DOE Hydrogen Program Record

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Title: Clean Hydrogen Production Cost Scenarios with PEM Electrolyzer Technology

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Item

This DOE Hydrogen Program Record documents the modeled levelized cost of clean hydrogen (LCOH) produced from renewable electricity using currently available proton exchange membrane (PEM) electrolyzer technology and various renewable energy sources[a] as approximately **\$5 to \$7 per kilogram (kg)** (in \$2022 dollars and without subsidies).[b] These values are based on a range of PEM electrolyzer installed capital costs (average of **\$2,000/kW**) using various references, real world data, and analytical models at low manufacturing volumes;[c] renewable electricity costs of roughly **\$0.03/kWh**; and capacity factors ranging from approximately **50 to 75%**. Additional cases with higher renewable costs and lower capacity factors (e.g., solar) can result in higher LCOHs. DOE will update these analyses regularly as data from demonstrations and deployments (e.g., hydrogen hubs) are provided.

Analytical Methodology

DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) has historically conducted regular cost analyses and benchmarking to assess the cost of hydrogen produced from various pathways, including electrolysis. In this Record, HFTO in conjunction with its H2NEW Consortium [1], summarizes techno-economic analyses based on the DOE Hydrogen Analysis (H2A) Production methodology [2] to estimate hydrogen production costs under different scenarios coupling PEM electrolyzers with diverse, clean energy sources. The H2A-Lite production model [3] provides a user-friendly, high-level techno-economic analysis based on generally accepted accounting principles, allowing for consistent and transparent reporting across hydrogen production technologies.[d]

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[a] This Record covers scenarios integrating renewable power with PEM electrolyzers where the effective capacity factor is 50% or greater. See the *Renewable Electricity Scenarios* section.

[b] For details, see the *Results* section.

[c] The baseline installed PEM electrolyzer capital cost of ~\$2,000/kW [in a 2022 dollar-year basis (2022\$/kW)] is based on ongoing modeling work within the H2NEW Consortium, has been vetted by domestic electrolyzer manufacturers, and is consistent with contemporary references. See the *Installed Capital Cost* section in the Appendix for additional details.

[d] The H2A Production tool is a discounted cash-flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for projecting levelized hydrogen production costs. The H2A-Lite production model (v1.01), a streamlined, more user-friendly version of the original H2A production model, was specifically employed in the analysis presented in this Record.

The LCOH results reported in this Record represent untaxed and unsubsidized costs[e] associated solely with hydrogen production (compression,[f] storage, distribution, and dispensing costs are not included). The LCOHs for the different scenarios, as well as the range of electrolyzer installed capital costs, are reported in a 2022-year dollar basis (2022$) to reflect current market conditions and for consistency with other contemporary reports,[g] such as the DOE *Pathways to Commercial Liftoff: Clean Hydrogen* report [4].

Table 1 includes key PEM electrolyzer parameters used in the analysis, representative of recent technology status. The system performance and lifetime parameters as well as plant parameters including capital and replacement costs, are consistent with an industry peer-review conducted in 2023 and with modeling conducted by the DOE H2NEW Consortium. Additional information on the analysis parameters in Table 1 related to the scenarios analyzed in this Record can be found in the Appendix.

Table 1. Key PEM electrolyzer parameters used in analysis reported in this Program Record.

Parameter	Value / Ranges
Electrolyzer system electricity usage	~57 kWh/kg
Electrolyzer system lifetime	30 yr
Plant capacity	50,000 kg/day
Installed capital costs	$1,500; $2,000; $2,500/kW [$2022]
Replacement cost interval	40,000 operating hours
Replacement cost	11% of total installed capital cost

In addition to the technical and financial parameters associated with the PEM electrolyzer systems, the levelized cost of hydrogen projected by the H2A analysis depends strongly on the capacity factors and electricity prices for the different scenarios being analyzed. The *Scenario Details* section provides additional details and references for each specific scenario.

Results

Table 2 and Figure 1 show results, which have been peer reviewed by industry and national labs, using the H2A analysis illustrating the cases resulting in an LCOH of $5 to $7/kg with an installed capital cost estimate of $2,000/kW under different renewable electricity scenarios.

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[e] Incentives such as the clean hydrogen production and renewable energy production tax credits are not considered in this analysis.

