Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers

Alex Badgett,[1] Joe Brauch,[1] Amogh Thatte,[1, 2] Rachel Rubin,[1] Christopher Skangos,[1] Xiaohua Wang,[3] Rajesh Ahluwalia,[3] Bryan Pivovar,[4] and Mark Ruth[1]

1 Strategic Energy Analysis Center, National Renewable Energy Laboratory
2 Advanced Energy Systems, Colorado School of Mines
3 Transportation and Power Systems Division, Argonne National Laboratory
4 Materials, Chemical, and Computational Science, National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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List of Acronyms

AC	alternating current
BOP	balance of plant
C	Celsius
CCM	catalyst-coated membrane
$/kW	dollars per kilowatt
DC	direct current
DOE	U.S. Department of Energy
ft^2	square feet
ft^3/min	cubic feet per minute
gal/min	gallons per minute
GDL	gas diffusion layer
GW	gigawatt
H_2	hydrogen
HLC	hydrogen levelized cost
hp	horsepower
HPWS	high-pressure water separation
hr	hour
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
L/min	liters per minute
LPHS	low-pressure hydrogen separation
m^2	square meter
m^3	cubic meter
MEA	membrane electrode assembly
mg	milligram
µm	micrometer
mm	millimeter
MW	megawatt
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PTL	porous transport layer
PV	photovoltaics
PVD	physical vapor deposition
R&D	research and development
R2R	roll to roll
s	second
TSA	temperature swing adsorption
V	volt
W	watt
yr	year

Executive Summary

Enabling rapid and extensive decarbonization within the electric power and industrial sectors is likely to require high levels of renewable energy deployment, supported by technologies that store and transform renewable electricity into other useful forms such as hydrogen. Within hard-to-decarbonize sectors such as organic chemicals and heavy-duty transportation, the use of low-carbon-intensity hydrogen as a fuel and chemical building block is emerging as a near-term alternative to reduce the sectors' fossil fuel dependency. Producing hydrogen via water-splitting electrolysis requires only water and electricity as inputs, eliminating the natural gas use in conventional steam methane reforming hydrogen production. When powered by low-carbon electricity, electrolysis represents an important pathway toward cross-sectoral decarbonization.

Proton exchange membrane (PEM) electrolyzers are a near-term technology for hydrogen production that could integrate with future grids that have a high clean-power penetration. As of 2023, the cost of hydrogen produced from PEM electrolyzers is higher than fossil-based production because of high costs of capital equipment and electricity (Vickers, Peterson, and Randolph 2020). Previous work (Badgett, Ruth, and Pivovar 2022) has found that PEM electrolyzers that operate dispatchably at low capacity factors could take advantage of times of low-cost electricity to produce hydrogen at lower costs. These systems would require low capital costs to avoid high cost penalties for underutilized capital.

This report presents a bottom-up manufactured cost analysis for a PEM electrolyzer stack and associated balance of plant (BOP) equipment. The electrolyzer design is intended to represent the current state-of-the-art (2022) stacks with respect to catalyst loadings (3 milligrams per square centimeter [mg/cm^2] total platinum group metal [PGM] loading) and material specifications. Near-term stack designs target significant reductions in loadings and the incorporation of advanced materials to reduce manufactured cost, increase efficiency, and reduce performance degradation over time. The cost reduction opportunities outlined in this analysis explicitly focus on the impact of manufacturing economies of scale and underscore the relevance of these advances and their potential impact on electrolyzer stack costs. For example, this analysis estimates a baseline low-volume manufactured cost for 1-megawatt (MW) electrolyzer systems manufactured at a rate of 10 MW/year of $890/kilowatt (kW) (2020-dolar year basis) not including manufacturer mark-up, installation and soft costs, and inflation which can add substantial additional costs. With current and planned domestic manufacturing capacity in the range from hundreds of MW/year to over 1 GW/year (IEA 2023), the estimated manufactured costs from this analysis range from $541-$703/kW; and with the additional cost factors for installation and soft costs, the installed cost for systems manufactured at similar rates could range from $1,300-$1,700/kW, consistent with recent Department of Energy Commercial Liftoff: Clean Hydrogen analysis (Murdoch et al. 2023). With current and near-term technologies for PEM electrolyzer stack and balance of plant (BOP), there is potential to reduce the manufactured cost to below $450/kW with economies of scale based on multi-GW/year production rates; with additional cost reductions through continued technology advances through RD&D.

It is important to note that the magnitude and share of stack and BOP costs relative to total system costs is representative of 1 MW electrolyzers and will likely shift as manufacturers produce systems at larger nameplate capacities. It is likely that electrolyzer systems with nameplates on the order of hundreds of MW to GW could experience large BOP cost reductions relative to the values shown here through equipment economies of scale, in similar fashion to economies of scale for conventional petrochemical processes. Manufacturing electrolyzer BOP systems at large nameplate capacities is a key BOP cost reduction pathway but is beyond the scope of this report.

This analysis focuses on pathways toward lowering the capital costs of PEM electrolyzers through avenues such as manufacturing economies of scale, advanced manufacturing techniques, and advanced system and materials engineering. Advanced stack manufacturing techniques, such as slot die roll-to-roll production of the catalyst-coated membrane, enable high throughput of these parts relative to slower batch-coating production methods. Achieving manufacturing economies of scale requires high utilization rates of manufacturing lines, reducing the manufactured cost per component across the electrolyzer stack, while bulk purchasing and high manufacturing throughput decrease the cost of BOP subsystems. These effects combined could result in a total system manufactured cost reduction of approximately 50% (Figure ES-1).

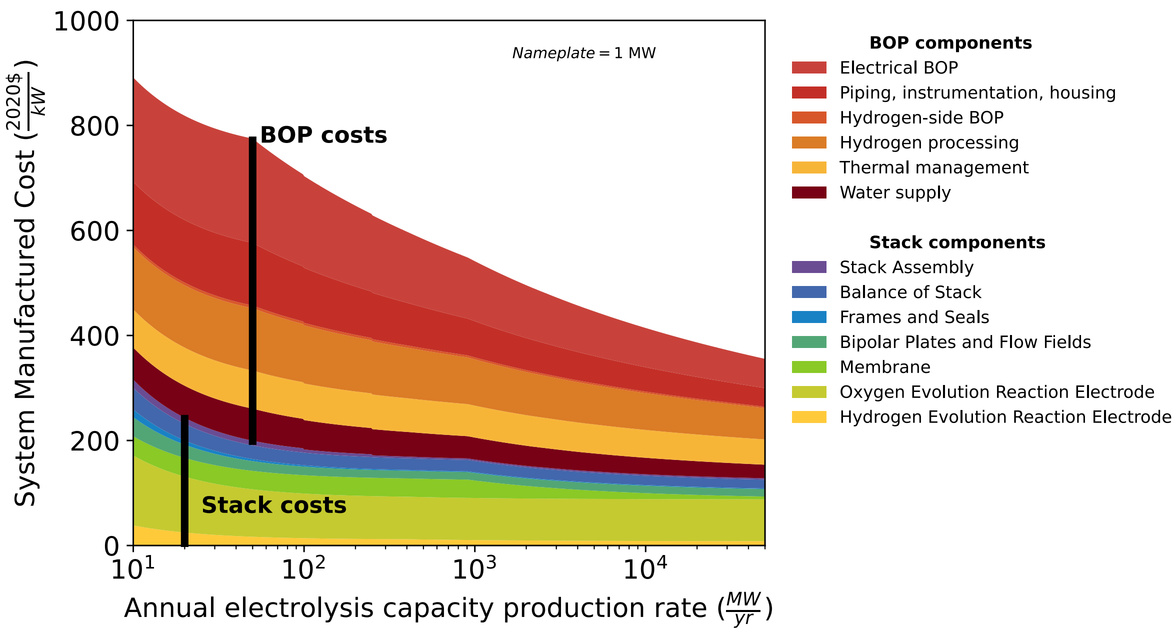

Figure ES-1. Impact of stack manufacturing economies of scale and BOP cost improvements across manufacturing rates, from low manufacturing rates to greater than 1 gigawatt per year (GW/yr) of manufacturing. NOTE: These costs are in a 2020 dollar basis, and DO NOT include manufacturers mark-up, installation and soft cost, or inflation factors.

