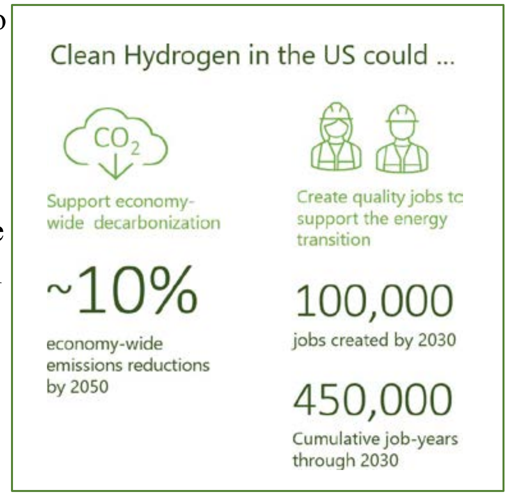
Executive Summary

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**
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> 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

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[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.

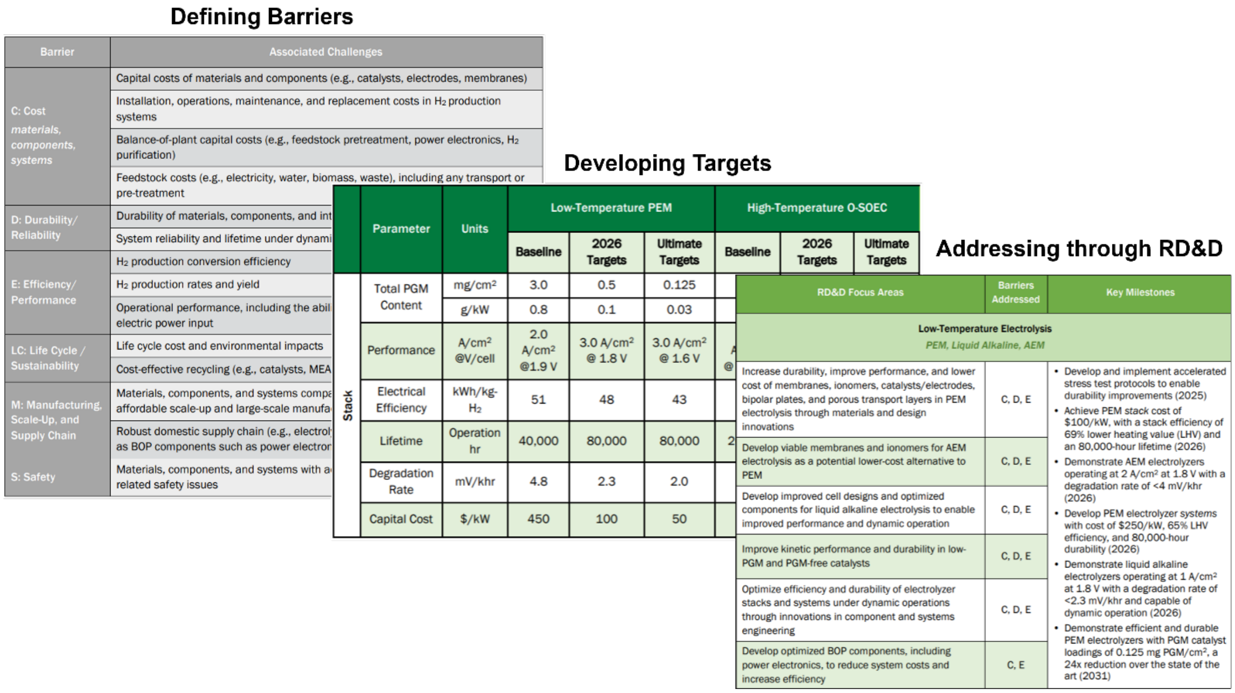

Figure ES.1. The *MYPP* defines barriers, develops targets, and lays out plans for meeting those targets. Shown here is an example of barriers, targets, and plans for electrolysis.

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.

