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# HYDROGEN SHOT:

## Water Electrolysis Technology Assessment

**Hydrogen Shot: Water Electrolysis Technology Assessment**

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# ACRONYMS

| | |
|---|---|
| AEM | alkaline exchange membrane |
| BOL | beginning of life |
| BOP | balance of plant |
| $CO_2$ | carbon dioxide |
| DOE | U.S. Department of Energy |
| GHG | greenhouse gas |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy use in Technologies |
| $H_2$ | hydrogen |
| H2A-Lite | Hydrogen Analysis Lite Production |
| HTE | high-temperature electrolyzer |
| LA | liquid alkaline |
| LCOH | levelized cost of hydrogen |
| LTE | low-temperature electrolyzer |
| O-SOEC | oxide-ion-conducting solid-oxide electrolyzer cell |
| PEM | proton exchange membrane |
| PGM | platinum group metal |
| P-SOEC | proton-conducting solid-oxide electrolyzer cell |
| PTL | porous transport layer |
| RD&D | research, development, and demonstration |
| RDD&D | research, development, demonstration, and deployment |
| SOFC | solid-oxide fuel cell |
| TRL | technology readiness level |

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# EXECUTIVE SUMMARY

In June 2021, the U.S. Department of Energy (DOE) announced the first of a series of department wide Energy Earthshots™ designed to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. The Hydrogen Shot™ seeks to reduce the cost of clean hydrogen ($H_2$) production to $1 per 1 kilogram in 1 decade (“1 1 1”). As part of this initiative, DOE is developing in-depth technology assessments of three general pathways to clean hydrogen production: *water electrolysis* using renewable- or nuclear-generated electricity (this report); *thermal conversion* (e.g., reforming of natural gas with carbon capture); and *advanced pathways* (e.g., direct solar water splitting or biological conversion of waste streams) [1]. As one in a series of Hydrogen Shot reports and assessments, this report, *Hydrogen Shot: Water Electrolysis Technology Assessment*, focuses primarily on current electrolyzer status and research, development, and demonstration (RD&D) needs to achieve \$1/kg $H_2$ based on current information and analysis. Updated assessments with more detailed analysis will follow as the technologies advance.

Water electrolysis, the process of using electricity to convert water into hydrogen and oxygen gases, is a rapidly growing industry for hydrogen production. When electrolysis uses clean electricity, clean hydrogen can be produced with zero or near-zero carbon dioxide ($CO_2$) emissions. However, hydrogen produced by water electrolysis is currently more expensive than incumbent hydrogen production methods that utilize fossil fuel feedstocks, such as natural gas. Steam methane reforming of natural gas is the most common method of low-cost hydrogen production today; however, this process emits approximately 10 tons of $CO_2$ for every ton of hydrogen produced. In the near term, carbon capture, utilization, and storage can be employed with steam methane reforming to reduce $CO_2$ emissions, but with added costs. In the long term, opportunities for deep decarbonization through clean hydrogen deployments will require sustainable approaches such as water electrolysis coupled with renewable and/or nuclear power generation. However, significant capital and operating cost reductions, as well as science and technology advancements, will be needed to meet the Hydrogen Shot goals and enable greater market demand for clean electrolytic hydrogen.

This report documents the current state of development of five different electrolyzer technologies: proton exchange membranes, liquid alkaline, oxide-ion-conducting solid-oxide electrolyzer cells, alkaline exchange membranes, and proton-conducting solid-oxide electrolyzer cells. Boundary-level techno-economic analysis—using grid scenarios for electricity cost—shows that the current cost of hydrogen produced from these types of electrolyzers ranges from approximately $6/kg to $8/kg (depending on the electrolyzer technology), while recognizing that grid electricity does not currently qualify as *clean*, and that indirect emissions from grid-connected electrolysis can be significant. Further analysis also shows that the Hydrogen Shot goal of $1/kg for clean hydrogen produced by water electrolysis powered by clean electricity is aggressive, but potentially achievable in the future, if we develop advanced technologies, manufacture them at scale, and leverage ongoing cost reductions in clean electricity generated by diverse renewable and/or nuclear resources across the nation. Since the Hydrogen Energy Earthshot was launched, supply chain issues, higher electrolyzer system installation costs, and inflation have increased costs, making this goal even more challenging to achieve. In light of such challenges, this report describes the critical technology and manufacturing advancements, as well as integrated energy system developments, that will be needed through continued RD&D efforts. While each electrolyzer technology has its own specific development needs, all technologies can benefit from at-scale manufacturing processes, balance-of-plant cost reductions, and system optimization with clean energy resources. Deploying water electrolyzers that utilize low-cost clean electrons at or near the site of electricity generation is an important potential pathway to producing low-cost, clean hydrogen meeting the Hydrogen Shot goal.

# INTRODUCTION

## Hydrogen Shot

The Hydrogen Shot[1] is the first Energy Earthshot launched under the U.S. Department of Energy's (DOE's) Energy Earthshots Initiative, which will accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. Achieving the Energy Earthshots will help America tackle the toughest remaining barriers to addressing the climate crisis and more quickly reach the Biden-Harris administration's goal of net-zero carbon emissions by 2050 while creating good-paying union jobs and growing the economy.

The first Energy Earthshot, launched June 7, 2021—Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1").

The Hydrogen Shot establishes a framework and foundation for the deployment of clean hydrogen ($H_2$) across multiple sectors of the economy—most importantly in "hard-to-decarbonize" applications. This framework includes support for research, development, demonstration, and deployment (RDD&D) projects. Industries are beginning to implement clean hydrogen to reduce emissions, yet many hurdles remain to deploying it at scale, requiring continued RDD&D. Currently, hydrogen from clean and renewable energy costs well over $5 per kilogram. Achieving the Hydrogen Shot's 80% cost reduction goal can unlock new markets for hydrogen, including steel manufacturing, clean ammonia, energy storage, and heavy-duty trucks. This would create more clean energy jobs, reduce greenhouse gas (GHG) emissions, and position America to compete in the clean hydrogen market on a global scale. The needed RDD&D efforts should ensure that environmental protection and benefits for local communities remain a priority.

## Impact

The Hydrogen Shot goal is aligned with the priorities for affordable clean hydrogen articulated in the ***U.S. National Clean Hydrogen Strategy and Roadmap*** [2]. If the national strategy is successfully implemented, scenarios show the opportunity for at least a fivefold increase in clean hydrogen use, including in end uses that are otherwise difficult to decarbonize. Estimates in the *U.S. National Clean Hydrogen Strategy and Roadmap* show the potential for clean hydrogen to contribute to substantial reductions in GHG emissions economywide by 2050, as well as the potential to create more than 100,000 direct and indirect jobs by 2030. The Hydrogen Shot will catalyze innovation in all clean hydrogen production pathways, encouraging investment in diverse regions across the country.

## Clean Hydrogen Technology Pathways

In pursuit of the Hydrogen Shot, DOE focuses on the research, development, and demonstration (RD&D) of multiple technology pathways with the potential to achieve affordable

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[1] www.energy.gov/eere/fuelcells/hydrogen-shot.

clean hydrogen production in the near and longer terms, leveraging different resources across the nation. These technology pathways fall broadly into three main categories:

- **ELECTROLYSIS**
  The ***electrolysis pathways*** are based on commercial and near-commercial technologies for splitting water into hydrogen and oxygen, which can be powered by low-carbon sources such as wind, solar, hydropower, or nuclear energy (among others) to produce clean hydrogen. Examples include low-temperature electrolyzers (LTEs) using liquid alkaline (LA) solutions or proton exchange membranes (PEMs) as ionic conductors, as well as higher-temperature solid-oxide electrolyzers with the potential for higher electricity-to-hydrogen conversion efficiency. Hydrogen Shot strategic priorities for electrolysis pathways include improving performance and cost of electrolyzer systems (e.g., stacks and balance of plant [BOP]) at gigawatt scales; optimizing integration of electrolyzer systems with renewable or nuclear power to leverage low-cost on-site electricity; and facilitating expanded domestic manufacturing capacity.

- **THERMAL CONVERSION**
  ***Thermal conversion*** processes use heat as a primary energy source to drive chemical reactions that convert carbon-based feedstocks into hydrogen and other byproducts. Examples include reforming, gasification, and pyrolysis processes. Carbon capture, utilization, and storage can be used in conjunction with thermal conversion to reduce the carbon footprint of the hydrogen produced. The Hydrogen Shot's strategic priorities for thermal conversion include improving the performance and cost of integrated systems for natural gas reforming with carbon capture, and storage to achieve emissions targets, as well as developing diverse options such as gasification of waste feedstocks with carbon capture and storage and pyrolysis of natural gas into hydrogen and solid carbon to meet cost and emissions goals. These priorities are examined in detail in the report *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*, which was released in December 2023 [1].

- **ADVANCED PATHWAYS**
  As part of the longer-term vision, clean hydrogen can also be produced through a variety of new and advanced pathways requiring little or no electricity inputs. Examples include photoelectrochemical and thermochemical processes for direct solar water splitting, and biological processes that can convert biomass or waste streams into hydrogen with value-added coproducts (such as purified water). Additionally, advanced hybrid approaches combining electrochemical, thermochemical, pyrolytic, and/or photoelectrochemical processes producing clean hydrogen from water, biomass, or wastes are being explored. Other interesting opportunities, such as geological hydrogen, are also being investigated. The Hydrogen Shot's strategic priorities for advanced pathways include high-risk, high-reward R&D to advance fundamental scientific understanding that can drive progress across multiple advanced hydrogen production pathways. These priorities will be examined in detail in the forthcoming report, *Hydrogen Shot Technology Assessment: Advanced Pathways*.

## Technology Assessment vs. Commercial Liftoff

This report provides a technology assessment of electrolysis pathways for clean hydrogen production covered by the Hydrogen Shot. As noted above, other documents will provide technology assessments of thermal conversion pathways and advanced pathways [1]. Consistent with methodologies adopted in all of DOE's Energy Earthshots, these assessments are intended to track status and RD&D improvements relative to a 10-year performance target that will directly support long-term national decarbonization goals. As such, a techno-economic framework has been adopted in this report referencing a static technology performance baseline separate from variable economic factors such as inflation. Specifically for the Hydrogen Shot, technology baselines for the various clean hydrogen production pathway costs were established on the basis of 2020 dollars (2020 $), and status and projected cost reductions compared to the baselines are reported in the same basis to emphasize the impact of RD&D on technology advancement and facilitate comparison between pathways, separate from consideration of macroeconomic factors. For consistency, all Energy Earthshots will use the same 2020 dollar basis for annual comparisons related to technology development but will also track corresponding values for nominal year dollars to facilitate comparisons with other analyses and reports.

For example, DOE, through its Pathways to Commercial Liftoff initiative, tracks year-over-year changes in the commercial deployment status and prospects of different clean energy technologies reflective of the present economywide realities, including inflation and supply chain factors. The resulting reports are intended specifically to provide valuable information for industry stakeholders and investors who have the potential to take action that will accelerate deployment. The ***Pathways to Commercial Liftoff: Clean Hydrogen*** report addresses electrolyzer technologies, as well as the other Hydrogen Shot pathways; however, the techno-economic framework is different and considers available costs in current-year dollars, as well as the impacts of various incentives [3]. The cost projections presented in this report are related to various cost scenarios in the *Pathways to Commercial Liftoff* report, including through the use of harmonized technical inputs and assumptions in both reports. However, it is important to emphasize that the interpretation of results relative to specific electrolyzer technologies must account for the different purposes of each document, as well as the different techno-economic frameworks employed.

This Hydrogen Shot technology assessment presents a snapshot of various electrolyzer technology pathways for clean hydrogen production, including technology status and envisioned approaches for achieving the Hydrogen Shot goals through RD&D advances. This document, as well as the *Pathways to Commercial Liftoff* report, will be updated periodically by DOE to reflect progress reported by stakeholders from industry, academia, and the national labs.

# WATER ELECTROLYSIS OVERVIEW

Hydrogen can be produced from water using electricity through an electrochemical process known as *electrolysis*. As shown in **Figure 1**, electrolysis splits water into hydrogen and oxygen gases; systems employing this process are called *electrolyzers*. Electrolyzer systems consist of *stacks (*groups of individual *cells*) and *BOP* equipment that manages the inputs (electricity and water) and outputs (hydrogen and oxygen) from the stack (**Figure 2**). The use of water electrolysis powered by the nation's abundant clean energy resources is aligned with the Hydrogen Shot mission and is expected to play a critical role in achieving national decarbonization goals [4].

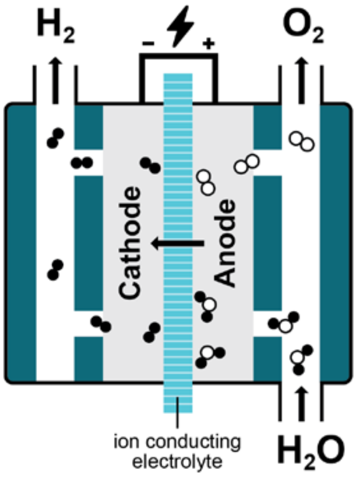

**Figure 1. PEM electrolyzer cell—showing water and electricity in and hydrogen and oxygen gases out.**

As electrolyzer technologies improve and their costs come down, global capacity is expected to increase substantially. By 2030, the global installed capacity of electrolyzers has the potential to grow to more than 300 GW (based on announced projects), from only about 1 GW installed as of October 2023 [5]. When these deployments are coupled with electricity from renewables or nuclear power, the clean hydrogen produced can offer significant decarbonization potential across multiple sectors [3] [6] [7].

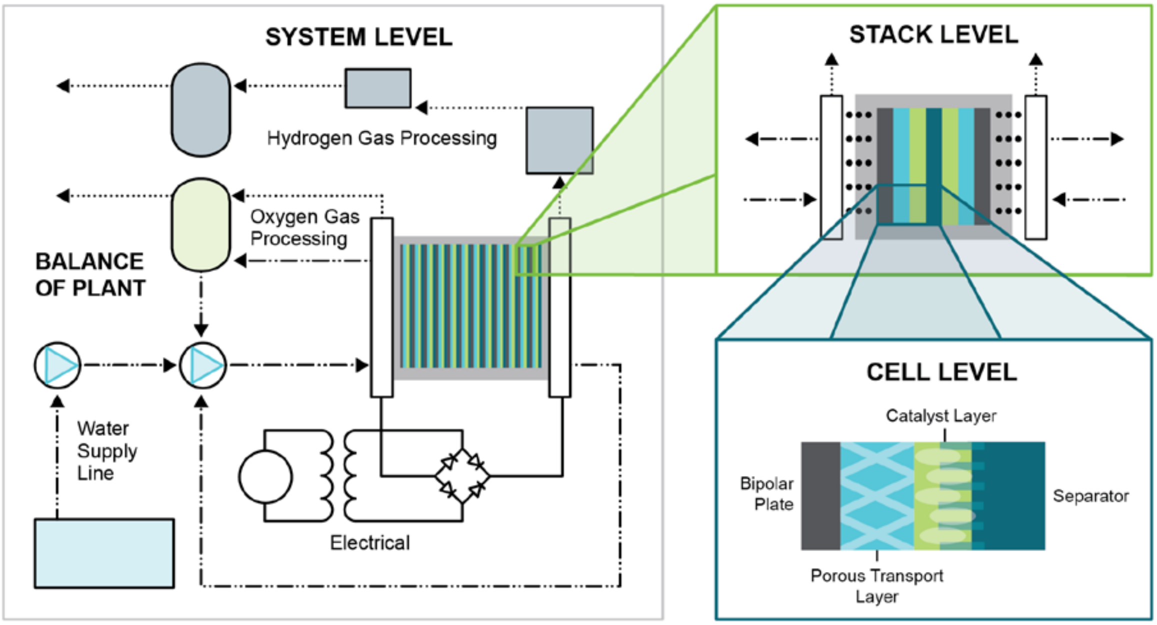

**Figure 2. Electrolyzer systems are composed of stacks and BOP components. Stacks are composed of individual cells. The size and number of cells in a stack, the number of stacks in a system, and the BOP equipment in a system can all vary depending on the system's configuration.**

Current electrolyzer technologies are at different technology readiness levels (TRLs), use different electrolyte materials (liquid, solid polymer membranes, or solid ceramics), and operate at different temperatures, typically determined by the limits of the electrolyte material. Electrolyzer technologies are commonly grouped into two categories based on operating temperature: LTEs and high-temperature electrolyzers (HTEs).

