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.

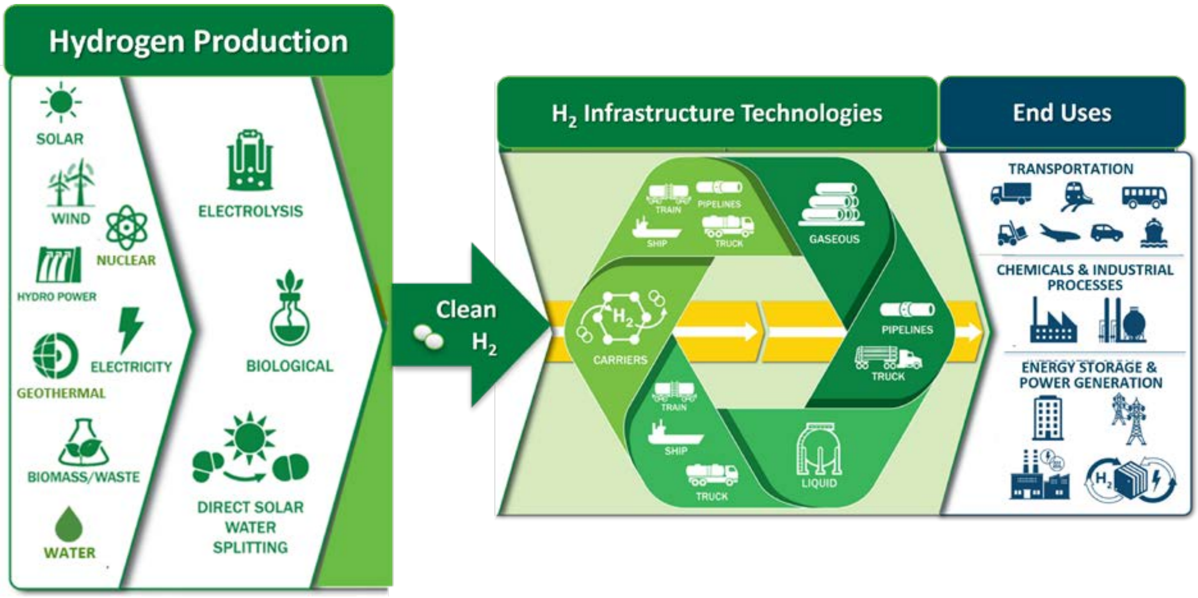

Figure 3.1. Clean hydrogen production leverages diverse clean energy options and abundant natural resources found across the United States for distribution to multiple end uses in support of national decarbonization goals.

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

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[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.

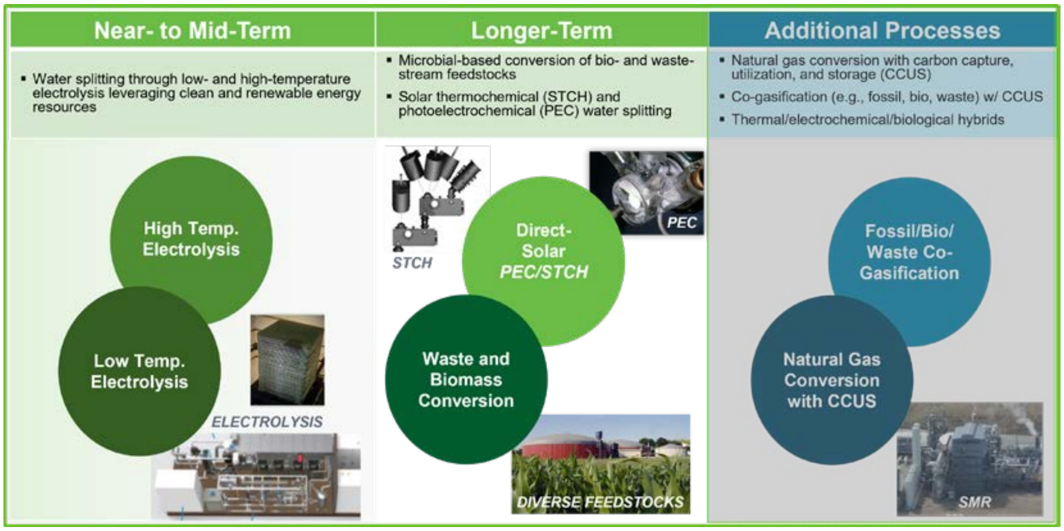

Figure 3.2. Clean hydrogen production pathways covered in the subprogram's RD&D portfolio

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.

