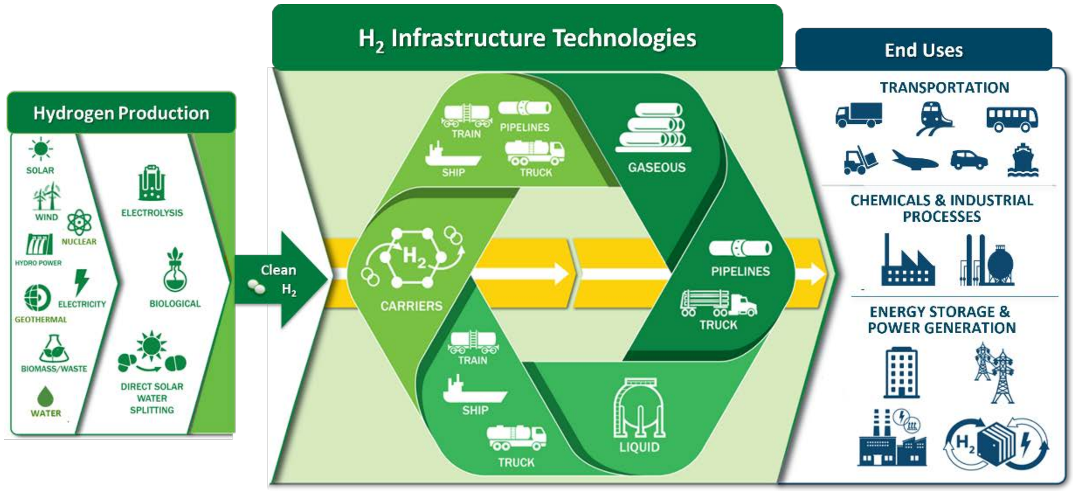


Figure 4.1. Hydrogen Infrastructure Technologies takes a holistic approach that considers the entire pathway from clean hydrogen production through delivery and storage, including storage both during delivery and at the end-use application.

Infrastructure Technologies for Hydrogen Delivery and Storage

RD&D in the Hydrogen Infrastructure subprogram focuses on advancing technologies to lower the cost while enhancing the performance and durability of diverse hydrogen delivery and storage options for different end use applications, specifically addressing market-driven requirements for technology development in each end use.

Hydrogen Delivery

Delivery is an essential component of any future hydrogen infrastructure. It encompasses those processes needed to transport hydrogen from a central or semicentral production facility to the final point of use and those required to feed the energy carrier directly to a given end-use application. Successful commercialization of clean hydrogen systems, including those used in vehicles, backup power sources, distributed power generators, and chemical processing, will likely depend on a hydrogen delivery infrastructure that provides the same level of safety, convenience, and functionality as existing liquid and gaseous fossil fuel-based infrastructures. Because hydrogen can be produced from a variety of domestic resources, its production can take place in large, centralized plants or in a distributed manner, directly at fueling stations, stationary power, and chemical and industrial process sites. As such, the hydrogen delivery infrastructure will need to integrate with these various hydrogen production options.

Hydrogen can be transported and distributed as either a compressed gas or a cryogenic liquid, or it can be bound within a chemical hydrogen-carrier material. Figure 4.1 illustrates the variety of options for delivering hydrogen from the point of production to the intended end use. Each of the transport and distribution methodologies requires a range of technologies, such as compressors, liquefiers, and dispensing technologies (which will need to meet the specific needs for each end-use application). The Hydrogen Infrastructure subprogram's RD&D focuses on developing these technologies to meet targets for dispensed hydrogen to the end user. It's also working to identify materials for hydrogen infrastructure technologies (e.g., pipelines, compressors, pressure vessels) that are compatible with hydrogen or hydrogen blends (e.g. hydrogen blended with natural gas) under various operating conditions.

The type of hydrogen delivery infrastructure installed in a region for a specific end use depends on several key aspects of hydrogen demand, including:

- The **quantity** of hydrogen that the end user requires, including if the demand is constant or intermittent.
- The **purity** or quality of hydrogen that the end user requires.
- The **location** of end users, including their proximity to one another and their proximity to hydrogen production.
- The **outlook** for hydrogen demand and the accuracy with which it can be predicted.
- The **price points** that hydrogen must achieve to be competitive in its end uses.

Hydrogen Storage

Technologies for enabling efficient and affordable hydrogen storage are key for the advancement of hydrogen and fuel cell technologies in an array of applications, including stationary power, portable power, and transportation. As an example, hydrogen can be used as a medium to store clean energy created by intermittent renewable power sources (e.g., wind and solar) during periods of high availability and low demand, increasing the utilization and benefits of the large capital investments in these installations. The stored hydrogen can be used during peak hours; as system backup; or for portable, transportation, or industrial applications.

Because of the low energy density of gaseous hydrogen at room temperature and pressure compared with conventional liquid fuels, hydrogen in current applications is most often *physically* stored as either a compressed gas in pressure vessels or geological formations, or as a cryogenic liquid in double-walled insulated vessels, as illustrated in Figure 4.2. Also shown in the figure are additional advanced *materials-based* approaches to meet storage targets for a growing number of end uses. Hydrogen storage options in the Hydrogen Infrastructure subprogram's RD&D portfolio include physical storage technologies as well as reversible and nonreversible materials-based storage. Approaches for very large-scale bulk storage (such as geological storage) are also under investigation. Infrastructure technologies supporting these different options are needed to accommodate the various scales of hydrogen storage and delivery for different end uses.

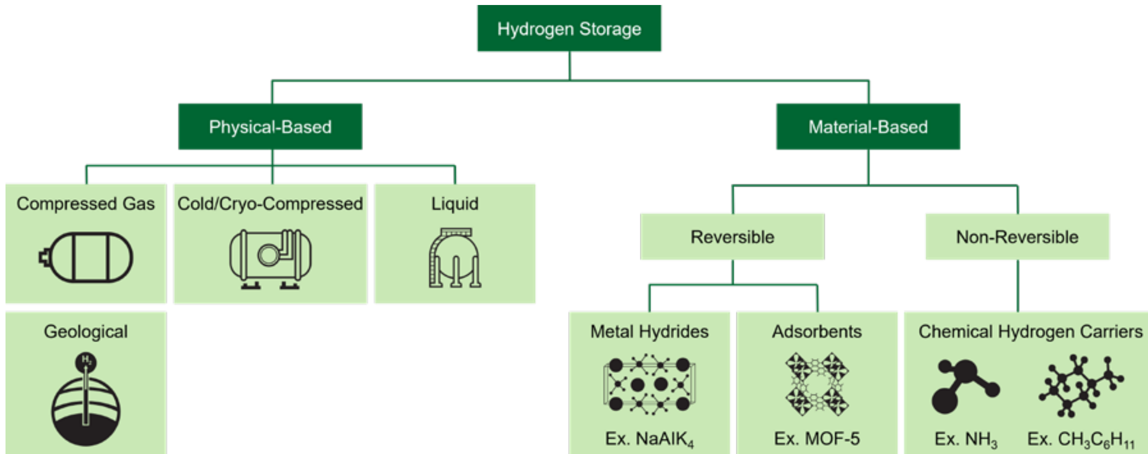


Figure 4.2. Multiple options for hydrogen storage to meet different storage, transport, and end-use requirements, including physical gaseous or liquid storage as well as storage in materials and chemical H_2 carriers

4.2 Strategic RD&D Priorities

The Hydrogen Infrastructure subprogram's overarching strategic framework addressing RD&D for clean hydrogen storage and delivery in the near-, mid-, and longer term is depicted in Figure 4.3. The subprogram works in close coordination with the other HFTO subprograms in support of strategic priorities described in the Introduction.

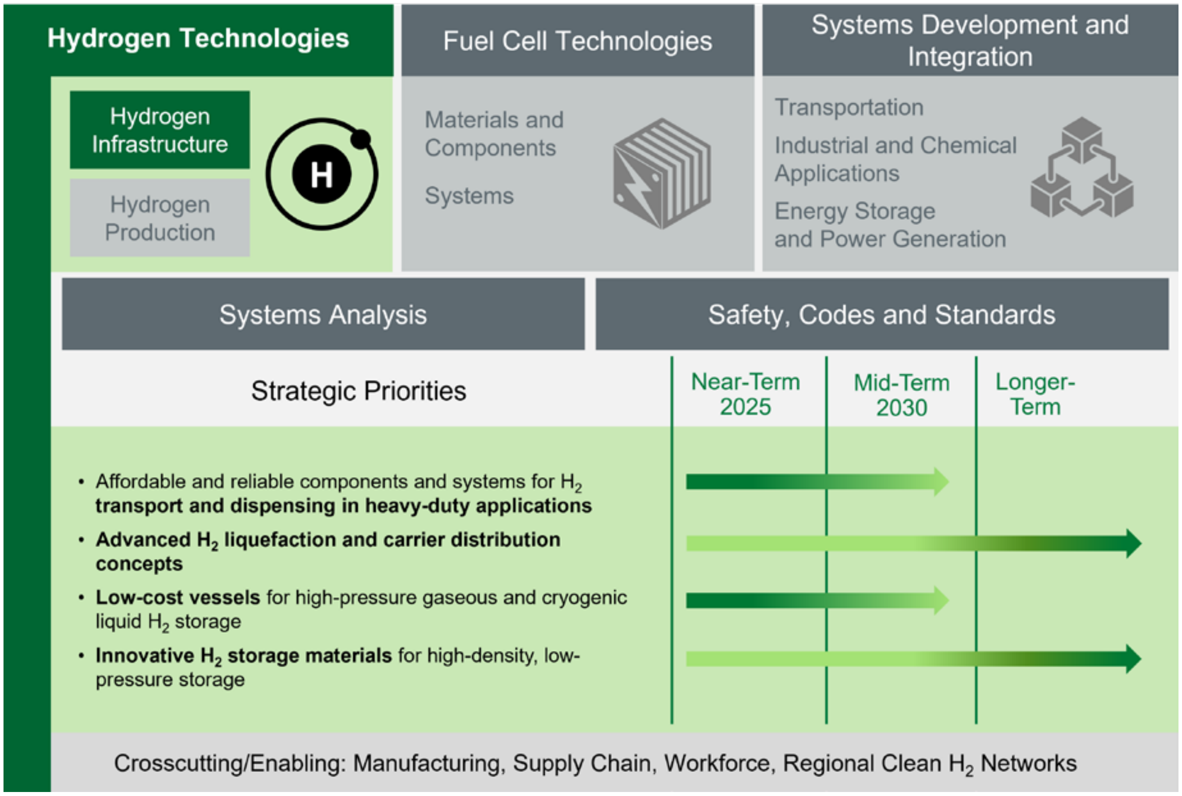


Figure 4.3. Strategic priorities guiding hydrogen storage and delivery infrastructure RD&D

Near- to Mid-Term Priorities

Hydrogen storage technology development for near-term, early market fuel cell applications is focused on developing technologies that can provide an adequate amount of hydrogen to enable efficient operation to meet customer-driven performance metrics in a safe, convenient, and cost-effective package. Targeted metrics are closely related to the operating requirements of the application, such as capacity (i.e., run-time), refill and discharge kinetics, durability, and operability. However, for hydrogen to be competitive with more established incumbent technologies such as batteries and diesel gen-sets, costs must be reduced for all system components, including hydrogen storage. In the near- to mid-term, strategic priorities include affordable and reliable components and systems for H_2 transport and dispensing in heavy-duty vehicle applications as well as materials and components for advanced H_2 liquefaction and carrier distribution concepts.

- **Low-Cost Vessels for High-Pressure Gaseous and Cryogenic Liquid H_2 Storage:** RD&D to improve physical storage methods is primarily focused on reducing cost and minimizing losses from tanks and other technologies in use today for compressed gaseous and liquid hydrogen storage. Compressed gaseous hydrogen can also be contained in bulk in caverns (i.e., underground rock-lined or salt caverns) for long-duration storage applications; however, this approach is limited to specific geographical areas. Novel physical storage technologies that address shortcomings of current technologies are also being investigated, such as compressed storage at subambient temperatures to increase the hydrogen density and subsurface storage options that are more geographically available. For all current and near-term hydrogen storge options, continued research and optimization are needed to reduce cost and ensure safety.

- **Near- to Mid-Term Hydrogen Transport and Dispensing for Heavy-Duty (and Other Near-Term) Applications:** In the near- to mid-term, for heavy-duty vehicle applications, it is expected that most of the hydrogen will be delivered as a compressed gas (either via pipeline or using high-pressure tanks), delivered as a cryogenic liquid, or produced onsite. Most hydrogen supplied via pipeline today is for use in petroleum refining. For other current end uses in the transportation, industrial, and chemical sectors, when large quantities of hydrogen are required, hydrogen production is in close proximity to the demand. Otherwise, hydrogen is commonly transported and stored as either a high-pressure compressed gas (via pipeline or truck) or cryogenic liquid (via tanker). As hydrogen production increases in geographic areas with excess clean renewable energy resources, and demand increases for new and emerging applications such as steel production, it is expected that additional hydrogen pipeline installations will occur. Hydrogen may also be blended with natural gas, thus enabling a partial decarbonization of natural gas use and making use of the extensive existing national pipeline network. To meet the needs of heavy-duty transportation applications, processes and hardware components that can meet the dispensing requirements, including fueling rates, need to be developed. Near- and mid-term RD&D efforts are focused on reducing the cost of these technologies, ensuring the safety of materials used in hydrogen operations and minimizing the losses of hydrogen that occur during transport and dispensing.

Mid- to Longer-Term Priorities

Longer-term RD&D in the Hydrogen Infrastructure subprogram is focused on developing low-cost solutions and new opportunities in affordable hydrogen storage.

- **Innovative Hydrogen Storage Materials for High-Density, Low-Pressure Storage:** Longer-term RD&D is focused on material-based options such as adsorbents, metal hydrides, and chemical hydrogen carriers to open new opportunities in affordable hydrogen storage. These approaches offer the potential to achieve comparable and potentially superior hydrogen storage densities, but at near-ambient operating conditions, without the need for high pressures (as in compressed hydrogen storage) or very low temperatures (as in liquid hydrogen storage), both of which add significant costs and expenditures of energy to the entire pathway. Some of these technologies may also be compatible with existing infrastructure currently in use for other applications, such as oil and gas infrastructure.

- **Advanced H_2 Liquefaction and Carrier Distribution Concepts:** In the longer term, the subprogram seeks to lower the cost of large-scale distribution infrastructure through breakthrough concepts for low-cost, scalable liquefaction and through the development of hydrogen carrier materials to enable bulk hydrogen transport (e.g., coast-to-coast or internationally). Additional RD&D that can support large-scale distribution includes materials research to enable leveraging of natural gas infrastructure in hydrogen use (e.g., hydrogen blending in pipelines) and high-throughput compressors to enable higher volume pipelines.

4.3 RD&D Targets

Target-Setting

The Hydrogen Infrastructure subprogram's RD&D strategy is driven by application-specific targets for the performance, durability, cost, and scale of hydrogen storage and delivery technologies needed to enable cost-competitiveness of clean hydrogen in diverse end uses. Different targets are developed holistically based on the ultimate life cycle cost of storing and delivering clean hydrogen meeting end-use-specific requirements for pressure, temperature, purity, etc. Target-setting is guided by comprehensive modeling and analysis of the different technology options at the materials, components, and systems level. Publicly available and industry-vetted manufacturing cost estimates are incorporated in the analysis to accurately gauge the status and future potential of the technology.

Hydrogen Infrastructure Interim Target Examples (2030)

Hydrogen Storage

- Onboard hydrogen storage systems for transportation: $8/kWh stored at 2.2 kWh/kg and 1.7 kWh/L
- High-volume cost of high-strength carbon fiber for tanks: $14/kg

Large-Scale Hydrogen Production, Delivery, and Dispensing

- $7/kg for transportation end uses in early markets
- $4/kg for ultimate market expansion for high-value products

Application-Specific Targets

As an example, specifically relevant to its near-term priorities in the transportation sector, the subprogram has developed interim and ultimate cost targets to enable market-competitiveness of onboard storage of pressurized hydrogen in carbon-fiber-wrapped tanks for heavy-duty fuel cell vehicles, as shown in Table 4.1. The technology-agnostic storage system cycle life target in the table represents the minimum number operational cycles required for the entire useful life of a vehicle used in long-haul operation. Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e. SAE J2579 and United Nations Global Technical Regulation No. 13), which require significantly more cycles than the storage system cycle life. The hydrogen storage system cost includes the storage tank and all necessary BOP components.

Table 4.1. Hydrogen Storage Targets for Class-8 Vehicles

Characteristic	Units	Interim Target (2030)	Ultimate Target
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life	cycles	5,000	5,000
Pressurized Storage System Cycle Life	cycles	11,000	11,000
Hydrogen Storage System Cost	\$/kWh (\$/kg H_2 stored)	9 (300)	8 (266)

Recognizing that both technology advancements as well economies of scale are needed for meeting the cost targets, the subprogram has identified key cost drivers related to materials, component, system, manufacturing, scale-up, and supply chain challenges, and it focuses RD&D to address these challenges. The waterfall chart in Figure 4.4 shows how addressing specific challenges can contribute to overall cost reductions aimed at meeting the ultimate cost target of \$8/kWh (\$266/kg H_2 stored) for a 700-bar onboard hydrogen storage system for long-haul tractor-trailer trucks.

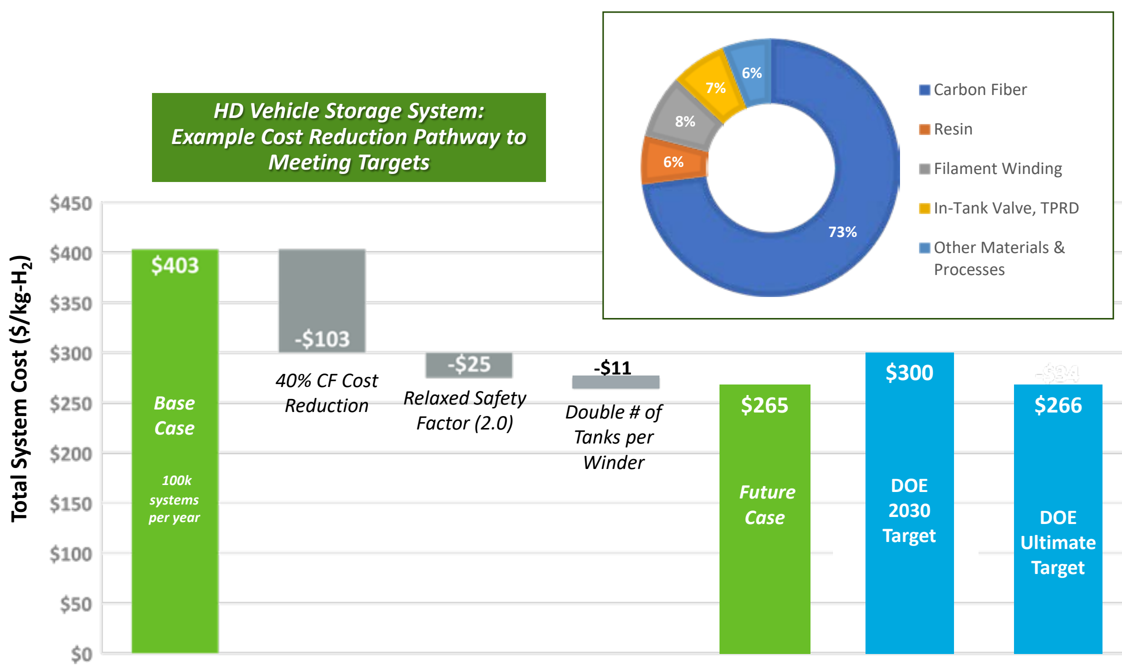


Figure 4.4. Potential pathway to meet ultimate DOE target for 700-bar onboard hydrogen storage system cost through technology advancements along with economies of scale, including cost breakdown for a single representative "behind-the-cab" composite overwrapped pressure vessel with ~12 kg capacity at manufacturing rates of ~100k systems per year

While achieving economies of scale is important, continued technology improvements through RD&D are still needed. For example, a major RD&D focus is needed to reduce the cost of the carbon fiber composite, which accounts for a significant fraction of the total system cost. This focus includes the development of novel, low-cost carbon fiber precursor materials and lower-cost precursor production processes such as melt-spinning, as well as faster and more efficient precursors to carbon fiber conversion processes. In addition, reducing the overall amount of carbon fiber required through improved winding patterns; real-time structural health monitoring; and reduction in carbon fiber manufacturing and winding coefficients of variations all offer potential cost saving strategies. Reducing cost for BOP components through lower-cost manufacturing, improved designs, and integration or elimination of components offers an additional strategy to help meet the ultimate cost target.

For all hydrogen delivery and storage infrastructure technologies, it is important to emphasize that application-specific requirements for performance and durability along with needs based on manufacturing scale and supply chain must be maintained in conjunction with the cost-reduction strategies. Spider charts such as the one illustrated in Figure 4.5 highlight that several subtargets must be addressed simultaneously to achieve a cost-competitiveness for the specific example of onboard hydrogen storage for heavy-duty applications.[49] The spider chart and the waterfall chart indicate the types of related improvements that need to be made simultaneously through comprehensive RD&D to achieve subprogram targets.

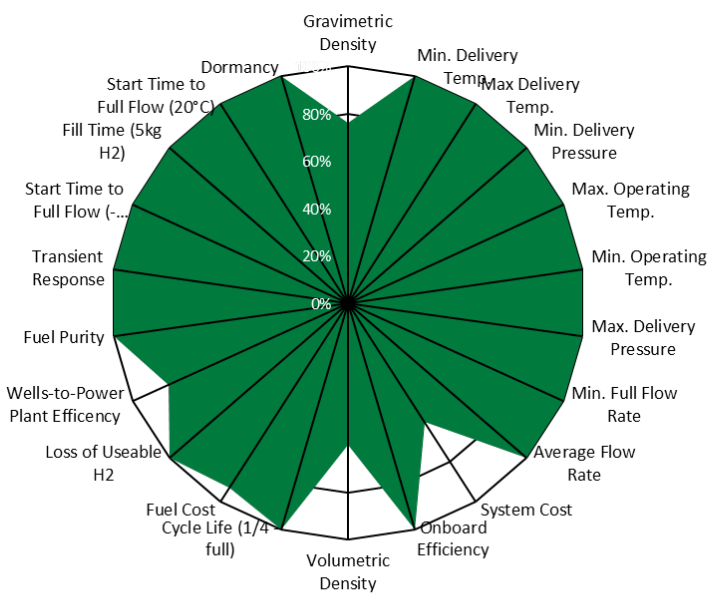


Figure 4.5. Spider chart showing performance of a state-of-the-art Type 4, 700-bar storage system compared against the onboard storage targets

[49] Performance shown is based on prior analysis for light-duty vehicle applications. An updated assessment for heavy-duty vehicle applications is in progress.

In all application areas for hydrogen delivery and storage infrastructure, 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. 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

4.4 Addressing Challenges

Volumetric Density Challenges

The Hydrogen Infrastructure subprogram's RD&D addresses critical challenges and barriers across the various pathways for *delivering* and *storing* hydrogen and the infrastructure technologies needed to support diverse end-use applications. A common delivery and storage challenge relevant to all end uses is the low volumetric density of hydrogen gas under nonextreme temperatures and pressures.