LTE technologies include:

- PEMs
- LA
- Alkaline exchange membranes (AEMs).

HTE technologies include:

- Oxide-ion-conducting solid-oxide electrolyzer cells (O-SOECs)
- Proton-conducting solid-oxide electrolyzer cells (P-SOECs).

**Figure 3** shows a classification of these key electrolyzer types according to operating temperature and electrolyte type. The color of each technology block represents the current domestic commercialization level, where dark blue is the most commercially mature.

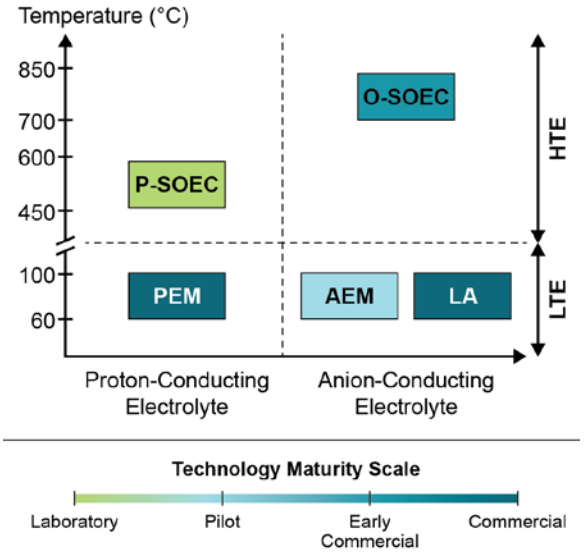

**Figure 3. Electrolyzer technologies as a function of electrolyte and operating temperature. The most commercially mature technologies are shown in dark blue.**

This assessment focuses on each of the five electrolyzer technologies described above. Each technology offers unique benefits and pathways to achieve the Hydrogen Shot goal (**Table 1**). The most commercially advanced technologies could more rapidly achieve manufacturing economies of scale, which would drive down capital costs and thereby reduce overall hydrogen cost, bringing it closer to the $1/kg-$H_2$ target. While they are not yet at the same level of commercialization, other technologies in the laboratory, pilot, and early commercial stages have certain advantages and the potential to achieve even lower costs in the future than commercial technologies.

**Table 1. Comparison of Electrolyzer Technologies**

| Technology | Commercial Status | Advantages |
|---|---|---|
| LA | Commercial | • Low-cost materials<br>• Proven long lifetime<br>• Established supply chain and manufacturing processes. |
| PEM | Commercial | • High current density at high efficiency<br>• Differential pressure operation<br>• Dynamic operation capability. |
| O-SOEC | Early Commercial | • High electrical efficiency<br>• Thermal energy integration. |
| AEM | Pilot | • Low-cost materials<br>• Dynamic operation capability. |
| P-SOEC | Laboratory | • High electrical efficiency<br>• Thermal energy integration<br>• Lower-cost materials and operating temperature than O-SOEC. |

The following section discusses the cost status of clean hydrogen production from the three most commercially mature electrolyzer technologies and the major common cost drivers of electrolytic hydrogen production. Achieving the Hydrogen Shot goal will require addressing a unique set of challenges and RDD&D needs for each technology, which are summarized later in this document.

# TECHNO-ECONOMIC ANALYSIS

The economics of clean hydrogen production via water electrolysis depend not only on the electrolyzer cost, performance, and system design, but also on the source of clean electricity. Some electrolyzer technologies may be better suited for integration with different clean energy sources or end uses, which can influence the optimal operating strategy and size of the electrolyzer system. For example, HTE technologies can take advantage of integration with thermal energy sources, such as those at nuclear power plants, while membrane-based LTE technologies are well suited for clean energy sources with either stable or variable energy output (both nuclear and variable renewable energy sources).

The levelized cost of hydrogen (LCOH) in 2020 $ was estimated for PEM, LA, and O-SOEC (the three most commercially advanced technologies to date) using a *simplified, boundary-level* set of parameters. The Hydrogen Analysis Lite Production (H2A-Lite) model, a peer-reviewed national-laboratory-developed model, was used to compare the technologies using a consistent financial analysis framework [8]. Key inputs into the model, such as electrolyzer cost and efficiency, are based on feedback from industry and national laboratory experts and are generally consistent with other reported values, including those in the recent DOE Hydrogen Program Record *Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology*, when the dollar-year basis is accounted for appropriately [9]. The *target-level* approach considers a broad range of electricity prices and capacity factors from current and future plausible scenarios resulting in a range of LCOH estimates.

As the Hydrogen Shot is directed at hydrogen production cost, the LCOH estimates in this document are focused on the hydrogen production component of the overall hydrogen production cost. Depending on the end use requirements (e.g., the need for a consistent hydrogen production rate, or capacity factor of the electricity source), there are other components (e.g., hydrogen storage) that will be needed that will add cost. In general, more hydrogen storage will be needed for systems with lower capacity factors to compensate for reduced hydrogen production at varying time intervals. There are other ongoing analyses that are investigating hydrogen cost for complete systems from the electricity source to the end use [10].

The LCOH can vary dramatically based on current technologies' capital cost and performance, and when electricity is supplied from different sources, such as the U.S. electrical grid, land-based wind, conventional nuclear power, or hybrid renewable energy systems [9]. **Figure 4** shows the projected LCOH using electricity from the current U.S. electrical grid (with limited renewable penetration), as well as conceptual scenarios for 2026 and 2031 for hydrogen production by different electrolyzer technologies using a projected future grid and different renewable and nuclear resources. The 2026 and 2031 *target scenarios* shown in the figure include projected electrolyzer technology and cost improvements over the current status, as well as aggressive reductions in the cost of renewable electricity generation. A detailed description of the analysis methods, key input parameters, references, and tabulated results for **Figure 4** can be found in the **Appendix**.

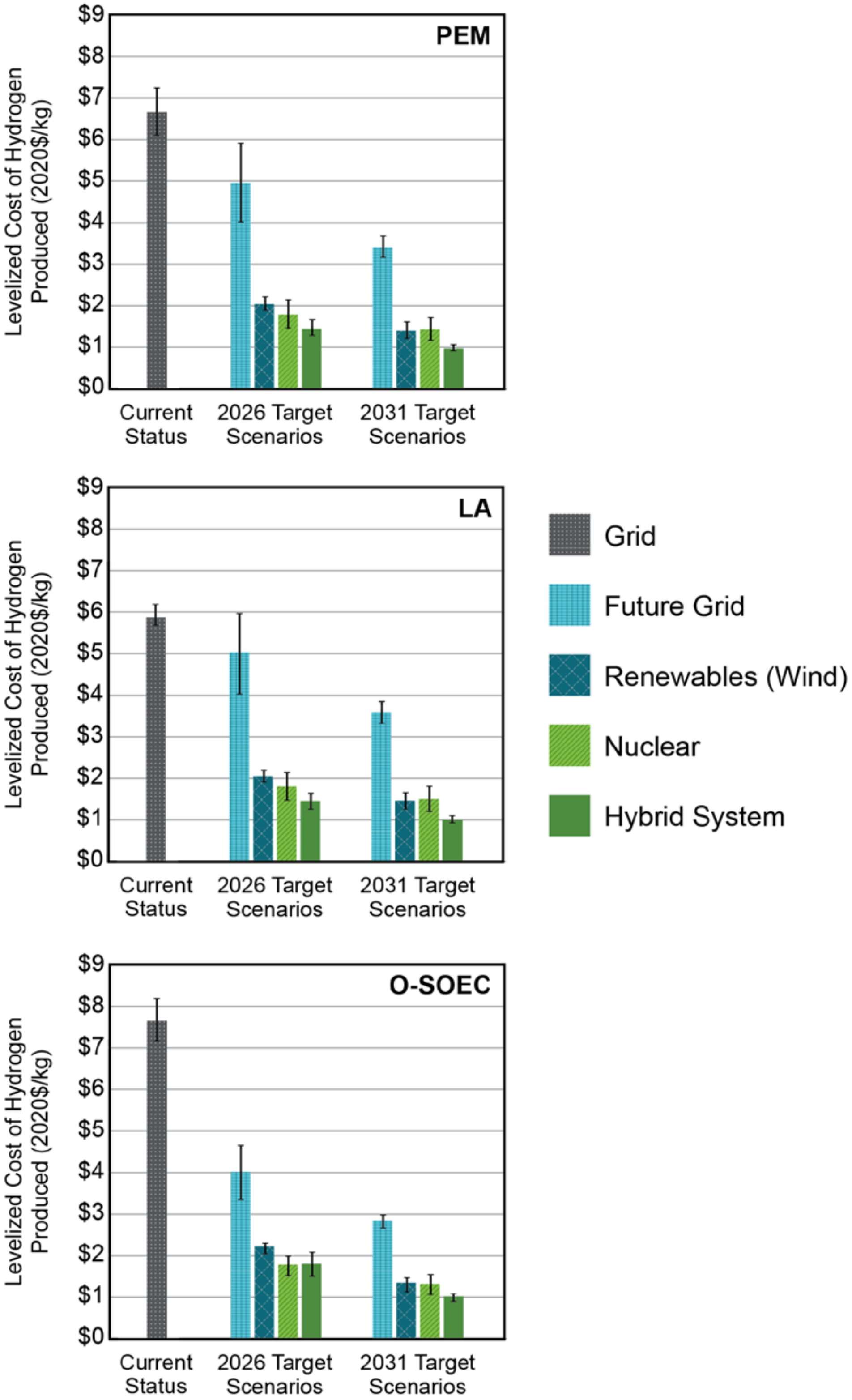

**Figure 4. Current and future LCOH from PEM, LA, and O-SOEC electrolyzers in 2020 \$ per kilogram $H_2$ for a range of scenarios based on different electricity sources. In the current case, error bars illustrate high and low LCOH due to a range of electrolyzer capital costs; in the future scenarios, error bars illustrate a range of costs based on different assumptions about the electricity source (e.g., future grid, wind, solar, nuclear, or hybrid wind and solar). See the Appendix for description of assumptions and corresponding cost data.**

For all electrolyzer types, the grid cases in **Figure 4** (with varying degrees of renewable penetration, including a range of electricity pricing from \$0.06/kilowatt-hour (kWh) to \$0.10/kWh, and assuming a 97% capacity factor)[2] result in the highest LCOH, due in part to the inclusion of transmission costs in the electricity prices. The hybrid renewable energy system cases included on-site electricity generation using both solar and wind power, assuming costs are reduced to \$0.012/kWh with tax credits, and an upper-end capacity factor of 74%).[3] The cases based on only direct coupling with the best available wind resources (with on-site electricity costs ranging from \$0.017/kWh to \$0.023/kWh in 2031, and a high-end capacity factor of 57%) still offer cost improvements relative to the grid cases, due to the low electricity generation costs and minimal or no transmission costs.[4] For reference, current best available wind resources are ~\$0.026/kWh and 51% capacity factor, highlighting the need for continued development of renewable energy technologies to enable the Hydrogen Shot goal [11].

When current technology (see appendix for assumed capital costs) and grid electricity are used, the analysis shows that LA electrolyzers have the potential to produce the lowest-cost hydrogen—at approximately \$5.80/kg, compared with PEM at approximately \$6.70/kg and O-SOEC at approximately \$7.60/kg.[5] This cost advantage can be attributed to LA electrolyzers' lower capital cost, a consequence of today's high-volume manufacturing and the relatively inexpensive materials used. In future years, PEM and LA capital costs will likely become more comparable, as the manufacturing rate of PEM technology continues to grow [3]. Compared with both PEM and LA, analysis shows future O-SOEC technology benefiting from higher electrical conversion efficiencies in cases where heat integration is available (e.g., at a nuclear power plant), helping to reduce the LCOH, in addition to significant reductions from increased manufacturing scale [12].

One key assumption made in this high-level techno-economic analysis is that each electrolyzer technology is capable of load-following dynamic power generation in the renewables (wind) and hybrid system scenarios. The demonstrated ability for PEM, LA, and O-SOEC electrolyzers to load follow in such configurations currently varies among the technology types, with PEM demonstrating the ability to load follow based on demonstrations to date [13]. Testing durability under dynamic loading in all electrolyzer technologies, as part of broader active research to

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[2] The current grid scenarios are based on data from the U.S. Energy Information Administration, and the future grid scenarios for 2026 and 2031 include corresponding levels of renewable penetration based on projections from a DOE study for achieving a 100% clean electricity grid by 2035. See the Appendix for further details and references. It should be emphasized that these cases are included for reference; they all entail different degrees of grid carbon dioxide ($CO_2$) emissions, and therefore the hydrogen produced does not qualify as clean.

[3] The hybrid renewable energy scenarios in 2026 and 2031 are based on a preliminary study of complimentary wind and solar resources. These include advanced electrolyzer technologies collocated with both wind and solar resources found in parts of Texas, with aggressive reductions in the on-site electricity generation costs, potentially leveraging regional renewable tax credits. Different hybrid scenarios studied include the case of equal sizing (100 MW) for each of the three components, as well as the case of an electrolyzer capacity of 100 MW that matches the total wind and solar capacity (200 MW). See the Appendix for further details and references.

[4] The renewable and hybrid scenarios in this report do not include battery or hydrogen storage as a potential mitigation strategy addressing intermittency; more comprehensive analysis of regionally dependent scenarios is ongoing, including cost optimization based on various combinations of wind and solar energy with storage. Results will be included in future report updates.

[5] Uninstalled capital cost, system efficiency, and replacement interval are consistent with the range of values in [3], [27], and [35].

optimize operating vs. capital costs, will contribute to meeting long-term goals for variable renewable energy resources.

It is expected that the future market could be served by a mix of electrolyzer technologies as each technology develops further. Specific deployment choices will likely be based on the match between an application's needs, including both end use and clean electricity source, and the electrolyzer's properties, operating capabilities, and cost. While the scenarios in **Figure 4** offer potential pathways for meeting LCOH cost targets, these scenarios depend on local availability of low-cost clean energy resources capable of providing high capacity factors, requiring significant electricity cost reductions and will require accelerated levels of technology and integrated systems RD&D focused on addressing key cost drivers for electrolyzers.

The factors summarized in **Figure 5** drive the cost of electrolytic hydrogen and are covered in much greater detail in subsequent sections of this document. Achieving the clean hydrogen cost target of $1/kg through electrolysis will require continued RDD&D to:

1. Reduce capital cost, improve efficiency and performance, and increase lifetimes through scientific breakthroughs and technology advancements.
2. Improve manufacturing processes and increase manufacturing throughput to reduce manufacturing costs and achieve economies of scale that drive down electrolyzer costs.
3. Optimize integration of electrolyzers with low-cost, clean electricity sources, including through direct coupling.

As shown by the large range of LCOH in **Figure 4**, the cost of clean electricity and the operating capacity factor[6] of installed electrolyzers will play a large role in the overall cost of clean hydrogen production from electrolyzers. The DOE Hydrogen Program continues to explore integrated systems that optimize electricity price and capacity factor.

Also of note is that since the Hydrogen Energy Earthshot was launched, supply chain issues, higher electrolyzer system installation costs, and inflation have increased costs, making the goal of \$1/kg $H_2$ more challenging to achieve.

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[6] Capacity factor is defined here as annual average input energy divided by nameplate capacity if operated during all hours of the year.

**Key Cost Drivers for Clean Hydrogen Production**

**Manufacturing Throughput**
- Automation
- Increased line speed
- Quality assurance/ quality control

**Electrolyzer Properties**
- System lifetime
- System performance and efficiency
- Material, component, and equipment costs

**Energy System Integration**
- Integration with clean energy sources
- Electricity price
- Capacity factor
- Installation costs

Figure 5. Key cost drivers for clean hydrogen production using electrolysis.