This work also outlines opportunities that exist for reducing the manufactured cost of stack and BOP equipment through the reduced use of expensive materials and alternative component designs. System and material engineering can drive manufactured costs lower through reduced dependency on expensive materials such as iridium and platinum (Figure ES-2). Of the strategies considered in this work, lower anode catalyst loadings and increased current densities could yield the largest cost reductions. Opportunities also exist for reducing the cost of BOP equipment through manufacturing economies of scale and potential cost reductions over time (e.g., learning).

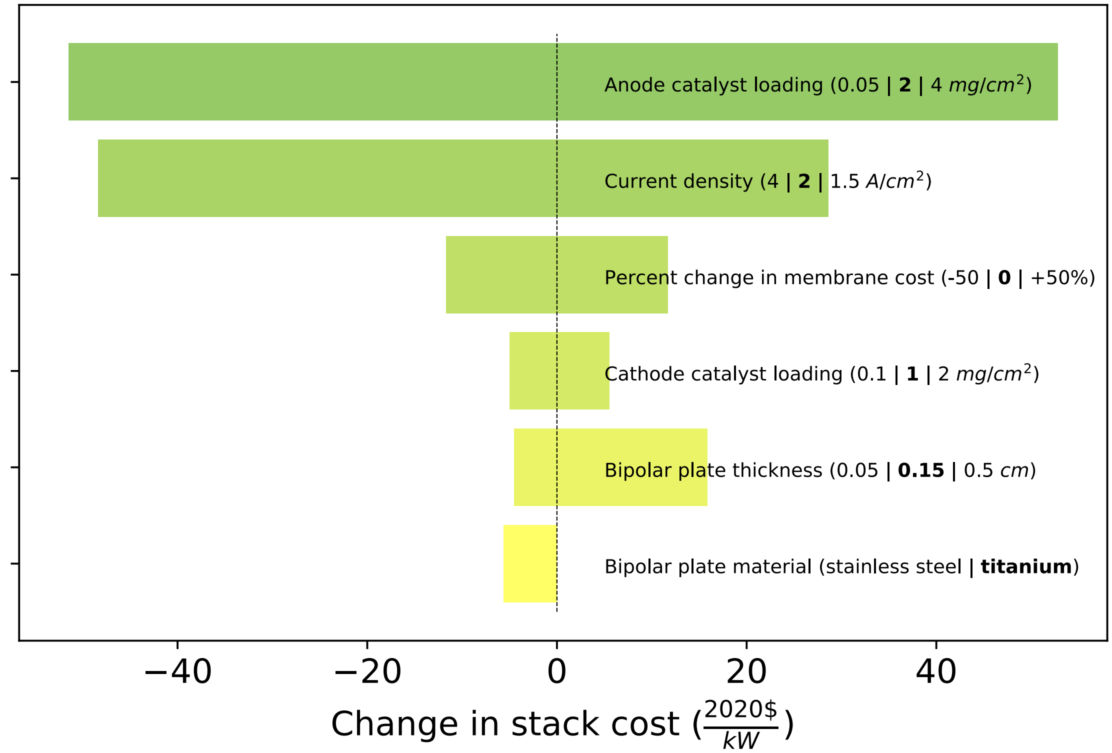

Figure ES-2. Impact of individual advances in stack design, materials reduction, and performance on manufactured costs relative to base case values, noted in bold. 1,000 MW/yr stack production rate assumed.

Although any one of these strategies can yield reductions in the manufactured costs of PEM electrolyzers, achieving cost reductions requires the incorporation of all these strategies (Figure ES-3). We show that advances in stack design, reductions in catalyst loadings, and higher manufacturing rates could yield significant reductions in the cost of manufacturing a PEM electrolyzer stack, especially when combined with manufacturing economies of scale. There are important connections between system design, manufacturing methods, and electrolyzer performance; achieving cost reductions requires consideration of the interplay between these factors. Figure ES-3 shows potential stack manufactured costs when reduced PGM loadings, higher current densities, and manufacturing economies of scale are combined. We estimate that these strategies combined could yield significant reduction in manufactured costs for the electrolyzer stack.

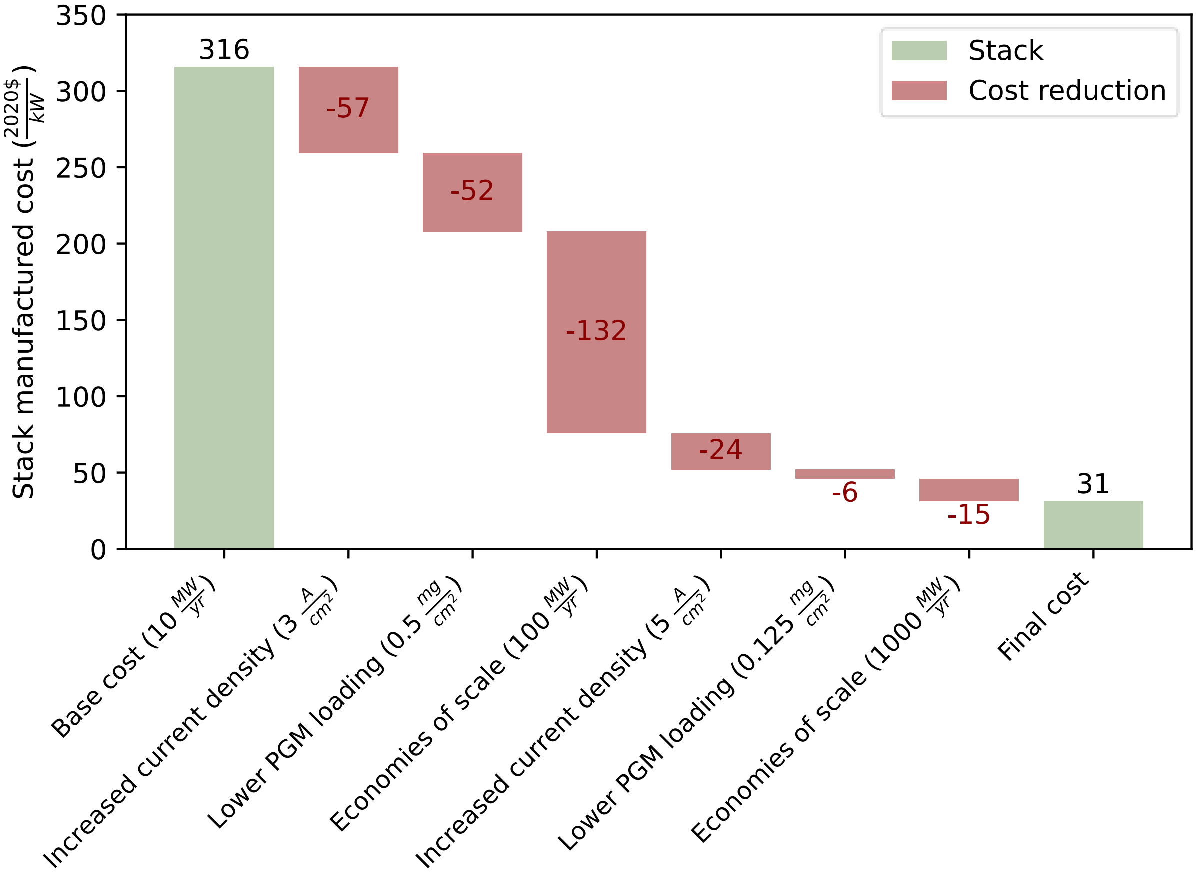

Figure ES-3. Waterfall chart showing the combined impacts of advances in the stack design and manufactured costs. Costs shown here are in 2020 dollars and do not include system markup. Please see Figure 28 for a full system waterfall chart.