On a mass basis, hydrogen has nearly three times the energy content of gasoline when comparing lower heating values (33 kWh/kg for hydrogen compared to 12 kWh/kg for gasoline). However, on a volume basis, the situation is reversed (approximately 1 kWh/L for 700 bar hydrogen at 15°C compared to 9 kWh/L for gasoline) as shown in Figure 4.6. Improved volumetric densities are achieved through high-pressure compression of gaseous hydrogen, cryogenic hydrogen liquefaction, or incorporation of hydrogen in materials or chemical carriers; but each of these approaches poses different challenges to the delivery and storage infrastructure needed for different end-use applications.

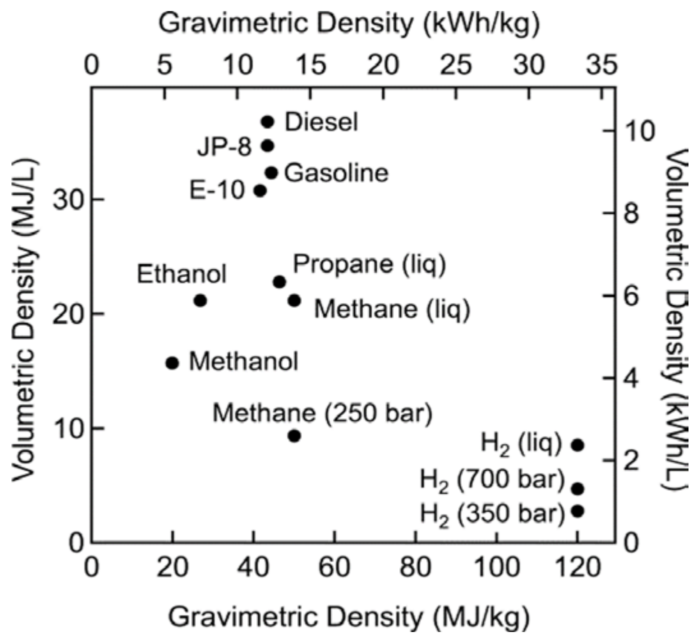


Figure 4.6. Comparison of the volumetric and gravimetric densities of various energy-rich fuels and chemicals

Delivery Challenges

Key challenges include reducing the cost, improving the reliability, and increasing the throughput of hydrogen delivery and dispensing systems and other related systems at the fueling station or point of use. Some specific challenges include: developing high-pressure liquid pumps to enable direct fueling of 350/700 bar; developing novel designs for compressors and other dispensing equipment to ensure sufficient throughput for the medium/heavy-duty market; conducting materials research to increase the life and capacity of high-pressure storage vessels; enhancing the reliability of materials used in dispensing hoses and seals (e.g., in compressors); and improving the life of dispensing hoses through novel designs.

General Hydrogen Delivery Challenges
• Ensuring materials compatibility for hydrogen service under a wide range of conditions • Developing affordable, innovative approaches to hydrogen liquefaction and cryogenic delivery • Improving hydrogen carrier materials and catalysts for hydrogen storage, transport, and release • Developing innovative components for low-cost distribution and dispensing (e.g., compressors, storage vessels, dispensers, nozzles) • Facilitating rights-of-way, permitting, and reduced investment risk of deploying delivery infrastructure

Storage Challenges

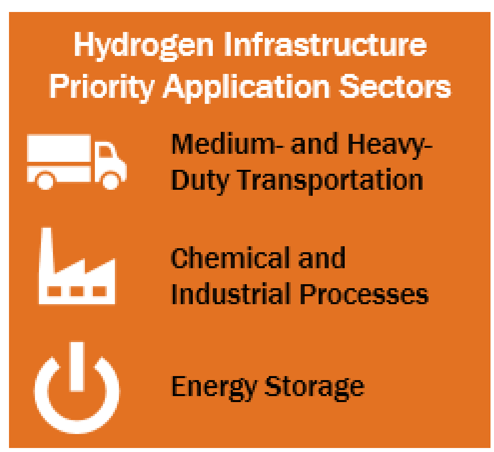
For onboard vehicle storage, hydrogen storage technology development is focused on developing systems that can provide an adequate amount of hydrogen to meet customer driving performance metrics in a safe, convenient, efficient, and cost-effective package. Targeted metrics are closely related to the operating requirements of the end-use application, such as capacity (i.e., run-time), refueling rates, durability, operability, and cost. For offboard or bulk storage, the focus is primarily on reducing cost and footprint while also addressing performance issues such as cycling and material compatibility and developing geographically agnostic technologies.

General Hydrogen Storage Challenges

- Reducing costs for materials, components, and systems
- Developing low-cost, high-strength carbon-fiber for high-pressure tanks
- Ensuring materials compatibility with hydrogen for durability and safety
- Developing innovations for cryogenic hydrogen storage, including liquid and cold/cryo-compressed
- Discovering and optimizing hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements
- Developing sensors and other technologies needed to ensure safe and efficient hydrogen storage
- Optimizing for round-trip efficiency using chemical hydrogen carriers
- Identifying, assessing, and demonstrating geologic storage of hydrogen
- Identifying pathways for the export of hydrogen and hydrogen carriers
- Defining targets for a broad range of storage options and end uses

Comprehensive Approach

HFTO's Hydrogen Infrastructure subprogram's comprehensive RD&D portfolio addresses key techno-economic challenges with respect to hydrogen delivery and storage options in priority application sectors.



The subprogram conducts ongoing and evolving scenario planning to prioritize and identify needs and challenges. This process involves prioritizing high-impact end-use application sectors and then outlining and illustrating appropriate scenarios within sectors. For example, in the medium- to heavy-duty transportation sector, only liquid hydrogen is projected to meet the near-term needs for the large-scale delivery and onsite storage to heavy-duty fueling stations, but gaseous and liquid fueling pathways are both viable onboard storage options being pursued by industry. The process further includes highlighting key components and processes and gathering key metrics through analysis and industry input. Key challenges are identified at the component and process level, leading to an understanding of what can and must be achieved to meet overall cost and performance targets for each of these scenarios.

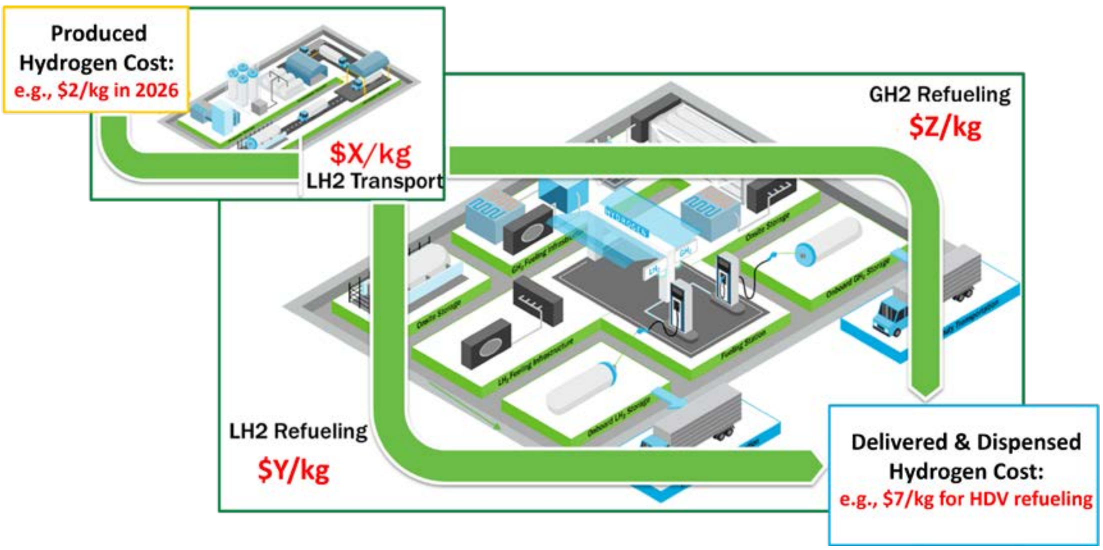


Figure 4.7. Scenario planning as a path to target-setting for infrastructure in the context of production and end-use targets. Figure depicts an example of liquid H_2 delivery to a fueling station, with both gaseous and liquid H_2 pathways for onboard dispensing to the vehicle. Final cost of dispensed H_2 equals the sum of the cost of H_2 production plus cost of delivery to the station, plus the cost of dispensing to the vehicle.

As illustrated in Figure 4.7, this approach to scenario planning is a path for the subprogram to set and revise cost and performance targets at the system and component level, within the bounds defined by targets for hydrogen production and the specific end use.

The three priority sectors—medium- and heavy-duty transportation, chemical and industrial processes, and energy storage—exhibit some overlap in technology needs, while also having distinct needs and opportunities that allow this approach to cover a wide spectrum of technologies and collaborate across the broader DOE Hydrogen Program.

To address hydrogen infrastructure challenges, the Hydrogen Infrastructure subprogram leverages the world-class capabilities of the national laboratories, which includes the formation of several national lab consortia to work with industry and university led projects to address key technology areas. These *c*onsortia that tackle hydrogen infrastructure challenges include HyMARC, H-Mat, and HyBlend.[50]

Consortia Supporting Hydrogen Infrastructure

HyMARC addresses unsolved scientific challenges in the development of viable materials-based storage of H_2 that could lead to more reliable and economic hydrogen use in diverse end uses: [HyMARC Consortium]

H-Mat focuses on crosscutting R&D on hydrogen materials compatibility to improve the reliability and reduce the costs of materials, and to inform relevant codes and standards: [H-Mat Consortium]

The HyBlend Pipeline Blending CRADA Project addresses technical barriers to blending H_2 in natural gas pipelines through materials compatibility RD&D and analysis that informs development of publicly accessible assessment tools on blending: [HyBlend Consortium]

HyMARC focuses on materials for hydrogen transport and storage. The consortium uses a comprehensive approach that incorporates computational modeling to understand the phenomena of hydrogen interactions with materials at the atomistic level, through to bulk materials and system requirements to meet end-use needs, advanced materials synthesis and characterization methods, and performance evaluation. By understanding system-level performance requirements to meet end-use needs, the team is able to "reverse engineer" to determine material level property requirements and identify materials best suited for specific applications. The team is then able to carry out RD&D to improve, characterize and demonstrate materials up through lab-scale demonstration prototypes.

H-Mat focuses on investigating the compatibility of metallic and non-metallic materials for use in hydrogen service. This work includes understanding the impact of hydrogen exposure on the materials' properties under a range of potential use conditions, such as stress-strain, cycle fatigue, and temperatures. The consortium employs computational modeling to understand the phenomena from the atomistic level to bulk properties, and empirical methods to determine the materials' characteristics and performance. Through an iterative approach, the consortium identifies modifications to the materials to improve performance for hydrogen applications. Results from the consortium can be used by industry to produce safe materials and products for

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

use in hydrogen applications and by committees for development of science-based codes and standards.

The HyBlend Pipeline Blending CRADA Project is an industry-focused initiative that includes a multitude of industrial partners working with the national laboratory partners. The consortium addresses key barriers and knowledge gaps related to blending hydrogen into the natural gas network. It includes understanding the potential hydrogen effects on materials used in existing natural gas infrastructure, impact of blended hydrogen on end-use applications, and the techno-economics of blending hydrogen into the natural gas infrastructure. The team also evaluates current regulations and identifies needs for new or revised codes, standards, and regulations regarding blending hydrogen into the natural gas network.

Beyond its consortium collaborations, the Hydrogen Infrastructure subprogram works in close concert with the Hydrogen Production and other HFTO subprograms, as well as across other DOE offices and external agencies to advance commercial liftoff of clean hydrogen technologies across priority application sectors. Leveraging expertise from other HFTO subprograms, DOE offices, and agencies accelerates innovation in clean hydrogen delivery and storage technologies across the spectrum of TRLs.

4.5 RD&D Focus Areas

Technical and economic barriers common to the challenges being addressed in the Hydrogen Infrastructure subprogram include: *Cost, Durability/Reliability, Efficiency/Performance, Life Cycle/Sustainability, Manufacturing/Scale-Up,* and *Safety*. These barriers are summarized in Table 4.2 with some specific examples of associated challenges being addressed for different storage and delivery pathways.

Table 4.2. Hydrogen Infrastructure Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost *materials, components, systems*	Capital costs of materials and components
	Operations, maintenance, and replacement costs
	Siting and permitting costs
D: Durability/ Reliability	Durability of materials, components, and integrated systems in hydrogen service (including pressure and temperature effects)
	System reliability and lifetime under dynamic operating conditions in hydrogen service (including pressure and temperature effects)
E: Efficiency/ Performance	H_2 losses in handling equipment and infrastructure
	Conversion and round-trip efficiency limits (e.g., in liquefaction and H_2 carriers)

	Mechanical and thermodynamic limits in H_2 processing (e.g., compression)
LC: Life Cycle/ Sustainability	Life cycle costs and environmental impacts
	Cost-effective recycling of materials and components
M: Manufacturing/ Scale-Up and Supply Chain	Materials, components, and systems compatible with processes for affordable scale-up and large-scale manufacturing, and addressing supply chain limitations
S: Safety	Materials, components, and infrastructure with adequate consideration of all hydrogen-related safety issues

The Hydrogen Infrastructure subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 4.2. The tables below provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for the different clean hydrogen storage and pathways, along with examples of key targeted milestones. These RD&D focus areas are aligned with the subprogram's near-, mid-, and longer-term priorities; and 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 Focus Areas

The subprogram's near- to mid-term priorities in hydrogen infrastructure include a focus on transmission and distribution; vehicle refueling (particularly for heavy-duty transportation applications); and near-term opportunities to advance technologies for pressurized gaseous and cryogenic liquid hydrogen storage. Specific RD&D focus areas addressing barriers and challenges are described in Table 4.3. These include areas that overlap both hydrogen delivery and storage and are synergistic with RD&D activities in other HFTO subprograms aimed at advancing hydrogen and fuel cell technologies.

Table 4.3. Infrastructure Focused on Near- to Mid-Term Priority Areas

Technology	RD&D Focus Area	Challenges Addressed	Key Milestones
Near- to Mid-Term Hydrogen Infrastructure for Heavy-Duty Applications			
Transmission & Distribution Infrastructure	Address materials compatibility RD&D to enable hydrogen blending and reductions in hydrogen pipeline and component costs	D, S	• Quantify compatibility of natural gas infrastructure with blends of hydrogen and natural gas, at concentrations spanning 0%–100% (2025) • Demonstrate boil-off rates below 0.1% in all liquid-H_2 systems (2025)
	Develop and validate innovative approaches to improve efficiency of liquid tanker-based pathways (e.g., to mitigate boil-off during transfers)	C, E, LC	
Hydrogen Fueling Stations for Transportation	Increase throughput and expand supply chain for dispensing components (e.g., nozzles, hoses, chillers, and balance of plant)	C, M	• Enable H_2 fill rates averaging at least 10 kg/min over the duration of the fill, a 5X increase relative to current methods (2025) • Enable up to 10X increase in throughput of liquid pumps (2030) • Enable up to 20X increase in rate of high-pressure (875-bar) hydrogen compression (2030)
	Develop high-throughput, low-boil-off cryopumps that vaporize and pressurize liquid hydrogen	C, E	
	Develop high-throughput mechanical compressors to meet heavy-duty fueling requirements through novel engineering design	C, D	
Near- to Mid-Term Hydrogen Storage Options			
Compressed Gaseous Hydrogen Storage	Develop advanced high-strength, low-cost carbon fiber composites	C, D ,E	• Lower the cost of carbon fiber by 50%, with sufficient properties for use in 700-bar H_2 tanks (2026) • Reduce total cost of compressed-H_2 storage systems to $9/kWh (2030)
	Reduce costs of metal tanks and balance of plant through manufacturing innovations	C, M	
	Materials RD&D and engineering to enable low-cost, bulk storage and transport	C, D, E, M	
	Identify optimized tank configurations and capacities to address volume and weight challenges for various use cases	C, D, E, M, S	
	Identify optimized configurations and end-use applications for liquid hydrogen storage	C, D, E, S, LC	

Overlapping RD&D In Areas Common to Delivery and Storage			
Gaseous Storage	Materials RD&D and innovations employing nondestructive evaluation to address vessel life and cost	C, D	• Lengthen lifespan of 875-bar stationary pressure vessels by 50% compared with current state-of-the-art systems (2025)
	Innovations in tank design to reduce precooling requirements at fueling stations, addressing system cost and lifetime	C, D	
Liquid/ Cryogenic Storage	Address challenges in materials compatibility and durability under cryogenic conditions	C, D	• Assess life of materials used in service at temperatures as low as 20°K, and develop strategies for extending their lifespan (2025)
	Develop strategies to mitigate boil-off losses (e.g., transfer methods, chilling components)	C, D	• Validate strategies that reduce boil-off to below 0.1% in all liquid-H_2 systems (2025)
Fueling Methods	Conduct experiments to inform development of fueling methods for heavy-duty applications, in conjunction with HFTO Codes and Standards activities	C, S	• Inform development of fueling methods that enable cost-competitive fueling averaging at least 10 kg/min over the duration of the fill (2030)

Longer-Term Focus Areas

The subprogram's longer-term priorities in hydrogen infrastructure include a focus on advanced technologies for transmission, distribution, and storage (including innovative liquefaction technologies, as well as materials storage and carriers); and next-generation vehicle refueling technologies. Specific RD&D focus areas addressing barriers and challenges are described in Table 4.4. These include areas that overlap both hydrogen delivery and storage and are synergistic with RD&D activities in other HFTO subprograms aimed at advancing hydrogen and fuel cell technologies.

Table 4.4. Infrastructure Focused on Emerging Opportunities and Longer-Term Priorities

Longer-Term Hydrogen Infrastructure Options			
Transmission & Distribution Infrastructure	Develop innovative methods of liquefaction to improve efficiency and reduce capital cost at smaller scales	C, E, LC	• Enable 50% reduction in the energy used during hydrogen liquefaction (2030)
H_2 Fueling Stations for Transportation	Develop novel approaches to hydrogen fueling (e.g., in liquid form, at low pressure, or at higher temperatures than current approaches)	C, D	• Validate hydrogen delivery and dispensing at $2/kg based on new approaches (2030)
Longer-Term Hydrogen Storage Options			
Materials-Based Storage (Metal Hydrides / Adsorbents)	Develop improved low-cost materials and engineered systems optimizing material capacity and reversibility	C, D, E	• Increase the energy density of current state-of-the-art storage materials by 2X (2030)
	Design materials and engineered systems tailored to application-specific requirements for temperature and pressure for H_2 charge/discharge	E	
	Develop engineered systems addressing application-specific requirements on H_2 discharge/fueling times	C, E	
Longer-Term Overlapping RD&D			
Hydrogen Carriers	Identify and develop carriers with hydrogen capacity, reversibility, and cost optimized for specific end uses (e.g., bulk storage at an industrial facility, bulk hydrogen distribution)	C, D, E, LC, S	• Identify seven carrier materials and associated processes for bulk hydrogen transport and storage (2030) • Develop carriers with capacities and overall efficiencies exceeding conventional compressed-H_2 or liquid-H_2 delivery systems (2030)
	Improve efficiency and cyclability of hydrogenation/dehydrogenation systems to enable commercial viability	E	

Crosscutting

In addition to the focus areas described in Tables 4.3 and 4.4, the subprogram also conducts crosscutting RD&D that is synergistic with activities in other HFTO subprograms and that supports broad strategic priorities relevant to the advancement of clean hydrogen and fuel cell technologies. Examples are included in Table 4.5.

Table 4.5. Hydrogen Infrastructure Crosscutting RD&D activities

Crosscutting RD&D	Barriers Addressed	Key Milestones
Develop standardized testing and validation procedures and protocols	D, E	• Ensure public access to integrated modeling tools to evaluate hydrogen infrastructure across production and end-use scenarios (2024) • Validate achieving hydrogen fuel cost targets for MD/HD transportation of $7/kg (2028) and $4/kg (2031)
Develop low-cost, high-throughput, high-quality manufacturing techniques	M	
Perform application-specific techno-economic analysis and life cycle assessments to inform RD&D priorities	C, LC	
Ensure adherence to rigorous safety standards and protocols	S	
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

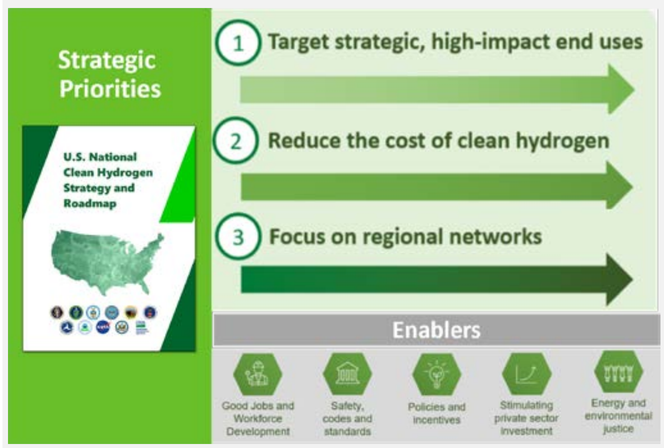
5 Fuel Cell Technologies

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

[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.

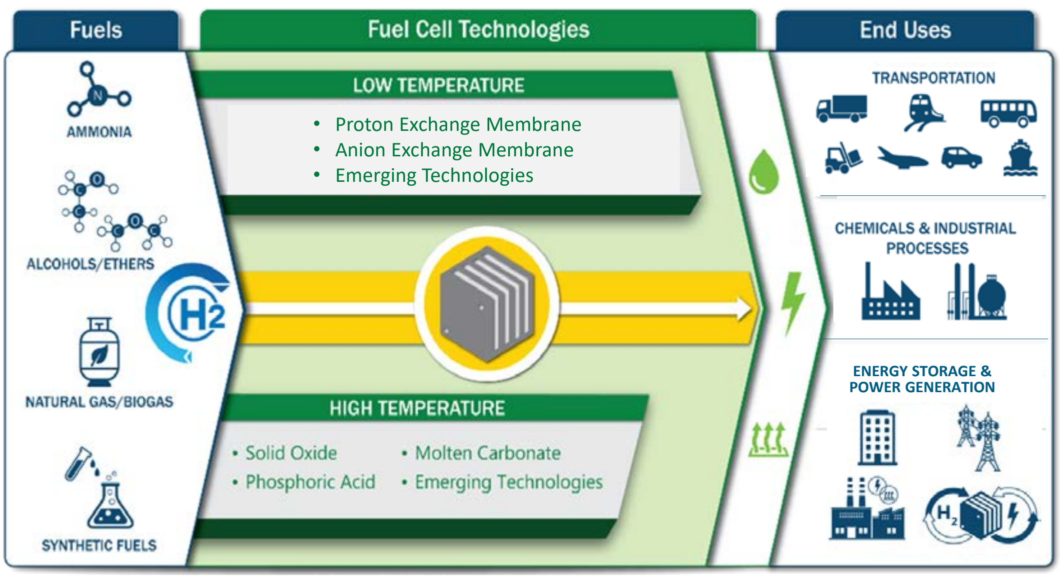


Figure 5.1. Versatility of diverse fuel cell technologies that convert clean hydrogen or other fuels into electricity, heat, and water for various high-impact end uses

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.