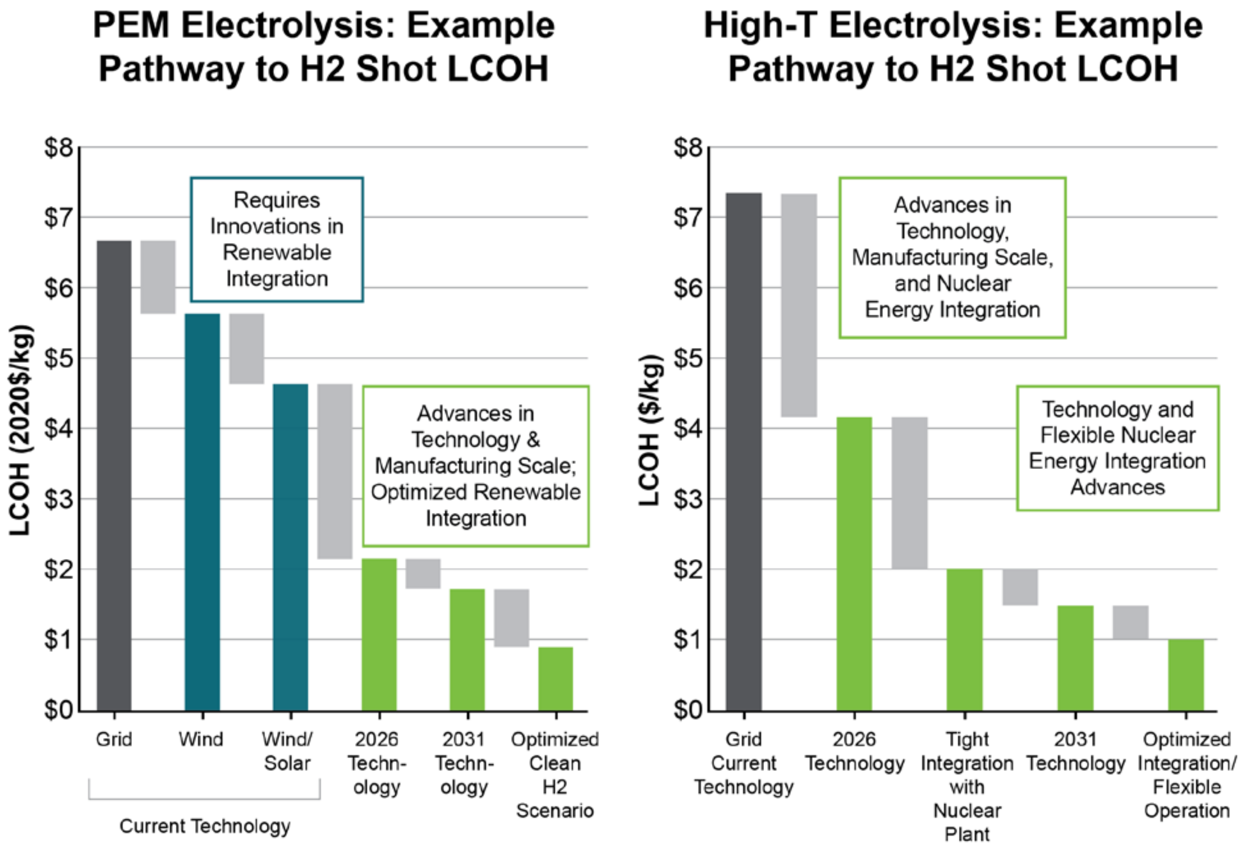

Figure 6. Waterfall charts illustrating potential pathways to achieve the Hydrogen Shot target for LTE (PEM) and HTE (O-SOEC).

The waterfall charts in **Figure 6** illustrate example pathways to achieve the Hydrogen Shot goal for LTE (PEM) and HTE (O-SOEC), respectively. See the appendix for further details, model assumptions and references. Similar to **Figure 4**, the 2026 and 2031 technology cases reflect improvements in electrolyzer cost, durability, and performance over the current technology case [14]. The first bar in each chart represents estimated LCOH based on today's electrolyzer technology manufactured at low volumes and using average grid electricity pricing based on data from the U.S. Energy Information Administration. For both PEM and O-SOEC, the cost reductions needed for achieving the \$1/kg-$H_2$ goal require a combination of continued electrolyzer technology advances (in performance, durability, and cost), improvements in manufacturing technologies and processes, achieving manufacturing economies of scale, and optimizing integration with low-cost, clean electricity using regionally specific resources such as solar, wind, geothermal, hydropower, and nuclear power.[7]

The grid cases for both PEM and O-SOEC are included for reference, but these do not qualify as clean hydrogen production cases due to the limited amount of clean energy resources in today's grid. DOE-supported studies analyzing scenarios for 100% clean electricity by 2035 project that clean electricity will cost approximately \$60–\$80/megawatt hour (MWh) on average across the United States, in part due to added transmission costs [15]. Even with optimized technology and economies of scale, achieving \$1/kg $H_2$ for PEM or O-SOEC electrolysis will require electricity costs less than approximately \$20–\$30/MWh with >90% capacity factor. Therefore, except for specific regional opportunities where renewable or nuclear power is sold at these low electricity rates and high capacity factors, grid-connected electrolysis will not generally achieve the Hydrogen Shot target. Other cases included in **Figure 6** leverage the lower costs enabled by optimal integration of electrolyzers with diverse renewable and nuclear power generation.

Regional opportunities based on collocation and tight integration of electrolysis with renewable or nuclear generation—with reduced or eliminated electricity transmission costs—offer potential pathways to meeting the Hydrogen Shot goal. The PEM example in **Figure 6** illustrates that direct coupling with wind energy using today's technology offers reduced LCOH compared with the grid case.[8] Still, the cost savings are limited by the capacity factor of the renewable resource (around 50% in regions with good wind resources), which results in reduction of electrolyzer utilization and need for hydrogen storage to ensure customers are delivered hydrogen when needed). In certain regions, hybrid energy systems with optimized integration with both solar and wind energy can have increased effective capacity factors (as high as about 75%) that in conjunction with technology advances and economies of scale offer a pathway to the Hydrogen Shot goal. The O-SOEC example illustrates that this goal can be met with continued technology and manufacturing improvements along with direct coupling and thermal integration with the current fleet of nuclear power plants where they currently produce electricity with a 95% capacity factor [16]. To meet the cost goal, the plants would need to continue to produce electricity at levelized costs less than approximately \$30/MWh; and a full accounting of both direct and indirect emissions will also be needed. Unlike with renewable integration, capacity factors can be near 100% in these cases, which is favorable to continuous hydrogen production at reduced cost. However, dynamic operation of the electrolyzer may be advantageous to allow varying rates of hydrogen production—for example, to ramp down the use of electricity for hydrogen production in favor of selling that electricity to the grid at times when market prices are favorable.

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[7] Note that the 2031 technology cases in each chart reflect electrolyzer technology advances projected by 2031 coupled with current conceptual designs for integration with renewable or nuclear power, which by themselves approach but do not reach the \$1/kg-$H_2$ target. Attaining the goal will require additional optimization of the integrated energy systems through continued RD&D innovations.

[8] For further details on the projected LCOH of grid- and renewable-connected PEM electrolysis, see [9], noting that results in this record are presented in inflated 2022 \$ compared to those in this document presented in 2020 \$, for reasons described in the Introduction.

# GHG EMISSIONS AND WATER CONSUMPTION

To assess the decarbonization potential for all electrolyzer technologies, techno-economic analysis must be coupled with life cycle analysis to address emissions, water usage, and other environmental concerns related to hydrogen production. This section discusses the environmental impacts of hydrogen production via electrolysis, using different clean energy sources.

The overall GHG emissions associated with hydrogen produced via electrolysis will be determined primarily by the electricity source and the upstream emissions that result from manufacturing processes. Currently, most analyses of GHG emissions from hydrogen production are conducted using a well-to-gate system boundary, which includes emissions associated with feedstock gathering, extraction, processing, and delivery to a hydrogen production facility (in the case of electrolysis, the feedstock is water, so associated emissions are minimal). It also includes the emissions associated with the hydrogen production process, inclusive of the electricity used by the hydrogen production facility.[9] Notably, this method does not consider embodied emissions from the manufacturing of the electrolyzer or the clean energy equipment (e.g., solar panels or wind turbines). More detailed life cycle analysis with different system boundaries that include embodied emissions is currently underway [17]. The findings of this analysis will be included in future versions of this report. A key aim of such analytical efforts is to ensure that neither benefits nor penalties are counted twice in the overall carbon footprint determination.

When the U.S. average grid mix is used as the electricity source for electrolysis, the direct GHG emissions calculated using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model are significant, at approximately 24 kg $CO_2e$/kg $H_2$ ($CO_2e$ is carbon dioxide equivalent). In contrast, when using electricity directly from nuclear, wind and/or solar, the model calculates near-zero well-to-gate direct GHG emissions [18].[10] When the GHG emissions from manufacturing of renewable energy systems (e.g., solar panels or wind turbines) are included, direct GHG emissions can still be low, as low as 1 kg $CO_2e$/kg $H_2$, depending on the specific sources of the manufactured equipment [19].[11] For electrolysis directly coupled with nuclear power, when using a conventional light water reactor, GHG emissions related to the uranium supply chain activities, which include mining, transportation, and enrichment, can also be modest, at approximately 0.1 kg $CO_2e$/kg $H_2$, depending on the electricity needs of the electrolyzer [20]. Producing clean hydrogen via electrolysis will clearly rely on the use of clean electricity sources, including a decarbonized grid and direct coupling to sources such as solar, wind, and nuclear power. However, all upstream emissions sources will need to be accounted for.

Water consumption requirements for electrolyzers depend on the electrolyzer and electricity source. Direct water consumption (the water consumed during electrolyzer operation, not including water used for cooling) is about 4 gallons per kilogram of hydrogen depending on the

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[9] These include direct emissions in the case of direct coupling with a power generation source, as well as indirect emissions associated with grid-connected cases; all emissions must be accounted for in a comprehensive life cycle analysis.

[10] This does not account for induced grid emissions.

[11] This does not account for induced grid emissions.

electrolyzer type and system size [21]. Additional consumption is required upstream of the point of hydrogen production to purify water and produce electricity. Including this upstream water consumption yields additional consumption of 3–65 gal $H_2O$/kg $H_2$, and this is highly dependent on the electricity source and electrolyzer system. The highest total water consumption occurs with geothermal- or nuclear-powered electrolyzers (about 69 gal $H_2O$/kg $H_2$ and 30 gal $H_2O$/kg $H_2$, respectively); though in the future, many of the advanced nuclear reactors will have a much smaller need for water.[12] As little as 7 gal $H_2O$/kg $H_2$ are required for electrolyzers operating on solar or wind electricity sources [22].

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[12] Advanced nuclear reactors will have a higher operating temperature, meaning more heat is converted into electricity, and they will be able to use dry cooling in areas where water is scarce. Some nuclear plants are also currently used for desalination and treating brackish water beyond power plant needs.

# OVERVIEW OF RD&D NEEDS TO ACHIEVE HYDROGEN SHOT GOALS

Current status and technical targets for PEM, LA, and O-SOEC stacks and systems have been developed to guide electrolyzer RD&D efforts toward the Hydrogen Shot goal (**Table 2**). Status and target values were developed in collaboration with national laboratories and industry partners and are consistent with ranges reported in the literature (see the **Appendix**). There are many combinations of performance and cost targets (efficiency, lifetime, and capital cost) that can achieve \$1/kg $H_2$; the ones listed here can be considered a starting guidepost for technology developers. The higher-TRL electrolyzers (PEM, LA, and O-SOEC) are targeting to meet the interim target of an LCOH of \$2/kg by 2026 and the ultimate target of \$1/kg $H_2$ by 2031.[13] AEM electrolyzers are aiming to achieve targets similar to PEM, and P-SOEC electrolyzers are expected to achieve targets similar to O-SOEC, though timelines for meeting cost goals will vary depending on investments. While the lower-TRL technologies may not achieve \$1/kg $H_2$ by 2031, investments in these technologies may eventually lead to even lower hydrogen production costs, as some approaches have advantages over current commercial technologies.

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[13] For a full description of assumptions to reach these LCOHs, see [14].

**Table 2. Status and DOE Intermediate and Ultimate Technical Targets for Mature LTE and HTE Technologies**[14]

| | Parameter | Units | PEM | | LA | | | O-SOEC | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Status | Interim Targets | Ultimate Targets | Status | Interim Targets | Ultimate Targets | Status | Interim Targets | Ultimate Targets |
| **Stack** | Total platinum group metal (PGM) content[15] | 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 | 0.5 A/cm$^2$ @ 1.9 V | 1.0 A/cm$^2$ @ 1.8 V | 2.0 A/cm$^2$ @ 1.7 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 | 51 | 48 | 45 | 34 | 34 | 34 |
| | Lifetime | Operation hours | 40,000 | 80,000 | 80,000 | 60,000 | 80,000 | 80,000 | 20,000 | 40,000 | 80,000 |
| | Average degradation rate | mV/kh | 4.8 | 2.3 | 2.0 | 3.2 | 2.3 | 2.1 | 6.4 | 3.2 | 1.6 |
| | Capital cost | $/kW | 450 | 100 | 50 | 250 | 100 | 50 | 300 | 125 | 50 |
| **System** | Energy efficiency[16] | kWh/kg $H_2$ | 55 | 51 | 46 | 55 | 52 | 48 | 47 | 44 | 42 |
| | Uninstalled capital cost | $/kW | 1,000 | 250 | 150 | 500 | 250 | 150 | 2,500 | 500 | 200 |

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[14] Target table reproduced from [14].

[15] Total PGM content includes both electrodes combined.

[16] For O-SOEC, energy efficiency includes both electrical and thermal energy inputs.

Manufacturing at high volume to achieve economies of scale, lower-cost manufacturing processes, and technology advances across the material, cell/stack, and system levels (including BOP components) are all critical to meet the targets outlined above. **Figure 7** shows key aspects of each technology that would benefit from RD&D to address capital cost, durability, or efficiency challenges facing current technologies. The remainder of this document describes the current status and highlights opportunities for development in electrolyzer manufacturing, properties and performance, and integration with clean energy.