[f] Hydrogen outlet pressure from the PEM electrolyzer system is 30 bar.

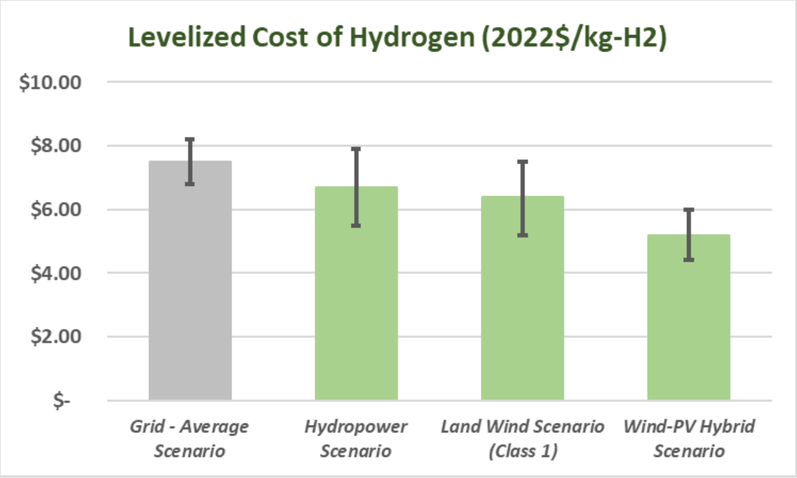
[g] Other DOE reports, such as the Hydrogen Shot Technology Assessments, use a 2020-year dollar basis to emphasize the impact of RD&D on technology advancement and facilitate comparison between pathways, separate from consideration of macroeconomic factors [34].

Table 2. Levelized costs of hydrogen (in 2022$) produced from current PEM electrolyzer technology for different scenarios based on electricity sources; with associated inputs of electricity capacity factor and price, and electrolyzer capital costs.

Scenario[h] *Based on Electricity Source*	**Capacity Factor** *(%)*	**Electricity Price** *(¢/kWh)*	**Electrolyzer Installed Capital Cost** ***(2022$/kW)***		
			$1,500	**$2,000**	$2,500
			Levelized H_2 Production Cost ***(2022$/kg)*** [i]		
Grid – Average Scenario	**97%**	**8.3¢**	**$6.80**	**$7.50**	**$8.20**
Renewable Electricity Scenarios					
Hydropower	**50%**	**3.4¢**	**$5.50**	**$6.70**	**$7.90**
Land-Based Wind ***(Class 1)***	**51%**	**2.9¢**	**$5.20**	**$6.40**	**$7.50**
Hybrid Wind-PV	**74%**	**3.3¢**	**$4.40**	**$5.20**	**$6.00**

To illustrate sensitivity to installed capital cost of the PEM electrolyzer, Table 2 also includes projected hydrogen production costs for each scenario corresponding to $1,500/kW and $2,500/kW.[j] Provided for added reference is a grid-connected electrolyzer scenario based on average U.S. grid electricity, which has limited renewable penetration. Since grid electricity costs and renewable content can vary widely by region, this analysis uses the average value. The hybrid wind-PV scenario offers the most favorable combination of electricity pricing and capacity factor for producing low-cost clean hydrogen. Details of the input assumptions for all the scenarios are included in following sections.

Figure 1. LCOH produced from today's PEM electrolyzers for the different scenarios; the solid bars represent costs associated with an installed electrolyzer capital cost of $2,000/kW, while the ranges reflect a cost spread relative to installed capital costs of $1,500/kW (low) and $2,500/kW (high).



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[h] Scenario descriptions along with associated parameter values, including electricity capacity factors and prices, are included in the Scenario Details section of this Record. All electricity prices are shown in a 2022-year dollar basis (2022¢/kWh).

[i] Projected levelized hydrogen production costs based on H2A methodology are shown in a 2022 dollar-year basis (2022$/kg) to facilitate comparisons with contemporary references. Results are rounded.

[j] Ranges for installed PEM electrolyzer capital costs [in a 2022-year dollar basis (2022$/kW)] are consistent with contemporary references described in this Record. See Installed Capital Cost section in the Appendix for additional details.