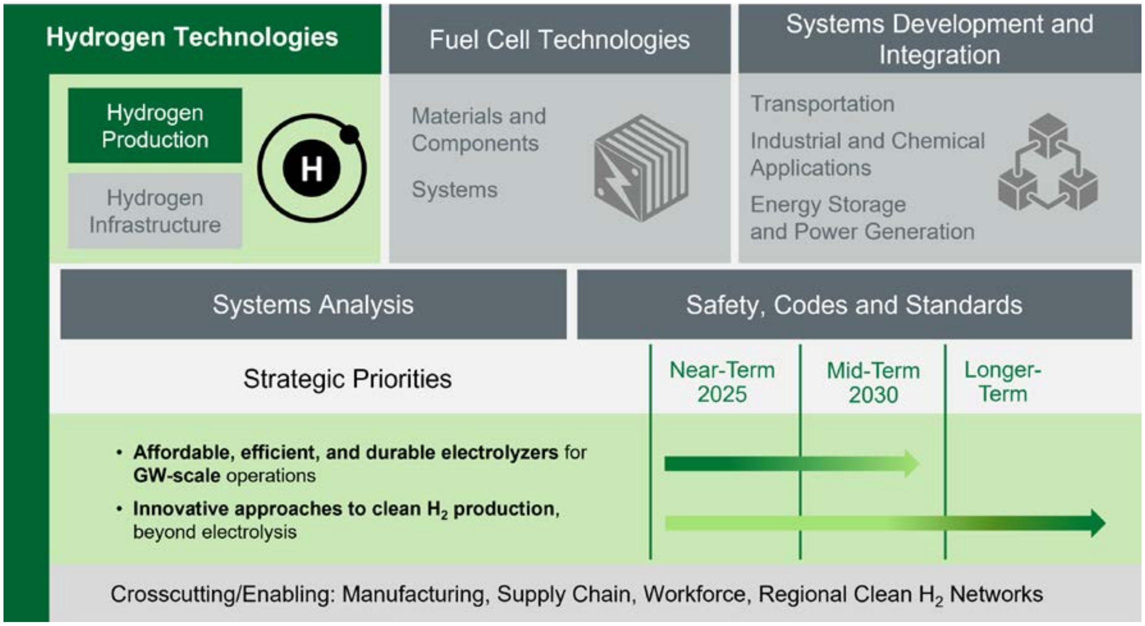

Figure 3.3. Strategic priorities guiding hydrogen production RD&D

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.

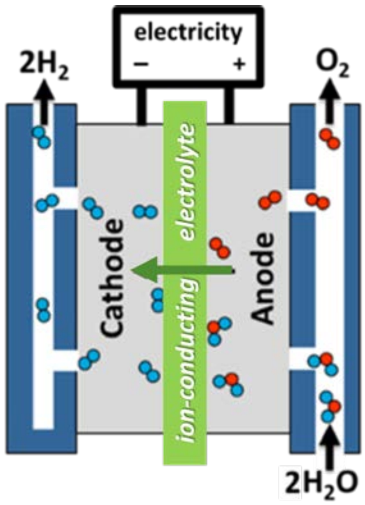

Figure 3.4. Electrolyzer cell: water and electricity in; H_2 and O_2 gases out

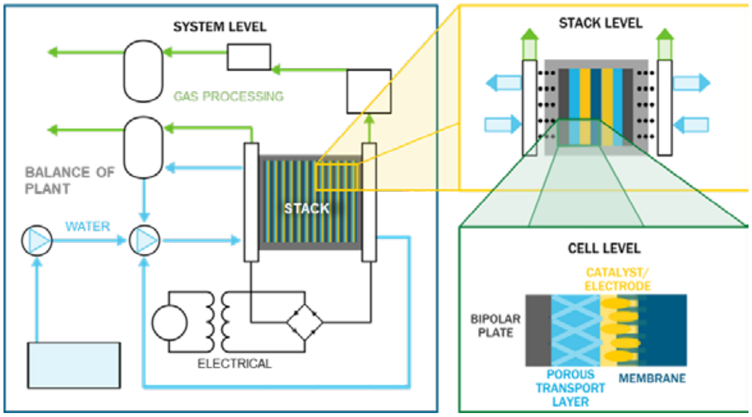

Figure 3.5. Electrolyzer systems are composed of stacks comprising multiple individual cells and balance-of-plant components

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.