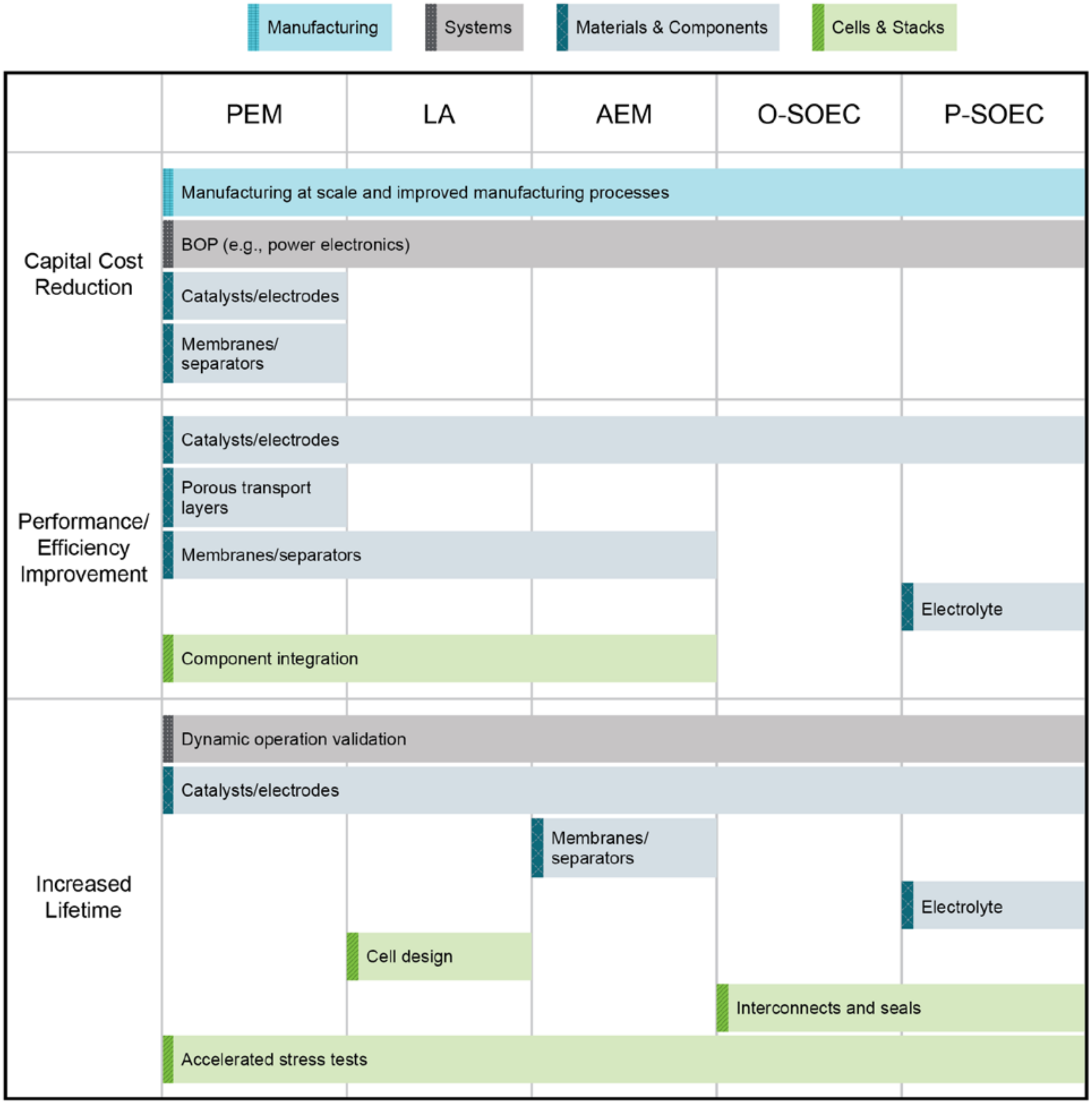

Figure 7. Overview of R&D strategies that address cost reduction opportunities.

# MANUFACTURING: STATUS AND COST REDUCTION POTENTIAL

**Manufacturing Throughput**

- Automation
- Increased line speed
- Quality assurance/quality control

The global manufacturing capacity for all electrolyzer technologies was about 10 GW per year in 2023 [23]. Projected growth in demand in 2025 and beyond will require significant manufacturing expansion, and—by one report—expansions could reach 155 GW per year by 2030 [5]. In 2020, 85% of manufacturing capacity was for LA electrolyzers, less than 15% was for PEM electrolyzers, and a very small fraction was for O-SOEC and AEM electrolyzers. Most electrolyzer manufacturing today occurs in Europe and China. While limited electrolyzer manufacturing exists in the United Staes today, plans for expansion by several domestic manufacturers are underway [24]. Recently, DOE made an investment of more than $300 million in electrolyzer manufacturing RD&D to reduce manufacturing costs and enable greater economies of scale through manufacturing innovations, including automated manufacturing processes, design for processability and scale-up, quality control methods to maintain electrolyzer performance and durability, reduced critical mineral loadings, and design for end-of-life recovery and recyclability [25].

Low-cost and high-throughput manufacturing of electrolyzer components, cells, stacks, and systems is key to achieve $1/kg $H_2$ across all electrolyzer technologies. As an example, a manufacturing cost curve for an electrolyzer is shown in **Figure 8**, which highlights the capital cost reduction potential through manufacturing at greater than gigawatt-scale volumes using currently available methods, and the potential for further cost reduction using advanced high-throughput methods. These manufacturing economies of scale generally apply to all electrolyzer technologies, though the exact cost curves and cost reduction potential differ.

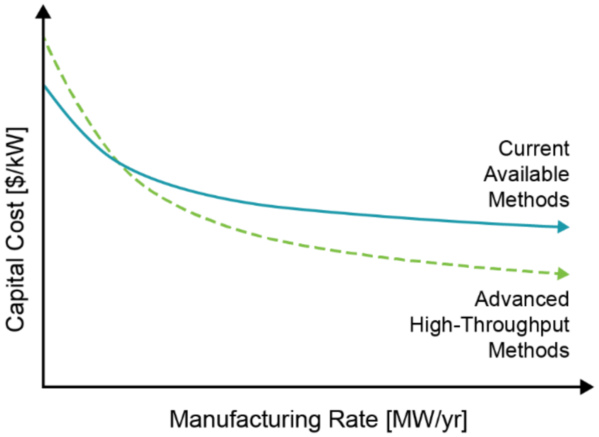

Figure 8. Schematic of capital cost as a function of manufacturing production rate using currently available methods (solid) and advanced high-throughput methods (dashed).

Scaling up manufacturing of newly developed materials requires either adjusting currently used manufacturing processes or designing and implementing new processes. While optimizing performance is a key design parameter for advanced materials, other considerations such as manufacturing scalability, end-of-life recovery, and use of environmentally friendly processing methods are also critical in achieving cost-effective and clean electrolysis.

Economies of scale can be achieved by reducing processing time to increase manufacturing rates, but specific approaches to reducing processing time differ for each electrolyzer technology given their different materials and cell designs. For PEM electrolyzers, roll-to-roll manufacturing is one strategy to facilitate fast manufacturing of catalyst-coated membranes and substrates. For LA electrolyzers, development or validation of manufacturing techniques for zero-gap and emerging cell designs is crucial for reducing processing times while still meeting performance goals. For O-SOEC, reducing the time, temperature, and number of thermal processing steps in sintering and interconnect material processing, as well as replacing batch with continuous processes, will be essential for achieving faster production rates and therefore higher-volume manufacturing and reduced cost.

For all electrolyzer technologies, automating cell/stack assembly and reducing the number of manufacturing steps can improve line throughputs and reduce costs. Challenges remain to implement quality control mechanisms for high-throughput processes, especially for large cell areas used in LTEs. The ongoing and rapidly advancing integration of manufacturing technologies and digitization (known as “Industry 4.0” or the “Fourth Industrial Revolution”) has the potential to vastly improve manufacturing capability and efficiency [26]. These new techniques can involve automating traditional manufacturing processes using any number of combinations of tools including robotics, Internet of Things, big data analytics, artificial intelligence, and autonomous systems. The primary challenge is to develop the high-throughput processes; once they have been established, expanding manufacturing capacity in the United States may occur more rapidly.

# ELECTROLYZER TECHNOLOGIES: STATUS AND COST REDUCTION POTENTIAL

Achieving electrolyzer manufacturing economies of scale is necessary but not sufficient for achieving the goal of producing hydrogen for $1/kg—further advances in electrolyzer technology will be needed. RDD&D is needed to reduce material and equipment capital costs, improve efficiency and performance, and extend the lifetime of electrolyzer stacks and systems. This section summarizes the current status and unique technical challenges facing each electrolyzer technology.

**Key Electrolyzer Properties**

- System lifetime
- System performance and efficiency
- Material, component, and equipment costs

## PEM Electrolyzers

Historically developed for use in underwater vessels and spacecraft for oxygen generation and applications requiring a small amount of hydrogen (e.g., gas chromatographs), PEM electrolyzers are now being developed for large-scale hydrogen production. Commercial stacks are typically 0.1–2.5 MW and can be combined to form multimegawatt (10–100-MW) systems [27]. The solid polymer membrane electrolyte allows for high-current-density operation with good efficiency that enables smaller system footprints compared to LA electrolyzers. The membrane also helps mitigate hydrogen gas crossover into the oxygen stream and allows for generation of hydrogen at differential pressure (e.g., 30 bar). The PEM electrolyzer design is amenable to fast, dynamic response, making it ideal for integrating with variable power sources such as wind and solar. The main drawback is the acidic operating environment, which limits the materials that can be used and currently requires the use of PGM catalysts and coatings.

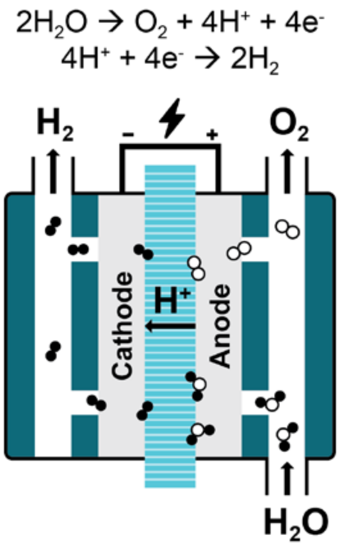

Figure 9. Schematic of PEM electrolyzer cell.

### SYSTEM COST ANALYSIS

Recent analysis has estimated the uninstalled capital cost of PEM electrolyzer systems at today's manufacturing volumes to be $700–$1,100/kW [9] [28].[17] At such capital costs, the LCOH ranges from $6.00 to $7.20/kg $H_2$ assuming grid electricity and high capacity factors (**Figure 4**). Reducing the capital cost of the electrolyzer system can make a substantial impact

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[17] Note that uninstalled capital cost applies a markup to the manufactured system cost.

on the LCOH and can enable these systems to operate at lower capacity factors, a key aspect of integrating electrolyzers with low-cost renewable power.
Capital cost reductions in the near term are expected to be driven by improved processes enabling increased manufacturing volumes to achieve economies of scale (as discussed above). However, to achieve the \$1/kg-$H_2$ target, advanced stacks and systems with improved performance, efficiency, and lifetime are needed in addition to reducing capital cost (**Table 2**).

As shown in **Figure 10,** for a 1-MW system manufactured at a rate of 1 GW per year, the stack constitutes about 30% of the system cost, with the greatest single contributor to the stack cost being the oxygen-evolution-reaction (OER) electrode, which includes the iridium catalyst. The membrane is another expensive component in the stack. RD&D efforts targeted at these high-cost components are important to reduce overall capital costs, though those efforts must also consider trade-offs with system lifetime and efficiency, parameters that impact operating and maintenance costs. Priority RD&D opportunities for PEM electrolyzers are highlighted in **Table 3** and discussed in greater detail below.

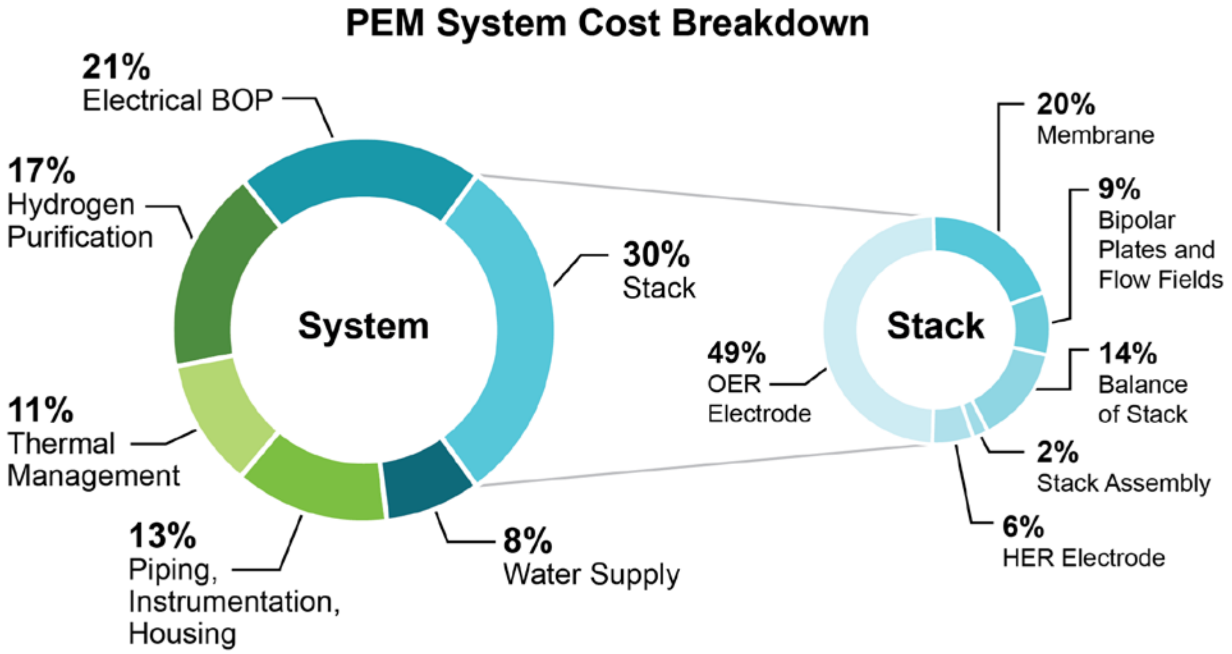

**Figure 10. PEM electrolyzer system and stack cost breakdown assuming a 1-MW stack, 1-MW system, and 1-GW/yr manufacturing rate [28]. Note: HER refers to the hydrogen evolution reaction.**

## RD&D APPROACHES FOR COST REDUCTION

### *Materials and Components*

PEM electrolyzer technology is proven and has been utilized in niche applications, such as submarines, for many years; however, these commercial electrolyzers have been overengineered with a focus on reliability over cost and efficiency. This overengineering includes the materials and components used in commercial systems today, such as high amounts of platinum and iridium catalysts and thick membranes.

**Table 3. Cost Reduction Opportunities for PEM Electrolyzers**

| Cost Reduction Opportunity | Approaches |
|---|---|
| Capital cost reduction | • Reduced precious metal catalyst loading<br>• Thinner membranes<br>• Manufacturing at scale<br>• Direct integration with renewables<br>• Standardize BOP, including power electronics. |
| Performance and efficiency improvement | • Thinner, engineered membranes<br>• Engineered interfaces<br>• High intrinsic catalyst activity and utilization<br>• Optimize porous transport layer (PTL) design for mass transport. |
| Longer lifetime | • Develop accelerated stress tests<br>• Optimize membrane/catalyst layer/PTL interfaces<br>• Improve and validate durability under dynamic operating conditions. |

One of the single most expensive components in the PEM electrolyzer stack is the iridium catalyst in the anode catalyst layer. Iridium is an expensive precious metal and suffers from a volatile market price, sensitive to disruptions in the supply chain and growing demand. Today's electrolyzers utilize about 2 $mg_{Ir}/cm^2$ (or 0.5–0.8 $g_{Ir}/kW$ assuming 1.9 V to operate at 2 $A/cm^2$) [27] [28]. Current research efforts explore how reducing the iridium loading by roughly an order of magnitude impacts the efficiency and durability of the stack. Near-term DOE targets for total PGM loading are 0.5 $mg/cm^2$, including both platinum and iridium [14]. Ongoing research is examining ways to replace iridium catalysts with transition metal alternatives, but that research is further from commercialization [29]. Developing a less expensive anode catalyst layer with high performance, durability, and efficiency is a critical area of research to achieve the Hydrogen Shot goal.

The membranes in commercial PEM stacks use perfluorinated polymers that are highly stable and have high proton conductivity. Such polymers have historically been employed in PEM fuel cells and chlor-alkali electrolyzers. However, membranes used in commercial PEM electrolyzer stacks today are fabricated thick enough to reduce hydrogen crossover and provide needed reliability. Developing novel membranes with properties optimized for electrolyzer operation, including reducing the membrane thickness by a factor of 3–4, will significantly improve the stack efficiency (by reducing resistive loss through the membrane) and decrease cost (by using less material). Membranes may need to be engineered to include gas recombination catalysts or reinforcement to achieve efficiency and durability targets. Furthermore, due to environmental concerns about "forever chemicals," government and industry are investing in research to reduce or eliminate the use of perfluorinated polymers in membranes. This research focuses on the development of suitable hydrocarbon membranes that will provide the needed reliability in a commercial electrolyzer.

PTLs influence stack performance and durability due to their mass transport properties and electrical resistance in PEM electrolyzer cells. PTL architectures need to be fully optimized for electrolyzers. In addition, current PTLs made of titanium require precious metal coatings at interfaces to prevent titanium oxidation, which leads to increased resistance and decreased efficiency. Significant cost reductions can be achieved by reducing material cost (without sacrificing performance, durability, or efficiency) and optimizing the PTL structure.