A: ampere; kW: kilowatt; MW: megawatt; mg: milligrams; cm^2: square centimeters

Contextualizing the results of this work with cost targets set by the Department of Energy Hydrogen and Fuel Cell Technologies Office (DOE HFTO) helps to both outline limitations of this study and identify strategies for further cost reduction (DOE HFTO 2023). While the scope and objective of this work is not to validate or map progress towards HFTO targets, we provide a brief discussion of the results of this analysis in the context of HFTO cost targets to inform readers. Readers should note that the majority of $/kW cost values reported in this document are without manufacturer markup and without costs associated with installation and inflation. HFTO cost targets for electrolyzer uninstalled capital costs include manufactured costs along with manufacturer markup, and the DOE cost targets for levelized cost of hydrogen by electrolysis take into account all contributing cost factors such installation factors and other soft costs. Assumptions in other public reports outlining PEM electrolyzer costs in $/kW must be considered carefully when comparing their results with those from this report (see Section 1.1 for further discussion).

HFTO stack capital cost targets are $100/kW and $50/kW for 2026 and ultimate, respectively (all including manufacturer markup). This analysis outlines cost reduction strategies for PEM stacks that are likely to result in the greatest impact, including but not limited to reduced loading rates of iridium and platinum metals, higher current densities, and manufacturing economies of scale. This analysis suggests that the combined impact of these cost reductions could yield manufactured stack costs near HFTO targets (Figure ES-3). While this work focuses only on pathways for minimizing manufactured costs, it should be noted that other constraints on how electrolyzers are deployed and operated such as capital utilization, electricity prices, and performance degradation with dynamic operation could influence how these systems might be manufactured to ensure that they produce hydrogen efficiently and operate at long lifetimes.

HFTO targets for uninstalled capital costs of PEM electrolyzers are $250/kW by 2026 with an ultimate target of $150/kW uninstalled capital cost (DOE HFTO 2023), which includes costs for the stack and BOP with manufacturer markup. Increasing the scale of PEM electrolyzer system BOP (e.g., moving from a single 1 MW BOP to multiple stacks sharing a single BOP) is a key opportunity for reducing the manufactured costs but is beyond the scope of this report. This analysis exclusively focuses on cost reduction strategies for manufacturing integrated 1 MW PEM electrolyzers (see Section 3.5), and it is likely that significant system BOP cost reductions could be achieved through manufacturing electrolyzers near GW-scale nameplate capacities. The electrolyzer system BOP consists of conventional chemical plant equipment whose cost benefits from large scales such as heat exchangers and drying columns. Integrated systems that utilize arrays of MW-scale stacks with a single cost-optimized system BOP upstream and downstream of the electrolyzer stacks are likely to yield significant cost reductions that are not estimated in this report. Although this analysis provides an incomplete picture of all possible BOP cost reduction strategies, our initial results identify several important strategies for driving BOP (and therefore system) costs down, meriting further analysis to understand which of these strategies should be prioritized to meet system cost targets. Quantifying these opportunities is the subject of ongoing work within the DOE HFTO, the H2NEW consortium, and the broader electrolysis community.

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1 Introduction

Hydrogen produced from the electrolysis of water is an emerging pathway for creating fuels and chemicals that do not rely on fossil fuels. When powered with renewable electricity, this electrolytic hydrogen offers a low-carbon-intensity pathway to producing fuels and chemicals that would otherwise be produced from fossil fuels such as oil and natural gas.

As of 2022, nearly all global hydrogen is produced from steam methane reforming, which uses natural gas as a feedstock (International Energy Agency 2022). This hydrogen could then be used in petroleum refining, ammonia production, glass production, and steel manufacturing. Although industrial applications represent the largest consumers of hydrogen today, future opportunities for hydrogen to support economywide decarbonization efforts are quickly emerging, including long-duration energy storage and heavy-duty transportation (Badgett, Brauch, et al. 2022). Enabling economywide decarbonization requires a significant increase in the adoption of water electrolyzers for hydrogen production, where these deployments could be facilitated by decreasing the cost of producing that hydrogen.

The current levelized production cost from steam methane reforming is roughly \$2/kilogram (kg) hydrogen (H_2) and \$5–\$6/kg from polymer electrolyzer membrane (PEM) electrolysis (Badgett et al. 2021; Vickers, Peterson, and Randolph 2020). For water electrolyzers that are operated at high capacity factors, the price of the electricity that is supplied to these systems is the largest component of the levelized cost of hydrogen that they produce (Badgett, Ruth, and Pivovar 2022). In most analyses, it is assumed that these systems pay a constant retail rate for industrial electricity, generally around \$0.05–\$0.07/kilowatt-hour (kWh). The capital costs of the electrolyzer system are the second-largest component of hydrogen levelized production costs, encompassing the costs of the electrolyzer stack and all required upstream and downstream balance of plant (BOP) equipment.

Recent work has investigated the potential for operating electrolyzers at lower capacity factors in locations where they can access wholesale power markets (Badgett, Ruth, and Pivovar 2022). Electrolyzers operating in these markets would experience electricity prices that vary by the hour and could achieve costs savings by only operating when electricity costs are low. The electrolyzer would need to be sufficiently durable to ensure that performance would not be compromised when the system cycles on and off, making the engineering and materials used in the system critical aspects of successful operation. For low-capacity-factor operation to be cost effective, the capital cost of the electrolyzer needs to be low because low-cost capital equipment requires less utilization to offset the initial investment cost. Therefore, a lower electrolyzer capital cost enables dispatchable operation at lower capacity factors.

This work presents a bottom-up manufactured cost analysis for a PEM electrolyzer stack and associated BOP equipment. The PEM system depicted in this work has a stack nameplate capacity of 1 megawatt (MW), direct current (DC) which corresponds to a production rate of approximately 470 kg/day of H_2 under the assumed stack efficiency (Table 1). All costs in this report are given in 2020 dollars.

1.1 Cost vs. Price Distinctions

This work uses a series of bottom-up manufactured cost models to depict the manufacturing cost for 1 MW PEM electrolyzers at various production rates (in MW/year [yr] manufactured). There is an important distinction between the manufactured costs discussed here and market prices for PEM electrolyzers today and in the future. The cost that a company pays to manufacture an electrolyzer is less than the market price for this system that a purchaser might pay (NREL 2019). Electrolyzer manufacturers include a markup in addition to the manufactured cost to generate profits and cover their other expenses, which could include research and development (R&D) investments, advertising, and uncertainty in materials and other commodity prices. This markup is a significant variable of the system that each manufacturer sets to ultimately arrive at a market price that is dictated by economic considerations such as competition and supply and demand (Figure 1).