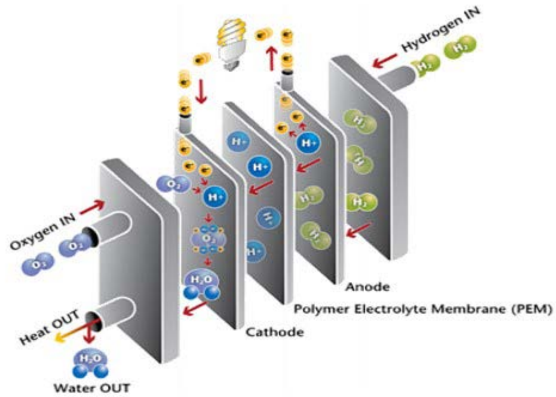


Figure 5.2. Basic operation of a PEM fuel cell, important to near-term high-impact end uses. Additional cells are stacked for more power in a fuel cell system.

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).

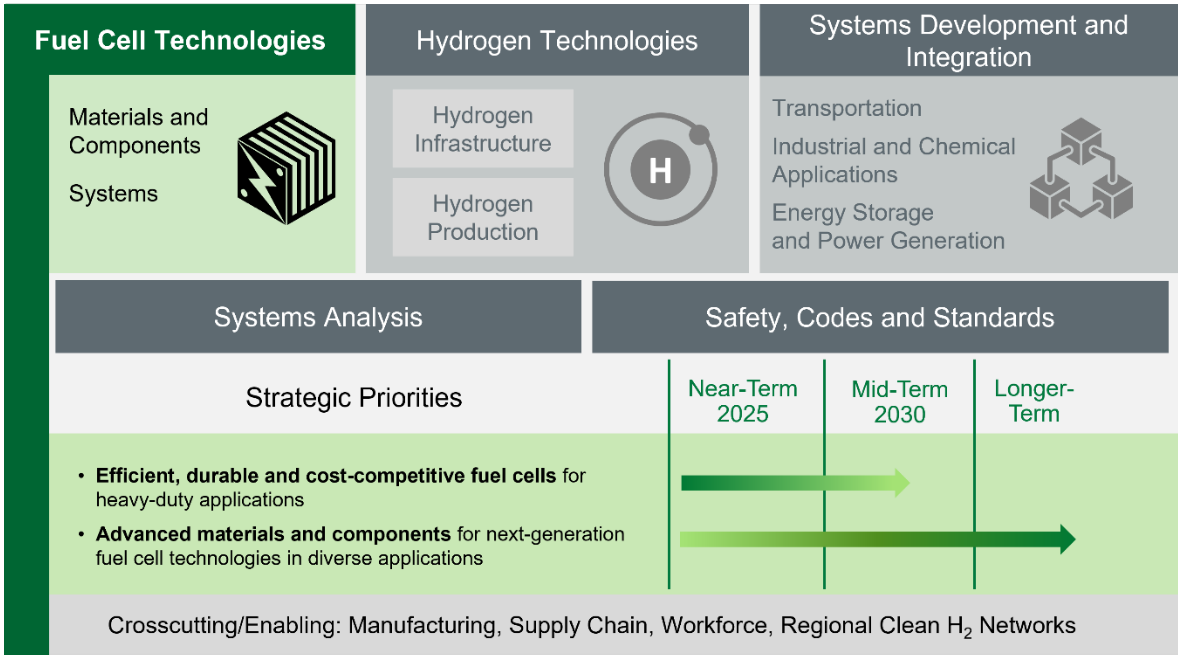


Figure 5.3. Strategic priorities guiding Fuel Cell Technologies RD&D

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.

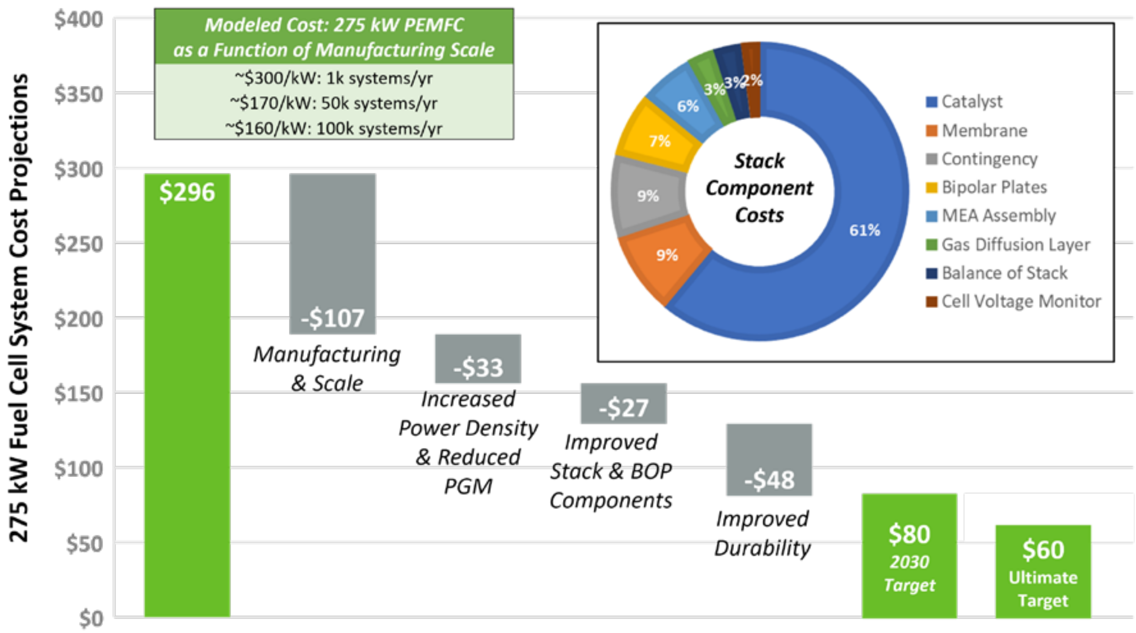


Figure 5.4. A pathway to achieve the 2030 and ultimate cost targets for a heavy-duty fuel cell vehicle system, specifically showing how RD&D can help achieve the target (based on recent analysis)

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.

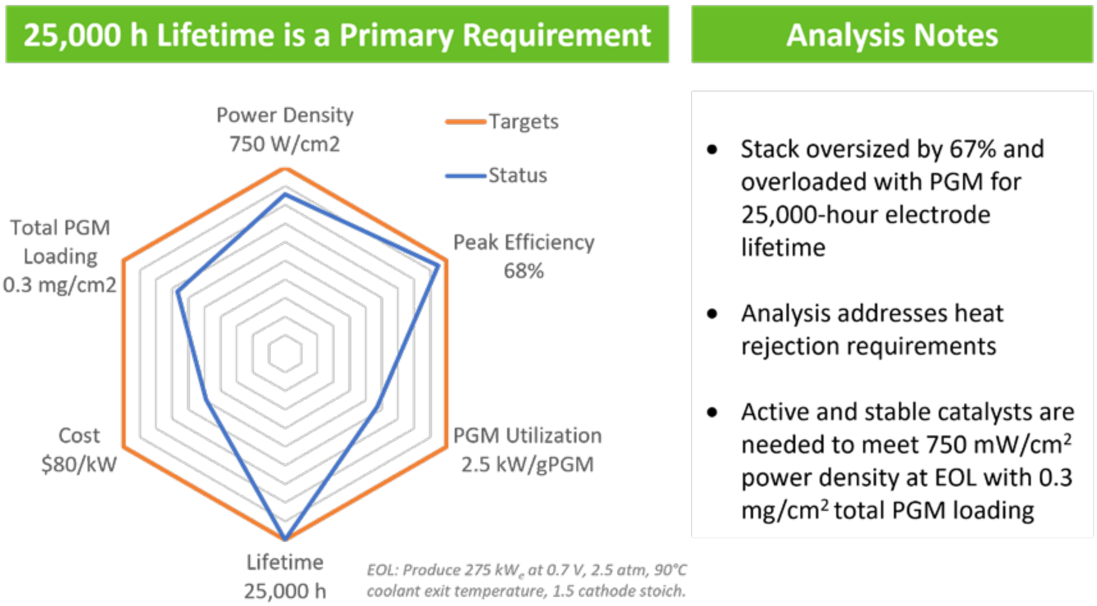


Figure 5.5. Illustrative spider chart for fuel cell system status versus targets. The line indicates the status as a fraction of the targets, from recent analysis assuming a stack oversized and overloaded with PGM meeting the 25,000-hour lifetime.

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.

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

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).

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

[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/cm²	• Cost $80/kW • Durability 25,000 h • Peak efficiency 68% • PGM loading ≤0.3 mg/cm²	• Cost $60/kW • Durability 30,000 h • Peak efficiency 72% • PGM loading ≤0.25 mg/cm²
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.

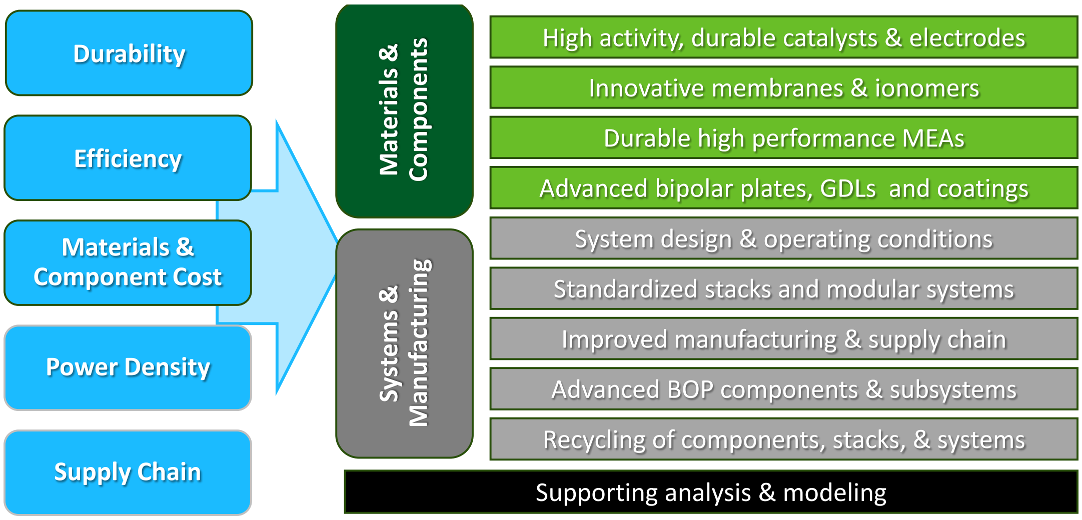


Figure 5.6. Comprehensive RD&D addressing fuel cell materials and components, as well as systems and manufacturing

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.

[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 — MILLION MILE FUEL CELL TRUCK — U.S. DEPARTMENT OF ENERGY

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 — Electrocatalysis Consortium

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

ROLL TO ROLL CONSORTIUM — U.S. DEPARTMENT OF ENERGY

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.

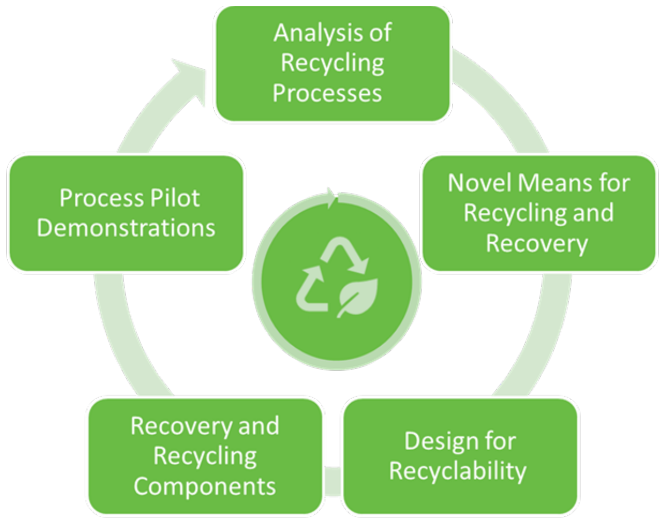


Figure 5.7. The holistic approach to address RD&D for recycling PEM fuel cells

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.

[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

<table>
<tr><th>RD&D Focus Areas</th><th>Barriers Addressed</th><th>Key Milestones</th></tr>
<tr><td colspan="3">Heavy-Duty Transportation</td></tr>
<tr><td>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</td><td>C, D, E</td><td rowspan="4">• 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)</td></tr>
<tr><td>Develop extremely durable, high mass-activity low-PGM catalysts to enable competitive fuel cell lifetime, efficiency, and cost</td><td>C, D, E,</td></tr>
<tr><td>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</td><td>C, D, E, LC</td></tr>
<tr><td>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</td><td>C, D, E, LC</td></tr>
</table>

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 $\mu A/m^2$ 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)

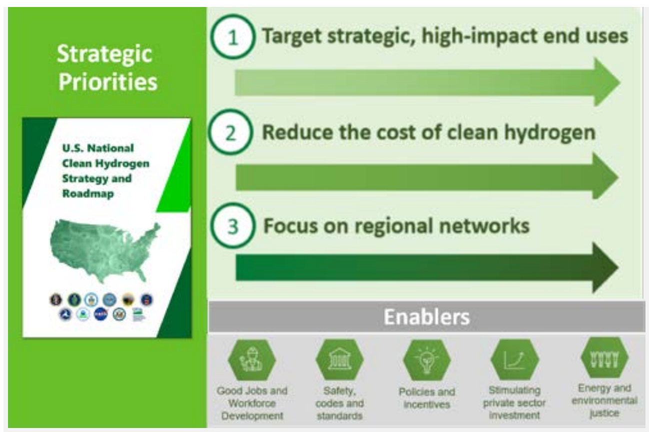
Leverage activities and work in partnership with minority-serving institutions and Tribal Nations, and engage with labor organizations for workforce development	LC	Provide training opportunities to over 50 minority-serving institution students, including from Tribal Nations, on hydrogen and fuel cell 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

6 Systems Development and Integration

6.1 Overview

Goals and Objectives

The **Systems Development and Integration** (SDI) subprogram conducts targeted hydrogen and fuel cell systems integration and demonstration activities to enable the **H2@Scale**[55] vision, supporting the ***U.S. National Clean Hydrogen Strategy and Roadmap*,**[56] and aligned with opportunities identified in the ***Pathways to Commercial Liftoff: Clean Hydrogen***[57] report. SDI coordinates closely with the other HFTO subprograms in the RD&D of hydrogen and fuel cell technology subsystems and systems integration. It also collaborates with other DOE offices, including collaborations with OCED on the Regional Clean Hydrogen Hubs program, as described in the Bipartisan Infrastructure Law.[58] The Clean Hydrogen Hubs provision in the law aims to enable the demonstration and development of networks of clean hydrogen producers, potential consumers, and connective infrastructure. The hubs themselves aim to advance the production, processing, delivery, storage, and end-use of clean hydrogen, enabling sustainable and equitable regional benefits, as well as market liftoff.



Supporting national decarbonization priorities, integrated energy systems leveraging clean hydrogen and fuel cell technologies in high-impact end uses are foundational to the H2@Scale vision and are core to the success of regional clean hydrogen networks.

The overarching goals of the SDI subprogram are to validate R&D innovations at a systems level under real-world conditions, determine gaps to help guide R&D programs, identify and demonstrate new and promising integrated energy systems for various end uses of clean hydrogen, and inform larger scale demonstration and deployment programs. The subprogram directly supports the strategic priority to target high-impact end uses and includes a portfolio of activities in transportation, industrial and chemical uses, as well as energy storage and power generation, including grid integration.

[55] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.
[56] 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.
[57] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/clean-hydrogen/.
[58] Infrastructure Investment and Jobs Act. Public Law 117–58. 2021. Section 40314, (42 U.S.C. 16161c). https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

Specific objectives include validating the performance of integrated hydrogen and fuel cell technologies; enabling cost reductions through economies of scale; and expediting private-sector commercialization. In support of these objectives, the SDI subprogram:

- Identifies hydrogen applications and system configurations that can provide affordable, reliable, and beneficial uses of clean hydrogen, aligned with national goals.
- Bridges the gaps between component-level RD&D and commercialization by integrating technologies into functional systems in first-of-a-kind demonstrations.
- Tests and validates integrated energy systems under actual and/or simulated real-world operating conditions, providing valuable feedback to guide RD&D priorities in hydrogen and fuel cell technologies.
- Generates data on integrated energy systems used in techno-economic assessments of market readiness relevant to manufacturers, investors, and potential end users.
- Coordinates with crosscutting and enabling activities (including systems analysis; safety, codes and standards; workforce development, supply chain development, and manufacturing RD&D) to accelerate pathways to commercialization and deployment.
- Coordinates with other programs and offices to foster activities promoting environmental justice, safety, and environmental stewardship.

Figure 6.1 illustrates how SDI helps bridge the gap between RD&D and deployments with first-of-a-kind demonstrations, including integrated clean hydrogen systems. The subprogram's project portfolio includes work to validate individual hydrogen or fuel cell technologies, as well as efforts to integrate multiple technologies into a system for evaluation in real-world environments. Results from these tests are used to assess the commercial readiness of the technology/system for the end users. The demonstration data are also supplied to the hydrogen and fuel cell RD&D teams and to the Systems Analysis subprogram. The feedback helps the subprograms to refine the technologies, analyze and model the results, and set new technical targets. The SDI subprogram also works closely with the enabling activities to allow for safe demonstrations and to identify manufacturing and workforce needs for commercialization of the technologies.

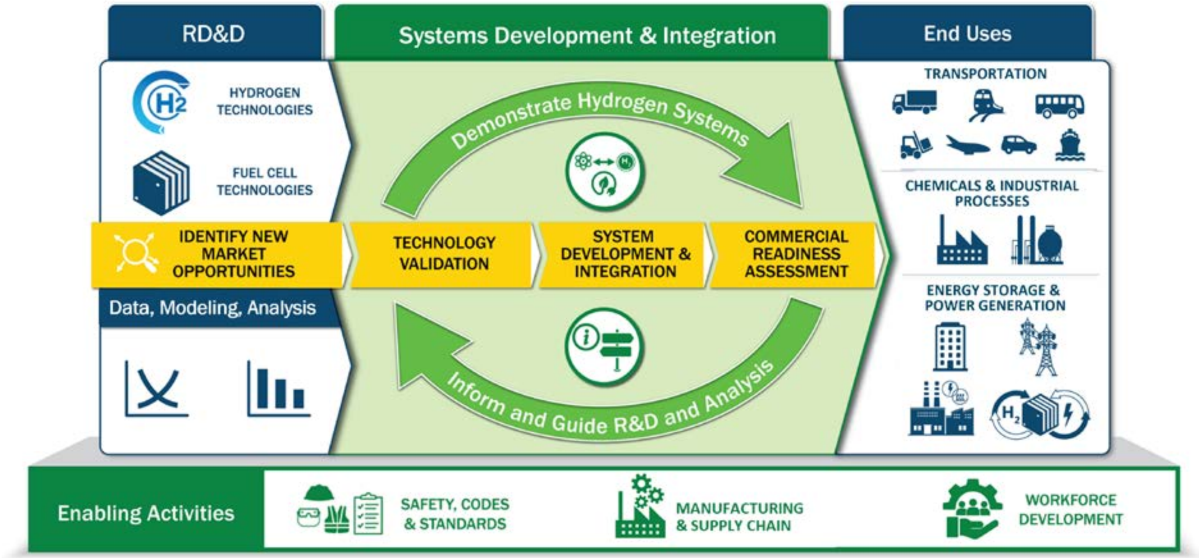


Figure 6.1. The Systems Development and Integration subprogram conducts technology and systems integration and validation activities to advance hydrogen and fuel cell commercialization and to provide data that feeds back to further guide hydrogen and fuel cell technologies RD&D

Technology Applications

The SDI subprogram focuses its activities on key emerging markets and technology applications relevant to the H2@Scale vision, illustrated in Figure 6.2, focusing particularly on high-impact end uses.

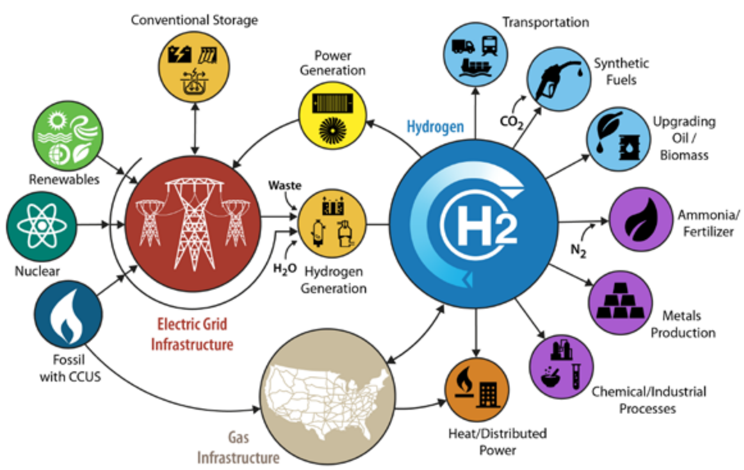


Figure 6.2. DOE's H2@Scale initiative to enable decarbonization across sectors using clean hydrogen

These high-impact end uses fall under three broad technology application areas:

SDI Focus Areas

Transportation and H_2 fueling demonstrations, including heavy-duty applications

Chemical and Industrial Processes integrating H_2 technologies, focusing on decarbonization

Energy Storage and Power Generation, including innovative hybrid energy systems

- **Transportation** applications include medium- and heavy-duty trucks, maritime, rail, offroad equipment, and other heavy-duty applications requiring significant power, range, and up-time. These applications also support the *U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation*.[59]
- **Chemical and industrial** applications include integrating clean hydrogen technologies into hard-to-decarbonize industrial sectors such as steel manufacturing and ammonia synthesis. These applications align with the DOE *Industrial Decarbonization Roadmap*.[60] Applications also include clean hydrogen as a feedstock in processing biomass to support the DOE Clean Fuels and Products Shot[61] and clean hydrogen in high-heat industrial processes, supporting the DOE Industrial Heat Shot.[62]
- **Energy storage and power generation** applications focus on grid integration and direct coupled renewable and nuclear hybrid systems, as well as distributed and backup power generation. These applications align with the DOE Long Duration Storage Shot[63] and the DOE Grid Modernization Initiative.[64]

6.2 Strategic Priorities

As shown in Figure 6.3, the SDI subprogram's strategy incorporates near-, mid-, and longer-term focus areas, aligned with national clean hydrogen priorities, and consistent with HFTO's overall strategic framework described in the Introduction. While there are near-term opportunities to address development and integration of hydrogen and fuel cell systems across all technology application areas (particularly in the heavy-duty transportation applications), it is expected that

[59] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.
[60] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. September 2022. https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[61] Office of Energy Efficiency and Renewable Energy. "Clean Fuels & Products Shot™: Alternative Sources for Carbon-Based Products." https://www.energy.gov/eere/clean-fuels-products-shottm-alternative-sources-carbon-based-products.
[62] Office of Energy Efficiency and Renewable Energy. "Industrial Heat Shot." https://www.energy.gov/eere/industrial-heat-shot.
[63] Office of Energy Efficiency and Renewable Energy. "Long Duration Storage Shot." https://www.energy.gov/eere/long-duration-storage-shot.
[64] U.S. Department of Energy. "Grid Modernization Initiative." https://www.energy.gov/gmi/grid-modernization-initiative.

the subprogram's RD&D activities in all high-impact end uses will continue into the mid- or long-term, to the point that industry commercialization has proven to be viable. Supporting the RD&D, enabling activities—including manufacturing RD&D, supply chain development, workforce development, and safety, codes and standards—fill out an integrated portfolio addressing challenges throughout all the phases of research, technology development, integration, demonstration, and commercial deployment.