### *Cells and Stacks*

As precious metal catalyst loadings are reduced, in order to maintain high performance and durability, it will be essential to have an optimally efficient and durable interface between the electrode structure and both the PTL and membrane.

A major unknown inhibiting the commercialization of next-generation electrolyzer technology is whether advanced materials and components can provide the lifetimes required to meet the technical targets in **Table 2**. This question is especially important when considering the dynamic operating and start/stop conditions arising from the coupling of an electrolyzer to renewable energy sources. The effect of turning the electrolyzer system on and off repeatedly over time also has not been adequately studied for its impact on stack durability. Realistically, lifetime testing for 5 years to prove durability is not feasible and would significantly delay the introduction of new materials and technologies. Hence, an improved understanding of electrolyzer degradation mechanisms can be used to project anticipated lifetime and develop stress tests that accelerate these degradation processes, allowing durability testing to be completed in a matter of weeks or months instead of years.

### *Systems*

BOP components represent a significant portion of overall system capital costs, especially as the cost of stacks comes down as stack manufacturing volumes increase and benefit from economies of scale. The BOP includes power electronics, heaters, pumps, and gas processing units. Of the BOP components, electrolyzer manufacturers have indicated that there is significant opportunity to reduce the cost of power electronics [30]. For example, standardized modular units reduce the need for custom designs and take advantage of economies of scale. This concept of standardization could apply to other BOP components as well. Modularizing the BOP or increasing the manufacturing capacity of BOP components may also lead to cost reductions.

In order to fully realize the potential for PEM electrolyzers to produce low-cost, clean hydrogen, it will be critical to improve their integration with variable renewable energy sources. PEM electrolyzers can quickly respond to changes in load, making them well suited to operate on variable or intermitted power [31]. However, there is a need for more demonstrations of PEM electrolyzers directly coupled to renewable energy sources (i.e., with minimal power conversion steps from the renewable energy source to the electrolyzer, without a grid interconnection). Additional demonstrations will improve our understanding of the electrical BOP equipment needs, operating strategies, and stack durability requirements.

## LA Electrolyzers

LA electrolyzers are the most mature electrolyzer technology today in terms of commercial availability and deployed capacity. Historically, the development of LA electrolyzer technology was driven by hydrogen demand for ammonia production in regions with low-cost hydroelectric power. Given the relatively steady availability of hydroelectricity, these systems were designed to operate on multimegawatt power continuously at steady state. Typical stack unit sizes range from 0.5 to 5 MW, and these can be combined into larger systems, with some current system installations greater than 100 MW [27] [32]. Today, LA electrolyzers are being deployed to produce hydrogen for a wider range of applications, including mobility and power generation. Still, the relatively large footprint and continuous operating needs of these conventionally designed systems remain issues that can be improved [33].

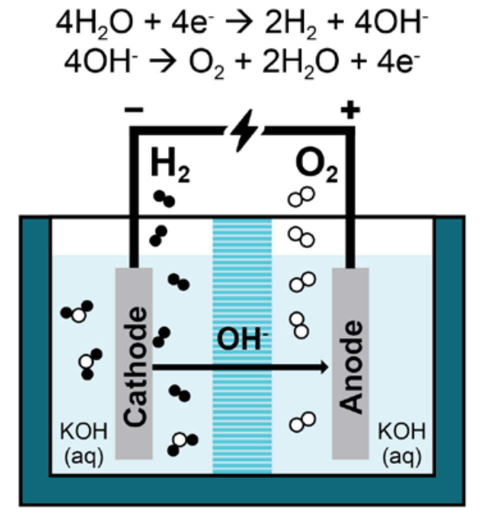

Figure 11. Schematic of an LA electrolyzer cell.

Traditional LA electrolyzers are designed to circulate concentrated alkaline electrolytes (e.g., 7-M KOH) instead of water to conduct ions between electrodes made primarily of nickel. A separator material, which is permeable to the electrolyte, mitigates hydrogen and oxygen crossover between the anode and cathode compartments, and the gaseous products are produced at near-atmospheric pressures. Historically, relatively large gaps between the electrodes resulted in a large ohmic resistance, and therefore it was economical to operate at low current density because it avoided high voltages, and hence low efficiencies. Zero-gap cells have been designed to address this issue by minimizing the distance between electrodes, but further improvements are still possible. Additionally, LA electrolyzer designs generally have not been amenable to dynamic operation (e.g., load-following solar or wind power) because they are vulnerable to both mechanical and chemical degradation under such variable operating conditions, and dynamic operation while using a hydrogen compressor is challenging. Despite limitations in current density and operating conditions, the alkaline operating environment allows for the use of low-cost materials such as stainless steel and non-precious-metal catalysts. As a result, while capital costs of LA electrolyzers are lower than their PEM counterparts, they are less efficient at higher current densities, so efficiency suffers at higher rates of hydrogen production.

### SYSTEM COST ANALYSIS

The capital cost of LA electrolyzer systems varies significantly depending on the manufacturer, ranging from \$500/kW to more than \$1,500/kW uninstalled cost, although most costs are in the \$500–\$750/kW range [3] [34] [35]. Such a low capital cost results in a low LCOH today using grid electricity (\$5.00–\$5.50/kg $H_2$, **Figure 4**). A recent design for manufacturing and assembly cost analysis of a 4-MW stack and 50-MW BOP module was conducted to determine how each component contributed to the overall cost of the stack and system (assuming a 1-GW/yr manufacturing rate and current electrolyzer design, **Figure 12**) [34]. The cost breakdown of the stack reveals that bipolar plates and cell frames are the largest contributors to stack capital costs. This result is consistent with the fact that catalyst materials in LA stacks are less costly than those in PEM stacks. Additionally, this analysis revealed that the BOP accounts for about 52% of the overall system capital cost, of which power electronics ("Electrical BOP" in **Figure 12**) are the most expensive element.

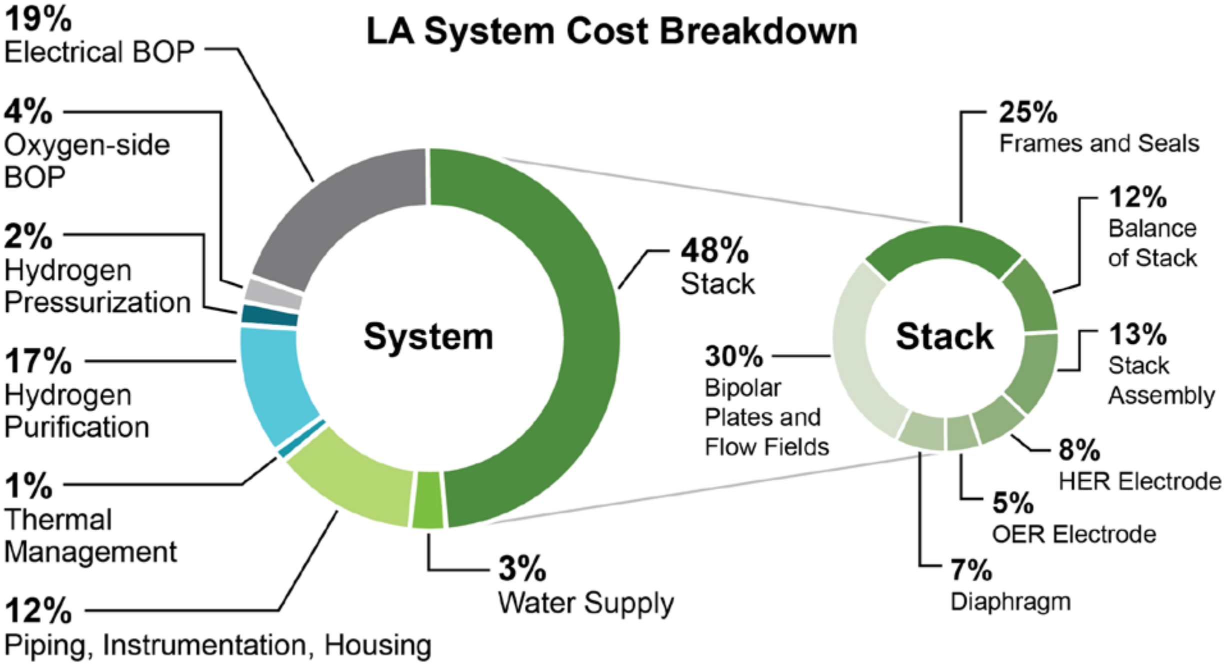

Figure 12. LA electrolyzer system (left) and stack (right) cost breakdown assuming a 1-GW/yr manufacturing rate, 4-MW stack, and 50-MW BOP module [34].

The system cost breakdown provides valuable insights for strategies to reduce capital costs. However, it is important to note that the high manufacturing capacities in place today for mature LA technologies result in a low system capital cost compared with other electrolyzer technologies [5].

## RD&D APPROACHES FOR COST REDUCTION

As a result of the relatively low system capital cost, improving system performance and efficiency while maintaining durability can drive significant cost reductions and progress toward the $1/kg goal. In addition, enabling variable and intermittent operation may be a significant driver of hydrogen cost reduction to enable LA electrolyzers to access low-cost electricity. These performance improvements will require RD&D of materials; interfaces; cell, stack, and system designs; and fabrication techniques. Specific RD&D needs and priorities are described further below and summarized in **Table 4**.

**Table 4. Cost Reduction Opportunities in LA**

| Cost Reduction Opportunity | Approaches |
|---|---|
| Capital cost reduction | • Novel components (e.g., separators) and cell/stack designs for high-current-density operation while maintaining efficiency.<br>• Standardized BOP, including power electronics.<br>• Manufacturing-advanced multimegawatt systems at scale. |
| Performance and efficiency improvement | • Engineered interfaces with high catalyst utilization.<br>• Novel separator materials and catalysts.<br>• Improved component integration strategies.<br>• Bubble management.<br>• Novel cell/stack design. |
| Longer lifetime | • Novel materials.<br>• Cell designs.<br>• Dynamic operation considerations. |

### *Materials and Components*

Discussion at a recent experts' meeting on advanced LA electrolyzers revealed that separator materials and catalysts have received little attention in recent decades [36]. Innovation in separator materials is necessary to reach higher current densities at lower voltages, which can drive down the capital cost (on a dollar-per-kilowatt or dollar-per-kilogram basis) and reduce operating costs via more efficient electrical operation. Ideal separator materials must be mechanically and chemically stable and tested at commercially relevant temperatures and pressures. While thinner separators can reduce resistance, and hence improve efficiency, mechanical stability can become a challenge, especially if operating the cell at elevated pressure. A balance is required between these two factors.

Electrodes in commercial LA cells commonly consist of a nickel catalyst coated onto a low-surface-area substrate (e.g., nickel-coated steel). The result is an extremely durable electrode but with relatively low performance. To achieve higher performance/efficiency, there remains a need for catalysts with higher intrinsic activity and for electrode structures with high surface area and catalyst utilization that are amenable to cell integration. To that end, understanding the relationship between structure, activity, and stability—and how different manufacturing processes affect structure—could lead to performance and efficiency improvements. Dynamic operation and advanced cell designs are also important considerations when developing catalysts and electrodes for next-generation LA electrolyzer technology.

### *Cells and Stacks*

Next-generation LA electrolyzer cells will likely have a different architecture than traditional LA electrolyzer cells. Already, developments in cell design have included "zero-gap" architectures that improve performance by minimizing the distance between the electrodes and the separator. A high-priority focus area is on developing advanced cells that demonstrate chemical and mechanical stability under variable operation with high efficiency. Such designs must overcome numerous challenges, particularly during operational periods at low current density. Such challenges include minimizing shunt currents and managing electrolyte levels. Additional opportunities for improvement include cells that can operate at higher pressures, which can help reduce downstream compression costs for hydrogen, and novel components that can withstand operating pressures near 30 bar.

Innovation in interface engineering and the integration of components into electrodes and cells could lead to improved efficiency, improved durability, and reduced cost. Interfaces and cell integration will become more critical with advanced cell designs. Leveraging PEM electrode developments, such as coating catalysts onto the separator material, could help achieve improved interfaces and higher manufacturing throughput. However, to design for improved performance, efficiency, and durability, additional research is needed to understand the interfaces in LA electrolyzer cells, which could include characterizing bubble and current distribution within the cell. As the dimensions of the cell increase from lab scale to commercial scale, it is also critical to characterize next-generation cells and stacks to determine degradation mechanisms.

Commercial LA cells and stacks have a very long lifetime; however, the impact of advanced materials, new cell and stack designs, and dynamic operating conditions on durability are unknown. Similar to PEM electrolyzers, developing accelerated stress tests to understand degradation mechanisms and determine lifetime in a much shorter time frame is important to expedite commercialization of next-generation technology.

### *Systems*

Similar to PEM electrolyzers, the BOP equipment represents a significant fraction of the overall system capital cost for LA electrolyzers (**Figure 12**), and the cost of power electronics are the dominant factor in BOP costs. Reducing the capital cost of the BOP equipment could include approaches such as process intensification and modularizing and standardizing components. For LA electrolyzers, reducing the need for BOP equipment for electrolyte management, such as eliminating the potassium hydroxide scrubber through innovative cell designs, could also reduce capital costs.

Systems for advanced LA electrolyzers could also be designed for dynamic operation. In traditional LA electrolyzers, rapid changes in current density and gas production create challenges for differential pressure control and electrolyte level control systems that can lead to safety hazards. Mitigating shunt currents in the system also becomes increasingly important when operating at low current densities. Innovative system designs that can overcome these challenges can result in more durable LA electrolyzers when coupled to variable clean energy sources.

## O-SOECs

O-SOECs operate at high temperatures, and they exhibit a higher electrical efficiency compared with LTEs. However, their shorter lifetimes and higher capital costs have hindered market entry and kept manufacturing volumes low. Their high-temperature operation (700°C–850°C) enables higher electrical efficiencies due to the improved kinetics of splitting water at higher temperatures. However, the high temperatures are also a major driver of lower cell durability and shorter stack lifetime. Thermal integration with a range of heat sources, including nuclear reactors and other industrial processes (e.g., steel production), can provide efficiency and cost benefits.

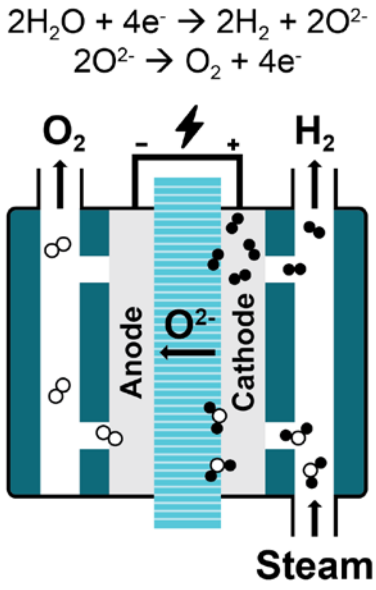

Figure 13. Schematic of an O-SOEC.

O-SOECs have benefitted from decades of R&D of solid-oxide fuel cells (SOFCs), which have more extensive commercial deployment worldwide. The technology is based on a solid ceramic electrolyte that conducts oxide ions at high temperatures. Many of the cell and stack components developed for SOFCs—including the metal interconnects and seals—can be leveraged for O-SOEC development. Additionally, given the similarities between SOFC and O-SOEC stacks, solid-oxide technologies have the potential to run as “reversible fuel cells”—to either generate electricity using hydrogen or generate hydrogen using electricity, with the same stack. This feature could make them an attractive technology for long-duration energy storage. O-SOECs have a lower TRL compared with PEM and LA electrolyzers, but early demonstrations (1–5-MW systems) have begun in the United States [33].

### SYSTEM COST ANALYSIS

There are far fewer publicly available data on the current cost of O-SOEC electrolyzers than for LTE technologies, which may be due to their lower levels of deployment. Leaders in O-SOEC technology development and evaluation at Idaho National Laboratory estimate their current uninstalled capital cost to be $2,000–$2,500/kW (2020 $). Under this assumption, current O-SOEC technology can produce hydrogen at a cost of $7.00–$8.00/kg using grid electricity and natural gas for heat (**Figure 4**). The natural gas for heat scenario was used to estimate current costs, as this is most representative of the current status. O-SOECs have high operating temperatures that require higher-grade heat, which can be provided from either a natural gas boiler or waste heat from a nuclear power plant or other high-temperature systems [12].