Scenario Details

Grid-Average Scenario

An average grid case is included in this Record as a reference point using industrial electricity prices from the Energy Information Agency (EIA) [5], which catalogues annual pricing across individual states and regions. The *Grid-Average Case* in Table 1 represents the U.S. average grid industrial electricity price for 2022 identified by the EIA. Since the renewable content of the grid varies widely by region and would not provide low carbon intensity hydrogen in most regions, the average grid is used for the purposes of LCOH comparison to renewable electricity scenarios.

Renewable Electricity Scenarios

Table 2 includes a range of electricity capacity factors and prices associated with the different renewable electricity scenarios. Because of the relatively high capital cost of the electrolyzer today, only scenarios with at least a 50% electrolyzer capacity factor[k] are considered in this Record. Additional cases with higher renewable costs and lower capacity factors (e.g., solar) can result in higher LCOHs. For example, modeled results for utility-scale solar photovoltaics (PV) with a capacity factor of ~35%[l] may result in a higher LCOH (~$9/kg) with a $2,000/kW installed capital cost.

The electricity prices assumed are based on the levelized cost of electricity (LCOE) and do not include incentives such as the renewable energy production tax credit. Note that while real world electricity prices vary widely, these values are generally consistent with those reported in other contemporary studies [6, 7] , which also include additional regional scenarios where hydrogen could potentially be produced at lower or higher costs. More specific details related to the scenarios included in this Record are provided below:

- **Hydropower:** The hydropower case study assumes an average wholesale electricity price and capacity factor from existing facilities in the Midwest region of the United States in 2020 [8]. For simplicity, this analysis assumes that the electrolyzer operates with the same capacity factor as the hydropower resource, which is a conservative assumption. In actual implementation, the power output of a hydropower resource could be much greater than the input requirements of the electrolyzer; so, the electrolyzer could continue to operate at its rated maximum power (at a higher capacity factor) even though the hydropower resource is outputting less than its maximum power. In addition, the analytical methodology assumes a constant electricity price and capacity factor for the duration of the electrolyzer's lifespan.
- **Land-Based Wind:** The wind case is derived from the National Renewable Energy Laboratory's (NREL) *2023 Annual Technology Baseline (ATB)* for land-based class-1[m] (best) wind conditions [9]. Many of the operational class-1 wind farms in the United States are in southern central California, western Texas, the plains states, and southern Minnesota [10]. Values from the *ATB* are generally consistent with power purchase agreements (PPAs) that have been established for some of the class-1 wind sites located in Colorado, Iowa, Illinois, Kansas, New Mexico, Texas,

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[k] Capacity factor defined as actual H_2 output relative to rated maximum H_2 output over a year.

[l] Utility-scale solar PV assumes class-1 (best) solar conditions based on installations modeled in the NREL ATB with high-resolution, location-specific resource data (34% capacity factor and $0.036/kWh LCOE).

[m] Class-1 wind conditions are defined by wind speeds of ~9 – 13 m/s. For reference, class-5 (moderate) wind conditions (~8.1 – 8.4 m/s) with a capacity factor of 44% and electricity price of $0.034/kWh can result in a levelized cost of $7.30/kg-$H_2$ assuming an installed electrolyzer capital cost of $2,000/kW.

and others. As an example, a PPA for a ~200-MW wind farm in the Southwest Power Pool region (a region that includes Iowa, Kansas, and Nebraska) had a price as low as ~$0.016/kWh [11, 12]. Real world PPA prices can vary widely and may not reflect values from the ATB. Regional average PPAs, that are not limited to class-1 conditions, can range from $0.03 - $0.07/kWh [13]. In this scenario, the analytical methodology assumes a constant electricity price and capacity factor for the duration of the electrolyzer's lifespan and assumes the capacity factor of the electrolyzer matches that of the clean energy source (51%). This simplified, unoptimized approach provides a conservative estimate for the levelized cost of hydrogen.

- **Hybrid Wind + Solar-PV:** This case reflects combined hourly generation from co-located 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. A location with high complementarity results in a high capacity factor because peak wind and solar power production typically occur at different times. The capacity factor and levelized cost of electricity assumed here were developed by the Grid Modernization Laboratory Consortium using actual historical weather data for a location in Texas with high complementarity [14]. Unlike the hydropower and land-based wind scenarios, the analytical methodology for this scenario assumes an electrolyzer capacity that is sized to 50% of the total solar and wind generation capacity (i.e., 100 MW electrolyzer and 200 MW of combined solar and wind), resulting in a high electrolyzer capacity factor. In this scenario, the analytical methodology assumes a constant electricity price and capacity factor for the duration of the electrolyzer's lifespan. There is ongoing work to optimize hybrid systems for low-cost, clean hydrogen production [15].