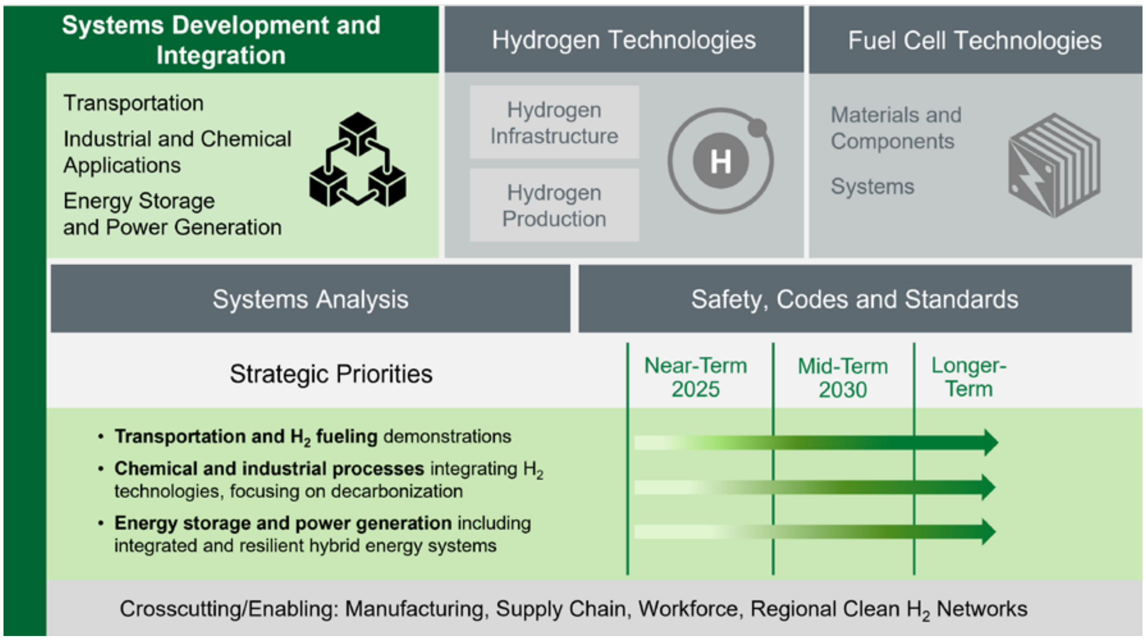


Figure 6.3. Strategic priorities guiding Systems Development and Integration RD&D

The three application categories shown in Figure 6.3 align with the near- to longer-term phases of clean hydrogen end-use adoption shown in Figure 6.4, reproduced from the *U.S. National Clean Hydrogen Strategy and Roadmap* and described in more detail below. The subprogram supports strategically targeted projects in these categories aimed at accelerating market adoption through technology validation and first-of-a-kind demonstrations of integrated systems. Developments and learnings from the projects in each category can often be applied to the others, and also provide valuable feedback to RD&D technology areas in other HFTO subprograms.

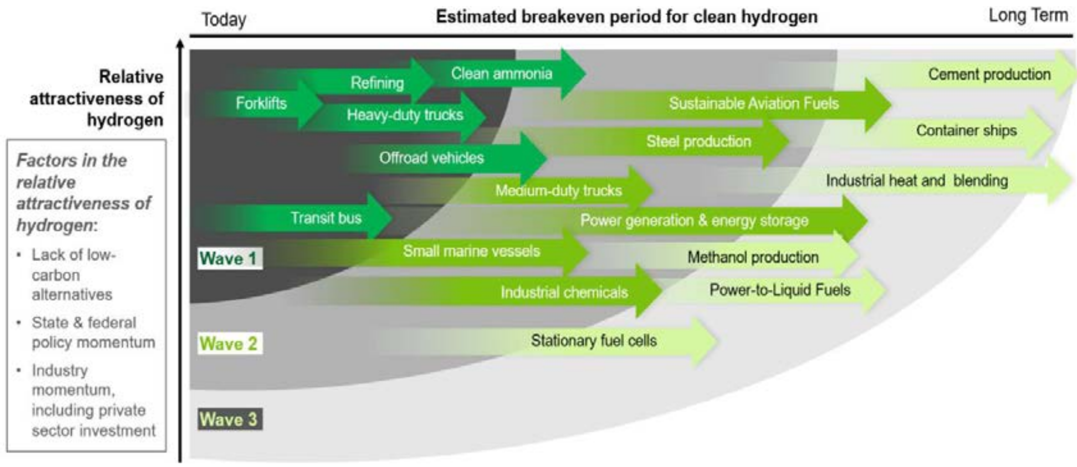


Figure 6.4. Clean hydrogen will be developed in waves, based on the relative attractiveness in each end-use application. Arrows depict the time frame when hydrogen is expected to be competitive with incumbent technologies at scale throughout the United States.

Transportation

Transportation activities focus on demonstrating medium- and heavy-duty fuel cell trucks and on low-cost, high-flow hydrogen fueling infrastructure that can be deployed in zero-emissions transportation corridors. The objective of these SDI projects is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow fueling to support these transportation modes. Analysis will be conducted to determine total cost of ownership and to define future requirements needed to compete with incumbent technologies.

In the near term, SDI projects in the transportation space will focus on accelerating commercial viability and adoption of medium and heavy-duty fuel cell electric trucks operating on clean hydrogen. The impact of these projects will reduce emissions and improve the energy and operational efficiency of moving freight while still providing operating range and fueling times on par with incumbent technologies. Technology advances will include optimized hybridization strategies, long-duration fuel cell systems, thermal management, onboard storage, and high-flow hydrogen fueling. In addition, new market opportunities for hydrogen and fuel cells in the other ultra-heavy-duty transportation sector such as marine, rail, and offroad equipment will continue to be evaluated. Transportation activities will be coordinated with EERE's Vehicle Technologies Office.

Chemical and Industrial Processes

Within hard-to-decarbonize chemical and industrial processes, SDI focuses on demonstrating the ability of clean hydrogen to be used as a feedstock (e.g., ammonia and synthetic aviation fuel production) or direct reducing agent (e.g., steel and float glass production) or to provide process heat (e.g., steel and cement production). The subprogram will coordinate these activities with EERE's Industrial Efficiency and Decarbonization Office, as well as other DOE offices such as Fossil Energy and Carbon Management, Nuclear Energy, and OCED.

One of the most promising industrial applications to decarbonize with clean hydrogen is iron and steelmaking, which is an essential segment of the U.S. economy. In iron and steelmaking processes, syngas (a blend of carbon monoxide and hydrogen) has potential to be used in direct iron ore reduction. Several RD&D and demonstration projects worldwide, including some in the U.S. funded through SDI, are exploring the use of clean hydrogen in iron ore refining. To validate technical and economic requirements in U.S. markets, additional demonstrations of iron ore reduction using hydrogen can assist enabling economies of scale for hydrogen, while ensuring higher energy efficiency compared to conventional blast furnaces.

In the chemical industry, the *DOE Industrial Decarbonization Roadmap* notes that using hydrogen as a feedstock provides an important option for decarbonizing the chemical industry. Clean hydrogen can serve as a precursor to provide a low-carbon route to methanol, ammonia, hydrazine, and other compounds that serve as feedstocks for other chemicals and fuels (e.g., sustainable aviation fuels).

Energy Storage and Power Generation

Hydrogen and fuel cells can be incorporated into existing and emerging energy and power systems to avoid curtailment of variable renewable sources such as solar and wind; enable a more optimal capacity utilization of baseload nuclear, as well as natural gas and other hydrocarbon-based plants; provide voltage and frequency stabilization support for the electric grid; and/or provide clean, reliable distributed and backup power generation. The use of hydrogen for energy storage can play a key role in these systems.

SDI projects in this application space will help enable the production, storage, and/or transport of low-cost clean hydrogen from intermittent and curtailed renewable sources, while providing grid reliability and dynamic response to match grid demands. They will also support market penetration of renewable energy systems such as wind and solar, and they will help provide additional revenue streams for nuclear power plants by producing clean hydrogen with otherwise curtailed power when power prices are low.

6.3 RD&D Targets

Target Setting

The SDI subprogram has adopted a holistic target-driven approach to achieve life cycle cost parity of hydrogen and fuel cell technologies with incumbent and emerging systems across diverse high-impact end uses under different demand scenarios. Figure 6.5 depicts scenarios for the demand projected for specific end-use sectors if clean hydrogen is available (produced, delivered, and dispensed) at the threshold price shown. For instance, approximately $5/kg for hydrogen produced, delivered, compressed, and dispensed would pave the way for early adopters in the fuel cell truck market. At DOE's 2030 target of approximately $4/kg,[65] scenario analyses have shown that 10 to 14% of all medium- and heavy-duty fuel cell trucks would demand about 5 to 8 MMT of hydrogen per year. The lighter shaded bars represent a more optimistic demand scenario for each market shown.

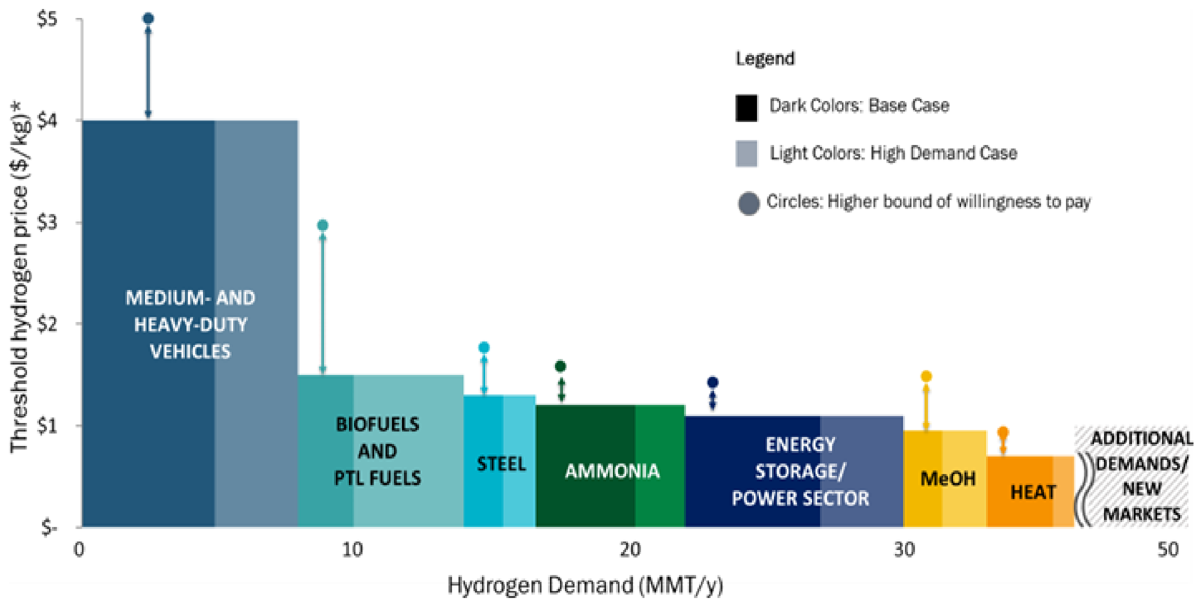


Figure 6.5. Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost

The subprogram develops technology- and system-level performance targets based on the application-specific threshold price ranges, specifically to guide and prioritize RD&D in areas that incentivize clean hydrogen adoption across the different sectors. These targets were developed using sophisticated techno-economic analysis with input from industry stakeholders and are updated regularly based on the latest data; they are used to guide subprogram activities and collaborations in systems integration, verification, and validation (including support of the Regional Clean Hydrogen Hubs).

[65] Satyapal, Sunita. June 5, 2023. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/plenary1_satyapal_2023_o.pdf. (slide #28)

End-Use Specific Targets

The SDI subprogram coordinates with other HFTO subprograms and DOE offices to address specific targets in alignment with DOE clean energy and decarbonization priorities in transportation, chemicals and industry, and energy storage and power generation.

> **Key DOE Target Examples Relevant to Systems Development and Integration**
>
> - 90% cost reduction in energy storage systems with 10+ hour duration by 2031
> - 100% clean electricity grid by 2035
> - 85% lower GHG emissions for industrial heat applications by 2035
> - 85% lower GHG emissions in clean fuels and products compared to fossil products by 2035
> - Conduct research and demonstrations of clean hydrogen refueling technologies to support the commercialization of trucks and other applications by 2030
> - Develop a flexible and scalable blueprint for a successful hydrogen station corridor that is investment-ready by 2025
> - Ensure that 100% of medium- and heavy-duty federal fleet acquisitions are zero-emissions by 2035

The SDI subprogram specifically works closely with the other HFTO subprograms to develop detailed technical targets for hydrogen and fuel cell technologies that are integrated into systems for commercial implementation. As an example, SDI has worked in concert with the Fuel Cell Technologies subprogram to develop technology targets for hydrogen fuel cells for use in commercial Class-8 long-haul heavy-duty trucks. The fuel cell system design parameter targets take into account the performance, durability, and cost requirements related to the specific drive-cycle and operations associated with this vehicle class. More detailed targets at the component or materials level (e.g., catalyst, membrane, MEA, bipolar plates, BOP components) are developed by the Fuel Cell Technologies subprogram.

Table 6.1 shows DOE's technical system targets for Class 8 long-haul tractor-trailer trucks powered by hydrogen and fuel cells. These targets were developed with input from the 21st Century Truck Partnership to provide the technical foundation for research priorities for hydrogen-fueled long-haul trucks. These hydrogen targets were developed for the long-haul use case, assuming trucks can be driven the maximum daily range (750 miles) between refueling. Additional background and assumptions can be found in the associated Program Record.[66]

[66] Marcinkoski, Jason. October 31, 2019. "Hydrogen Class 8 Long Haul Truck Targets." DOE Hydrogen Program Record #19006. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.

Table 6.1. Technical System Targets for Class 8 Long-Haul Tractor-Trailers (With Detailed Notes and Assumptions)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[i]
Fuel Cell System Lifetime[a, b]	Hours	25,000	30,000
Fuel Cell System Cost[a, c, d]	$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life[e]	Cycles	5,000	5,000
Pressurized Storage System Cycle Life[f]	Cycles	11,000	11,000
Hydrogen Storage System Cost[d, g, h]	$/kWh ($/kg H_2 stored)	9 (300)	8 (266)

[a] The fuel cell system excludes hydrogen storage, power electronics, batteries, and electric drive.
[b] The lifetime target is intended to cover the entire useful life of the vehicle. Fuel cell system lifetime is defined as hours of use with an appropriate duty cycle that considers real-world driving conditions (i.e., not steady-state operation). Corresponding vehicle lifetime range is 1M miles (Interim) and 1.2M miles (Ultimate) based on an average speed of 40 mph.
[c] Interim and ultimate cost targets assume 100,000 units per year production volumes (except where specified within parenthetical references). Note that meeting fuel cell and hydrogen storage component cost targets may require leveraging automotive production volumes to achieve the necessary economies of scale for cost competitiveness. 2019 heavy-duty vehicle fuel cell technology was estimated to cost ~$190/kW at 1,000 units per year manufacturing volume (Fuel Cell Systems Analysis, 2019 DOE Hydrogen and Fuel Cells Program Review Presentation, https://www.hydrogen.energy.gov/pdfs/review19/fc163_james_2019_o.pdf).
[d] Costs are in 2016 dollars.
[e] The storage system cycle life target is intended to represent the minimum number of operational cycles required for the entire useful life of a vehicle used in long-haul operation. This target is technology-agnostic.
[f] Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e., SAE J2579 and United Nations Global Technical Regulation No. 13). These codes and standards cycle life requirements require significantly more cycles than Storage System Cycle Life. For example, the baseline initial pressure cycle life in the United Nations Global Technical Regulation can require 11,000 cycles for a heavy-duty application.
[g] Hydrogen storage system cost includes the storage tank and all necessary BOP components. This target is technology-agnostic.
[h] A 700-bar hydrogen storage system was estimated to cost ~$36/kWh at 1,000 units per year manufacturing volume and $15/kWh at high volume (extrapolated from DOE Hydrogen and Fuel Cells Program Record #15013 "Onboard Type IV Compressed Hydrogen Storage System—Cost and Performance Status 2015," https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/15013_onboard_storage_performance_cost.pdf). Note: Hydrogen storage targets will be updated and are currently based on U.S. DRIVE fuel cell electric vehicle targets.
[i] Analysis based on 2050 simple cost of ownership assumptions and reflects anticipated time frame for market penetration.

DOE's hydrogen fill rate target for Class 8 long-haul trucks listed in Table 6.1 was determined based on the desired filling time comparable to incumbent technologies (i.e., 6 minutes) to deliver approximately 60 kg H_2, which would achieve a 750-mile range assuming a 12.4 mpkg fuel economy. The fueling rate requirements for other applications will depend on onboard hydrogen capacity needed for that specific application and the flow rate that the hydrogen can be dispensed at while also meeting applicable codes and standards. Figure 6.6 shows approximate fill rates required for various transportaton applications powered by hydrogen.

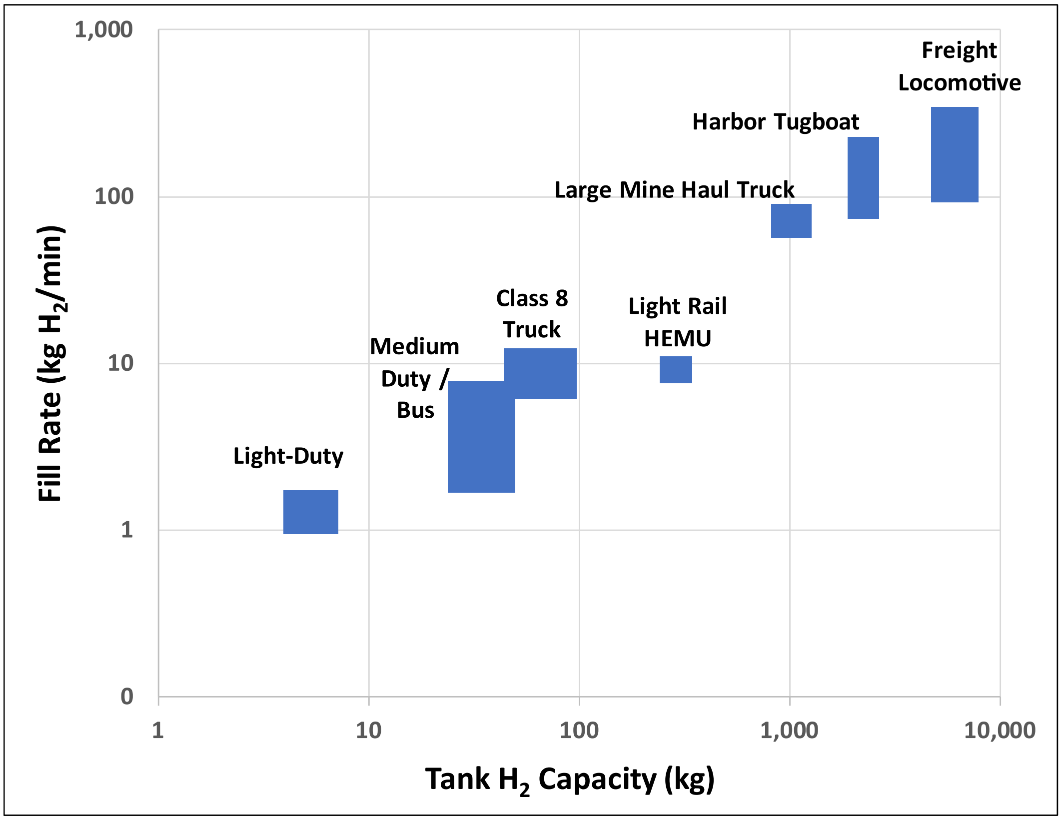


Figure 6.6. Approximate hydrogen fill rates required for various transportation applications

Related to the long-haul truck targets, the SDI and Fuel Cell Technologies subprograms have developed preliminary interim and ultimate targets covering a broader range of ultra-heavy-duty transportation end uses, including ferries, rail, and mining equipment, among others. These are shown in Table 6.2. These targets were developed based on analysis of competitiveness with incumbent technologies in these ultra-heavy-duty end uses; for example, multiple unit rail and passenger ferries are projected to be cost-competitive with incumbent diesel options when ultimate targets in the table have been met, including a clean hydrogen cost of $4/kg H_2.

Table 6.2. System Design Targets for Ferries, Rail, Mining Equipment, and Other Ultra-Heavy-Duty Transportation Applications Powered by Hydrogen Fuel Cells

Characteristic	Units	Interim Target	Ultimate Target
Fuel Cell System Lifetime	Hours	25,000	30,000
Fuel Cell System Cost	$/kW	80	60
Beginning-of-Life Fuel Cell System Efficiency at Rated Power	%	55	55

End-of-Life Fuel Cell System Efficiency at Rated Power	%	50	50
Hydrogen Storage System Cost	$/kWh	9	8
H_2 Storage System Life	Cycles	5,000	5,000
Liquid H_2 Dispensed Cost	$/kg	7	4

In addition to targets for heavy-duty and ultra-heavy-duty transportation applications, the SDI subprogram continues to develop and refine targets in other high-impact end uses, including those in the industry and chemicals application areas, as well as the energy storage and power generation applications. The technology baselines and targets in all areas are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

For example, the SDI subprogram is also supporting projects that address the Hydrogen Production Technical Targets for Electrolyzer Stacks and Systems shown below in Table 6.3 through validation of electrical efficiency improvements leading to lower hydrogen production costs. [67]

Table 6.3. Hydrogen Production Technical Targets for Electrolyzer Systems

Technology	Characteristic	Units	Baseline	2026 Target	Ultimate Target
PEM	Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	51 (65%)	46 (72%)
Liquid Alkaline	Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	52 (64%)	48 (70%)
High-Temperature Electrolysis	Energy Efficiency[a]	kWh/kg H_2 (% LHV)	47 (71%)	44 (76%)	42 (79%)

[a] Includes both electrical and thermal energy inputs. The difference between "electrical efficiency" and "energy efficiency" values is the thermal energy input.
LHV: lower heating value.

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

[67] Office of Energy Efficiency and Renewable Energy. "Water Electrolyzer Technical Targets." https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links#targets.

6.4 Addressing Challenges

While technical and economic challenges related to hydrogen production, delivery, storage, and conversion technologies are addressed through ongoing RD&D in other HFTO subprograms, the SDI subprogram addresses important component and integrated system issues aimed at achieving performance targets under real-world operating conditions at scale and enabling market adoption across sectors.