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.

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 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.

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[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.

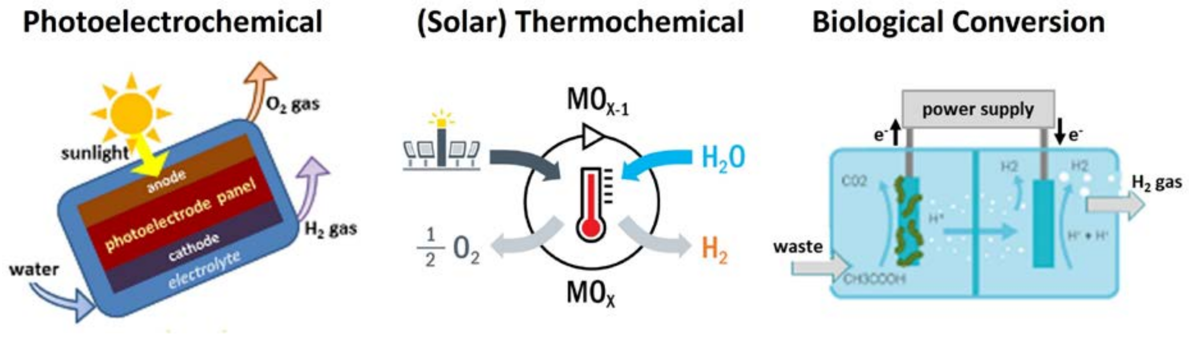

Figure 3.6. Categories of advanced pathways for clean hydrogen production

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.

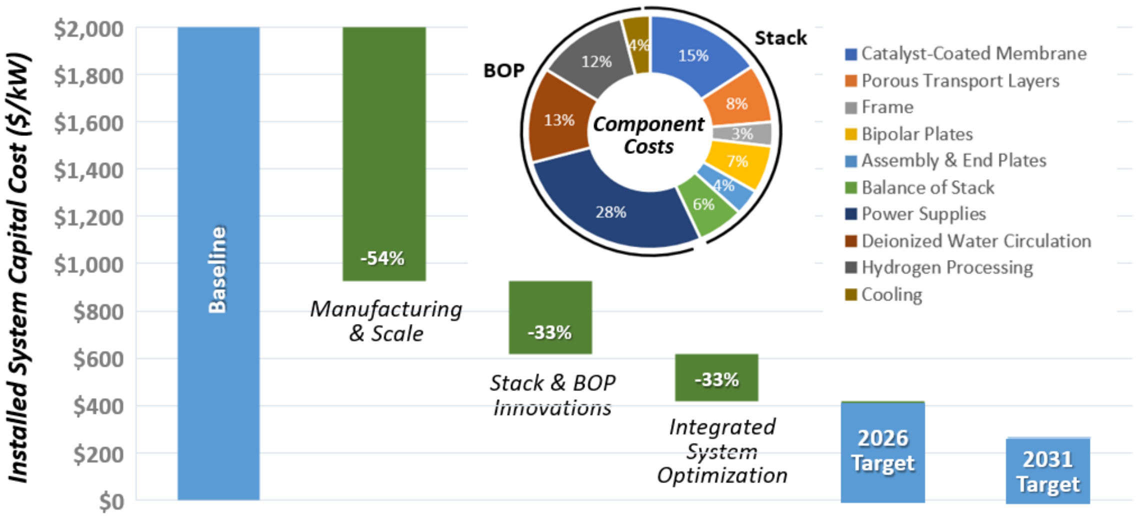

Figure 3.7. Reducing electrolyzer capital costs will require innovating the electrolyzer stack and BOP components and also reaching economies of scale.

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

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[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.