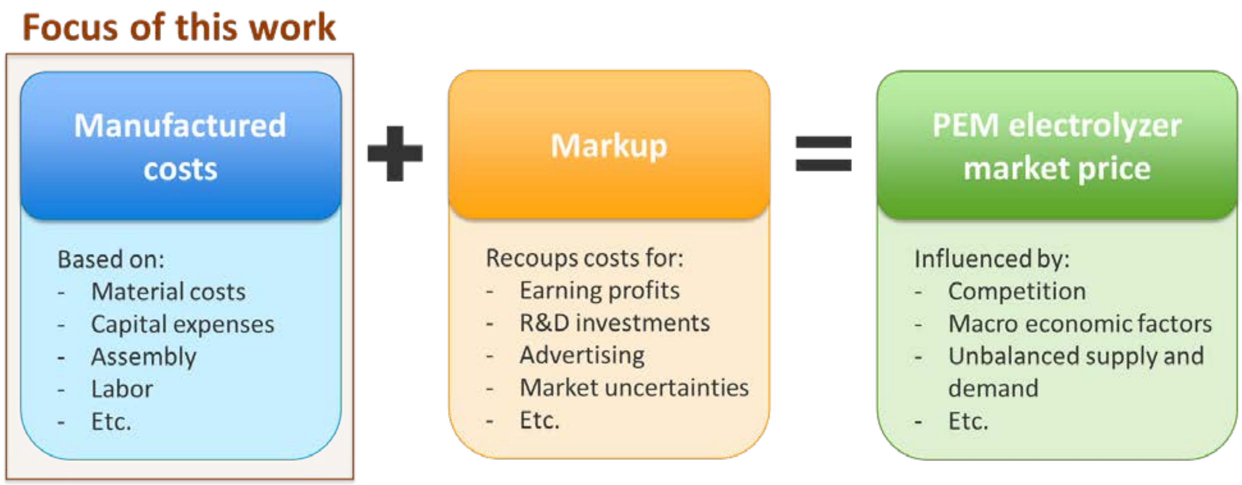


Figure 1. Summary of cost vs. price considerations in the context of this analysis

The analysis results shown in this report primarily focus on manufactured costs and do not consider the nuances that can drive electrolyzer market prices. We include examples of possible markups later in Table 10 and incorporate the "marked-up manufactured costs" as proxies for electrolyzer purchase prices in determining levelized cost of hydrogen production from various electrolyzer manufacturing rates and designs (Section 3.6).

This report does not attempt to predict market prices for PEM electrolyzers; rather, it focuses on drivers of and opportunities to reduce manufactured costs. Although manufactured costs are likely a significant driver of electrolyzer market prices, they are only one of several possible costs that are included in a market price set by a manufacturer. We encourage readers to carefully consider these nuances between cost and price in the context of the results provided here.

2 Materials and Methods

This work uses a bottom-up manufacturing process model to estimate the costs of manufacturing modular 1 MW PEM electrolyzer stacks, assigning each component of the electrolyzer stack a specific manufacturing process. We estimate and aggregate the costs of producing and assembling each component and add an assembly cost to estimate stack manufacturing costs. Such an approach allows for detailed depiction of the impact that performance and material use have on the cost of manufacturing a PEM electrolyzer as well as the impact that manufacturing economies of scale have on costs.

This work also estimates costs for BOP equipment associated with a PEM electrolyzer stack. The BOP comprises more standard equipment and unit operations such as piping, water deionization, and flash separations. As such, we estimated BOP costs using a combination of cost scaling functions and vendor quotes for each component. Assuming that electrolyzers are sold as a package with the stack and BOP integrated into a single modular unit, we include costs for purchase and assembly/construction of the BOP for a complete electrolyzer system manufactured cost.

A process flow diagram for the 1 MW electrolyzer system is depicted in Figure 2, showing the electrolyzer stack and various BOP unit operations upstream and downstream of the stack. This work uses an electrolyzer system design based on process modeling from Argonne National Laboratory as part of the H2NEW consortium (Wang, Star, and Ahluwalia 2023). Note, however, that this work does not focus on specific design choices for an electrolyzer system; rather, it estimates manufactured costs given this design. For further details of the system design and process model, see Wang, Star, and Ahluwalia (2023).

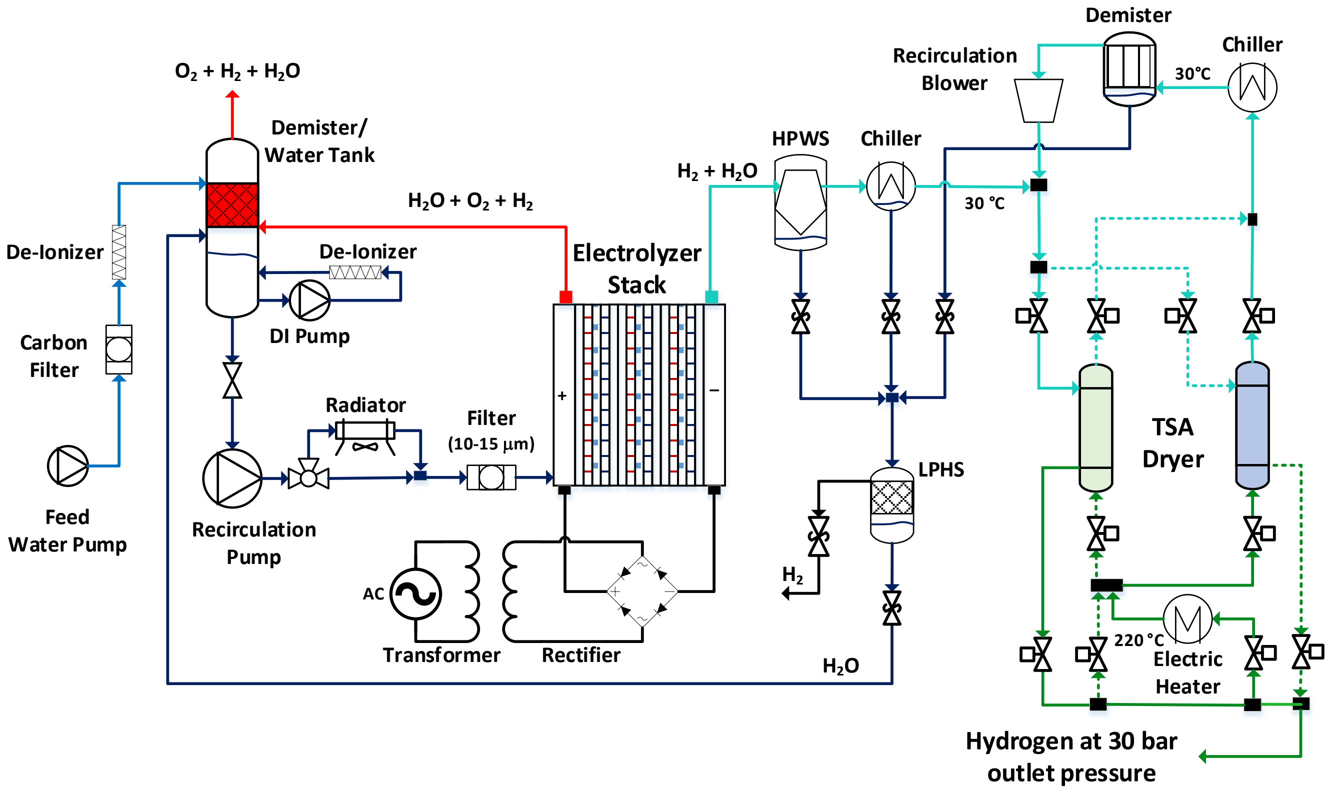


Figure 2. Process flow diagram for baseline 1 MW PEM electrolyzer considered in this work.

Image from (Ruth and Ahluwalia 2022; Wang, Star, and Ahluwalia 2023)

DI: deionization; AC: alternating current; HPWS: high-pressure water separation; LPHS: low-pressure hydrogen separation; TSA: temperature swing absorption

The 1 MW system includes subsystems for purification and deionization of supply water, thermal management of the electrolyzer stack and process streams, separation of electrolyzer outlet water and hydrogen, and hydrogen drying through temperature swing adsorption (TSA). The electrolyzer stack is assumed to operate at 80˚ Celsius (C) and at differential pressure, with the inlet water and oxygen side at near-ambient pressure and the hydrogen side, hydrogen processing, and outlet hydrogen at 30 bar. Targeted purity for outlet hydrogen from the electrolyzer system is 99.97%. Inlet water quality is assumed to be tap water, with impurity concentrations based on generalized water quality reports across municipalities in the United States.