Systems Integration Challenges

Hydrogen and fuel cell technologies offer a number of opportunities to provide value to diverse sectors through their integration into hybrid energy systems, which are broadly defined as systems that integrate functions, components, or cross-sector applications such as electricity generation, energy storage, and/or energy conversion technologies through an overarching control framework to achieve enhanced capabilities, value, and/or cost savings compared to the standalone alternatives.[68] Figure 6.7 illustrates an example where electrolyzers and fuel cells can be integrated into an energy system powered by multiple generation sources and serving multiple end uses. Demonstrating these complex first-of-a-kind systems presents technical, system integration, and scale-up challenges.

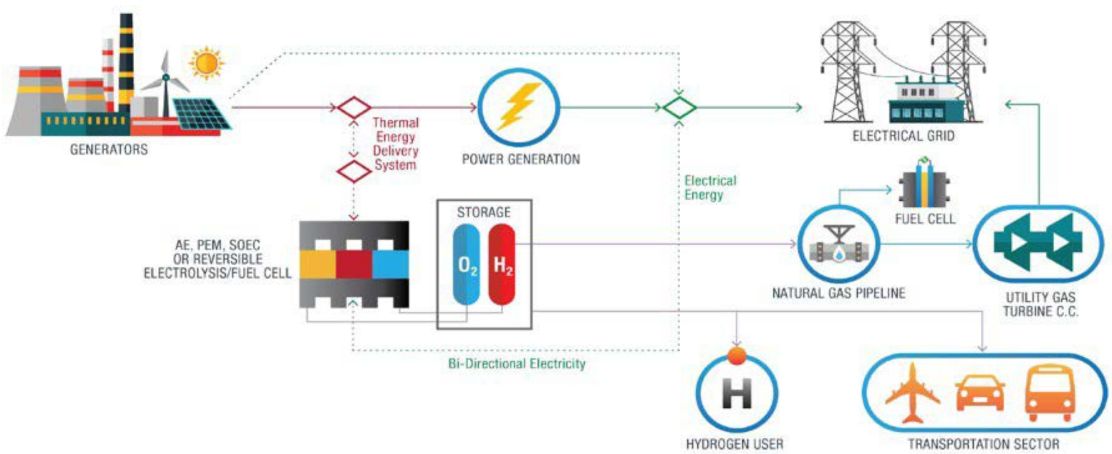


Figure 6.7. Diagram of a generalized hybrid energy system enabled by hydrogen and fuel cell technologies, leveraging multiple generation sources with potential service to multiple end uses

68 Office of Energy Efficiency and Renewable Energy. "Hybrid Energy Systems: Opportunities for Coordinated Research." https://www.energy.gov/eere/analysis/hybrid-energy-systems-opportunities-coordinated-research.

Example Challenges in Systems Integration

- Development of rigorous application-specific targets for hydrogen utilization
- Cost, durability, reliability, and efficiency in industrial-scale electrolyzers, fuel cell systems integrated into hybrid energy systems
- Component- and system-level integration and optimization, including BOP components and subsystems
- Optimized controls of integrated systems, including cybersecurity
- Affordable manufacturing and scale-up, including process intensification
- Safe use of materials, components, and subsystems requiring hydrogen use under pressure and/or temperature in diverse end uses
- Harmonized codes and standards, including refueling protocols
- System-level life cycle assessments of environmental and social impacts

While integrated hybrid energy systems with hydrogen and fuel cell technologies offer benefits across sectors, this can come at the expense of added complexity and potentially higher capital and operations costs. Systems integration must provide performance and durability at scale, while addressing complex challenges associated with integrating components, and subsystems for hydrogen use in different applications. In addition to effective management and controls of interdependent mechanical, electrical, electrochemical, and thermal functionalities in such systems, materials compatibility in hydrogen services at required temperatures and/or pressures must be addressed, as well as overall system safety. Continued RD&D and related enabling activities are needed to develop and demonstrate cost-competitive integrated systems that are efficient, durable, and safe. These include optimized component and subsystem integration schemes; innovations in manufacturing to enable scale-up and help address supply chain bottlenecks; data and information sharing in hydrogen safety awareness; and specialized workforce development meeting diverse end-use needs.

Diverse Cross-Sectoral Opportunities

There are many examples of integrated energy systems incorporating hydrogen and fuel cell technologies, each with its own set of end-use requirements, challenges, and opportunities. Tri-generation technologies refer to systems where hydrogen, electricity, and heat are produced; the high efficiency and low emissions of local production of hydrogen, electricity, and heat may make tri-generation systems a bridge technology for introducing and sustaining hydrogen infrastructure. An example of an integrated hybrid system in the transportation sector includes heavy-duty vehicles that incorporate hydrogen fuel cell systems (including hydrogen storage, electrical and thermal management, etc.) as well as batteries to meet energy capacity and dynamic response requirements of the respective drive cycles. Another example is a hydrogen emergency relief vehicle including hydrogen storage and fuel cells for providing load-following exportable power. In the industrial and chemicals space, systems integrating clean hydrogen production and/or storage with processes for steel production or ammonia synthesis offer an important strategy for decarbonization. In the energy storage and power generation sectors, integrated energy systems incorporating hydrogen and fuel cell technologies offer unique benefits in both on-grid and off-grid applications. Examples include mid- to long-duration/seasonal energy storage; grid leveling and stabilization services; and highly reliable backup power, e.g., for data centers.

Comprehensive Approach

To address the challenges across hydrogen and fuel cell technologies in integrated systems across end uses, the SDI subprogram supports a portfolio of RD&D projects implemented through funding mechanisms described in the Program Implementation section. This portfolio is closely coordinated with activities in the other HFTO subprograms and across the DOE Hydrogen Program,[69] as illustrated in Figure 6.8. The SDI subprogram supports first-of-a-kind demonstrations; it is critical that lessons learned from those demonstrations are fed back to the applied research programs so that innovative solutions are developed to challenges identified in the demonstrations.

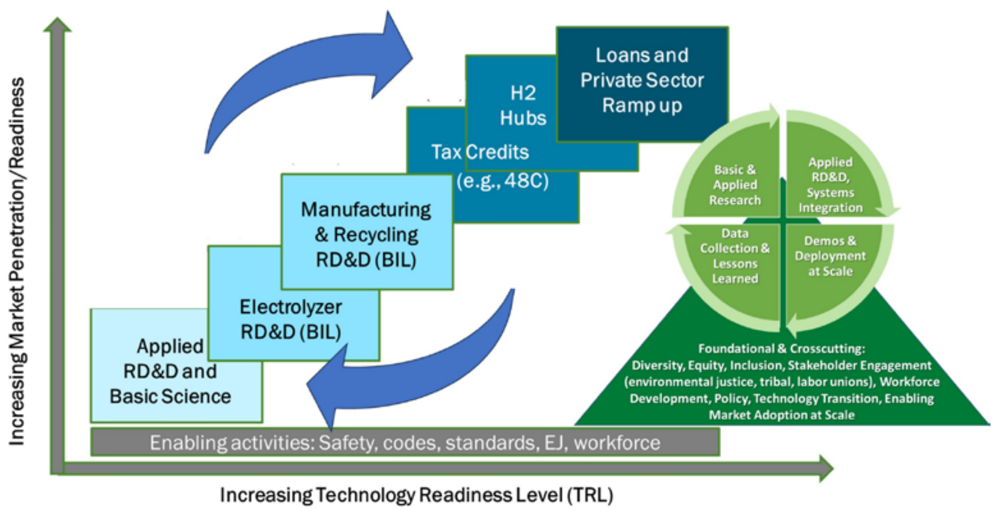


Figure 6.8. SDI integrates hydrogen and fuel cell technologies into systems that are validated in real-world conditions, through first-of-a-kind demonstrations, enabling commercial deployments (e.g., in the Regional Clean Hydrogen Hubs).

The SDI subprogram identifies potential end-use applications and uses hydrogen and fuel cell system components to assemble an integrated system that meets end-user needs. The system undergoes testing and evaluation during assembly and is then taken to the field or laboratory proving site for validation of the integrated technologies; this can include integration with actual

[69] U.S. Department of Energy. "Hydrogen Program." https://www.hydrogen.energy.gov/.

components (such as wind turbines or nuclear plants), or with virtual hardware-in-the-loop. The first-of-a-kind demonstration of the integrated system is then tested and evaluated under real-world operating conditions. Data collection is used to analyze system performance and durability, which in turn provides valuable feedback for continued optimization at the component, subsystem, and system levels, including through RD&D prioritization in SDI and the other HFTO subprograms.

In addition to the close coordination within HFTO and DOE's Hydrogen Program, SDI also works closely with other DOE offices and with other federal agencies. As examples, the SDI team works closely with OCED on the implementation of the Regional Clean Hydrogen Hubs including the gathering of data and lessons learned to help inform future RD&D priorities within SDI and HFTO. In addition, industrial decarbonization RD&D leveraging hydrogen and fuel cell technologies is coordinated with DOE's Industrial Efficiency and Decarbonization Office, and manufacturing innovations are coordinated with the DOE Advanced Materials and Manufacturing Office. Outside of DOE, SDI engages with the Hydrogen Interagency Taskforce to help ensure that clean hydrogen activities are well coordinated across federal agencies and also participates in key partnerships with private-sector and nonprofit stakeholders to ensure that the RD&D efforts of government, academia, and industry are well aligned, their diverse capabilities are well integrated, and their resources are effectively utilized. Examples of successful partnerships have included U.S. DRIVE,[70] the 21st Century Truck Partnership,[71] and the H2@Scale project consortium.[72]

H2@Scale℠ U.S. Department of Energy

Stakeholders participate in cooperative research and development agreement (CRADA) projects with DOE's national laboratories in support of H2@Scale, leveraging world-class laboratory capabilities in systems integration and demonstration including NREL's Advanced Research on Integrated Energy Systems, or ARIES, platform.

6.5 RD&D Focus Areas

Technical and economic barriers common to the challenges addressed by the Systems Development and Integration subprogram include *Cost; Durability/Reliability; Efficiency/Performance; Life Cycle/Sustainability; Systems Integration; Safety, Codes and Standards; Manufacturing/Scale-Up; and Operations Support*. These barriers are summarized in Table 6.4 with some application-specific examples of the associated challenges related to components, subsystems, and/or systems.

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[70] Vehicle Technologies Office. "U.S. DRIVE." https://www.energy.gov/eere/vehicles/us-drive.
[71] Vehicle Technologies Office. "21st Century Truck Partnership." https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.
[72] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.

Table 6.4. Systems Development and Integration Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost *components, subsystems, systems*	• Validated data on total cost of ownership compared with incumbent and emerging technologies • Standardized/modular designs to achieve economies of scale for multiple applications • Operations, maintenance, and replacement costs • Feedstock costs • Siting and permitting costs
D: Durability & Reliability	• System reliability and lifetime under real-world, dynamic operating conditions
E: Efficiency/Performance	• System operating performance that meets all targets/requirements under real-word, dynamic operating conditions • Fuel cell and hydrogen storage performance necessary to meet performance and range for transportation applications • Hydrogen refueling rate • Round-trip efficiency
LC: Life Cycle Impacts / Sustainability	• Validated data on life cycle environmental impacts • Standard recycling/disposal processes for sustainable use of critical materials
SI: Systems Integration	• Integration of electrolyzers with various power sources including the grid, behind-the-meter renewables, and nuclear (including both low- and high-temperature electrolyzers) • Data on large-scale hydrogen production from renewable resources: operational, dynamic response, cost, durability, and efficiency • Integration of hydrogen and fuel cells into industrial processes (e.g. steel, ammonia) needs to be developed to assess energy efficiency and potential emissions reduction • Integration of hydrogen fuel cells and hydrogen storage systems into transportation applications • Thermal and electrical integration of various systems including required power electronics and thermal management • Hybridization of various systems including integration of fuel cells with batteries for transportation applications • Complete system integration/design from renewables/nuclear, to hydrogen production, storage, transportation, and end use to balance performance, cost, and reliability
S: Safety, Codes & Standards	• Speed and cost of permitting

	• Protocols such as hydrogen fueling protocols for large transportation applications • First responder training • Code official training • Public awareness
M: Manufacturing, Scale-Up, and Supply Chain	• Number of parts in a component and the number of processing steps to scale-up manufacture of components • Materials, components, and systems compatible with processes for affordable scale-up and large-scale manufacturing • Limited domestic supply chain and manufacturing facilities
OS: Operations Support	• Manufacturing supply chain availability/diversity/resiliency • Supply chain for replacement parts for routine or unplanned maintenance • System operators and maintenance workforce development and training • Manufacturing workforce development and training

The SDI subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 6.4. Tables 6.5 through 6.7 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for different applications in various 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 portfolio is assessed on a regular basis and is refined to align with the technology applications and system integration activities that can have the greatest impact on accelerating hydrogen and fuel cell technology commercialization and achieving economies of scale across sectors.

Heavy-Duty Transportation

The subprogram's strategic priorities in transportation include end uses such as medium-/heavy-duty trucks, as well as maritime, rail, and other offroad applications. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.5.

Table 6.5. SDI Focus Areas Addressing Transportation Applications

Application	RD&D Focus Area	Barriers Addressed	Example Milestones
Medium-/ Heavy-Duty Trucks	Validate technical and cost performance relative to conventional diesel engine trucks	C, D, E, LC, SI	• With EERE's Vehicle Technologies Office, complete prototype commissioning of multiple Class 4-8 fuel cell electric trucks through the SuperTruck 3 program to demonstrate how a substantial
	Demonstrate fuel cell durability of 30,000 hours under real-world driving conditions	D, SI	

	Validate fuel economy of various classes of hydrogen fuel cell trucks with different duty cycles as well as Class 8 long-haul range of 750 miles on single fill	E	reduction of 75% or greater in GHGs and local pollutants can be achieved relative to diesel-equivalent trucks by 2028 • Complete I-10 H_2 fueling corridor study in collaboration with Vehicle Technologies Office by 2025
	Develop flexible, low-cost heavy-duty stations able to achieve a 10 kg/min fueling rate	E, S	
Maritime	Demonstrate hydrogen fuel cell cargo handling equipment at a port including necessary hydrogen infrastructure / fueling equipment	D, E, LC, S	• Demonstrate zero-emissions cargo movement at ports using clean hydrogen by 2030
	Demonstrate portside power (hoteling loads) using hydrogen for oceangoing vessels	D, E, LC, S	
	Analyze potential of hydrogen for small marine equipment such as ferries	C, D, E	
	Analyze potential for multi-use offshore wind power platform for hydrogen production, energy storage, and vessel refueling	E, SI, S	
Rail	Develop and integrate hydrogen storage and fuel cell systems on board trains	D, E, LC, SI, S	• Perform gap assessments for large-scale H_2 applications including bulk storage and rail by 2026
	Demonstrate integration of hydrogen production, storage, distribution, and refueling for rail applications	C, E, SI, S	
Aviation	Analyze potential for onboard fuel cell and hydrogen storage systems with comparable payload and range capability for urban and regional aircraft	C, D, E, LC, SI, S	• By 2035, validate fuel storage and power system for urban and regional aircraft
Off-Road	Validate the technical and cost performance relative to diesel-powered mining/construction equipment	C, D, E, SI	• By 2028, validate technical and economic performance of hydrogen and fuel cell integration in offroad applications
	Design and integrate hydrogen production (on- or off-site), hydrogen storage, and/or distribution infrastructure at mining and construction sites	C, D, E, SI	

Chemical and Industrial Processes

The subprogram's strategic priorities in chemical and industrial processes include metals refining as well as synthesis of clean fuels and products. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.6.

Table 6.6. SDI Focus Areas Addressing Chemical and Industrial Applications

Applications	Activities	Barriers Addressed	Example Milestones
Metals	Optimize key aspects of existing processes that use hydrogen (e.g., operating temperature and pressure, iron ore particulate size and morphology, kinetics)	D, SI	• Demonstrate 1 metric ton/week direct reduction of iron with H_2 by 2024, and pathway to 5,000 metric tons/day
	Demonstrate integration of hydrogen systems with iron reduction technologies	C, D, E, LC, SI, S	• By 2025, show the technical and economic feasibility of the thermal and process integration between an SOEC module and a direct reduced iron furnace with an electric-to-hydrogen production efficiency of < 35 kWh/kg of H_2 • By 2025, complete a location-specific reference design where hydrogen can be produced at less than $2/kg for an off-grid behind-the-meter renewable power-to-hydrogen integrated energy system that includes an industrial end-use application
	Enable large-scale deployments through pre-front-end engineering and design (FEED) and FEED studies, market analysis, workforce analysis, techno-economic analysis/life cycle analysis	C, E, LC, SI	• Complete pre-FEED studies for the integration of clean hydrogen in hard-to-decarbonize industrial processes by 2027 to allow industry to develop a more detailed understanding of cost, performance, and emissions
Chemicals	Integrate and optimize key aspects of existing processes that use hydrogen	D, SI	• Validate emerging concepts for integration with industrial processes for synthetic fuels and chemicals by 2025
	Identify opportunities to reduce costs through innovative integration (e.g., thermal and chemical)	C, D, E, SI	

	Enable large-scale deployments through pre-FEED and FEED studies, market analysis, workforce analysis, TEA/LCA	C, E, LC, SI	• Enable four or more end-use demos (e.g., steel, ammonia, storage) at scale by 2036; Demonstrate that clean hydrogen can enable 85% GHG emissions reductions at an industrial facility, either as a feedstock input or direct use for heating

Energy Storage and Power Generation Systems

The subprogram's strategic priorities in energy storage and power generation focus on grid integration of hydrogen and fuel cell technologies; integration with renewables and nuclear power; and primary or backup power, such as for data centers. Specific RD&D focus areas addressing barriers and challenges are described in Table 6.7.

Table 6.7. SDI Focus Areas Addressing Energy Storage and Power Generation Applications

Applications	Activities	Barriers Addressed	Example Milestones
Grid Integration and Renewable Hybrid Systems	Validate dynamic response, efficiency, and durability of electrolyzers	D, E, SI	• Demonstrate at least six integrated electrolyzer systems by 2025 with a combined total capacity greater than 3 MW, using at least two different electrical generation sources and targeting at least three different hydrogen end-use applications • Develop 10-MW low- and high-temperature electrolysis validation facilities by 2027
	Demonstrate reliable, quick-response performance of hydrogen-producing electrolyzers for at-scale energy storage that support the grid through ancillary services and demand response	D, E, SI	
	Validate communications and controls, including cybersecurity requirements for successful participation in electricity markets and demand response programs	E, SI	
Nuclear Hybrid Systems	Develop and validate a hybrid nuclear hydrogen production system (in collaboration with the DOE Office of Nuclear Energy)	D, E, SI, S	• Demonstrate integrated (behind-the-meter) 1.25-MW PEM electrolyzer installation at nuclear plant for H_2 production by 2024 • Test 250 kW high-temperature electrolysis system using fully emulated nuclear integrated test stand by 2025
	Demonstrate 90% efficiency using high-temperature electrolysis technology and nuclear power plant thermal energy	E, SI	

<table>
<tr><td rowspan="3">Distributed Power Systems</td><td>Demonstrate and validate prime power and/or backup power systems to meet data center reliability requirements</td><td>D, E</td><td rowspan="3">By 2024, validate an integrated minimum of 1-MW H_2 fuel cell system at a real-world data center; conduct performance tests operating the system between 24 and 48 hours to evaluate the system’s ability to
Ramp up to full power and maintain that power for any necessary power outages
By 2025, evaluate in the lab and demonstrate in the field a grid-forming fuel cell inverter that can provide grid-forming services in a microgrid while utilizing hydrogen’s energy storage scalability</td></tr>
<tr><td>Design and integrate hydrogen production (on- or off-site), hydrogen storage, and/or distribution infrastructure with data centers</td><td>D, E, SI</td></tr>
<tr><td>Evaluate and demonstrate the operation of hydrogen systems to support microgrids for remote or underserved communities</td><td>D, E, SI, S</td></tr>
</table>

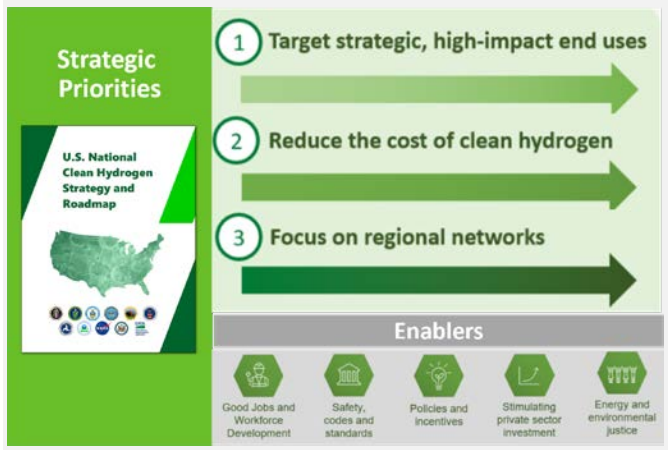
7 Systems Analysis

7.1 Overview

Goals and Objectives

The **Systems Analysis** subprogram is a crosscutting HFTO function, informing direction, prioritization, and decision making. The program funds analyses to identify technology pathways that can facilitate large-scale use of clean hydrogen and fuel cell systems to enable decarbonization, enhance energy system flexibility and resilience, and advance energy and environmental justice.

The overarching goal of the Systems Analysis subprogram is to inform the HFTO decision-making process, supporting RD&D to enable the adoption of hydrogen and fuel cell technologies across applications and sectors at scale, with focus on hydrogen from diverse clean and renewable resources. To achieve this goal, the Systems Analysis subprogram:



Rigorous data, modeling, and analysis activities support all aspects of the ***U.S. National Clean Hydrogen Strategy and Roadmap***, enabling strategic planning in RDD&D to achieve commercial liftoff of clean hydrogen and fuel cell technologies.

- Identifies strategic markets for hydrogen and assesses the associated benefits to inform HFTO strategy.
- Develops tools that characterize the cost and value proposition of hydrogen to inform real-world deployments.
- Quantifies the cost, emissions, and sustainability impacts of hydrogen production, delivery, fuel cell, and other end-use technologies to inform market models and real-world deployments.

Analytical Portfolio

The Systems Analysis subprogram's goals and objectives are addressed by implementing a portfolio of models and tools indicated in Figure 7.1. Techno-economic assessments, shown at the bottom of the pyramid in the figure, focus on key resource, technology, and economic issues, and form the basis of all Systems Analysis activities. Results and data generated from techno-economic assessments are leveraged to develop a wide range of higher-level analysis capabilities, including supply chain, impact, life cycle, decision, workforce, and market analyses, as well as more forward-looking or strategic planning, system optimization, and scenario development capabilities, as shown in upper portions of the pyramid.