Conclusion

The purpose of this Program Record is to document LCOH calculation methodologies and results for current PEM electrolyzer technology based on techno-economic analysis of different scenarios leveraging diverse renewable electricity sources. It helps to frame the status relative to the cost target of \$2/kg-H_2 by 2026 established by the Clean Hydrogen Electrolysis Program in the Bipartisan Infrastructure Law (BIL),[n] and ultimately towards the Hydrogen Shot cost target of \$1/kg-H_2 by 2031 [16, 17].

This Record shows that the levelized cost of clean hydrogen produced from today's low volume PEM electrolyzers ranges from **~\$5 to \$7/kg-H_2** [2022\$] based on current PEM technology at an installed capital cost of **\$2,000/kW** and for renewable energy sources with capacity factors of 50-75%. As installed capital costs and power prices decrease and as electrolyzer capacity factors and efficiencies increase, the LCOH will be substantially lowered.

Clean hydrogen produced by coupling PEM electrolyzers with single renewable power sources such as wind or hydropower typically costs more compared with the hybrid wind-PV scenario, primarily due to lower capacity factors; but these could still be more economical than hydrogen produced from grid-tied electrolyzers that pay average industrial rates for electricity. As an example, coupling of electrolyzers

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[n] The Clean Hydrogen Electrolysis Program was established as part of the 2021 Bipartisan Infrastructure Law (BIL): https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

with land-based wind power in regions with abundant wind resources (e.g., class 1 wind), offers projected costs lower than current grid-coupling based on average electricity prices, representing one of several promising pathways to affordable clean hydrogen production. Also of note, and for the reasons stated above, the cost projections provided here are conservative estimates for the single renewable power source cases. Optimal siting and integration approaches to best leverage regional renewable sources will play a key role in all scenarios producing clean hydrogen with PEM electrolysis.

Independent of the electricity source, projected costs of hydrogen production from PEM electrolysis are expected to decline over time. These declines will be driven by technology advancements (including reductions in electrolyzer capital costs [18]), economies of scale, and other factors:

- Advances in PEM electrolyzer efficiency and durability, and the associated extension of electrolyzer lifetime (e.g., through *Clean Hydrogen Electrolysis Program* research, development, and demonstration (RD&D)).
- Utilization of less-expensive system components with robust supply chains, innovative approaches to manufacturing, and recycling (e.g., through *Clean Hydrogen Electrolysis Program* RD&D).
- Economies of scale in system size and manufacturing volumes (e.g., facilitated by the development and deployment of *Clean Hydrogen Hubs*, and the current growth in domestic PEM electrolyzer manufacturing capacity led by multiple industrial stakeholders).
- Continued development of advanced integrated energy systems coupling electrolysis with renewable energy sources, including innovative hybrid approaches that utilize multiple renewable sources such as wind, solar, and hydropower for optimized capacity factor (e.g., through *Clean Hydrogen Electrolysis Program* RD&D, and leveraging DOE lab resources such as the NREL ARIES[o] facility).
- Declines in renewable electricity generation costs (e.g., through RD&D investments and industry scale up).

With recent historic investments through the BIL Clean Hydrogen Electrolysis, Hydrogen Hub, and other programs, the DOE along with industry stakeholders are well positioned to lower the cost of clean hydrogen production through electrolysis, by supporting research, development, demonstration, and deployment activities in these and other relevant areas to achieve the BIL and Hydrogen Shot goals.

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[o] Advanced Research on Integrated Energy Systems: https://www.nrel.gov/aries/

Appendix – Analysis Parameters

System Capacity and Design

The modeled PEM electrolyzer system reflects a centralized plant with nominal hydrogen production capacity of 50,000 kg/day.[p] This system size is large compared to installed systems today but is consistent with the current trend in U.S. electrolyzer installations to date [19]. As a result, economic assumptions are reflective of early market deployments. Technical assumptions are based on a generalized PEM electrolyzer system using input from several key industry collaborators with commercial experience in PEM electrolysis and system and subsystem techno-economic models. Full details associated with both the electrolyzer stack and the full system represented in this Record can be found elsewhere [20, 21, 22].