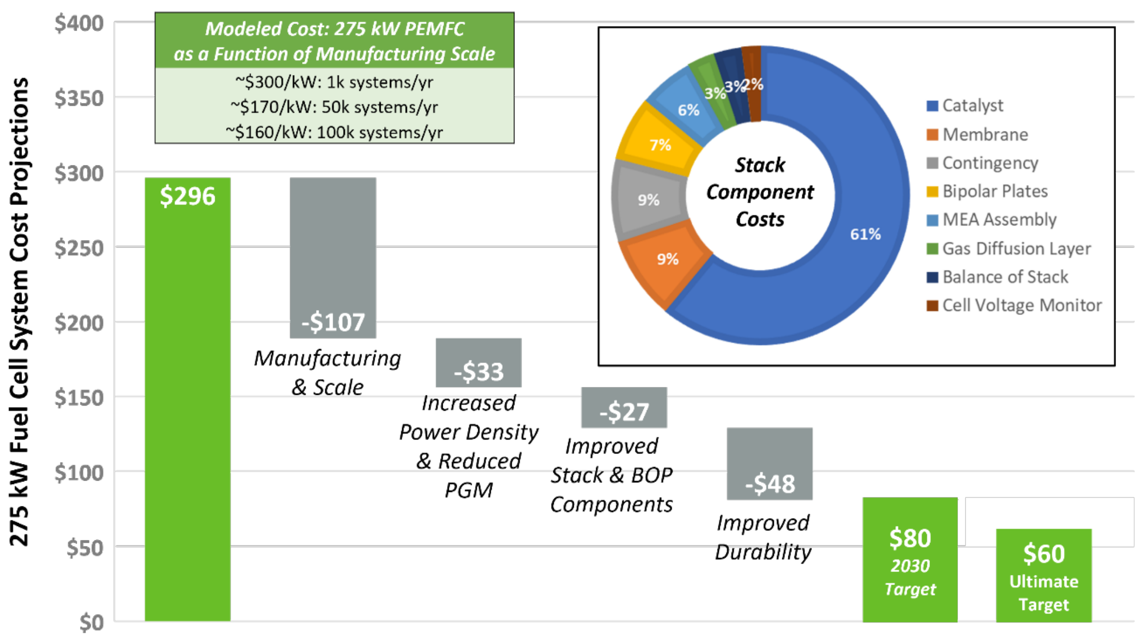

Figure ES.2. Example of "waterfall" chart showing pathways to meeting HFTO cost-reduction targets

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.

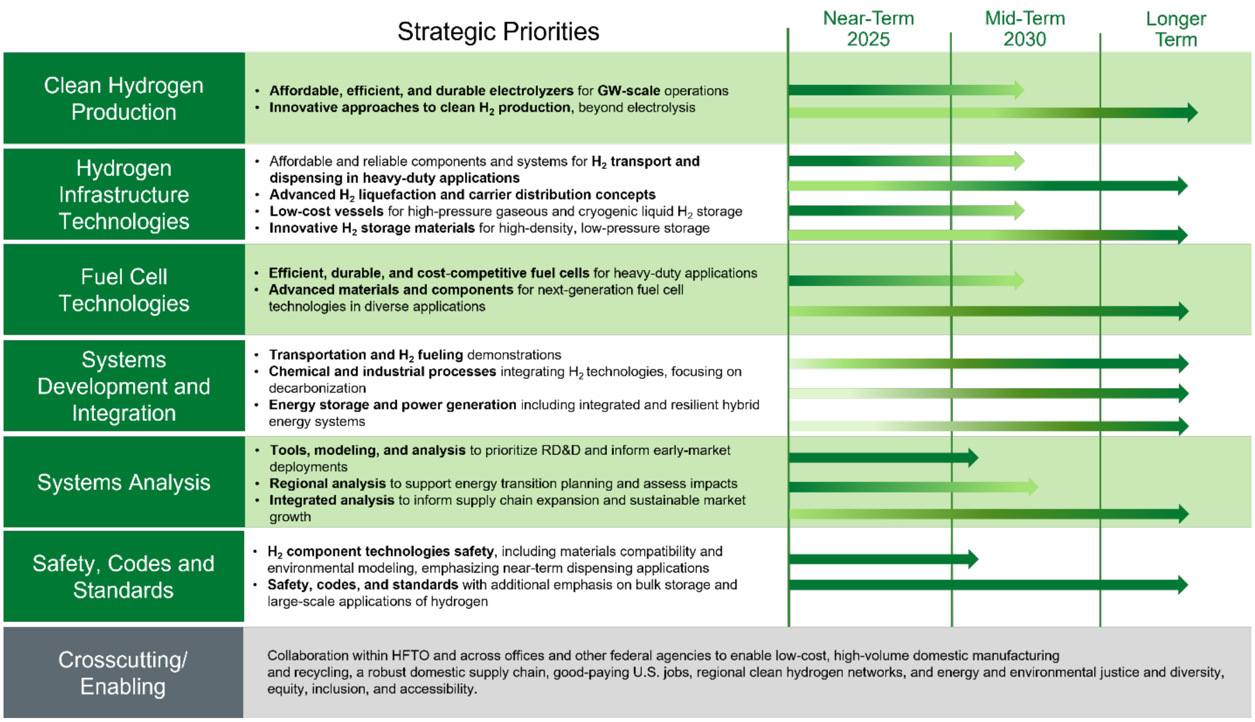

Figure ES.3. Strategic RD&D priorities in HFTO's portfolio, illustrating the multipronged approach—which includes near- to mid-term and longer-term priorities across most focus areas.

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.