2.1 Electrolyzer Stack

This section outlines materials and designs used in the 1 MW PEM electrolyzer stack design as well as the processes used to manufacture each component of the electrolyzer stack. Key materials and performance parameters for the 1 MW electrolyzer stack are given in Table 1. The materials and catalyst loadings shown are intended to capture today’s (2022) state of the art for electrolyzers being sold. For further information, refer to Mayyas et al. (2019). PGM loading rates assumed here are not intended to capture recent advances in alternative materials or performance driven by experimental research; rather, they provide a baseline reference to quantify the cost impacts of these recent advances, which are considered in Section 3.5.

Table 1. Key Design Specifications for Baseline 1 MW PEM Electrolyzer

System Parameter	Assumption
Anode PTL	Platinum-coated sintered titanium
Anode catalyst	Iridium
Anode ionomer	Nafion D2020
Cathode GDL	Carbon paper
Cathode catalyst	Platinum
Cathode ionomer	Nafion D2020
Frame material	Thermoplastic
Membrane	Nafion 117
Bipolar plate material	Platinum-coated titanium
Anode catalyst loading	2 (milligrams per square centimeter [mg/cm^2])
Cathode catalyst loading	1 (mg/cm^2)
Cell voltage (BOL)	1.9 (volts [V])
Current density	2 (amperes per square centimeter [A/cm^2])
Catalytic active area	0.0877 (square meters [m^2]/cell)
Number of cells per stack	300 (for 1 MW)
Stack inlet water temperature	80˚C
Anode side pressure	Atmospheric
Cathode side pressure	30 bar
Stack efficiency (BOL)[1]	51.1 (kilowatt-hours per kilogram [kWh/kg])
BOP electricity consumed (BOL)[1]	4.2 (kWh/kg)

[1] (Ruth and Ahluwalia 2022)

GDL: gas diffusion layer

PTL: porous transport layer

EOL: end of life

BOL: beginning of life

The total active area of the catalyst-coated membrane (CCM) in an individual cell is approximately 900 cm^2 (Figure 3). This work assumes that the manufactured electrolyzer uses a square design, with equal dimensions in the X and Y directions. This system depicts an electrolyzer with equal edge lengths, although rectangular and circular cell geometries are other possible approaches. Other commercial systems have used circular or rectangular designs to optimize the use of materials or cell compression. The CCM active area on the cell is bordered by a sealant area and external edges of the bipolar plates to ensure uniform cell compression. The CCM, porous transport layer (PTL), and gas diffusion layer (GDL) extend to the full CCM active area plus an additional 10% buffer area for processing materials using die cut processes.

Designs for future PEM electrolyzers intend to achieve significantly higher current densities, increasing the total current through the stack and as well as the hydrogen output for a given cell geometry and number of cells within a stack. This total active area is a relatively conservative estimate and is not intended to depict more advanced system designs.

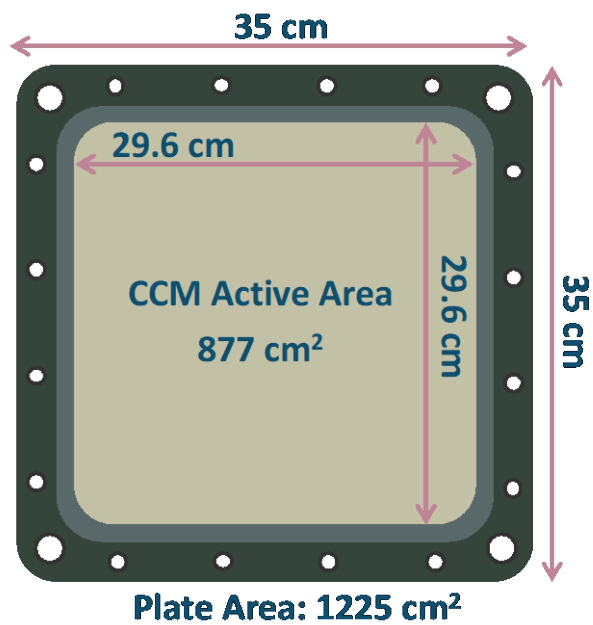


Figure 3. Baseline electrolysis cell dimensions.

CCM: catalyst-coated membrane

The bottom-up manufacturing process model assumes a manufacturing process for each component of the electrolyzer that uses raw input materials to manufacture a finished part (Figure 4). We assume a 15% cost factor for balance of stack added onto stack manufactured costs (Mayyas et al. 2019) to capture additional costs and manufacturing contingencies beyond the scope of the models developed here. There are various ways to manufacture electrolyzer components, and the process used here depicts current methods used to manufacture these systems. Improving the efficiency and speed with which electrolyzer components are manufactured is the subject of ongoing research within the U.S. Department of Energy's (DOE's) Hydrogen Fuel Cell Technologies Office program portfolio, including the H2NEW consortium (U.S. DOE 2021) and other emerging R&D activities facilitated by the Bipartisan Infrastructure Law.

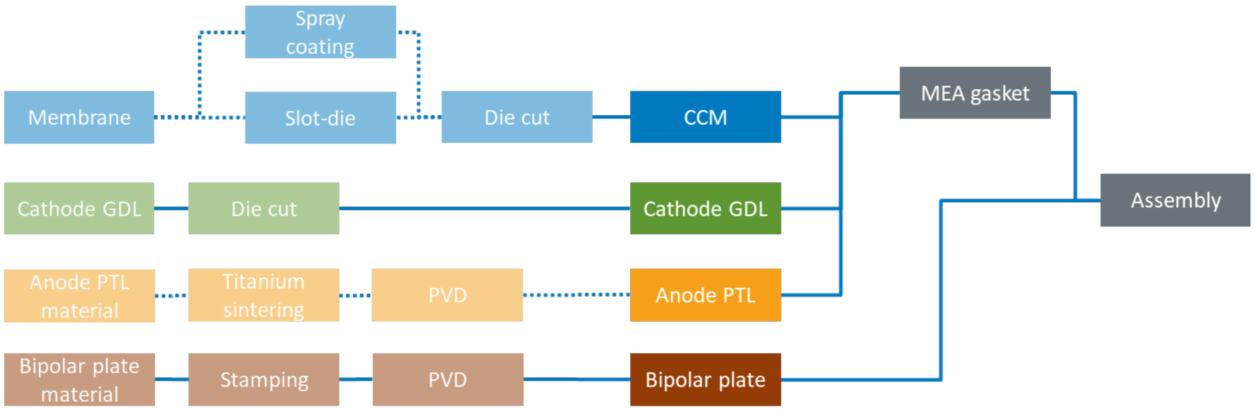


Figure 4. PEM cell manufacturing workflow illustrating various production processes for electrolyzer components.

CCM: catalyst coated membrane

MEA: membrane electrode assembly

GDL: gas diffusion layer

PVD: physical vapor deposition

The processes shown in Figure 4 represent different unit operations that manufacture a specific component of the electrolyzer stack. Each of these systems exhibits a unique capital cost and set of operational parameters that determine the maximum throughput of the system, which are shown in Appendix A. Assumptions for each manufacturing step determine how the costs for producing a part evolve at different throughputs.

Key among these assumptions are capital costs and process throughput. To maximize cost reductions with manufacturing economies of scale, selecting manufacturing processes that can achieve high throughputs is essential. Advanced roll-to-roll (R2R) systems capable of achieving these high throughputs generally exhibit higher capital costs but produce more components annually, lowering the manufactured cost on a per-component basis. An electrolyzer manufacturing facility producing one-off systems at small scales might be better suited to leverage manufacturing processes such as ultrasonic spray coating. However, given the anticipated growth in demand for water electrolyzers in the United States and worldwide (Badgett, Brauch, et al. 2022), this analysis focuses on the higher throughput electrolyzer manufacturing processes needed to achieve scale-up in manufacturing these systems.