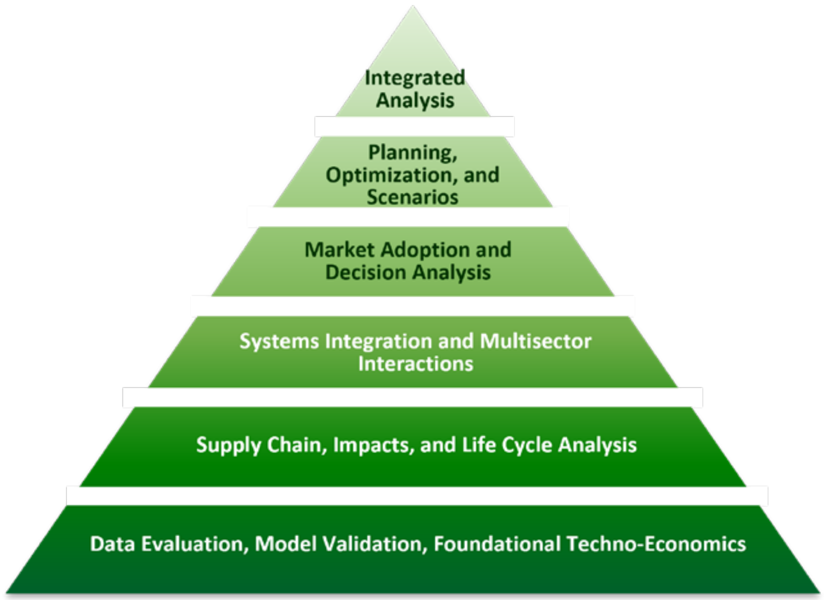


Figure 7.1. The Systems Analysis portfolio pyramid ranging from foundational tools and modeling capabilities through sophisticated integrated analysis of hydrogen and fuel cell technologies in promising market scenarios

Brief descriptions of each of the categories in the analytical portfolio are provided below:

- **Techno-Economic Analysis:** This category of model and tool capabilities provides several types of detailed technology assessments, including estimates of the cost of hydrogen production and delivery in potential future scenarios, sensitivities emerging by varying key input parameters (e.g., R&D advancement, electricity prices, natural gas prices), and total costs for hydrogen and fuel cells in specific applications and scenarios of interest (e.g., for medium- and heavy-duty transportation).
- **Supply Chain, Impact and Life Cycle Analysis:** These efforts account for a wide range of different impacts, such as life cycle emissions and energy consumption, water use and land use restrictions, and employment and gross domestic product impacts. The analysis scope can be very broad, allowing for technology comparisons useful for prioritization, sensitivity runs, and cost-benefit analyses.
- **Systems Integration and Multisector Interactions:** These models contribute a higher-level perspective on integrated systems. Analyses evaluate the relationships between hydrogen and other energy sectors, such as the electricity grid; large-scale infrastructure rollout scenarios; and sector-wide impacts, such as workforce analysis or system-wide costs. These models build upon the more discrete, component-level techno-economic and life cycle models, and they add value by generating results based upon an integrated

systems analysis. As more clean hydrogen facilities are deployed worldwide, these analyses will be informed by real-world data. Key metrics of interest in the early years of large-scale deployment will include the number and types of jobs created; real-world costs and impacts of economies of scale; financial parameters; and regional impacts on energy systems.

- **Market Assessment and Decision Analysis:** The impacts and benefits of many technology innovations depend upon market acceptance and consumer decisions**.** This analysis capability examines market dynamics and associated impacts on technology RD&D priorities and investment decisions. Analysis topics include hydrogen demand analysis, market barrier analysis, market simulations, and market-segmentation analysis, which characterizes the cost and potential market adoption of hydrogen and fuel cells relative to current and emerging alternatives.
- **Planning, Optimization and Scenario Development:** Analytical tools in this category focus on scenario development to inform planning and optimization of hydrogen and fuel cell technology systems in diverse end-use applications, taking a high-level view considering integrated systems and multisector interactions as well as market dynamics. Examples include infrastructure planning to support multisector coupling, including transportation fueling; supply chain optimization to minimize costs and increase resource utilization efficiency; and scenario development to provide insights into a range of future market conditions and uncertainties, stakeholder strategies and initiatives, and external market constraints and drivers.
- **Integrated Analysis:** Integrated and macro-system models link other models in the Systems Analysis portfolio as well as data and modeling resources from external stakeholders and facilitate consistency and communication between them in high-level assessments of technologies, resources, and markets. As an example, Systems Analysis continues to refine and update regional analyses across the hydrogen value chain, including supply based on the availability of clean electricity, water, and other resources, as well as demand. Using data from national laboratory and industry analyses, the technical potential for producing hydrogen from diverse domestic clean and renewable resources was estimated as shown in Figure 7.2 (left). This figure represents a compilation of analysis addressing domestic resources such as wind, solar, biomass, and hydropower. Integrated analysis has also projected ranges in potential hydrogen demand in 2050 in five key sectors: transportation; biofuels and power-to-liquid fuels; industry; blending; and energy storage and grid balancing, as illustrated in Figure 7.2 (right).[73]

[73] Clean hydrogen supply and demand potential analysis included in: 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.

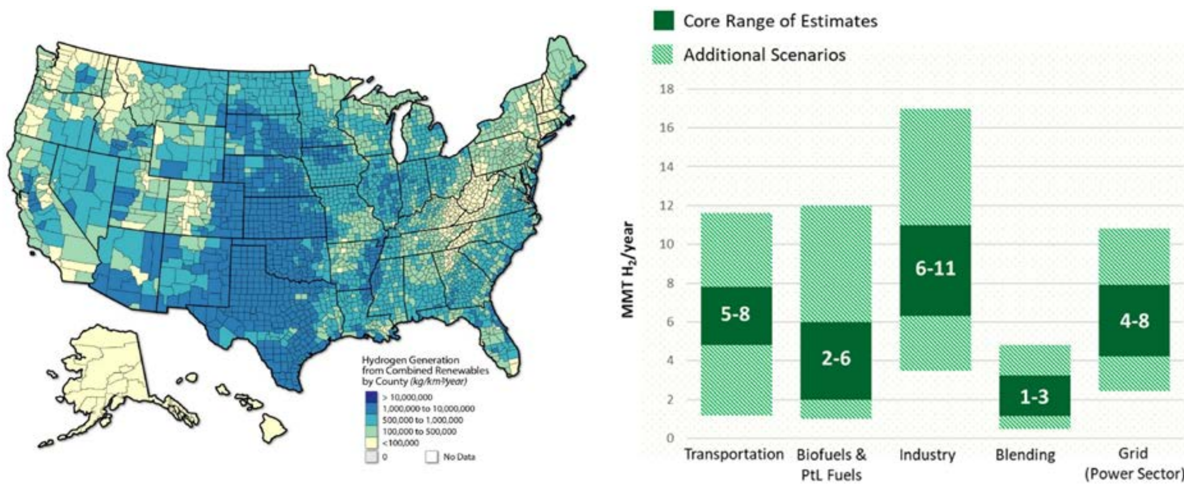


Figure 7.2. Examples of clean hydrogen supply and demand scenario analysis: production potential of hydrogen across the United States (left); potential hydrogen demand by sector in 2050 (right)

7.2 Strategic Priorities

As shown in Figure 7.3, the Systems Analysis subprogram addresses ongoing priorities to inform RD&D across all the HFTO subprograms and broader DOE and interagency efforts, as well as near-, mid-, and longer-term strategic priorities to accelerate planning and implementation of a clean energy transition leveraging hydrogen and fuel cell technologies. This is consistent with HFTO's overall strategic framework described in the Introduction and supports national clean hydrogen priorities.

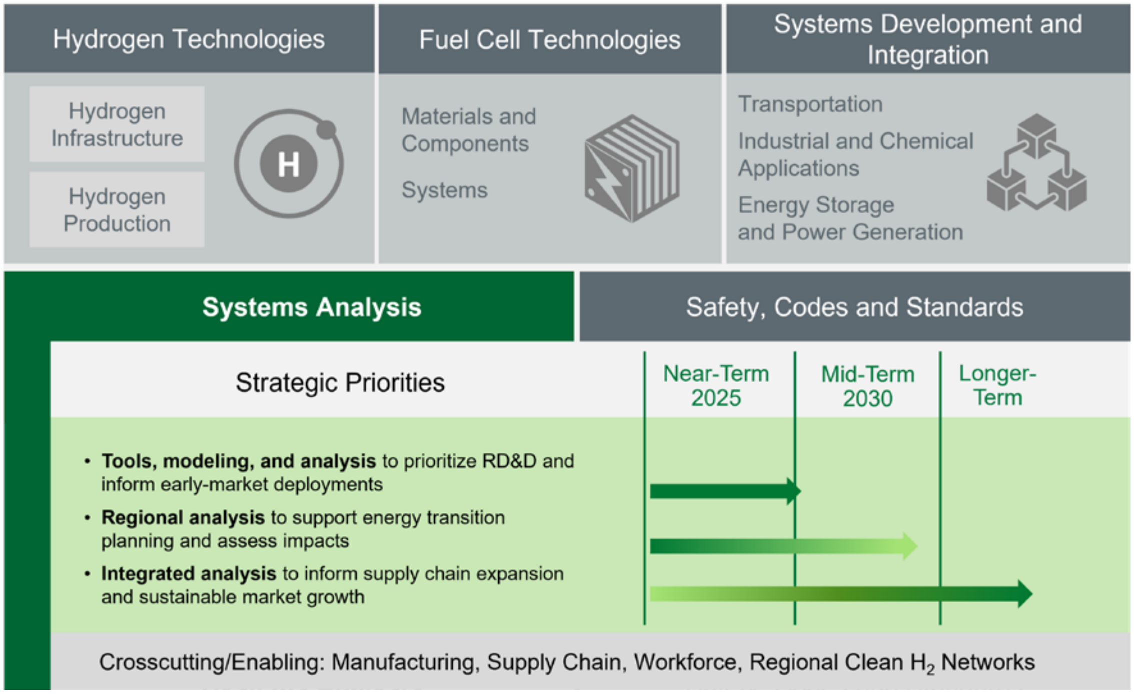


Figure 7.3. The Systems Analysis subprogram supports all HFTO subprograms and the overall national vision to enable the adoption and benefits of hydrogen and fuel cell technologies.

Near-Term Priorities

Tools, modeling, and analysis to prioritize RD&D for early markets: The Systems Analysis subprogram develops, refines, and uses analytical models and tools and helps to develop technology targets and milestones as well as technology readiness goals relevant to RD&D supported by other HFTO subprograms. Modeling and analysis elucidate the total cost of ownership of hydrogen and fuel cell technologies in specific sectors; cost and performance requirements to displace incumbent fuels; regional impacts of deployments on criteria pollutant emissions, water, and land resources; potential for job creation; and impacts on national climate goals. Systems Analysis results also provide assessments of hydrogen and fuel cell technologies in the context of the energy transition, and they inform decisions made by stakeholders with different concerns and decision time frames, such as informing community benefits plans and providing transparency for disadvantaged communities, tribal communities, and others not as familiar with hydrogen technologies. The initial focus is on identification and support of hydrogen and fuel cell technologies for early-market opportunities consistent with the national strategy, such as existing end uses in refining, chemicals, and industrial applications.

Mid-Term Priorities

Assess niche and early to mid-term market entry opportunities, with associated RD&D needs: The Systems Analysis portfolio's activities include techno-economic modeling to identify cost and performance requirements for hydrogen and fuel cell technologies to enter new markets and to identify sectors that may be early adopters. Examples of these efforts include **H2@Scale** analyses that characterize the potential for hydrogen demand in varying future scenarios of RD&D, impact of policies (e.g., tax credits), target-setting exercises, cradle-to-grave emissions analyses, and updates to the Annual Technology Baseline for Transportation. Additionally, models developed with the Systems Analysis subprogram's support, such as the Hydrogen Analysis (H2A) and Hydrogen Delivery Scenario Analysis Model (HDSAM) tools to estimate the costs of hydrogen production, delivery, and dispensing, are routinely updated and refined for use by external stakeholders in the development of RD&D plans and technology outlooks.[74]

Assess opportunities in major growing markets and inform multisector coupling RD&D: As hydrogen and fuel cell technologies are commercialized, real-word data regarding cost, performance, durability, and emissions are used to validate and refine existing models and inform macro-scale estimates of sector outlooks and sector coupling. These efforts account for multisector connections, supply chain expansion dynamics, policy impacts (e.g., tax credits, demand side incentives) and interactions between regional, national, and international developments such as exports.[75] These macro-scale estimates typically rely on capabilities higher up in the pyramid in Figure 7.1. Examples of recent efforts in this space include techno-economic analysis of the cost of clean hydrogen supply to industrial end uses, such as steelmaking, being informed by early relevant demonstrations.

Longer-Term Priorities

Inform large-scale production and manufacturing decisions, as well as supply chain expansion, and energy transition implementation: Adapting to increasing uncertainties and disruptions in domestic and international energy markets will require new analytic tools and strategies. Key focus areas of long-term analysis efforts include enhancing estimates of the export potential and supply chain for hydrogen to address increasing global demand, employment analyses to support the development of a workforce trained to develop and operate hydrogen and fuel cell technologies, manufacturing and supply chain analyses to inform scale-up of hydrogen and fuel cell technologies, and analyses to characterize the impacts of new technology trends, such as automation, on the value proposition of hydrogen and fuel cell technologies.

7.3 RD&D Targets

The Systems Analysis subprogram supports the development of technology targets and milestones as well as technology readiness goals relevant to RD&D supported by other HFTO subprograms, relying on its diverse portfolio of both focused and integrated models that characterize technology costs, performance, impacts, and cross-sector market potential.

[74] Office of Energy Efficiency and Renewable Energy. *2019 Fuel Cell Technologies Market Report.* September 2020. ANL-20/58. https://publications.anl.gov/anlpubs/2021/08/166534.pdf.
[75] Reeves, Martin, and Johann Harnoss. June 6, 2017. "The Business of Business is No Longer Just Business, The Boston Consulting Group. https://www.bcg.com/publications/2017/corporate-strategy-business-no-longer.

Examples of recent analyses that have informed strategic program documents, such as the *U.S. National Clean Hydrogen Strategy and Roadmap*, the *U.S. National Blueprint for Transportation Decarbonization*,[76] and *Clean Hydrogen: Pathways to Commercial Liftoff* report[77] include:

- Life cycle analyses that inform annual updates to Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, which is used to characterize the emissions reduction potential of hydrogen.[78]
- Vehicle cost and choice modeling to identify priority market segments for fuel cell vehicles in the heavy-duty trucking sector.[79] Underlying assumptions on vehicle costs in business-as-usual scenarios and scenarios where R&D targets are achieved are described in DOE's Annual Technology Baseline website.[80]
- Development and use of the National Renewable Energy Laboratory's (NREL's) H2A tools to characterize the cost of hydrogen production under varying scenarios of energy cost and capacity factor,[81] infrastructure modeling tools such as Argonne's HDSAM,[82] and models such as NREL's Hydrogen Financial Analysis Scenario Tool (H2FAST) that evaluate financial performance of user-defined systems.[83]
- Use of the state-of-the-art grid models such as NREL's Regional Energy Deployment System (ReEDS)[84] model, as well as newly developed models of energy storage such as StoreFAST,[85] to characterize the role of hydrogen in a clean grid.[86]

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[76] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.
[77] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/clean-hydrogen/.
[78] Argonne National Laboratory. R&D GREET. https://greet.anl.gov/.
[79] Ledna, Catherine, Matteo Muratori, Arthur Yip, Paige Jadun, and Chris Hoehne. March 2022. "Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis." National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/82081.pdf.
[80] National Renewable Energy Laboratory. "2020 Transportation Annual Technology Baseline." https://atb.nrel.gov/transportation/2020/index.
[81] National Renewable Energy Laboratory. "H2A-Lite: Hydrogen Analysis Lite Production Model." https://www.nrel.gov/hydrogen/h2a-lite.html.
[82] Argonne National Laboratory. "Hydrogen Delivery Scenario Analysis Model." https://hdsam.es.anl.gov/index.php?content=hdsam.
[83] National Renewable Energy Laboratory. "H2FAST: Hydrogen Financial Analysis Scenario Tool." https://www.nrel.gov/hydrogen/h2fast.html.
[84] National Renewable Energy Laboratory. "Regional Energy Deployment System." https://www.nrel.gov/analysis/reeds/.
[85] National Renewable Energy Laboratory. "StoreFAST: Storage Financial Analysis Scenario Tool." https://www.nrel.gov/storage/storefast.html.
[86] Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf.

7.4 Addressing Challenges

General Challenges

Fidelity of Existing Tools and Models

The existing suite of models and tools address a wide range of topics, but as industry markets and applications expand in scope, the analysis portfolio must expand accordingly. This can include new applications, new technologies, and new market interactions. Core assumptions within hydrogen models and analyses must also be continuously informed by real-world data. Key aspects of near-term deployments that can inform ongoing analyses include real-world financial metrics, technology costs, and system performance.

Future Consumer, Stakeholder and Market Behavior

Understanding underlying factors and expected trends in future markets is critical to the development of robust analytic tools to assess the costs, benefits, potentials and strategic advantages of hydrogen and fuel cell technologies. Consumer and stakeholder behavior can play important roles in new and emerging energy markets, especially as key strategic decisions can influence market transformation dynamics. To better understand the role of hydrogen and fuel cell applications in future markets, forward-looking analysis efforts must continually update assumptions and data related to consumer, stakeholder, and market behavior.

Regional Deployments Analysis

Regions can have unique resources, industrial capabilities, demand trends, and other market drivers or constraints that need to be considered in market assessments and scenario planning. Hydrogen supply chain networks will tend to expand outward from high-activity industrial clusters, metropolitan regions or megaregions, or along key transportation corridors. Positive economic conditions and economies of scale must be achieved early on within such clusters to reach market competitiveness. Planning processes and government-industrial initiatives are often focused on regions with strong policy drivers, low-cost energy, or concentrated demands. In addition, specific regional impact analyses for disadvantaged communities and other stakeholder groups such as tribal communities are lacking.

Specific Challenges and Opportunities

In addition to addressing general challenges, the Systems Analysis subprogram continually updates and improves its modeling tools and analysis in all categories of the portfolio pyramid. Examples of challenges and opportunities in these categories include:

Technoeconomic Analysis

- Providing updated current and future cost and technology performance estimates for fuel cell and hydrogen production, storage, delivery, and dispensing technologies.

- Integrating empirical data and stakeholder feedback into ongoing analysis projects and initiatives to improve model validation, refine project scope and align with industry and market priorities.
- Updating resource utilization and market potential estimates.

Supply Chain, Impact and Life Cycle Analysis

- Estimating current and future supply chain needs (e.g., critical materials, recycling potential), life cycle greenhouse gas emissions, air quality impacts, resource limitations (e.g., land and water requirements) and other social and environmental impacts associated with the deployment and market adoption of hydrogen and fuel cell technologies.
- Estimating market adoption impacts, including employment effects, revenue potential, and GDP.
- Providing a quantitative basis for a broad range of sustainability indicators across hydrogen and fuel cell technology supply chains and life cycles.

Systems Integration and Multisector Interactions

- Assessing technology and market opportunities to support electricity grid services, including ancillary services and long-duration energy storage.
- Improving characterizations of technology and market opportunities for hydrogen and fuel cells in industrial applications (steel, fertilizers, chemicals), liquid transportation fuels (biofuels and synfuels), and emerging transportation applications (rail, marine, aviation).
- Identifying opportunities to enable and optimize efficient utilization of resources across energy, transportation, and industrial sectors, as well as optimization for specific use cases such as industry clusters, ports, offroad vehicles, or microgrids.
- Identifying and characterizing synergies across applications and sectors, including advanced clean technologies and fuel pathways.

Market Assessment and Decision Analysis

- Estimating mid- and long-term market potential for fuel cell applications and hydrogen utilization across multiple sectors and market segments, including policy impacts (e.g., tax credits, demand side strategies to avoid stranded assets).
- Examining infrastructure investment decisions with respect to future market constraints, various financial metrics, technology path-dependencies, policies, and potential technology innovations.

Planning, Optimization, and Scenario Development

- Improving resource assessments and technology characterizations to include metrics for systems resilience and sustainability.

- Enhancing long-term models to account for multisector coupling opportunities and balance supply and demand trends using market feedback mechanisms.
- Developing and optimizing assessments for regional cluster developments, including colocating large-scale production with multiple end-use applications (e.g., ports, industrial clusters).
- Coordinating with federal and state agencies and the private sector to optimize investment decisions and leverage resources.

Comprehensive Approach

The Systems Analysis subprogram coordinates closely across HFTO, DOE, and interagency programs as well as external collaborators in the continued development and validation of tools, models, and analysis comprising an analytic portfolio suited to the challenges and opportunities facing hydrogen and fuel cell technologies. Examples of tools widely used by stakeholders include the GREET model, which has over 50,000 users spanning industry, regulatory bodies, and academia; the H2A Production Case Studies, which have costs and performance estimates for current and future hydrogen production technologies; HDSAM, which characterizes cost of hydrogen infrastructure, including fueling stations; and H2FAST, which characterizes financial performance of user-defined facilities.

These and other tools have become more sophisticated in scope and increasingly refined over time through empirical validation with RD&D advances, bench-scale and demonstration project results, and an increasing number of real-world commercial applications. As hydrogen and fuel cell technologies expand rapidly around the world, opportunities to validate and expand analysis tools will increase by incorporating additional technical characterizations, empirical data, and stakeholder feedback. This feedback process of empirical validation and capability refinement and expansion is illustrated in Figure 7.4, which includes examples of specific tools and models implemented in the different analytical categories in the portfolio pyramid as well as the feedback loop advancing all categories.

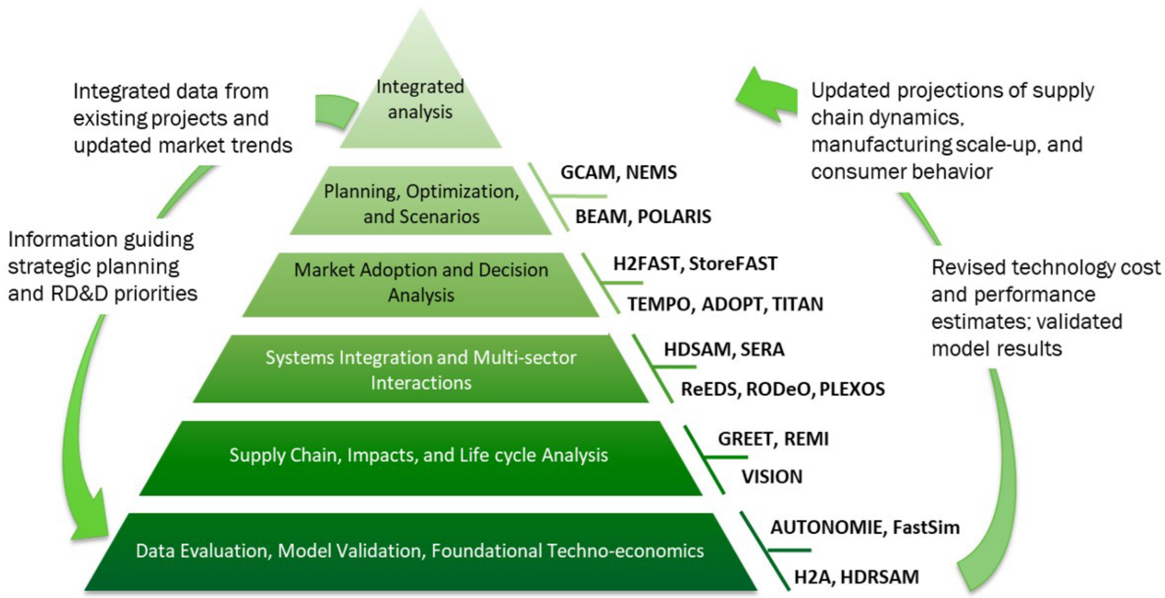


Figure 7.4. Process diagram of the Systems Analysis subprogram's comprehensive approach, including data inputs and exchanges with external activities and between models (see Table 7.1 for definition of acronyms)

Table 7.1 provides a more complete list of the tools and models in the Systems Analysis portfolio.