Recent design for manufacturing and assembly analyses have found that the capital cost of about $950/kW for O-SOEC systems could be achievable when stacks and systems are manufactured at the gigawatt scale with today’s technology [37]. This finding is significantly lower than today’s *observed* uninstalled cost ($2,000–2,500/kW) due to the specific scenario studied: 1-GW/year stack manufacturing is considerably higher than most commercial production volumes today, and the 1-GW system size is much larger than typical system sizes available today, which are generally less than 1 MW [5]. Nonetheless, the design for manufacturing and assembly results provides useful information about the costs of equipment and components of the stacks and systems.

The cost breakdown shown in **Figure 14** is based on a 1-GW system (sized to match a single nuclear reactor) with 50-kW stacks produced at a manufacturing rate of 1 GW/year. The BOP represents about 85% of the overall system capital cost, while the stack represents only about 15%. At a lower stack manufacturing rate (50 MW/year), the stack contribution is higher, about 25% of the overall system cost [37]. Of the stack components, interconnect (bipolar plate) materials and supporting stack infrastructure (end plates) are the biggest contributors to overall cost.

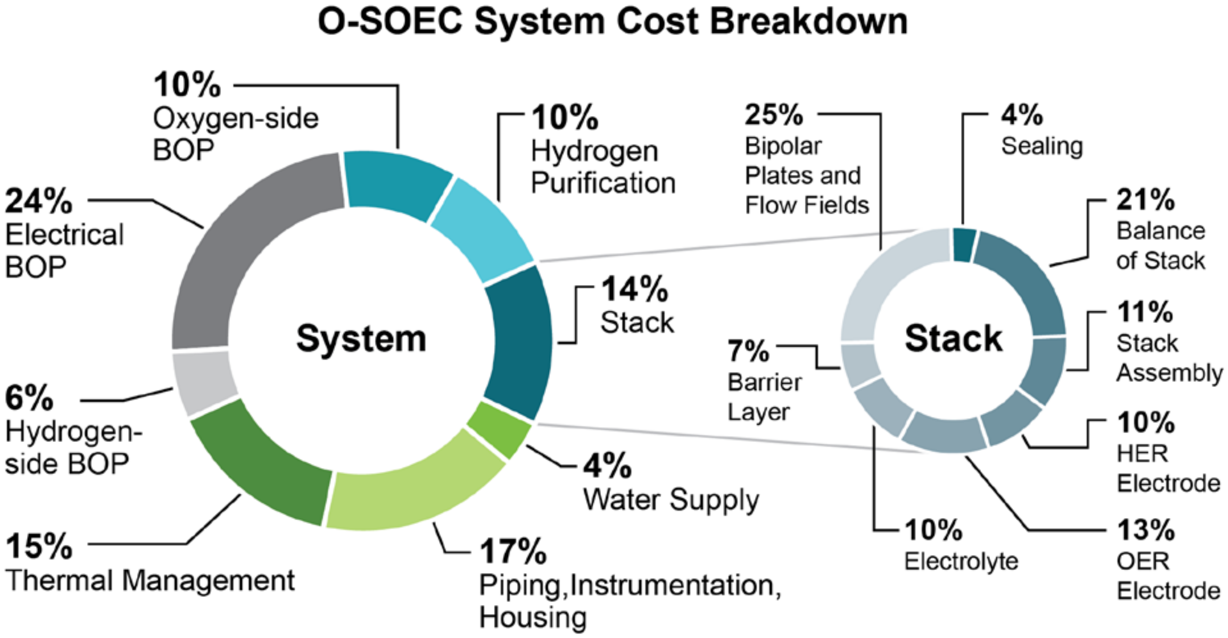

Figure 14. O-SOEC stack and system cost breakdown based on a 1-GW system and a 50-kW stack, with a manufacturing rate of 1 GW/year [12].

## RD&D APPROACHES FOR COST REDUCTION

Key cost reduction pathways include extending the lifetime of O-SOEC cells and stacks, developing a robust supply chain for BOP components, and decreasing stack and BOP capital costs. Achieving economies of scale in O-SOEC stack and system manufacturing will also be critical to meeting the capital cost target (**Table 2**). Here, we describe specific opportunities at the component, cell, and system levels.

Table 5. O-SOEC Cost Reduction Opportunities

| Cost Reduction Opportunity | Approaches |
|---|---|
| Capital cost reduction | • Develop low-cost interconnect materials and fabrication processes.<br>• Enable lower-temperature operation to reduce thermal management costs.<br>• Standardize BOP, including power electronics and heat recuperators.<br>• System design and optimization for low capital costs.<br>• Develop high-throughput manufacturing techniques. |
| Performance and efficiency improvement | • Decrease cell resistance.<br>• Improve material contact.<br>• Improve thermal integration.<br>• Enable dynamic operation to access low-cost electricity scenarios. |
| Longer lifetime | • Reduce operating temperature.<br>• Reduce electrode contamination and degradation.<br>• Reduce degradation of interconnects.<br>• Improve material stability with temperature cycling.<br>• Develop accelerated stress tests to identify additional opportunities to improve lifetimes. |

### *Materials and Components*

Degradation of cells and stacks is a key reason for the shorter lifetimes of O-SOECs compared with the lifetimes of PEM and LA electrolyzers. Degradation generally would be reduced if lower operating temperatures were possible without affecting overall performance. Higher temperatures lead to accelerated degradation of interfaces in the cells, which can result in reduced performance of electrodes and/or electrolyte. Another source of degradation is the presence of impurities, which can come from glass seals and the inlet gas stream [38]. This process is also accelerated at higher temperatures. These impurities block active sites on both electrodes. Developing novel seal materials with less volatile components and scrubbing the inlet stream of impurities would help mitigate this source of degradation.

In the hydrogen electrode, nickel depletion from the electrode-electrolyte interface and migration to the support layer is another source of degradation. The reason for this migration is unclear and requires further research. The oxygen electrode is a perovskite material, typically lanthanum strontium ferrite cobaltite (LSFC), and other perovskite oxides are being investigated as well. This high-performing electrode can suffer from degradation when directly in contact with the yttria-stabilized zirconia electrolyte. To mitigate oxygen electrode degradation, a barrier layer of gadolinium-doped ceria is commonly placed between the electrolyte and the electrode. Improvements to the oxygen electrode include focusing on controlling the LSFC oxidation state, particularly at the interface.

Lastly, there is some evidence that high oxygen pressure within the electrolyte itself can result in crack formation between the electrolyte and the oxygen electrode, which can also reduce life spans. The cause of the high oxygen pressures is not well understood, but improvements to the performance of the oxygen electrode may reduce this issue.

### *Cells and Stacks*

Metal interconnects complete the cell circuit and keep adjacent cells in the stack separate from each other. Most research on metal interconnects has been performed on SOFCs, but it is expected that the issues related to the interconnect are applicable to O-SOECs as well. High-chromium-containing alloys are a common interconnect material, and they benefit from the formation of chromium oxides, which prevent breakaway oxidation while remaining electrically conductive. However, they are also prone to chromium volatilization, which causes contamination that reduces the stack's durability. Degradation also occurs due to oxidative and reductive gas exposure at high temperature. The addition of protective coatings for the interconnects is being investigated, particularly for the oxygen electrode side.

Silica glasses are a common seal material used in O-SOEC stacks. As described above, the seals are a potential source of contamination that contribute to stack degradation. These seals are a carryover from SOFC stacks, which suggests that there may be opportunities to reduce degradation by using seals optimized for O-SOEC operation, including under high steam concentration. The seals also contribute to limitations in the thermal cycling of these high-temperature stacks. Therefore, a low-cost, easily processable seal material that can withstand many thermal cycles would be advantageous.

As in the case of next-generation PEM electrolyzers that use new, low-cost materials, commercialization of O-SOEC technology will be hindered by the need to demonstrate improved lifetimes (e.g., 5 years). It will be important to complete lifetime testing in weeks or months instead of years. Hence, one of the biggest needs for O-SOEC technology development is to greatly improve the understanding of electrolyzer degradation mechanisms, which may require development of stress tests that effectively accelerate relevant degradation processes.

### *Systems*

Thermal cycling during startup and shutdown periods exacerbates degradation, leading to shorter lifetimes. Changes in temperature expand and contract all stack components. If the thermal and chemical expansion of the various components are not adequately matched, the ceramic cells can fracture, resulting in stack failure. O-SOEC stacks can rapidly respond to changing loads; however, the impact on lifetime is unknown, and the ability for the overall system to respond rapidly needs to be further investigated. Larger system demonstrations can help to understand the ability of the *overall system* to respond to load cycling, as well as the impact of load cycling on system lifetimes.

The high operating temperatures of O-SOECs enables extremely efficient use of electricity to produce hydrogen, and this efficiency can be further improved through integration with an external heat source. Designing systems that are well thermally integrated with heat sources is important to maximize the overall efficiency for hydrogen production and make the most of the available external heat source. Demonstration of O-SOEC systems that are highly integrated with external heat sources (e.g., heat from nuclear reactors, process heat from manufacturing) is key to maximizing the high electrical efficiency advantages of O-SOECs.

BOP components represent a significant fraction of capital costs for O-SOECs, and this contribution to overall cost is expected to grow as stack costs come down through economies of scale. The BOP includes power electronics, steam generators, high-temperature heat exchangers, pressure vessels, pumps, and water and gas processing units. Of these components, power electronics are the most expensive. As with other electrolyzer types, developing a standard off-the-shelf modular unit is one approach to reduce the cost of power electronics. For power electronics or other BOP components, applying principles of process intensification to reduce the number of components may also lead to overall cost reductions. In addition, the stack operating temperature directly impacts the cost of the BOP. Based on current standards, at temperatures above about 650°C, more expensive nickel-based steel alloys are needed for some of the heat exchangers and piping in an O-SOEC, while lower temperatures would allow for the use of less expensive metals. Additional research on non-nickel-based materials for high-temperature operation may reduce the cost of the BOP without sacrificing thermal efficiency.

### AEM Electrolyzers

AEM electrolyzers are a promising, lower-TRL hydrogen production technology. AEM electrolyzers operate at low temperature and use a solid polymer membrane to transport hydroxide ions between electrodes (**Figure 15**). The AEM electrolyzer design aims to combine the advantages of both PEM and LA electrolyzers: the alkaline environment enables the use of non-precious-metal catalysts and less expensive metal bipolar plates, and the membrane enables differential pressure operation and operation at higher current densities than traditional LA electrolyzers. Due to the inherent alkalinity in the membrane, pure water can be fed to the electrolyzer instead of alkaline electrolyte, although current technology performs better and has higher durability with an alkaline electrolyte feed. Research efforts are underway to optimize the electrolyte feed configuration and other components for high efficiency and durability.

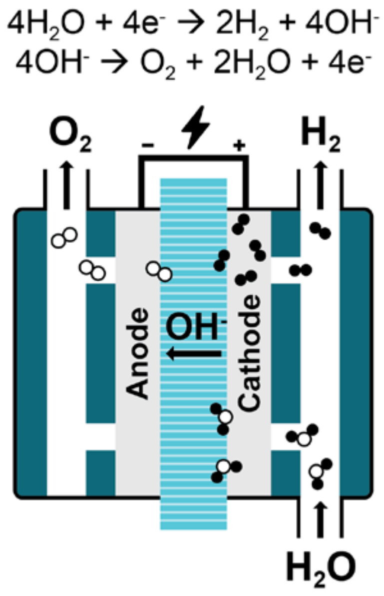

Figure 15. Schematic of AEM electrolyzer cell.

## STATUS AND R&D COST REDUCTION APPROACHES

A more thorough techno-economic analysis is ongoing to estimate the potential manufactured system cost of AEM electrolyzers produced at scale. Although they are still at low TRL and not produced commercially today, preliminary results suggest that AEM stacks may cost about $200/kW when manufactured at relatively low production volumes (about 20 MW/year) and ultimately have the potential to be even less expensive once higher manufacturing volumes (about 300 MW/year) are achieved [39]. This potential for low capital cost is mainly due to lower material costs in AEM stack designs (e.g., using non-precious-metal catalysts like stainless steel and inexpensive membranes).

The potential of this technology has been demonstrated, but to compete with existing technologies, AEM electrolyzers still require significant development to improve stability and performance while maintaining their low cost. AEM electrolyzers could ultimately achieve system costs lower than what is projected for PEM electrolyzers due to the lower material costs, assuming similar efficiency and durability targets can be met. The commercial development of AEM electrolyzers will likely benefit from the system design (including BOP) and high-throughput manufacturing techniques developed for PEM electrolyzers, capitalizing on cost reductions achieved in processes and equipment that are common to both electrolyzer types.

A summary of priority R&D areas for AEM electrolyzers is included in **Table 6**, with more detailed descriptions provided below.

Table 6. Priority R&D Opportunities for AEM

| Technology Area | Priority R&D Opportunities |
|---|---|
| Materials and components | • Durable membranes and ionomers with high conductivity.<br>• PGM-free electrodes with high catalyst activity, utilization, and durability. |
| Cells and stacks | • Understanding the role of supporting electrolyte and degradation.<br>• Opportunities to eliminate electrolyte.<br>• Component integration strategies. |

### *Materials and Components*

R&D of chemically and thermally stable membranes and ionomers with high ionic conductivity could enable the longer stack lifetimes required for deployment of reliable AEM electrolyzers. Ionomers are the polymeric backbone of the membrane and serve as the catalyst binder in the electrode. The ionomer provides the ion-conducting properties both as electrolyte for the cell and as ion transport to and from the active catalyst sites. These materials can degrade in both the membrane and the catalyst layer (e.g., via oxidation reactions) and reduce the lifetime of the cell. Key design parameters for alkaline exchange ionomers and membranes include fast hydroxide ion transport, low chemical degradation rates, and thermal stability. More research is needed to understand the impacts of the electrolyte on membrane and ionomer stability.

Improvements in cell and stack efficiency can be achieved through enhanced catalyst activity, greater catalyst utilization, and optimized electrolyte conditions. The catalytic needs for AEM electrolyzers are similar to those of LA electrolyzers. There are several PGM-free materials currently being researched to serve as the hydrogen and oxygen catalysts [40]. As with LA electrolyzers, nickel or nickel alloys are common catalyst materials, but other catalyst classes are being investigated as well. There has been limited testing of PGM-free catalysts in full cell configurations. Incorporating the catalyst into an electrode structure that also contains an ionomer has been challenging due to catalyst delamination and/or ionomer loss. Understanding the durability of electrodes as a function of ionomer, catalysts, the ionomer/catalyst interface, and supporting electrolyte is a significant challenge that requires additional research to improve AEM electrolyzer durability and performance.

### *Cells and Stacks*

One potential advantage of AEM electrolyzers compared with LA electrolyzers is the use of pure water electrolyte instead of concentrated alkaline electrolyte. However, performance and durability can be significantly improved when a low concentration of supporting electrolyte (e.g., <0.5-M KOH or $Na_2CO_3$) is added to the water feed. A better fundamental understanding of the impact of supporting electrolyte on AEM cell, component, and material performance and durability is needed to determine if this performance and durability gap between pure water and supporting electrolyte operation can be closed. Following such studies, the trade-offs between performance (i.e., efficiency and durability) and cost (i.e., feedstock and maintenance) can be better quantified. Ultimately, the decision on whether to feed pure water or a low-concentration electrolyte to the electrolyzer will be based on overall economics across the lifetime of the electrolyzer.

To achieve commercial viability, AEM electrolyzers will need carefully optimized improvements in membrane electrode assembly fabrication. A catalyst-coated membrane technique, similar to that used in PEM electrolyzers, is one approach for fabrication. However, there are a host of issues in applying this method to AEM electrolyzers. The hot-pressing technique used in PEM electrode design cannot be used for current AEM electrolyzer materials because it can damage the membrane and/or electrodes. Catalyst-coated, membrane-based cells can suffer from delamination of the catalyst layer, membrane degradation, ionomer degradation, drying of the membrane due to gas phase evolution, and loss of electrical contact with current collectors. Improved interface engineering between the membrane and catalyst layers, as well as optimization of the electrode structure and components, could alleviate these issues.