Depending on the specified manufacturing rate (in MW/yr) in the model, a different number of process equipment will be required to meet the specified production rate for a given part or subcomponent. For example, one stamping system is needed to meet a production rate below 660 parts/hour (hr), but any production rate higher than that requires a second set of stamping equipment, any rate higher than 1,320 parts/hr requires at third set, and so on. These discrete steps in manufacturing equipment may create steps in the resulting cost curves as a function of manufacturing quantity. The use factor of the equipment, defined as the ratio of the actual throughput to maximum throughput, changes based on the production rate specified. To maximize the utilization of capital investments, higher use factors are preferrable.

2.1.1 Transport Layers

The anode PTL used in this system model is sintered titanium coated in a thin layer of platinum. The production process for this component is assumed to be in-house, with a bottom-up manufactured cost model used for the titanium sintering (Figure 5) and physical vapor deposition (PVD) coating process to manufacture this component. Titanium powder is converted to a finished titanium sinter. This sintered material is then die cut to specific sizes for assembly into the electrolyzer stack. Scrap material is assumed to be lost, though recycling this material could be an avenue for modest cost reduction.

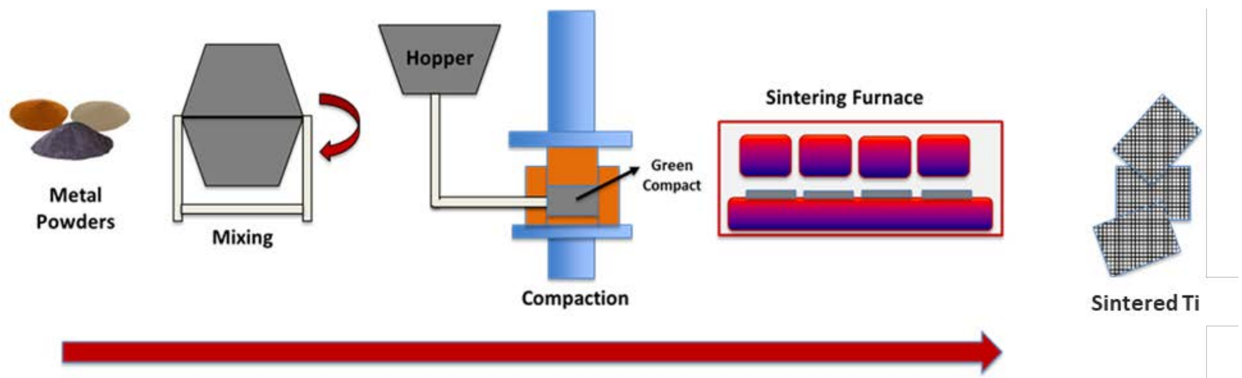


Figure 5. Manufacturing process flow diagram for titanium sintering process.

Image from (Mayyas et al. 2019)

The cathode GDL is simply purchased and die cut into the appropriate size.

2.1.2 Catalyst-Coated Membrane and Membrane Electrode Assembly

The membrane electrode assembly (MEA) comprises the CCM and the cathode and anode transport layers. Conventional production of MEAs for PEM electrolyzers uses spray coating to deposit a catalyst-ionomer mixture onto the membrane to form the CCM, which is then assembled with the transport layers to form the MEA.

The CCM is historically the largest component of stack costs (Mayyas et al. 2019) and as such has received a significant amount of research on opportunities for cost reduction. This work considers two pathways for manufacturing a finished CCM: ultrasonic spray coating and slot die coating. Spray coating represents current experimental and conventional production approaches to coating proton exchange membranes with catalysts and is a slower process that does not scale as easily to large production rates. Slot die coating is an R2R process and can achieve higher throughput and greater economies of scale.

For spray coating processes depicted in this work, we assume that the ultrasonic spray coater is used in an R2R process to deposit catalyst-ionomer mixtures onto the membrane at a higher rate than the one-off spray coating systems currently used in electrolyzer R&D applications (Figure 6). The spray coating system is integrated with an R2R drying system that also monitors the quality of coated and uncoated membrane throughout the process.

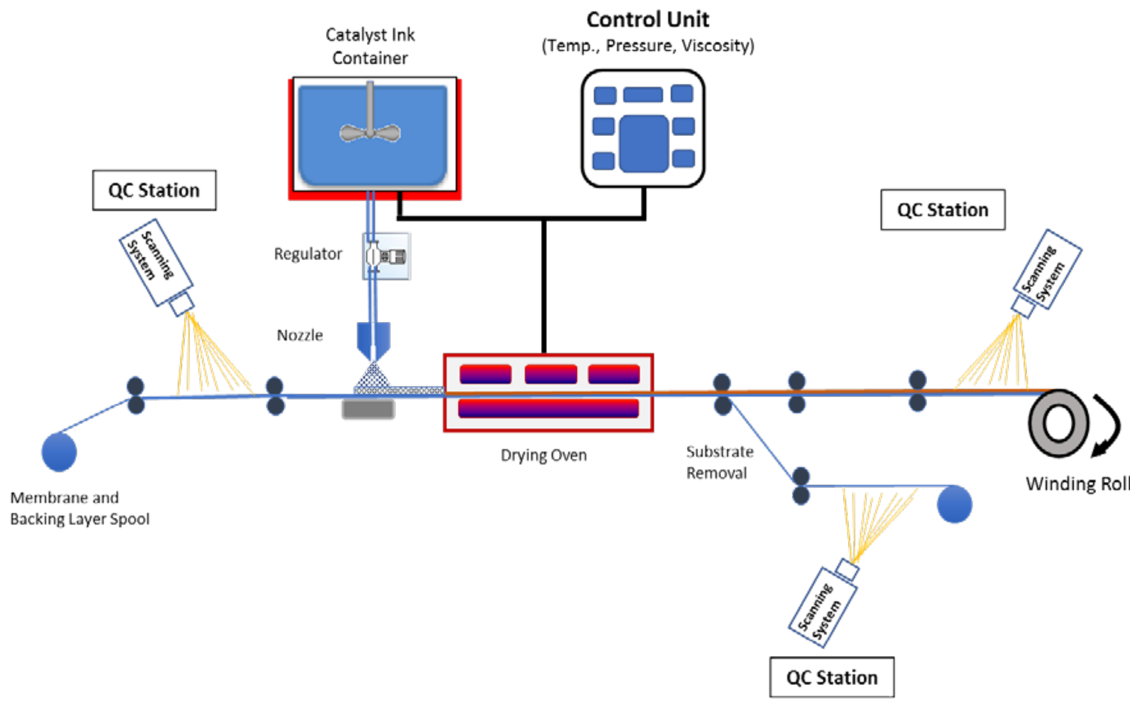


Figure 6. Manufacturing process flow for catalyst deposition via spray coating.

Image from (Mayyas et al. 2019)

Achieving higher throughput in catalyst deposition onto membranes is likely to require the development of R2R processing methods and the use of coating technologies capable of faster deposition of catalyst-ionomer mixtures. This analysis depicts the use of slot die coating in the place of ultrasonic spray coating because slot die can coat membranes at higher rates than spray coating and is emerging as a possible way to increase the rate of CCM and MEA production for polymer electrolyzer membrane electrolyzers (Stähler et al. 2019; Park et al. 2020). Supporting equipment for the slot die coating system is similar to the spray coating process, including R2R spooling equipment and quality control systems (Figure 7).