Table 7.1. Systems Analysis Capabilities and Tools

Model/Tool	Short Description
Scenario Evaluation and Regionalization Analysis Model (SERA)[87]	Designs cost-optimal hydrogen supply chain infrastructure for user-provided scenarios of hydrogen demand.
Global Change Analysis Model (GCAM)[88]	Energy system tool that simulates scenarios that can achieve national and global decarbonization goals. Model is used in international climate modeling, such as reports of the Intergovernmental Panel on Climate Change, and hydrogen representation is currently being expanded.
Hydrogen Financial Analysis Scenario Tool (H2FAST)	Simulates financial performance (e.g. cash flow, levelized cost) of user-defined systems, such as fueling stations, production facilities, infrastructure.

[87] National Renewable Energy Laboratory. "SERA: Scenario Evaluation and Regionalization Analysis Model." https://www.nrel.gov/hydrogen/sera-model.html.
[88] Joint Global Change Research Institute. "GCAM: The Global Change Analysis Model." Github. https://github.com/JGCRI/gcam-core.

Hydrogen Delivery Scenario Analysis Model (HDSAM)	Simulates cost and design of hydrogen infrastructure, including fueling stations, under user-defined scenarios of fleet size, utilization rate, region, etc.
Regional Energy Deployment System Model (ReEDS)	Simulates makeup of electricity grids under future scenarios of load and capacity expansion, technology cost, and policy drivers.
PLEXOS[89]	Simulates prices of electricity under future grid scenarios.
Revenue Operation and Device Optimization Model (RODeO)[90]	Price taker optimization model for the design and optimization of energy conversion and storage systems
Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET)	Simulates life cycle emissions of hundreds of fuel pathways, including hydrogen production, infrastructure, and use.
AUTONOMIE[91]	Simulates cost and performance of current and future vehicles, accounting for cross-sector technology improvements, such as in fuel cell cost, storage cost, and lightweighting.
Hydrogen Analysis (H2A)	Models cost of hydrogen production technologies based on bottom-up modeling of system design.
Future Automotive Systems Technology Simulator (FASTSim)[92]	Optimizes design of fuel cell, battery, and internal combustion engine vehicles based on consumer preferences and impacts of technology cost and performance on vehicles.
TEMPO	A consumer choice model that estimates shares of fuel cell electric vehicles, battery electric vehicles, and combustion engine vehicles in future scenarios of technology and fuel price.
National Energy Modeling System (NEMS)[93]	Projects future prices, production, and consumption of fuels. Used in EIA's Annual Energy Outlooks

Ongoing analysis projects are focused on informing real-world deployments, using long-standing expertise in hydrogen technologies to inform other offices (OCED, Office of Technology Transitions, etc.), and better quantifying the role of hydrogen technologies in a net-zero economy. Example objectives of these projects include:

[89] Energy Exemplar. "PLEXOS." https://www.energyexemplar.com/plexos.
[90] Eichman, Josh, Mariya Koleva, Omar J. Guerra, and Brady McLaughlin. 2020. *Optimizing an Integrated Renewable-Electrolysis System.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-75635. https://www.nrel.gov/docs/fy20osti/75635.pdf.
[91] Argonne National Laboratory. "Autonomie Vehicle System Simulation Tool." https://www.anl.gov/es/autonomie-vehicle-system-simulation-tool.
[92] National Renewable Energy Laboratory. "FASTSim: Future Automotive Systems Technology Simulator." https://www.nrel.gov/transportation/fastsim.html.
[93] U.S. Energy Information Administration. "Documentation of the National Energy Modeling System (NEMS) Modules." https://www.eia.gov/outlooks/aeo/nems/documentation/.

- Harmonizing methods of life cycle analysis and verification internationally, through partnerships such as with IPHE.
- Characterizing indirect impacts of hydrogen, including as an indirect greenhouse gas, emissions associated with component manufacturing, and impacts on the electricity grid.
- Developing criteria to assess sustainability, and environmental and environmental justice impacts of hydrogen deployments.
- Assessing cost and emissions of novel and emerging methods of hydrogen production and infrastructure (e.g. geologic hydrogen, methane pyrolysis).
- Enhancing hydrogen representation in market models, such as Pacific Northwest National Laboratory's Global Change Assessment Model (GCAM) or the National Energy Modeling System (NEMS), to ascertain the role of hydrogen relative to other decarbonization solutions.

As RDD&D projects progress, developments and improvements in hydrogen technologies and fuel cell systems are incorporated into the models, and new simulations help guide future HFTO RD&D activities. Likewise, data from demonstrations are incorporated into the models to allow for higher fidelity assessments and guidance for RD&D activities along with support and guidance for clean hydrogen and decarbonization activities.

Stakeholder Engagement and Collaboration

The Systems Analysis subprogram works closely on joint analysis projects, such as roadmap and strategy documents; updates to crosscutting tools, such as GREET; potential demand sectors for hydrogen; and cost and rollout of hydrogen production and infrastructure.

Systems Analysis works across EERE on studies and roadmaps to identify optimal pathways for decarbonizing industry, transportation, and the grid through clean fuels and electrification.

Systems Analysis also collaborates with other federal agencies and external organizations through formal partnerships, merit reviews, workshops, and listening sessions.

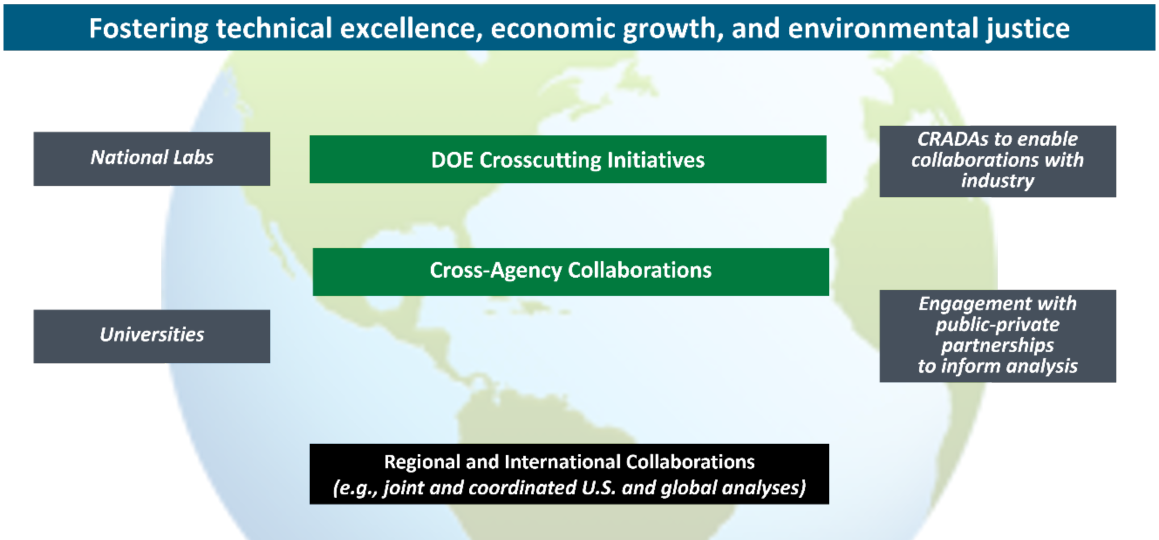


Figure 7.5. Systems Analysis collaboration network

Examples of recent and ongoing collaborations are shown in Figure 7.5. These include:

- The Analysis and Global Competitiveness working group being launched under the HIT. This working group will be led by DOE, the U.S. Environmental Protection Agency, and the Department of Commerce and will comprise representatives from across federal agencies. The working group will address priority crosscutting areas of analysis, such as sustainability and verification.
- Task forces within IPHE. The United States has co-led and supported activities within various IPHE working groups and task forces, including the Hydrogen Production Analysis and Certification task forces, which published two white papers documenting best practices associated with analysis of emissions associated with hydrogen production and infrastructure.[94,95]
- Interagency agreements, such as the one recently launched between DOE and the National Oceanic and Atmospheric Agency to evaluate the indirect global warming potential of hydrogen. This interagency agreement followed a workshop that was co-organized by the European Commission and the DOE to identify gaps in knowledge

[94] International Partnership for Hydrogen and Fuel Cells in the Economy. "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen." October 2021. https://www.iphe.net/iphe-working-paper-methodology-doc-oct-2021.
[95] International Partnership for Hydrogen and Fuel Cells in the Economy. "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen." July 2023. https://www.iphe.net/iphe-wp-methodology-doc-jul-2023.

associated with indirect impacts of hydrogen, and the capabilities of hydrogen sensor technologies.[96]

- The 21st Century Truck Partnership and U.S. DRIVE, two public-private partnerships between DOE and members of the transportation industry. These partnerships jointly execute analyses, such as the quadrennial cradle-to-grave analysis of emissions associated with fuel cell, battery, and combustion engine-based vehicles.[97]
- Listening sessions and opportunities for public comment on key strategic DOE documents, such as the *U.S. National Clean Hydrogen Strategy and Roadmap* and the *Clean Hydrogen Production Standard*.[98]

Internationally, the United States was co-lead with the IPHE to publish best practices associated with life cycle analysis of hydrogen production and the associated infrastructure. In association with the IPHE and the International Energy Agency, the United States supports the development of best practices associated with emissions verification. Examples of key Systems Analysis collaborations are depicted in Figure 7.5.

7.5 Subprogram Support

The Systems Analysis subprogram supports other HFTO subprograms through development and implementation of its tools and models. Examples are included in Table 7.2 below.

Table 7.2. Examples of Systems Analysis Support to Other HFTO Subprograms

Analysis Capability Type	Models and Analysis Methods	Main Subprograms Supported
Techno-Economic Assessment	• Hydrogen production case studies (H2A) • Hydrogen refueling station analysis (HDSAM) • Vehicle simulation (AUTONOMIE)	• HP • HI • MO, HI, FC, SDI
Supply Chain, Impacts and Life Cycle Analysis	• Life cycle analysis (GREET) • Resource analyses (estimates of technical potential, economical potential) • Manufacturing analysis (Design for Manufacturing and Assembly methods)	• MO • MO • HI, FC, HP, SDI

[96] Arrigoni, Alessandro, and Laura Bravo Diaz. 2022. *Hydrogen emissions from a hydrogen economy and their potential global warming impact*. EUR 31188 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-55848-4. https://publications.jrc.ec.europa.eu/repository/handle/JRC130362.
[97] Kelly, Jarod C., Amgad Elgowainy, Raphael Isaac, Jacob Ward, Ehsan Islam, Aymeric Rousseau, Ian Sutherland, et al. June 2022. *Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies*. Argonne National Laboratory. ANL-22/27. https://publications.anl.gov/anlpubs/2022/07/176270.pdf.
[98] U.S. Department of Energy. "Clean Hydrogen Production Standard Guidance." https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard.

Systems Integration and Multi-sector Interactions	• Hydrogen delivery scenario analysis (HDSAM) • Electricity grid integration and services (PLEXOS, ReEDS, RODeO) • Hydrogen infrastructure planning (SERA)	• HI • MO, SDI • MO, HI
Market Assessment and Decision Analysis	• Estimating future vehicle market share (TEMPO) • Financial and investment decision analysis (H2FAST)	• MO • MO
Planning, Optimization and Scenario Development	• Future market prices and production volumes (NEMS) • Optimal future decarbonization scenarios (GCAM)	• MO • MO
Program area acronyms: HP - Hydrogen Production, HI - Hydrogen Infrastructure Technologies, FC - Fuel Cells, SDI - Systems Development and Integration, MO - Multiple Offices and Subprograms		

Key deliverables and milestones that correspond to these modeling tools include:

- Life cycle analyses of hydrogen pathways, such as:
  - Near-term:
    - Improved interface to enable user-friendly assessments of emissions of user-defined hydrogen production, infrastructure, and end use pathways.
    - Representation of new hydrogen production pathways (e.g. pyrolysis, geologic hydrogen).
  - Mid-term:
    - Improved background assumptions, such as regional values of upstream methane emissions.
    - Representation of indirect greenhouse gas impacts of hydrogen, based on atmospheric modeling and experimentation completed by the National Oceanic and Atmospheric Administration.
- Improved representation of hydrogen in market models, such as:
  - Near-term:
    - Endogenous representation of hydrogen energy storage in state-of-the-art grid models, such as NREL's ReEDS model
    - Assessments of infrastructure requirements for heavy-duty vehicles.
  - Mid-term:

    - Simulation of industrial hydrogen end uses in global decarbonization models, such as GCAM.
    - Analysis of hydrogen cost and supply and demand potential given new policies enacted by the Inflation Reduction Act.

- Annual updates to standard hydrogen modeling resources, such as:
    - Updates to the Transportation Annual Technology Baseline website to reflect best available information regarding the cost and performance of hydrogen fuel cell vehicles.
    - Updates to H2A and HDSAM to reflect current and potential future costs of hydrogen production and infrastructure.

As real-world deployments and RD&D advance, the Systems Analysis portfolio will continuously adapt to ensure that projects are addressing priority knowledge gaps, conducted transparently, coordinated with other programs and offices, and using the best available information to inform underlying assumptions.

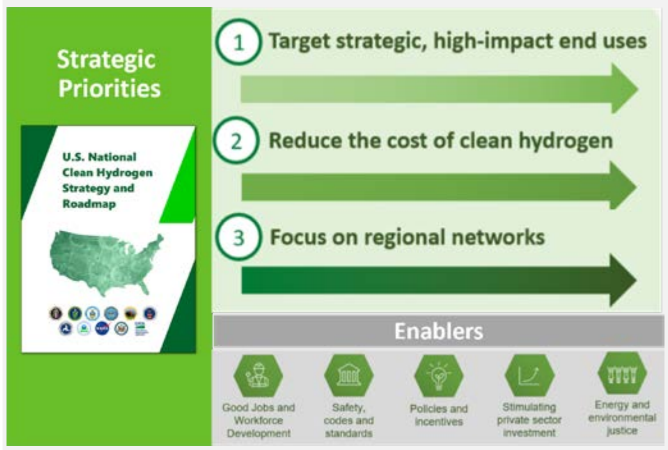
8 Safety, Codes and Standards

8.1 Overview

Goals and Objectives

The overarching goal of the **Safety, Codes and Standards** (SCS) subprogram is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that stakeholders have confidence in their safety, reliability, and performance. The subprogram pursues this goal through its RD&D activities that enable the development and revision of regulations, codes, and standards.

The SCS subprogram supports key strategic priorities identified in the ***U.S. National Clean Hydrogen Strategy and Roadmap*** to enable the safe and consistent deployment and commercialization of clean hydrogen and fuel cell technologies in multiple applications. The subprogram is identified as an essential enabler supporting all strategic priorities within the *U.S. National Clean Hydrogen Strategy and Roadmap* and works closely with other HFTO subprograms to ensure relevant safety, codes and standards are considered when developing and deploying clean hydrogen and fuel cell technologies.



Safety, codes and standards are recognized as a key enabler by the *U.S. National Clean Hydrogen Strategy and Roadmap*, providing an essential basis for the safe and consistent deployment and commercialization of clean hydrogen and related fuel cell technologies.

Two overarching goals which guide SCS RD&D priorities are: (1) enabling RCS for global harmonization, safety, and commercial readiness; and (2) prioritization of safety by sharing resources, best practices, and lessons learned.

Specific objectives of the SCS subprogram aligned with these guiding principles include:

- Supporting RD&D to provide an experimentally validated fundamental understanding of the relevant physics, critical data, and safety information needed to define requirements for technically sound and defensible RCS.
- Identifying and evaluating risk management measures that can be incorporated into RCS and integrated into hydrogen deployment practices to reduce the risk and mitigate the

consequences of potential incidents that could hinder the widespread commercialization of these technologies.

- Promoting collaborative efforts among government, industry, RCS development organizations, model code development organizations, universities, and national laboratories to harmonize domestic and international RCS.
- Informing RCS for the safe deployment of hydrogen and fuel cell technologies based on sound and traceable technical and scientific data and analysis.

To ensure a harmonized, widely accepted, and safe global hydrogen economy, RCS must be developed in conjunction with domestic and international stakeholders. Safety is paramount, and the SCS subprogram shares resources, best practices, and lessons learned to inform RCS and promote a strong culture of safety.

Priority Topics in SCS RD&D

The SCS subprogram supports RD&D on a wide range of topics, including hydrogen behavior, hazard analysis, material and component compatibility, and hydrogen sensor technologies. Using the results from these RD&D activities, SCS experts actively participate in discussions with RCS development organizations such as the National Fire Protection Association (NFPA), the International Code Council, SAE International, the CSA Group, and the International Organization for Standardization (ISO) to promote domestic and international collaboration and harmonization of RCS that are technically sound and defensible.[99] Implementation of these RCS enables the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies. SCS activities also identify and evaluate safety and risk management measures that are used to define requirements and to close the knowledge gaps to continue development of RCS in a timely manner.

This broad SCS RD&D portfolio is organized into the following five priority topical areas:

- Hydrogen behavior and risk research and development
- Component research, development, and validation
- Materials compatibility research and development
- Codes and standards harmonization
- Safety resources and support.

[99] The full text of relevant RCS can be found at their respective codes and standards development organization websites: NFPA (https://www.nfpa.org/), International Code Council (https://www.iccsafe.org/), SAE International (https://www.sae.org/), CSA Group (https://www.csagroup.org/), and International Organization for Standardization (https://www.iso.org/home.html).

Hydrogen Behavior and Risk Research and Development

SCS supports RD&D to establish a scientific basis for sound safety practices and for the development and incorporation of requirements in RCS for hydrogen and fuel cell technologies. The RD&D is focused on hydrogen behavior, risk assessment and mitigation, and quantitative risk assessment tools to support safety best practices and RCS development.

Component Research, Development, and Validation

SCS develops and validates test measurement protocols and methods to address needs for harmonization of testing and certification of hydrogen and fuel cell components, systems, and subsystems. Test methods must be developed and validated so that the performance of components, subsystems, and systems under real-world operational and environmental conditions can be replicated and understood to enable their safe and effective deployment. Component RD&D also includes hydrogen sensor development, validation, best practices, and component failure data collection and quantification.

Materials Compatibility Research and Development

SCS supports materials compatibility RD&D with the goals of optimizing test methods for structural materials and components in hydrogen gas, generating critical materials behavior data to enable technology development, and maintaining information resources. The development of test methods particularly reduces the testing burdens and associated costs for manufacturers. This RD&D effort further informs the development and revision of RCS that are critical for all hydrogen technology end uses. SCS materials compatibility R&D is performed in coordination with the H-Mat and HyBlend consortia.

Codes and Standards Harmonization

SCS supports and facilitates coordinated national development and refinement of essential RCS to enable safe and widespread deployment of hydrogen and fuel cell technologies. SCS works with

Examples Codes and Standards Being Informed by SCS RD&D

Hydrogen Fueling Stations

- ISO 19885-1 Gaseous hydrogen — Fueling protocols for hydrogen-fueled vehicles — Part 1: Design and development process for fueling protocols" in the Draft International Standard phase; Parts 2 and 3 under development
- The 2023 Edition of NFPA 2 Hydrogen Technologies Code has been published, reducing the calculation of setback distances for cryogenic hydrogen storage systems by up to 40%

Pipelines

- ASME B31.8 contains relationships for natural gas pipelines
- ASME B31.12 contains requirements for hydrogen pipelines

Electrolyzers

- The ASME Boiler and Pressure Vessel Code Committee for Section VII (Rules for Construction of Pressure Vessels) includes a revised code case which addresses electrolyzer cell stack assemblies

Sensors

- ISO 26142 Hydrogen Detection Apparatus describes performance requirements for stationary hydrogen detection technologies domestic and international RCS development organizations to facilitate development of performance-based standards. These standards are in building and other codes to expedite regulatory approval of the installation and deployment of hydrogen and fuel cell technologies and facilities. Along with the domestic effort, SCS engages key international bodies and forums to harmonize requirements and test procedures used to qualify hydrogen and fuel cell components and systems in all major market applications.

Safety Resources and Support

Comprehensive safety management applies systematic assessment methodologies to reduce the likelihood that a potential risk may be overlooked and allows for a consistent measure of safety across HFTO projects such as through Hydrogen Safety Panel review of all HFTO project safety plans. Safety plans for HFTO-funded projects as well as lessons learned from RD&D, testing, and demonstration and deployment projects play an important role in developing safe practices for hydrogen and fuel cell commercialization.

8.2 Strategic Priorities

As shown in Figure 8.1, the SCS subprogram has two RD&D priorities: development and validation of hydrogen component technologies and materials with emphasis on dispensing, environmental modeling, and safety; and supporting the development of RCS with emphasis on bulk storage and large-scale applications of hydrogen.

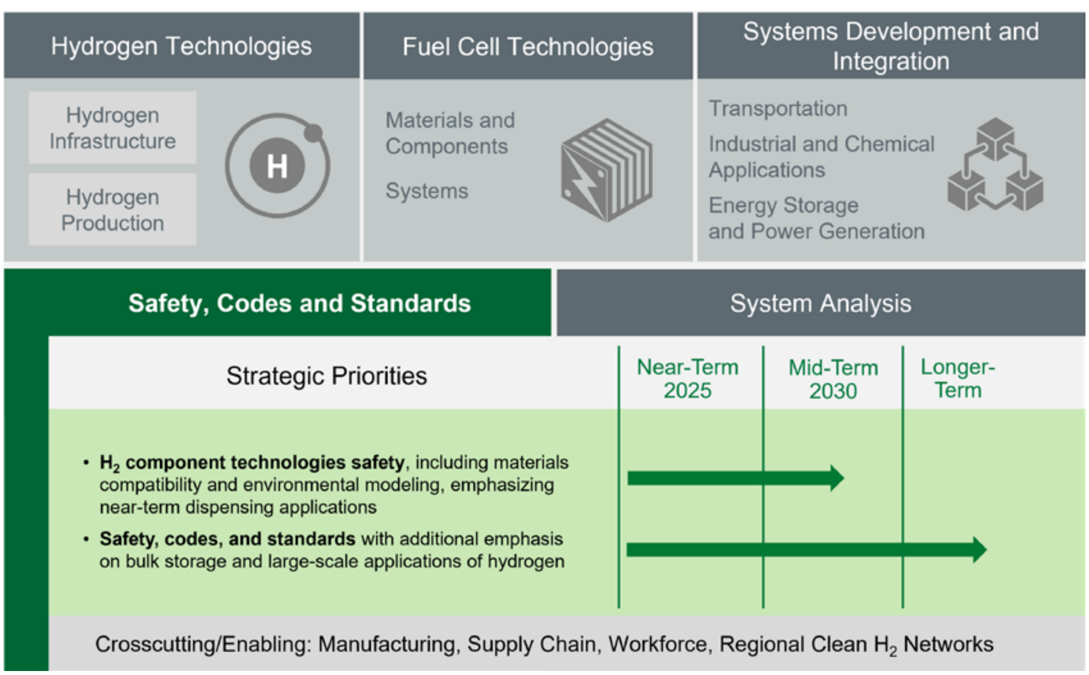


Figure 8.1. Strategic priorities guiding Safety, Codes and Standards RD&D

Near-Term Priorities

In the near-term, the SCS subprogram prioritizes RD&D to develop and validate hydrogen component technologies, including materials compatibility in hydrogen environments. Specific areas of emphasis include developing and validating sensing technologies for both operational safety and environmental detection of unintentional hydrogen releases, where ppb-level sensitivity may be required. This is being addressed in the near-term through field deployment, technology validation, and the development of best practices for sensor technology deployment. Supporting the development and harmonization of RCS for hydrogen fuel dispensing, particularly in mid- to heavy-duty transportation applications, is also a near-term priority. In particular, the SCS subprogram supports RD&D to validate fueling protocols in development and evaluate components for high-throughput gaseous hydrogen transfer and contributes learning from these RD&D activities to the appropriate standards committees.