Installed Capital Cost

The total installed PEM electrolyzer capital cost of ~$2,000/kW [2022$] was derived based on ongoing work within the H2NEW Consortium to estimate the manufactured cost of a 1-MW system manufactured at a range of production rates from today's low volumes (used here) to >1 GW/yr and was vetted by domestic electrolyzer manufacturers [22]. Assumptions for manufacturer mark-up, installation/indirect costs, and inflation were applied to the manufactured cost to arrive at the total installed capital cost.[q] Large systems (>100 MW) will ultimately be at a lower cost per MW than a 1-MW system due to optimized balance of plant configurations. These cost reductions, in addition to refined installation cost assumptions, will be captured in future Program Records as more real-world data becomes available for such large systems.

The range presented here also agrees with costs reported in literature (Figure 2). References for current estimates include S&P [23], Hydrogen Council & McKinsey [24], Lazard [25], and BNEF [26]. Collectively, these show that electrolyzer total capital costs may range from $1,400/kW to $2,500/kW, an increase from a previously estimated range of $1,000/kW to $1,800/kW reported by Lazard [27], S&P [28], IRENA [29], BNEF [30], and DOE's Initial Liftoff Report [4]. This increase has been mainly attributed to an increase in installation costs (rather than system costs) due to inflation and other unforeseen costs during implementation of early market deployments. Further discussion of electrolyzer market development will be included in a forthcoming update of the DOE *Pathways to Commercial Liftoff: Clean Hydrogen* report.

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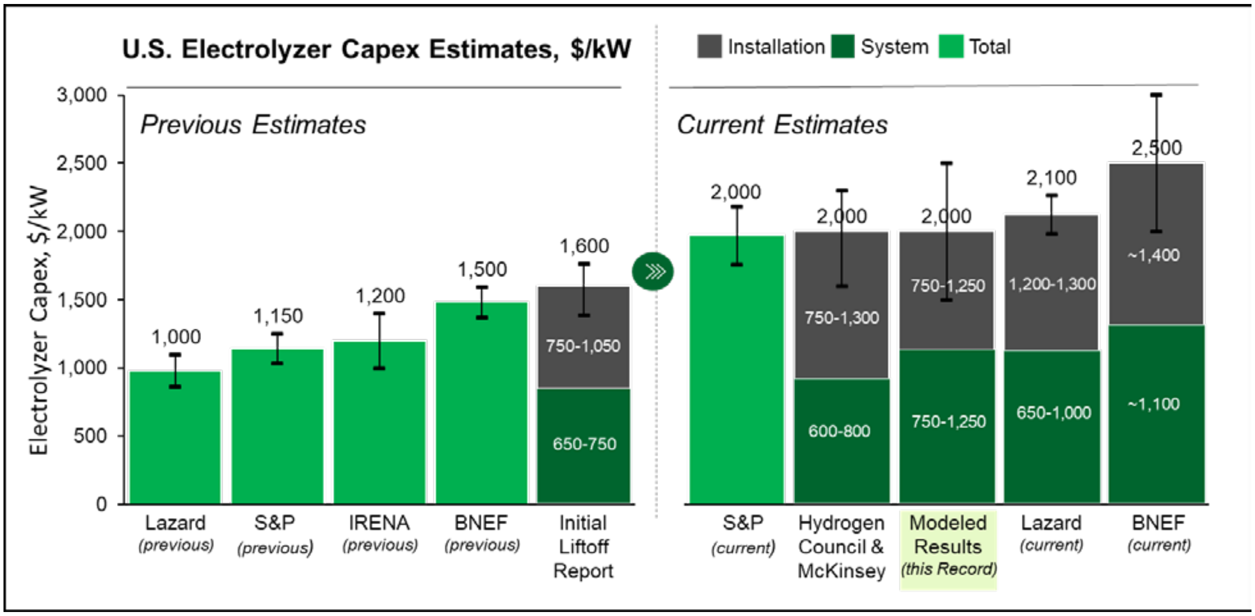
[p] Corresponding to system power requirement of 115 MW_{AC} and a stack power requirement of 106 MW_{DC} at beginning of life (BOL).