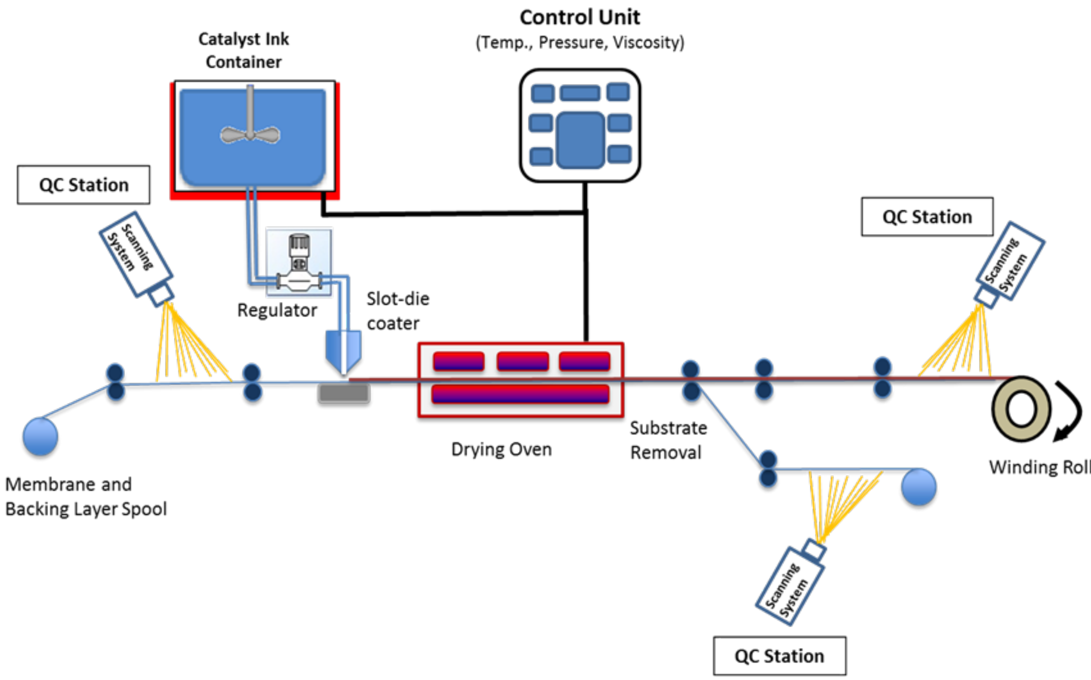


Figure 7. Manufacturing process flow for catalyst deposition via slot die coating.

Image from (Mayyas et al. 2019)

Following CCM production via either spray coating or slot die coating, the MEA is assembled from the CCM and transport layers.

2.1.3 Bipolar Plates

Bipolar plates separate MEAs in the electrolyzer stack and facilitate the flow of reactants and products to and from the MEA. In Mayyas et al. (2019), bipolar plates are constructed of 316L stainless steel. In contrast, this analysis assumes that coiled titanium is used to form bipolar plates, which are then coated in a thin layer of platinum via physical vapor deposition. The thickness of bipolar plates used in PEM electrolyzers can vary widely, with ranges in literature from 5 to 0.1 millimeters (mm) (Taner, Naqvi, and Ozkaymak 2019; Mayyas et al. 2019). In this analysis, we selected a bipolar plate thickness of 1.5 mm, excluding the added thickness of the platinum coating layer.

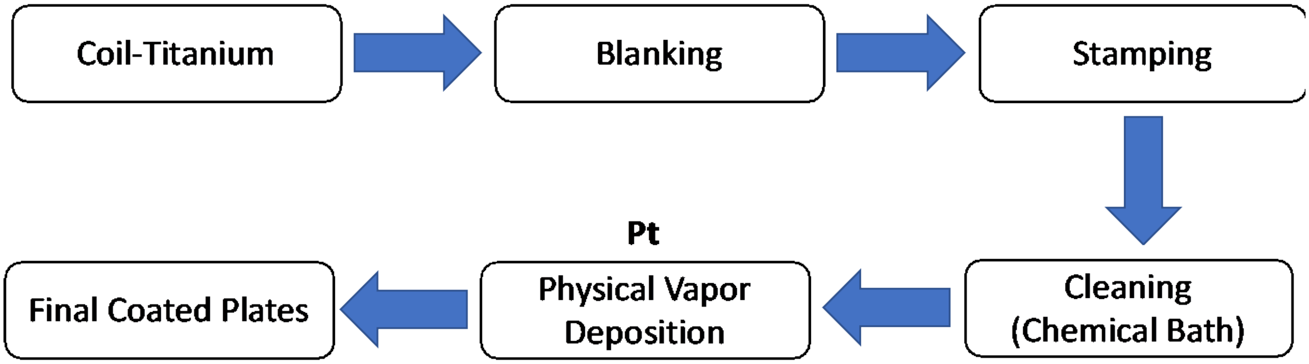


Figure 8. Manufacturing process for bipolar plates.

Image from (Mayyas et al. 2019)

2.1.4 Cell and Stack Assembly

Following the manufacture of individual components, the components must be assembled and integrated into cells and stacks (Figure 9). First, individual cells are assembled; separate cells are then stacked and pressed together to form a stack. To form an assembled cell, a bipolar plate receives a screen-printed gasket, and the membrane electrode assembly (including the CCM, PTL, and GDL) is added to the plate. The assembly is cured and added to other assembled cells in the stack. Once the stack is fully assembled, hardware to compress and protect the cells is added.

The stack assembly models consider several tiers of automation based on the scale of throughput. At low throughputs, the assembly process is fully manual, requiring individual workers to perform each assembly process—overseeing the assembly of the stack at each step. Manual assembly requires more workers and operates more slowly than automated processes. At higher throughput, assembly operations are assumed to shift to semi and fully automated (at 100 and 250 MW/yr, respectively, based on assumptions from Mayyas et al. [2019]), leveraging robotic assembly operations where possible. These assembly processes have a higher initial capital cost for the equipment but require less labor and can assemble stacks at higher rates with lower overall costs.

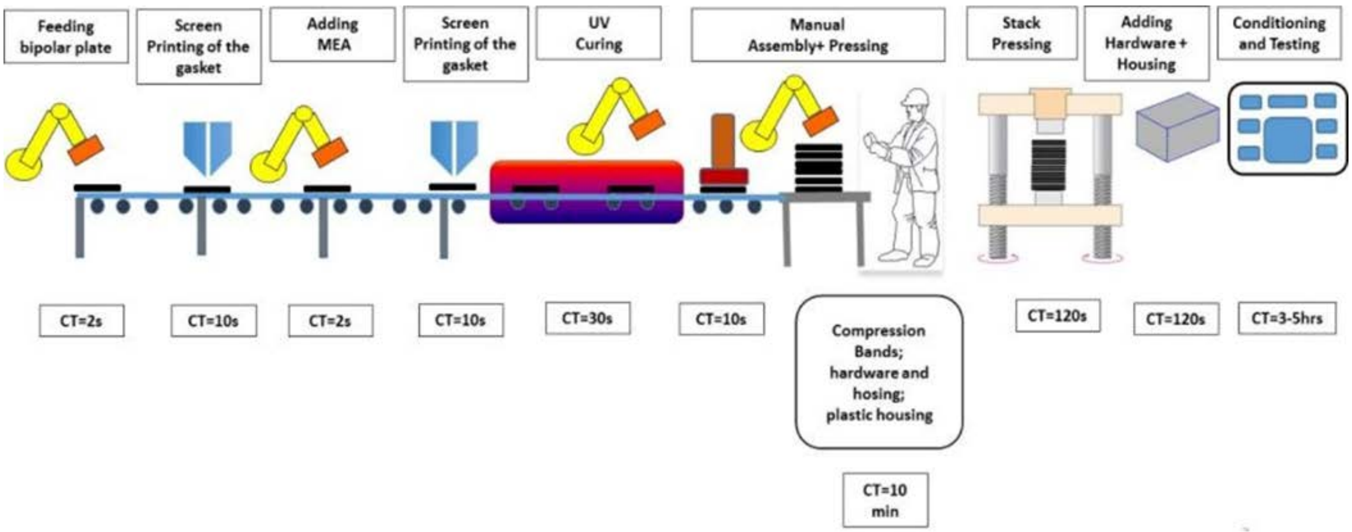


Figure 9. Stack assembly process.