## P-SOECs

P-SOECs are being developed as a lower-temperature (450 Celsius [°C]–650°C) alternative to O-SOECs. The combination of lower operating temperatures and proton conduction provide cost advantages over O-SOECs. Lower temperatures are made possible by the lower activation energy of proton-conducting ceramic electrolytes compared with oxide-ion-conducting electrolytes. P-SOECs also have the potential for high efficiencies, similar to O-SOECs. However, significant advances are needed to move this low-TRL technology from the R&D phase to commercial readiness.

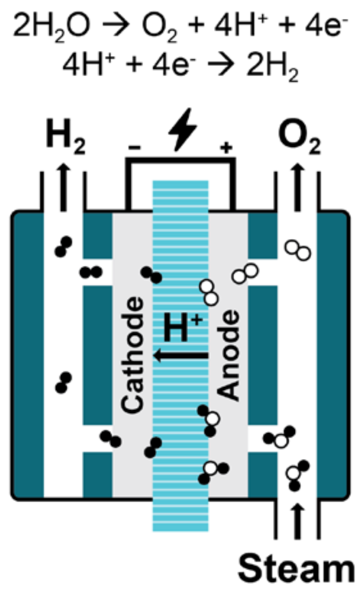

Figure 16. Schematic of a P-SOEC.

### STATUS AND R&D COST REDUCTION APPROACHES

Preliminary results indicate the costs associated with P-SOEC stacks can be similar to those of O-SOECs, given their similar cell design and energy efficiency [39]. P-SOECs have the potential for lower capital costs than their O-SOEC counterparts because their lower operating temperature enables the use of less expensive metals in both the stack and BOP. Additionally, P-SOECs can directly produce dry hydrogen, removing the need for an additional hydrogen-drying system and providing opportunities to pressurize within the stack. Pressurizing within the stack can simplify the system design and reduce the overall cost of operation. The main barriers to commercial development of P-SOECs are the challenge of achieving both the needed material strength *and* high protonic conductivity (which are inversely related), and, similar to O-SOECs, the high cost of thermal treatment to make dense electrolyte powders. Additional R&D will be needed in these areas to produce stable, efficient P-SOECs at low cost.

Given the relatively low TRL and lack of commercial P-SOECs today, this technology may not be manufactured at a large enough scale to significantly contribute to commercial production of hydrogen that meets the Hydrogen Shot target by 2031. However, if P-SOECs can meet similar performance, efficiency, and durability targets as O-SOECs (**Table 2**), it is anticipated that P-SOECs could ultimately achieve system costs lower than what is projected for O-SOECs. This is largely due to lower material costs (e.g., the potential to use conventional stainless steels instead of costly nickel-based superalloys or ceramic components) and simplified BOP. P-SOECs will also benefit from the development, manufacturing, and commercialization of O-SOECs due to similarities in system design, cell design, and some materials. A summary of priority areas for R&D of P-SOEC electrolyzers is shown in **Table 7**, with more detailed descriptions provided below.

Table 7. P-SOEC Priority RD&D

| Technology Area | R&D Opportunities |
|---|---|
| Materials and components | • Stable, efficient, mechanically robust electrolyte capable of scale-up.<br>• Improved oxygen electrode. |
| Cells and stacks | • Development of lower-cost metal interconnects.<br>• Novel engineering solutions and fabrication methods. |

### *Materials and Components*

Electrolytes for P-SOECs must have high proton conductivity, low electronic conductivity, and sufficient mechanical properties and stability to withstand high-humidity atmospheres with either strong reducing or oxidizing effects. The leading candidates for these electrolytes are doped $BaZrO_3$ and $BaZr_{1-x}Ce_xO_3$ perovskite oxides. The former is relatively stable in steam environments; however, it has a relatively low proton conductivity and can suffer from poor sinterability and mechanical properties. The latter is an improvement on the $BaZrO_3$-based material for sinterability and improved protonic conductivity but has limited stability in a high steam environment. Also, under some operating conditions relevant to P-SOEC electrolyzer operation (steam concentration, current density/voltage, and temperature), these materials, especially those with ceria, exhibit significant electronic conduction through the electrolyte, resulting in a decrease in cell and stack electrical efficiency. Additionally, these materials are not as mechanically strong as O-SOEC electrolytes. Materials R&D is needed to find the required combination of electrical, mechanical, and chemical properties to arrive at an electrolyte material that displays high performance, high efficiency, and long lifetime under the range of electrolyzer operating conditions of interest (e.g., less than 600°C, high steam concentration).

### *Cells and Stacks*

Another approach to overcoming the challenges with the proton-conducting electrolyte is to engineer around the materials-based limitations. Possible approaches include depositing a very thin layer of a different compatible proton-conducting electrolyte on the $BaZr_{1-x}Ce_xO_3$ electrolyte that is stable in steam, adding a sintering aid to decrease the sintering temperature of $BaZrO_3$, and engineering the interfaces to improve electrochemical performance and durability. Also, new fabrication techniques that facilitate the manufacture of larger cells are needed to overcome the poor mechanical properties of some of these materials.

As with O-SOECs, chromium poisoning from the metal interconnects is a concern, even at reduced temperatures. It is expected that the poisoning of the electrolyte and oxygen electrode with chromium species would reduce the lifetime of P-SOECs, perhaps even more significantly than in O-SOECs, due to the higher volatility of chromium species in the “wet” oxidizing environments unique to P-SOECs. However, few studies have investigated the effect of chromium on P-SOECs. Lower-cost metallic interconnects could also be an option to significantly reduce costs, but more research needs to be done to understand the corrosion and oxidation behavior in typical P-SOEC operating conditions and how this might affect lower-cost metals.

# ENERGY SYSTEM INTEGRATION: STATUS AND COST REDUCTION POTENTIAL

**Key Factors for Energy System Integration**

- Integration with clean energy sources
- Electricity price
- Capacity factor
- Installation costs

To produce clean hydrogen, electrolyzers must be able to use electricity generated from renewable or nuclear energy sources. As the grid is decarbonized with renewable and nuclear energy, electrolyzers could tie directly to the grid to produce clean hydrogen. However, electricity price forecasts for a decarbonized grid are significantly higher than what is needed for electrolyzers to achieve the Hydrogen Shot [15]. While it may not be possible to achieve the Hydrogen Shot using electricity purchased from the grid, there may be economically viable opportunities for electrolyzers to use grid electricity. For example, renewable electricity that would otherwise be curtailed can be used to produce hydrogen for long-duration energy storage, thereby providing additional revenue to renewable generators and increasing the value of renewable electricity sources to the grid [41].

In addition to helping to meet the Hydrogen Shot goal, tying electrolyzers directly to renewable energy sources can also provide other advantages. For example, electrolyzers can be coupled to wind farms awaiting grid interconnection (which can involve delays of months or years) to start utilizing the available clean electricity immediately and avoid the costs associated with unused capital-intensive assets. The direct coupling of power from wind turbines or solar panels to electrolyzers can also eliminate some electrical BOP equipment, reducing the overall system cost.

However, there are challenges that must be overcome to realize the full benefits of directly coupled electrolyzers. For example, an electrolyzer directly coupled to a variable renewable power source is likely to have a limited capacity factor, determined by the availability of renewable energy. Low capacity factors will drive up the cost of hydrogen, even more so with electrolyzers that have high capital cost. In addition, more research is needed to understand and quantify the impact of variable power load profiles on electrolyzer performance and lifetime. This is an active area of research supported by the DOE Hydrogen Program [42]. Potential solutions to these challenges could include:

- **Hybrid energy systems** with multiple clean energy sources and backup energy storage systems can increase the electrolyzer's capacity factor. In addition, there are opportunities for more complex, fully integrated hybrid systems to produce lower-cost hydrogen. For example, nuclear-renewable-hydrogen hybrid systems can provide grid services and coproduce low-cost, clean hydrogen (which can be used directly as a fuel or as a feedstock in the production of e-fuels) [43]. System-level decisions, such as the inclusion of load-leveling batteries, can also influence electrolyzer operation requirements (e.g., ramp rate, minimum turndown) that ultimately impact electrolyzer durability and replacement costs. Holistic system techno-economic analyses are important in quantifying those trade-offs and the overall impact on the cost of hydrogen.

- **Optimizing operating strategies**, such as turning down the electrolyzer rather than turning it off, to reduce wear related to startup and shutdown processes [10].

- **Redesigning renewable energy technologies**, such as wind turbines, for optimal hydrogen production instead of optimal electricity production [44].

The DOE Hydrogen Program is investigating a number of scenarios to better understand the impact on overall system economics of the variable renewable power load profiles involved in direct coupling. The program is also conducting ongoing analysis to quantify potential cost reductions and other benefits associated with direct coupling of electrolyzers to renewable power and integration with thermal energy sources at existing nuclear power plants [45] [46].

While RD&D efforts to reduce hardware costs (for stack and system) and operating costs of electrolyzers are important to enable commercial deployment, it is also important to look beyond hardware and operations costs and consider balance-of-system costs, or “soft” costs, associated with electrolyzer deployment, installation, and overall integration into the energy system. Soft costs include all expenses that can contribute to the total cost of ownership of the electrolyzer system, except for electrolyzer system hardware, feedstock, electricity, operations, and maintenance. Examples include site preparation (e.g., concrete pads, water and electrical hookups), land, permits, commissioning, and delivery. These costs today are nontrivial and can be comparable to system capital costs. Some soft costs may decrease as the industry matures and more large-scale (>100-MW) electrolyzer systems are installed. Optimizing system designs to minimize installation complexity, potentially through modularization and/or standardization, will also help reduce these costs. As hardware and operating costs continue to decrease, soft costs are becoming increasingly important to the economics of electrolytic hydrogen production [47].

Current analysis tools for electrolyzer technologies, such as DOE’s H2A tool, estimate soft costs assuming a certain percentage of capital expenses, following guidance provided by the Association for the Advancement of Cost Engineering International [8]. However, it is important to differentiate between types of electrolyzer technologies, system sizes, end uses, and site locations, because those factors could significantly affect the soft costs. With a growing number of electrolyzer installations both domestically and internationally, more real-world soft cost data are becoming available. Quantifying soft costs from past and current installations will not only improve general understanding of electrolyzer economics, but also provide insight into potential impediments to deployment. Potential approaches to reducing soft costs for electrolyzer projects may include providing technical assistance to state and local governments to accelerate planning, siting, and permitting activities; developing modularized, designed-for-installation systems to reduce construction, installation, and engineering costs; and creating training materials and programs that support the growth of a skilled workforce.

# CONCLUSION

The use of water electrolyzers for hydrogen production will be critical to meeting DOE's Hydrogen Shot goal. This technology assessment pulls from numerous resources to summarize the current state of the field in terms of cost, commercial and manufacturing readiness, performance, lifetime, and deployment, while highlighting opportunities for advances through RDD&D across several different types of electrolyzers: PEM, LA, O-SOEC, AEM, and P-SOEC.

With well-focused, sustained investments in RDD&D, and based on specific scenarios integrating with renewable and/or nuclear power generation, the three most commercially mature electrolyzer technologies—PEM, LA, and O-SOEC—show the potential to achieve the Hydrogen Shot goal and realize an LCOH of $1/kg within a decade. In the longer term, the two lower-TRL technologies—AEM and P-SOEC—have potential advantages over these three with successful further technology developments. The techno-economic analysis conducted here utilized technical inputs from a number of sources referenced throughout this document, using published electrolyzer technical targets. It is based on clean energy scenarios representing the current grid, current clean energy resources, and future projections of hybrid clean energy systems. Other factors that influence cost, such as the sale of byproducts or the Clean Hydrogen Production Tax Credit (45V), were not considered in this analysis but could further reduce the LCOH.

The five electrolyzer technologies included in this assessment are on different technology development timelines and at different levels of commercialization. Furthermore, the different technologies will be more competitive in some end uses and with certain clean energy resources than others. With government and industry projections of significant growth in demand for clean hydrogen for multiple end uses, it is likely that there will be viable and important roles for all of these technologies. And with such a diverse array of applications for hydrogen across multiple sectors, each with their own particular needs, it appears unlikely that only one or two electrolyzer technologies will completely dominate the market.

The key RDD&D opportunities to achieve the Hydrogen Shot goals can be bundled into three main areas: technology advancements, manufacturing and economies of scale, and clean energy system integration. Efforts in all three areas are needed; innovations in one alone will not be sufficient to reduce the cost of hydrogen to $1/kg. Achieving the Hydrogen Shot goal will require a strategic allocation of resources and efforts across these areas. DOE's Hydrogen Program, as well as the Hydrogen Interagency Task Force, are well positioned to address these broad RD&D needs to enable cost-effective, clean $H_2$ production in the years to come, and to play an important role in achieving national climate and energy goals [48].

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# APPENDIX

The Hydrogen Analysis Lite Production (H2A-Lite) model, a peer-reviewed, national-laboratory-developed model and simplified successor to the original Hydrogen Analysis (H2A) model, was used to determine the levelized cost of hydrogen (LCOH) production in units of 2020 \$/kg $H_2$ for **Figure 4** [8]. The modeled systems are stand-alone, grid-connected electrolyzers with a nominal hydrogen production capacity of about 50,000 kg/day.[18] Methods from previously published H2A production models and reports were used to determine inputs into H2A-Lite [49]. Key assumptions summarized in the following tables are based heavily on U.S. Department of Energy (DOE) water electrolysis technical targets developed for generalized proton exchange membrane (PEM), liquid alkaline (LA), and oxide-ion-conducting solid-oxide electrolyzer cell (O-SOEC) electrolyzers using inputs from several key industry and national laboratory collaborators with relevant experience in electrolyzer technology and techno-economic analysis [14]. Assumptions are also consistent with a number of previous reports.[19] All other required parameters in H2A-Lite default to the assumptions for the “Central Grid Electrolysis (PEM)” (PEM and LA) and “Central Grid Electrolysis (SOEC)” (O-SOEC) case studies embedded in the model.

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[18] This system size is consistent with the current trend in deployed electrolyzer systems.

[19] Uninstalled capital cost, system efficiency, and replacement interval are consistent with the range of values in [3], [27], and [35].

## Table A-1. Key Parameters Used To Determine Hydrogen Levelized Cost for PEM Electrolyzers in H2A-Lite[20]

| Parameter | PEM – Current Status | PEM – 2026 Target | PEM – 2031 Target |
|---|---|---|---|
| Nominal hydrogen production capacity | 50,000 kg/day | 50,000 kg/day | 50,000 kg/day |
| Stack rated power requirement (BOL) | 106 MW | 100 MW | 90 MW |
| System rated power requirement (BOL) | 115 MW | 106 MW | 96 MW |
| System rated power requirement (average) | 120 MW | 111 MW | 100 MW |
| Plant startup year | 2020 | 2020 | 2020 |
| System life | 30 yr | 30 yr | 30 yr |
| Uninstalled capital cost (2020 $)[21] | $700–$1,100/kW | $250/kW | $150/kW |
| Total installed capital (2020 $)[22] | $1,400–$2,200/kW | $385/kW | $210/kW |
| Annual fixed operating cost (2020 $/yr)[23] | $70–$110/kW/yr | $19/kW/yr | $11/kW/yr |
| Stack operating point (BOL) | 2 A/cm$^2$ @ 1.9 V/cell | 3 A/cm$^2$ @ 1.8 V/cell | 3 A/cm$^2$ @ 1.6 V/cell |
| Stack replacement interval[24] | 40,000 operating hours | 80,000 operating hours | 80,000 operating hours |
| Voltage degradation rate | 4.8 mV/kh | 2.3 mV/kh | 2 mV/kh |
| Replacement costs[25] | 11% of total installed cost | 11% of total installed cost | 11% of total installed cost |
| Stack electricity usage (BOL) | 51 kWh/kg | 48 kWh/kg | 43 kWh/kg |
| System electricity usage (BOL) | 55.2 kWh/kg | 51 kWh/kg | 46 kWh/kg |
| System electricity usage (average) | 57.5 kWh/kg | 53.3 kWh/kg | 47.9 kWh/kg |
| System thermal energy usage | - | - | - |
| Water/steam usage | 3.78 gal/kg | 3.78 gal/kg | 3.78 gal/kg |

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[20] Parameters for all years based on [14].