[q] Installation/indirect costs approximately equal to uninstalled system costs (i.e., the total installed cost is ~2 times the uninstalled system cost), representative of early market deployments [35], [36] with inflation from 2020$ to 2022$. Parameters will vary depending on the manufacturer and the installation site, but a range of realistic assumptions based on modeled systems and domestic electrolyzer manufacturers' feedback has led to a baseline installed capital cost of ~$2,000/kW.

Figure 2. Previously estimated costs for electrolyzer installations published up to year-end 2023 (left) compared to more current estimated costs for electrolyzer installations published in 2023-2024 (right). Where available, system costs are shown in dark green and installation costs are shown in gray. For bars with estimated ranges, the bar height represents the range midpoint.[r]



System Electricity Usage and Lifetime

Though there is a range of electrical efficiencies reported for PEM technologies, the average system electricity consumption used in this analysis is 57.5 kWh/kg. A beginning-of-life electrolyzer system electricity usage of 55.2 kWh/kg hydrogen is assumed here as a representative value, which was based on studies within the DOE H2NEW Consortium and has been vetted by industry [20, 21]. This includes both stack (51 kWh/kg, assuming an operating point of 2 Amps (A) per cm^2 at 1.9 Volts (V) per cell) and balance of plant (4.2 kWh/kg) energy consumption. The stack voltage is assumed to degrade at a rate of 4.8 mV/khr over the 40,000 hr lifetime of the stack, resulting in an end-of-life stack electricity consumption of 55.6 kWh/kg and an average stack electricity consumption of 53.3 kWh/kg. Assuming that the BOP electricity consumption remains constant, the average system electricity consumption used in this analysis is 57.5 kWh/kg. The operating point, electricity usage, and voltage degradation values used here are consistent with the “2022 Status” for PEM electrolyzers recently reported in HFTO’s technical targets for current PEM systems [31]. The stack and system efficiency values assumed in this analysis generally align with values reported in literature [29, 32]. While some studies show higher efficiencies, these conservative values were selected based on most of the commercial PEM systems deployed today.

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[r] As a note, the DOE range includes balance of plant (BOP) in “system” costs (e.g., water treatment, power electronics, thermal management, hydrogen drying), whereas the other sources only include electrolyzer/stack costs in “system” costs and classifies BOP costs as installation. McKinsey estimates these BOP costs to be ~$200-300/kW, which helps explain the difference in the split of system and installation costs between DOE range and others. Here, “installation” includes labor costs, piping, transportation costs, permitting, contingency, EPC, and all other expenses incurred to bring the system to a condition where it can be used.

Fixed Operating and Replacement Costs

Fixed annual operating costs (without stack replacements) are assumed to be 5% of the total installed capital cost, which is generally consistent with default H2A assumptions. Electrolyzer replacement costs[s] of 11% of the total installed capital costs[t] are assumed to be incurred every 40,000 hours of operation, consistent with H2A methodology and other reports [29, 32, 33]. Because system degradation is assumed to take place only when the system is operating, the interval (in years) over which replacement costs occur depends on the capacity factor. For example, if the electrolyzer is operated at a 50% capacity factor, the replacement interval is assumed to be approximately twice as long as one operated at a 100% capacity factor. This approach does not take into account variations in degradation rate due to different duty cycles. These considerations and assumptions are the subject of ongoing research in the H2NEW Consortium.

Financial Specifications

Financial specifications were selected to result in a ~10% nominal weighted average cost of capital (WACC). This analysis assumes a real return on equity of 10.89%, a debt-to-equity ratio of 0.62, and an interest rate of 5%. The electrolyzer system is assumed to depreciate over 20 years following the MACRS depreciation method. The total income tax rate is assumed to be 25.74%. One month of available cash on hand is assumed. Appropriate assumptions around financial analysis, such as WACC and analysis period, can highly influence the LCOH and fluctuate over time as markets evolve. Financial assumptions in this Record were generally consistent with those used on other recent DOE market analyses at the time that this record was written.

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[s] Replacement costs primarily cover stack replacement but also include minor components that may need replacement or overhaul.

[t] 11% of total installed capital cost assumed in this analysis is consistent with ~15% of direct capital cost used in H2A methodology.

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