Mid- to Long-Term Priorities

As the hydrogen economy matures, developing and implementing RCS for bulk storage of hydrogen and large-scale applications of hydrogen technologies will be critical. For large-scale applications, high-throughput transfer of both gaseous and liquid hydrogen will require development of additional standards and validation of components for those processes. Another key concern around the deployment of large-scale hydrogen storage is the potential for prohibitive setback distance requirements as storage volume increases. Ongoing RD&D on the behavior of bulk gaseous and liquid hydrogen will inform modeling efforts and applied risk assessment activities to inform RCS development. Further, international harmonization of RCS will continue to be imperative to ensure that technology developers do not unintentionally create barriers to adoption.

8.3 RD&D Targets

Target-Setting

The SCS subprogram sets targets by considering stakeholder input across a range of topics from components across the value chain, such as sensors and fueling infrastructure, to end uses such as energy storage and power generation. Many of the milestones and targets presented in the *MYPP* appear in the *U.S. National Clean Hydrogen Strategy and Roadmap* and have been vetted by research, industry, and government stakeholders. Within the SCS subprogram, additional stakeholder input is obtained through engagement with the committees responsible for developing RCS and through the National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee.[100] Internationally, the subprogram participates in the HySafe Research Priorities Workshop, which undertakes RD&D prioritization for hydrogen safety on a biennial basis.[101]

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[100] Fuel Cell & Hydrogen Energy Association. "National Hydrogen and Fuel Cell Codes and Standards Coordinating Committee." https://www.hydrogenandfuelcellsafety.info/mission.

[101] HySafe. "Research Priorities Workshops." https://hysafe.info/activities/research-priorities-workshops/.

Specific Targets

The SCS subprogram supports RD&D for a diversity of needs; for example, some RD&D supports technology development, like improved sensors for hydrogen detection, while some RD&D provides the technical underpinnings for standards or protocol development, such as fueling protocols for heavy-duty trucks. Example targets are described in the inset box.

SCS Technologies Interim Target Examples

Hydrogen Detection

- Develop and validate hydrogen sensors with ppb-level sensitivity by 2026
- Develop and validate technologies with capability for quantitative measurements at ppb-level resolution by 2029

Hydrogen Codes and Standards

- Streamline guidance for gaseous bulk storage (>10,000 lb) by 2025
- Develop RCS and validate component for liquid hydrogen fuel transfer for heavy-duty applications by 2030
- Inform the development of fueling methods for medium- and heavy-duty vehicles in alignment with industry priorities by 2025
- Inform development of component standards for hydrogen fueling at 10 kg/min by 2027
- Model behavior of hydrogen blends for at least three blend levels to quantify risk and inform development of RCS by 2027
- Identify and inform relevant RCS for clean hydrogen use in industrial and grid energy storage applications by 2030

Hydrogen Detection Example

Hydrogen sensor RD&D continues to improve hydrogen sensors that detect hydrogen leaks and to minimize the interference of other compounds, such as hydrocarbons, that could interfere with hydrogen detection. For example, current specific technical targets for hydrogen safety sensors are included in Table 8.1.[102] Instruments resulting from this work would be incorporated as a safety alert into current and future systems to measure the hydrogen concentration around hydrogen systems.

A new area of interest for HFTO is to better understand and quantify environmental impacts of leaked hydrogen leakage. The highly sensitive hydrogen safety sensors described above would also support environmental detection of leakage from hydrogen infrastructure, while leakage data will inform analysis of hydrogen's environmental impacts and modeling of global warming potential. As this is a new area for HFTO, properties of interest for hydrogen sensors for emissions detection are still under development. Preliminary targets in this emerging area are also included in Table 8.1, and these will evolve as we learn more about the environmental impacts of hydrogen. As sensor targets are updated for both safety and emissions detection purposes, new targets will be posted.

[102] Specific technical targets for hydrogen safety sensors were included in the Safety, Codes and Standards Section of the 2015 Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRD&D) Plan (https://www.energy.gov/sites/default/files/2015/06/f23/fcto_myrdd_safety_codes.pdf).

Table 8.1. DOE Hydrogen Sensor Targets and Properties of Interest

Metric	H_2 Safety Sensors *Current Targets*	H_2 Emissions Detection *Properties of Interest*
Measurement Range	0.1%–10%	ppb-level sensitivity detection with quantification capability
Operating Temperature	-30°–80°C	-30°–80°C
Response Time **Recovery Time**	Less than one sec	Less than one sec Less than 60 sec
Accuracy	5% of full scale	5% of full scale
Gas Environment/ **Relative Humidity Range**	Ambient air 10%–98%	Ambient air 10%–98%
Lifetime	10 years	10 years
Interference Resistant	Hydrocarbons (e.g.)	Hydrocarbons (e.g.)

The SCS subprogram develops targets related to safety, codes and standards covering diverse hydrogen and fuel cell technologies, specifically aimed at achieving safe commercial liftoff. These targets are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

Information on the different safety, codes and standards activities can be found at the website:
www.energy.gov/eere/fuelcells/safety-codes-and-standards

8.4 Addressing Challenges

Comprehensive safety management is a challenge because best practices for safety developed by industry to comply with regulations and to meet criteria required by insurance providers typically are not publicly available due to proprietary or liability concerns. The scientific and technical basis for best safety practices must then be inferred and validated by RD&D and testing.

These technical challenges must be overcome with solutions that are reliable, safe, and cost-effective. System safety must be convincingly communicated to enablers of fuel cell and hydrogen technologies, including regulatory authorities and the public. The technical challenges addressed in each of the SCS subprogram's five topical areas are highlighted below.

Hydrogen Behavior and Risk Research and Development

A difficult challenge for research and development is the lack of predictive engineering tools that describe hydrogen behavior and data needed to develop and validate scientifically based RCS. Specific R&D needs and challenges are described under Technical Approach above. The RD&D

performed in support of RCS development must also be harmonized internationally to enable deployment of hydrogen technologies in markets worldwide.

A major challenge is to develop and implement methods to perform risk assessments of hydrogen installations and infrastructure. Risk-informed methods are most useful when real operational and safety data are used for analysis inputs, but such data are often proprietary and difficult to obtain. Risk-informed approaches must also allow for analysis of mitigation methods, both active and passive.

Component Research, Development, and Validation

In the area of component research, development, and validation, sensors provide several challenges. Robust guidance on best practices for safety sensor deployment are critical to the efficacy of those sensor technologies. RD&D on the behavior of hydrogen in diverse scenarios (e.g., confined or congested flow) is critical to informing the development of those best practices. In addition, best practices for deploying various sensing technologies are necessary.

Challenges to the monitoring and mitigation of hydrogen emissions include both development and validation of novel components. Sensors capable of achieving the properties of interest outlined in Table 8.1 must be developed, and techniques for validating their performance must be developed. Best practices for deployment of these sensors, in alignment with the best practices for safety sensors, must be identified and implemented.

Materials Compatibility Research & Development

The key technical challenge is to provide the scientific basis for internationally harmonized, robust, validated test measurement protocols, so that a system qualified for service in one country will be accepted by other countries. Test measurement protocols must be developed for all relevant pressure and temperature environments that materials are subjected to during hydrogen service and must account for relevant manufacturing variables such as welds and other process effects. In addition, measurement protocols and test methods must be optimized to minimize the time and cost of qualification and enhance the timely development and deployment of new materials, components, and systems.

The cost of qualifying hydrogen components and systems can be prohibitive, and if test methods are too time consuming, new technology deployment can be delayed. Accelerated testing methodologies must be developed for materials, components, and system qualification that resolve the relevant physics and adequately emulate operational conditions. These test measurement protocols and methodologies must be documented rigorously such that they can be implemented by standards development and testing organizations.

Codes and Standards Harmonization

The key challenge is to facilitate the development of clear and comprehensive RCS to ensure consistency and facilitate deployment of hydrogen and fuel cell technologies. Uniform standards are needed because manufacturers cannot cost-effectively manufacture multiple products that would be required to meet different and inconsistent standards. Availability of applicable standards also facilitates approval by local code officials and safety inspectors.

Another challenge is to reduce competition between individual RCS development organizations and to minimize duplication in domestic codes and standards development. International standards developed by ISO and the International Electrotechnical Commission will have an increasing impact on U.S. hydrogen and fuel cell interests, and cooperative and coordinated development of international standards is also a key challenge. Further, international cooperation through the development of regulations such as the United Nations Global Technical Regulation No. 13 is critical, as it is expected to inform the U.S. Federal Motor Vehicle Safety Standards.

Safety Resources and Support

The key challenge is a general lack of understanding of hydrogen and fuel cell safety needs among local government officials, fire marshals, and the public. For example, local public opposition has prevented or delayed construction and operation of hydrogen fueling stations. In other cases, the local regulatory authority may view one or more hydrogen properties (e.g., flammability at low concentrations) in isolation without considering other characteristics that could mitigate danger (e.g., rapid dispersion when released). Failure to comprehensively consider the properties and behavior of hydrogen may lead to overly restrictive policies that preclude or delay deployment of hydrogen and fuel cell technologies. Other challenges include establishing mandatory reporting for safety and reliability of hydrogen and fuel cell systems that meet the needs of insurance providers and other stakeholders and training and educating government officials and authorities having jurisdiction.

The key challenge to comprehensive safety management is to achieve 100% compliance with a requirement that all projects supported by the HFTO submit safety plans for review by the Hydrogen Safety Panel. Safety planning can ensure that mitigation measures are implemented to address known hazards and that response plans are in place for when incidents do occur. SCS will systematically collect, analyze, and report all safety incidents and near misses that take place on the HFTO's projects. In this way, SCS will take up the challenge to achieve zero safety incidents in hydrogen and fuel cell projects funded by the HFTO.

Comprehensive Collaborative Approach

The SCS subprogram's comprehensive approach to addressing priorities in hydrogen safety and in RCS, relies on collaborations with strong stakeholder engagement across HFTO subprograms, with other DOE offices and labs, with public-private partnerships in the United States, and with the global hydrogen community.

Figure 8.2 illustrates the subprogram's process involving interactive engagement with multiple stakeholders in efforts to best inform the continual development of safety best practices and robust RCS. Stakeholder engagement occurs in the United States and in the international hydrogen community and includes organizations such as the Center for Hydrogen Safety and The International Associations for Hydrogen Safety. Foundational RD&D investigates areas such as hydrogen behavior, risk assessment, and component RD&D.[103] Combining these scientific results and the RD&D performed in other subprograms with stakeholder input, SCS participates in code- and standard-development organization committees to inform the updates, revisions, and approvals for U.S. and international RCS used in hydrogen and fuel cell applications.

Figure 8.2. SCS approach to interactive engagement with multiple stakeholders in efforts to inform the continual development of safety best practices and robust RCS

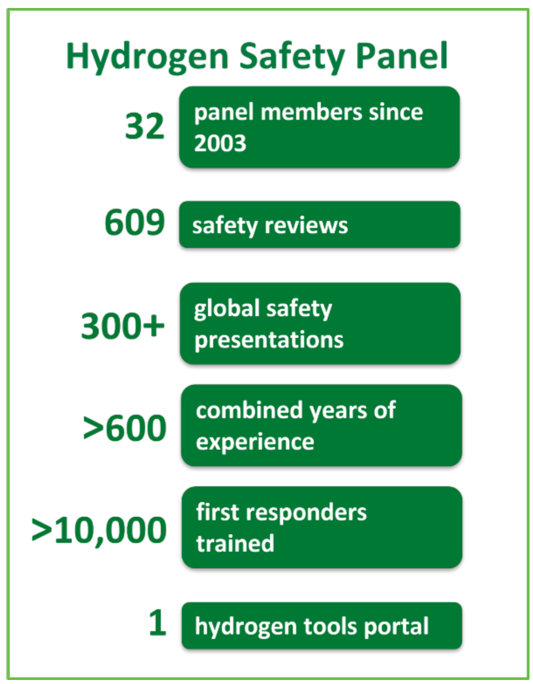
The development of RCS in the United States relies mainly on the voluntary participation of experts representing interested stakeholders who, through a consensus process, prepare requirements to help ensure that, within acceptable levels of risk, products are safe, perform as designed, and are compatible with the systems in which they are used. Table 8.2 summarizes the various roles that the private and government sectors have in the RCS development process. Further detail about the existing U.S. federal regulatory framework for hydrogen, organized by production, storage, delivery, and end use, can be found in the *U.S. National Clean Hydrogen Strategy and Roadmap*.[104]

[103] Program records for the Safety, Codes and Standards activities with key source data, inherent assumptions, and calculation methodologies can be found at https://www.hydrogen.energy.gov/program_records.html#standards.
[104] See Tables 2 and 3, pp. 64–67: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

Table 8.2. Private and Federal Sector Role in Regulations, Codes, and Standards Development

Private Sector		Government Sector	
Standard/Model Code Development Organizations	**Other Private Sector Firms**	**Federal[a]**	**State & Local**
Develop consensus-based codes and standards with open participation of industry and other stakeholders	Develop hydrogen and fuel cell technologies and work with SDOs to develop standards	Perform underlying research to facilitate development of RCS, support necessary research and other safety investigations, and communicate relevant information to stakeholders (including state and local government agencies)	Evaluate codes and standards that have been developed and decide whether to adopt in whole, in part, or with changes

[a] Examples of regulatory activities by U.S. agencies can be found in the *U.S. National Clean Hydrogen Strategy and Roadmap* (Page 64).



Collaborations with the DOE national laboratories are a key part of the government sector's role. Comprehensive safety management supported by the national labs enables HFTO-funded projects to be conducted while reinforcing safety culture. The Hydrogen Safety Panel was formed at Pacific Northwest National Laboratory in 2003 by HFTO to help develop and implement practices and procedures that improve safety in the operation, handling, and use of hydrogen and hydrogen systems. The Hydrogen Safety Panel's primary objective is to enable the safe and timely transition to hydrogen and fuel cell technologies by providing expertise and recommendations. The panel also assists the SCS subprogram in identifying safety-related technical data gaps, best practices, and lessons learned for safety planning and safety practices that are incorporated into hydrogen and fuel cell technology projects supported by HFTO. This approach helps to mitigate risk to facilitate and promote the safe technology adoption by external stakeholders. Hydrogen Safety Panel statistics over the past twenty years are shown in the inset.[105]

Collaborations with the national labs outside of the Hydrogen Safety Panel are also important to SCS's RD&D portfolio. For example, SCS-funded RD&D at Sandia National Laboratories developed the methodology and performed the underlying calculations and analyses that form the basis for bulk liquid hydrogen setback distances. The results of this research were formally documented in a Sandia report[106] that detailed the technical justifications for code revisions to liquid hydrogen exposure distances. This RD&D informed updates to NFPA 2 2023[107] that have been published with updated bulk liquid storage setback distance requirements. Similarly, RD&D on the performance and deployment of hydrogen safety sensors has led to science-based guidance and the placement of hydrogen sensors within hydrogen equipment enclosures and buildings.[108]

The SCS subprogram's national lab collaborations are also important to ensuring safety of bulk hydrogen storage, which faces both technical challenges, including materials compatibility, and regulatory challenges, such as consistency of RCS. Streamlined RCS for bulk hydrogen storage are necessary to achieve safe deployment and reasonable safety distances. As storage volumes increase, logistically prohibitive setback distances and additional standards oversight (e.g. the Occupational Safety and Health Administration's 29 CFR 1910.119) could be required. Ongoing RD&D on the behavior of bulk gaseous and liquid hydrogen performed in coordination with HFTO's H-Mat and HyBlend national lab consortia[109] will inform modeling efforts and applied risk assessment activities to inform RCS development.

RCS development and refinement also requires international collaboration and harmonization, including test procedures to qualify hydrogen and fuel cell components and systems. In addition to the RCS development organizations listed earlier, SCS also works directly with stakeholders in the international RCS community such as the United Nations Economic Commission for Europe on the Global Technical Regulations, the International Association for Hydrogen Safety (HySafe), IPHE, the Hydrogen Council, and others to ensure that DOE research is utilized in regulations, codes, and standards development as appropriate. SCS ensures timely and accurate

[105] Satyapal, Sunita. June 5, 2023. "U.S. DOE Hydrogen Program Annual Merit Review (AMR) Plenary Remarks." https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/plenary1_satyapal_2023_o.pdf.
[106] Ehrhart, Brian D., Ethan S. Hecht, and Benjamin B. Schroeder. February 2023. *Technical Justifications for Liquid Hydrogen Exposure Distances*. Sandia National Laboratories. Sandia Report SAND2023-12548. Accessible at https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/.
[107] National Fire Protection Association. 2023. *NFPA* 2. https://www.nfpa.org/codes-and-standards/nfpa-2-standard-development/2.
[108] Andrei V. Tchouvelev, William J. Buttner, Daniele Melideo, Daniele Baraldi, and Benjamin Angers. March 2021. "Development of risk mitigation guidance for sensor placement inside mechanically ventilated enclosures – Phase 1." *International Journal of Hydrogen Energy*. 2021;46:12439–54. https://doi.org/10.1016/j.ijhydene.2020.09.108.
[109] Additional information on HFTO's consortia approach to RD&D can be found in this report's Program Implementation chapter.

dissemination of relevant information to enable the timely development of harmonized RCS and also provides improved and focused knowledge tools and training for key constituents of the hydrogen safety community, such as through materials published at H2Tools.org.[110]

In 2019, Pacific Northwest National Laboratory and the American Institute of Chemical Engineers partnered to form the Center for Hydrogen Safety, a global nonprofit dedicated to promoting hydrogen safety and best practices worldwide by supporting and promoting the safe handling and use of hydrogen across applications in the energy transition and providing a common communication platform with a global scope to ensure safety information, guidance, and expertise is available to all stakeholders.[111]

8.5 RD&D Focus Areas

The SCS subprogram tackles barriers related to *Cost*, *RCS Consistency*, *Safety Resources*, *Technical Data*, *Usage and Access Restrictions*, and *Technology.* These barriers are summarized in Table 8.3 with some specific examples of associated challenges that are addressed through the SCS RD&D portfolio.

Table 8.3. Safety, Codes and Standards Barriers and Associated Challenges

Barriers	Associated Challenges
C: Cost- *materials, components, systems*	Capital costs of materials, components, equipment, and land (e.g., setback distances required for safety codes)
R: RCS Consistency	Gaps in RCS and lack of consistency limit market penetration and technology deployment
S: Safety Resources	New stakeholders lack hydrogen experience
	Need for improved safety culture
	Limited accessibility to data and documented experiences
T: Technical Data	Insufficient technical basis for RCS
	Lack of data on component failure, incidents, root cause analysis, etc.
U: Usage and Access Restrictions	Access restrictions, such as parking structures, tunnels, etc.
TE: Technology	Lack of available technology to meet specifications, such as sensors requiring ppb-level detection

[110] Pacific Northwest National Laboratory. "H2 Tools." https://h2tools.org/.
[111] Center for Hydrogen Safety. https://www.aiche.org/chs.

The SCS subprogram's comprehensive portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described above in Table 8.3. Tables 8.4 and 8.5 provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges within the five priority topical categories, along with examples of key targeted milestones.

Table 8.4. Near-Term R&D Focus Areas for SCS

Priority Topic	Focus RD&D	Barrier Addressed	Milestones
Hydrogen Behavior and Risk R&D	Model tunnel risk scenarios for common tunnel designs		• Lay regulatory groundwork for larges-cale clean hydrogen deployments across production, processing, delivery, storage, and end use (2025)[a] • Develop streamlined guidance on hydrogen pipeline and large-scale project permitting with stakeholder engagement and addressing environmental, energy, and equity priorities (2025)[a] • Develop hydrogen sensors with low-level (ppb-level) detection limits (2025) • Develop hydrogen release quantification technologies to monitor emissions for environmental monitoring (2025)
	Expand quantitative risk assessment capability to include H_2 blends		
	Validate ignited H_2 behavior and proposed mitigations in support of code development		
	Model high flow hydrogen transfer risk using quantitative risk assessment tools Validate hydrogen release models for bulk behavior and blended hydrogen behavior	C, R, S, T	
Component RD&D	Develop highly sensitive sensors for environmental detection of unintentional hydrogen releases and expand validation capability	T, U, TE	
	Develop method for *in situ* leak quantification		
	Complete validation of high-flow fueling protocol and components for heavy-duty applications		
Materials Compatibility RD&D	Validate test methodologies to qualify materials for hydrogen service	C, R, T	
	Develop and validate methodology for quantifying cycle life or materials in service		
Codes and Standards Harmonization	Support development of liquid H_2 fueling protocols		
	Expand scope of HySCAN tool		

	Develop portfolio of activities to reduce permitting burden for H_2 technologies		
Safety Resources and Support	Develop university and professional workforce curriculum through H_2EDGE		
	Support safe R&D and deployment activities via the Hydrogen Safety Panel		
	Develop sensor use guidance and wide area monitoring capabilities to help address improper or inadequate deployment of safety sensors	S, T, U, TE	

[a] Milestone is derived from the *U.S. National Clean Hydrogen Strategy and Roadmap*.

Table 8.5. Longer-Term R&D Activities for SCS

	Focus RD&D	Barrier Addressed	Milestones
Hydrogen Behavior and Risk R&D	Support RD&D for development of codes and standards for bulk storage and large-scale applications of hydrogen	C, S, U	• Enable international harmonization of codes and standards related to hydrogen technologies (2030)[a] • Address regulatory challenges to increase electrolyzer access to renewable and nuclear energy (2030)[a] • Develop national guidance for blending limits (2030)[a] • Enable access to tunnel infrastructure for fuel cell electric vehicles in at least one new region (2030) • Support development of a Federal Motor Vehicle Safety Standard for hydrogen vehicles (2030)
	Model risk scenarios for underground storage of hydrogen, both for caverns and for vaulted storage		
	Develop reliable source of liquid H_2 leak frequency data and inform changes to quantitative risk assessment models		
	Model risk scenarios for heavy-duty maintenance facilities		
Component RD&D	Validate highly sensitive sensors for environmental detection of unintended hydrogen releases		
	Support the validation of a liquid H_2 fueling protocol		
Materials Compatibility RD&D	Validate test methodologies to qualify materials for hydrogen service		

Codes and Standards Harmonization	Continue committee coordination to ensure RD&D results are accurately reflected in RCS		
	Enable reduction of permitting burden for hydrogen technologies, including enabling timely handling of permit requests		
Safety Resources and Support	Support safe R&D and deployment activities via the Hydrogen Safety Panel		
	Conduct workforce development activities for hands-on work environments		

[a] Milestone is derived from the *U.S. National Clean Hydrogen Strategy and Roadmap*.

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