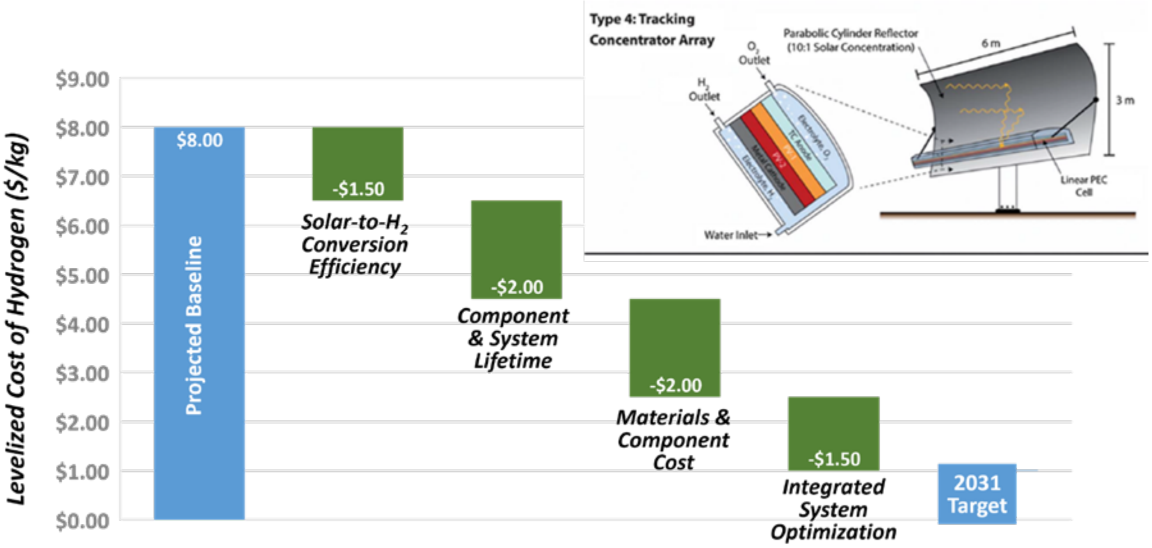

Figure 3.8. Boundary-level analysis of a conceptual Type-4 PEC system (i.e., photoelectrode-based with nominal solar concentration and tracking), illustrating a cost-reduction pathway to meeting the Hydrogen Shot goal

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:

ELECTROLYSIS

- **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.

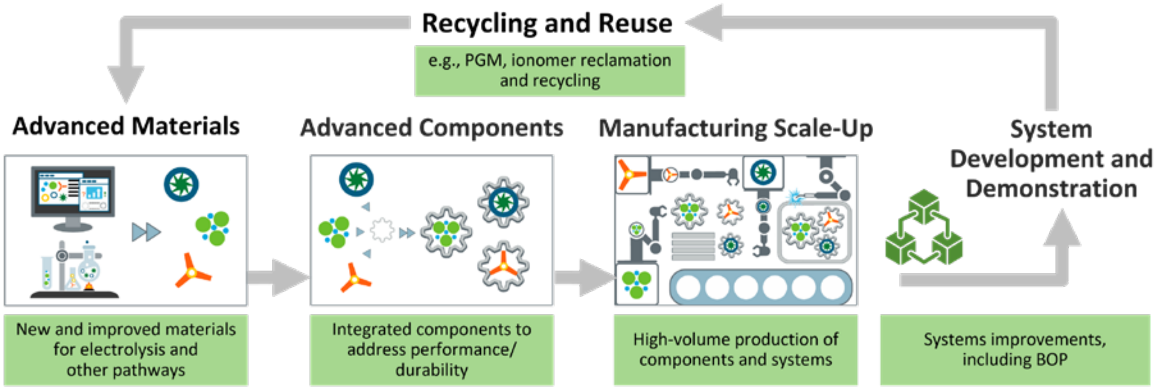

Figure 3.9. Comprehensive materials-, component-, and system-level RD&D across the near- and longer-term clean hydrogen production pathways takes into account requirements for manufacturing and scale-up as well as the systems integration and end-of-life recycling and reuse.

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.

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[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.

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.

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.

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	

High-Temperature Electrolysis *O-SOEC, P-SOEC*		
Improve understanding of degradation mechanisms to increase durability of cell and stack components in SOEC technologies	D	• 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/cm^2 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)
Develop advanced cell and stack materials and components with improved performance and decreased degradation	D, E	
Address thermal management issues in stacks and systems	D, E	
Develop efficient technologies operating at reduced temperatures (<700°C) through materials and design innovations (e.g., P-SOEC)	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	
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	D, E	
Develop standardized accelerated stress testing procedures and protocols	D, E	

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 $\$2/\text{kg-H}_2$ (2026) and $\$1/\text{kg-H}_2$ (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