[21] Uninstalled electrolyzer system capital cost in 2020 $/kW, which includes the cost of the electrolyzer stack and balance of plant (BOP) (including markup from the manufacturer), normalized by the rated beginning of life (BOL) stack power.

[22] Total installed capital cost normalized by the rated BOL stack power. Total installed capital estimated as about 2 times (Current Status), 1.55 times (2026 Target), and 1.4 times (2031 Target) the uninstalled capital cost to represent learning in installations over time from first-of-a-kind (Current Status) to nth-of-a-kind plants (2031 Target).

[23] Fixed operating costs estimated as 5% of the total installed capital cost and normalized by the rated BOL stack power.

[24] Replacement intervals given in units of operating hours will have variable replacement intervals in years depending on the capacity factor.

[25] 11% of total installed cost corresponds to about 15% of direct capital cost, consistent with H2A methodology.

### Table A-2. Key Parameters Used To Determine Hydrogen Levelized Cost for LA Electrolyzers in H2A-Lite [26]

| Parameter | LA – Current Status | LA – 2026 Target | LA – 2031 Target |
|---|---|---|---|
| Nominal hydrogen production capacity | 50,000 kg/day | 50,000 kg/day | 50,000 kg/day |
| Stack rated power requirement (BOL) | 106 MW | 100 MW | 94 MW |
| System rated power requirement (BOL) | 115 MW | 108 MW | 100 MW |
| System rated power requirement (average) | 119 MW | 113 MW | 105 MW |
| Plant startup year | 2020 | 2020 | 2020 |
| System life | 30 yr | 30 yr | 30 yr |
| Uninstalled capital cost (2020 $)[27] | $500–$750/kW | $250/kW | $150/kW |
| Total installed capital (2020 $)[28] | $1,000–$1,500/kW | $385/kW | $210/kW |
| Annual fixed operating cost (2020 $/yr)[29] | $50–$75/kW/yr | $19/kW/yr | $11/kW/yr |
| Stack operating point (BOL) | 0.5 A/cm$^2$ @ 1.9 V/cell | 1 A/cm$^2$ @ 1.8 V/cell | 2 A/cm$^2$ @ 1.7 V/cell |
| Stack replacement interval[30] | 60,000 operating hours | 80,000 operating hours | 80,000 operating hours |
| Replacement costs[31] | 11% of total installed cost | 11% of total installed cost | 11% of total installed cost |
| Voltage degradation rate | 4.8 mV/kh | 2.3 mV/kh | 2.1 mV/kh |
| Stack electricity usage (BOL) | 51 kWh/kg | 48 kWh/kg | 45 kWh/kg |
| System electricity usage (BOL) | 55 kWh/kg | 52 kWh/kg | 48 kWh/kg |
| System electricity usage (average) | 57.3 kWh/kg | 54.3 kWh/kg | 50.4 kWh/kg |
| System thermal energy usage | - | - | - |
| Water/steam usage | 3.78 gal/kg | 3.78 gal/kg | 3.78 gal/kg |

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[26] Parameters for all years based on [14]. Additionally, range of capital cost for Current Status based on 4.5-MW stacks and 10-MW system modules from [32].

[27] Uninstalled electrolyzer system capital cost in 2020 $/kW, which includes the cost of the electrolyzer stack and BOP (including markup from the manufacturer), normalized by the rated BOL stack power.

[28] Total installed capital cost normalized by the rated BOL stack power. Total installed capital estimated as about 2 times (Current Status), 1.55 times (2026 Target), and 1.4 times (2031 Target) the uninstalled capital cost to represent learning in installations over time from first-of-a-kind (Current Status) to nth-of-a-kind plants (2031 Target).

[29] Fixed operating costs estimated as 5% of the total installed capital cost and normalized by the rated BOL stack power.

[30] Replacement intervals given in units of operating hours will have variable replacement intervals in years depending on the capacity factor.

[31] 11% of total installed cost corresponds to about 15% of direct capital cost, consistent with H2A methodology.

## Table A-3. Key Parameters Used To Determine Hydrogen Levelized Cost for O-SOEC Electrolyzers in H2A-Lite[32]

| Parameter | O-SOEC – Current Status | O-SOEC – 2026 Target | O-SOEC – 2031 Target |
|---|---|---|---|
| Nominal hydrogen production capacity | 50,000 kg/day | 50,000 kg/day | 50,000 kg/day |
| Stack rated power requirement (BOL) | 71 MW$_{\text{el}}$ | 71 MW$_{\text{el}}$ | 71 MW$_{\text{el}}$ |
| System rated power requirement (BOL) | 100 MW<br>*(79 MW$_{el}$, 21 MW$_{th}$)* | 93 MW<br>*(75 MW$_{el}$, 18 MW$_{th}$)* | 89 MW<br>*(73 MW$_{el}$, 16 MW$_{th}$)* |
| System rated power requirement (average) | 103 MW<br>*(82 MW$_{el}$, 21 MW$_{th}$)* | 97 MW<br>*(79 MW$_{el}$, 18 MW$_{th}$)* | 92 MW<br>*(76 MW$_{el}$, 16 MW$_{th}$)* |
| Plant startup year | 2020 | 2020 | 2020 |
| System life | 30 yr | 30 yr | 30 yr |
| Uninstalled capital cost (2020 $)[33] | $2,000–$2,500/kW | $500/kW | $200/kW |
| Total installed capital (2020 $)[34] | $4,000–$5,000/kW | $775/kW | $280/kW |
| Annual fixed operating cost (2020 $/yr)[35] | $200–$250/kW/yr | $39/kW/yr | $14/kW/yr |
| Stack operating point (BOL) | 0.6 A/cm$^2$ @ 1.28 V/cell | 1.2 A/cm$^2$ @ 1.28 V/cell | 2 A/cm$^2$ @ 1.28 V/cell |
| Stack replacement interval[36] | 20,000 operating hours | 40,000 operating hours | 80,000 operating hours |
| Replacement costs[37] | 11% of total installed cost | 11% of total installed cost | 11% of total installed cost |
| Voltage degradation rate | 6.4 mV/kh | 3.2 mV/kh | 1.6 mV/kh |
| Stack electricity usage (BOL) | 34 kWh/kg | 34 kWh/kg | 34 kWh/kg |
| System electricity usage (BOL) | 38 kWh/kg | 36 kWh/kg | 35 kWh/kg |
| System electricity usage (average) | 40 kWh/kg | 38 kWh/kg | 37 kWh/kg |
| System thermal energy usage[38] | 9 kWh/kg | 8 kWh/kg | 7 kWh/kg |
| Water/steam usage | 2.38 gal/kg | 2.38 gal/kg | 2.38 gal/kg |

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[32] Parameters for all years based on [14]. For Current Status, uninstalled capital cost range is based on input from Idaho National Laboratory and is consistent with [3].

[33] Uninstalled electrolyzer system capital cost in 2020 $/kW, which includes the cost of the electrolyzer stack and BOP (including markup from the manufacturer), normalized by rated BOL stack power.

[34] Total installed capital cost normalized by the rated BOL stack power. Total installed capital estimated as about 2 times (Current Status), 1.55 times (2026 Target), and 1.4 times (2031 Target) the uninstalled capital cost to represent learning in installations over time from first-of-a-kind (Current Status) to nth-of-a-kind plants (2031 Target).

[35] Fixed operating costs estimated as 5% of the total installed capital cost and normalized by the rated BOL stack power.

[36] Replacement intervals given in units of operating hours will have variable replacement intervals in years depending on the capacity factor.

[37] 11% of total installed cost corresponds to about 15% of direct capital cost, consistent with H2A methodology.

[38] Natural gas assumed to be the thermal energy source in the LCOH calculation using default H2A-Lite price assumptions. In some applications, thermal energy may be provided by industrial processes.

**Table A-4. Financial Assumptions for All Scenarios (All Technologies, All Years)**

| Financial Assumptions | |
|---|---|
| Real return on equity | 10.89% |
| Debt/equity | 0.62 |
| Interest rate | 5% |
| Depreciation type | Modified accelerated cost recovery system (MACRS) |
| MACRS depreciation period | 20 yr |
| Total income tax rate | 25.74% |
| Cash on hand | 1.0 month of operating expenses |
| Dollar-year basis | 2020 |

Financial specifications were selected to result in a ~10% nominal weighted average cost of capital (WACC).

### Table A-5. LCOH (2020 $/kg) for Each Electricity Scenario Shown in Figure 4

| **Scenario** | **Electricity Price** ***(cents/kWh)*** | **Capacity Factor**[39] ***(%)*** | **LCOH** ***(2020 $/kg)*** | | |
|---|---|---|---|---|---|
| | | | **PEM** | **LA** | **O-SOEC** |
| **Current Technology Status** | | | | | |
| Grid, U.S. average industrial | 7.4 | 97% | 6.07–7.23 | 5.56–6.17 | 7.15–8.14 |
| **2026 Target Scenarios** | | | | | |
| Future grid, low estimate | 6.5 | 97% | 4.00 | 4.06 | 3.35 |
| Future grid, high estimate | 10.0 | 97% | 5.89 | 5.98 | 4.69 |
| Land-based wind, Class 1, 2026 advanced | 2.0 | 54% | 1.90 | 1.91 | 2.11 |
| Land-based wind, Class 1, 2026 conservative | 2.4 | 50% | 2.17 | 2.19 | 2.34 |
| Conventional nuclear power, low estimate | 1.8 | 97% | 1.46 | 1.48 | 1.56 |
| Conventional nuclear power, high estimate | 3.0 | 97% | 2.11 | 2.14 | 2.02 |
| Hybrid system, half size (with aggressive renewable generation cost reductions) | 1.2 | 74% | 1.26 | 1.27 | 1.52 |
| Hybrid system, same size (with renewable generation PTC) | 1.0 | 40% | 1.62 | 1.62 | 2.09 |
| **2031 Target Scenarios** | | | | | |
| Future grid, low estimate | 6.0 | 97% | 3.17 | 3.33 | 2.66 |
| Future grid, high estimate | 7.0 | 97% | 3.65 | 3.84 | 3.03 |
| Land-based wind, Class 1, 2031 advanced | 1.7 | 57% | 1.23 | 1.28 | 1.21 |
| Land-based wind, Class 1, 2031 conservative | 2.3 | 51% | 1.56 | 1.64 | 1.48 |
| Conventional nuclear power, low estimate | 1.8 | 97% | 1.14 | 1.19 | 1.10 |
| Conventional nuclear power, high estimate | 3.0 | 97% | 1.72 | 1.80 | 1.54 |
| Hybrid system, half size (with aggressive renewable generation cost reductions) | 1.2 | 74% | 0.91 | 0.95 | 0.94 |
| Hybrid system, same size (with aggressive renewable generation cost reductions) | 1.0 | 40% | 1.03 | 1.08 | 1.10 |

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[39] This value corresponds to “Utilization” in the H2A-Lite tool.

## Table A-6. LCOH (2020 $/kg) for the PEM Electrolysis Pathway to H2 Shot Shown in Figure 6

| Technology Year[40] | Electricity Scenario | Electricity Price *(cents/kWh)* | Capacity Factor[41] *(%)* | LCOH *(2020 $/kg)* |
|---|---|---|---|---|
| Current | Grid, U.S. average industrial | 7.4 | 97% | 6.65 |
| Current | Land-based wind, Class 1, 2023 moderate, without renewable generation PTC | 2.6 | 51% | 5.64 |
| Current | Hybrid system, half size, without renewable generation PTC | 2.9 | 74% | 4.65 |
| 2026 | Hybrid system, half size, without renewable generation PTC | 2.9 | 74% | 2.18 |
| 2031 | Hybrid system, half size, without renewable generation PTC | 2.9 | 74% | 1.73 |
| 2031 | Hybrid system, half size, with renewable generation PTC | 1.2 | 74% | 0.91 |

## Table A-7. LCOH (2020 $/kg) for the High-Temperature Electrolysis Pathway to H2 Shot Shown in Figure 6

| Technology Year | Electricity Scenario | Electricity Price *(cents/kWh)* | Capacity Factor[42] *(%)* | LCOH *(2020 $/kg)* |
|---|---|---|---|---|
| Current | Grid, U.S. average industrial | 7.4 | 97% | 7.34 |
| 2026 | Grid, U.S. average industrial | 7.4 | 90% | 4.17 |
| 2026 | Tight Integration with Nuclear Plant | 3.0 | 95% | 1.99 |
| 2031 | Tight Integration with Nuclear Plant | 3.0 | 95% | 1.50 |
| 2031 | Optimized Integration/Flexible Operation[43] | 2.0 | 95% | 1.00 |

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[40] Current technology cases assume an average of high and low capital cost estimates from Table A-1.

[41] This value corresponds to “Utilization” in the H2A-Lite tool.

[42] This value corresponds to “Utilization” in the H2A-Lite tool.

[43] Includes oxygen sales offset of $0.1/kg-H2.

**Table A-5** shows the range of hydrogen levelized cost for PEM, LA, and O-SOEC technologies based on the parameters in **Table A-1–Table A-4** for the different electricity source scenarios further detailed below:

- **Grid:** While not considered “clean,” grid cases are included here as reference points using industrial electricity prices from the U.S. Energy Information Administration, which catalogues annual pricing across individual states and regions [50]. The average case represents the U.S. average grid electricity price for 2022 identified by the U.S. Energy Information Administration.
- **Future grid:** The future grid scenarios are based on the *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* report [15]. The electricity prices are based on net system costs of achieving a 100% clean electricity grid by 2035, and combine electricity system costs, health costs, and climate costs. The 2026 scenario reflects an approximately 65% clean grid, and the 2031 scenario reflects an approximately 85% clean grid.
- **Land-based wind:** The wind case is based on installations modeled in the National Renewable Energy Laboratory’s 2023 Annual Technology Baseline for land-based Class 1 (best) wind conditions with high-resolution, location-specific resource data [11]. This case assumes R&D financial assumptions and does not include the renewable generation production tax credits (PTC). Values are adjusted from reported 2021 $ to 2020 $ based on a 4.7% inflation rate. Many of the operational Class 1 wind farms in the United States are in south-central California, western Texas, the Plains states, and southern Minnesota [51]. Power purchase agreements have been established for some of the Class 1 wind sites located in Colorado, Iowa, Illinois, Kansas, New Mexico, Texas, and others. As an example, a power purchase agreement for an approximately 200-MW wind farm in the Southwest Power Pool region (which includes Iowa, Kansas, and Nebraska) had a price as low as about $0.016/kWh [51] [52]. While wind power purchase agreements vary, this example shows that high-quality wind resources are promising for low-cost hydrogen production in the near term.
- **Nuclear:** Assumptions for the nuclear power scenario are based on baseload power from an existing conventional nuclear power plant that includes only operating, maintenance, and fuel costs in the levelized cost of electricity [16].
- **Hybrid wind + solar:** This case reflects combined hourly generation from collocated solar and wind energy sources in a hybrid system to produce low-cost electricity with a high capacity factor. The location was selected based on the complementarity of solar and wind resources, where a location with high complementarity will result in a high capacity factor due to the fact that wind and solar production happen at different times. The capacity factor and levelized cost of electricity assumed here were developed by the Grid Modernization Laboratory Consortium based on a published methodology [53] and actual historical weather data for a location in Texas with high complementarity. The “half-size” configuration is for an electrolyzer capacity sized to 50% of the total solar and wind generation capacity (i.e., 100-MW electrolyzer and 200 MW of combined solar and wind), while the “same-size” configuration is for an electrolyzer capacity equal to the total solar and wind generation capacity (i.e., 200-MW electrolyzer and 200 MW of combined

solar and wind). Where specified, the levelized cost of electricity values include the renewable generation production tax credit (PTC) of $17/MWh.