Image from (Mayyas et al. 2019)

CT: cycle time

2.2 Balance of Plant

BOP components for the baseline 1 MW electrolyzer encompass equipment both upstream and downstream of the electrolyzer stack; this equipment supplies deionized water to the system, manages thermal energy throughout the system, and separates outlet hydrogen from other molecules such as water vapor.

The following sections briefly describe BOP processes that have been grouped into several categories:

- Water supply
- Thermal management
- Hydrogen-side BOP
- Hydrogen processing
- Piping, instrumentation, and housing
- Electrical BOP

We estimate the cost of BOP components using a combination of cost-scaling functions and vendor quotes. Where available and applicable, we use empirical cost correlations from literature based on chemical processes to estimate appropriate capital costs of equipment based on the required size (e.g., a water tank sized proportionally to mass flows). These correlations can provide costs at different system sizes corresponding to different electrolyzer nameplate capacities. For some components, however, the size of the unit is fixed or is well below the minimum size for typical size-cost correlations. In these cases, we estimate costs based on one or more quotes from vendors and engineering judgment.

Two empirical cost functions adopted from literature are used in this work, shown in Eq. (1 and (2 (Seider et al. 2016; Sinnott and Towler 2020a; ChemCatBio 2021). These functions scale the estimated cost of the component, C_{base}, by the sizing parameter S and function parameters $a, b, c, d,$ and e:

$$C_{base} = a + bS^c \tag{1}$$

$$C_{base} = e^{a+bln(S)+cln(S)^2+dln(S)^3+e\ln(S)^4} \tag{2}$$

Values for these parameters corresponding to equipment analyzed in this work are shown in Table 2. Equations (1 and (2 provide base equipment costs at a given time (i.e., dollar value from a specific year) for a standard material. The base costs are then adjusted to reflect the use of alternative materials using a material factor F_{mat} and are converted to 2020 dollars using the Chemical Engineering Plant Cost Index for 2020 of 596.2 (Chemical Engineering News 2020) (Eq. (3):

$$C = C_{base}F_{mat}\left(\frac{CEPCI_{2020}}{CEPCI_{base}}\right) \tag{3}$$

Table 2. Cost Methods, Sizing Parameters, and Cost Coefficients for Key BOP Equipment (Seider et al. 2016; Sinnott and Towler 2020a; ChemCatBio 2021)

Equipment	Costing Method	Sizing Parameter	Parameter Bounds	*a*	*b*	*c*	*d*	*e*
Water tank	Eq. 1	Tank capacity (cubic meters [m^3])	10–4,000	5,800	1,600	0.7		
Demisters (approximated with stainless steel packing)	Eq. 1	Volume (m^3)	Not applicable (n/a)	0	7,600	1		
Recirculation pump	Eq. 2	Flowrate (gallons per minute [gal/min])	10–900	8.28	-0.29	0.074	0	0
Pump motor	Eq. 2	Power (horsepower [hp])	1–700	5.93	0.17	-0.11	0.071	-0.0064
Air-cooled radiator	Eq. 1	Heat transfer area (square feet [ft^2])	40–150,000	0	2,835	0.4		
Chillers (plate heat exchangers)	Eq. 1	Heat transfer area (ft^2)	11–5,400	1,600	22	0.95		
Cyclone	Eq. 2	Gas flow (cubic feet per minute [ft^3/min])	200–100,000	9.35	-0.79	0.085	0	0
TSA dryer columns and flash tank (vertical pressure vessel)	Eq. 1	Shell mass (kilograms [kg])	120–250,000	17,400	79	0.85		
Recirculation blower	Eq. 2	Power (hp)	1–1,000	7.72	0.79	-0.013	0	0

Note that each cost correlation described by Eq. (1 and (2 has bounds for its sizing parameter as reported in the fourth column of Table 2. Because of the small, modular scale of electrolyzer systems, some pieces of equipment have sizing parameters that are beneath the lower bound in their cost correlation. For simplicity, we use the lower bound of the correlation to determine costs in these cases. This may slightly overestimate costs for those components. However, often these components approach practical lower-bound sizes where size reductions are challenging or do not yield significant cost reductions.

2.2.1 Water Supply

Inlet water consumed in the electrolyzer is sourced from a municipal water supply and requires pretreatment and removal of impurities prior to entering the electrolyzer stack. A carbon filter removes organic contaminants and is followed by a deionization unit, which removes further impurities and ensures that the water supplied does not poison catalysts or other materials in the electrolyzer stack. The deionizer comprises three separate ion exchange tanks filled with mixed-bed deionization resin. Three tanks are used to allow for adequate deionization capacity and resin recharging (Figure 10). Note that inlet water quality can vary significantly with factors such as location. Water conditions different from those assumed in this work could warrant alternative inlet water treatment designs or additional treatment, such as a disinfection step to treat biological contaminants.

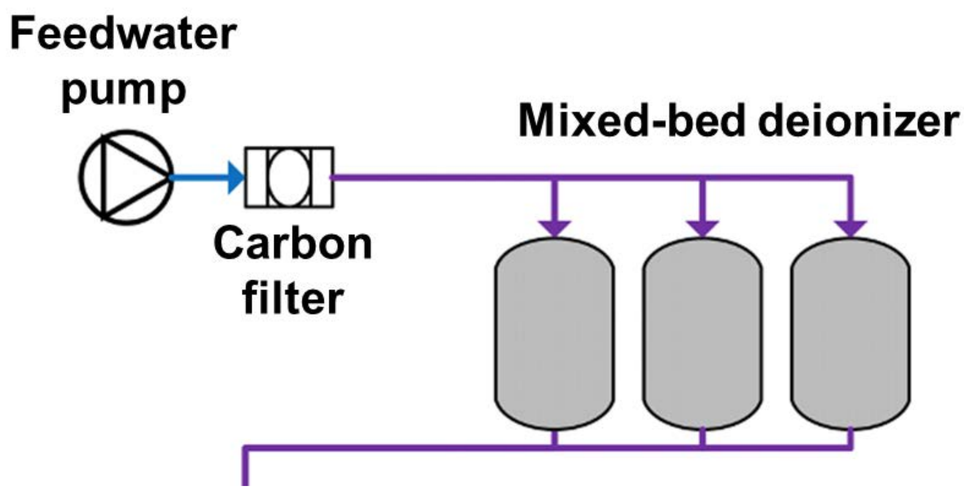


Figure 10. Water filtering and deionization components

Water flows from this deionization system and combines with recirculating water in a primary feed water tank. A smaller polishing deionizer system cycles water directly to and from the primary feed tank. The polishing deionizer system includes just two tanks—one for active use while the other recharges. The primary feed tank also includes a demister pad to help collect water droplets out of warm streams of recycled water that are fed into the tank (see Figure 2 and Section 2.2.3).

Water is fed through a final filter into the electrolyzer stack at a high flow rate (8.9 kg/second [s] in the 1 MW baseline system), a small portion of which is consumed to produced hydrogen. Water that is not consumed in the water-splitting reaction is recirculated back into the main water tank. The flow into the electrolyzer stack and back into the water tank is large but primarily comprises recirculating water. The water supply subsystem is connected to the oxygen side of the electrolyzer stack and thus operates at near-ambient pressure.

Table 3 shows the component sizing, cost methods, and estimated costs for the water supply subsystem.

Table 3. Water Supply Equipment and Costs

Component	Costing Method	Sizing Parameter or Criteria
Feedwater pump	Quote	4 liters per minute (L/min) flow rate
Carbon filter	Quote	4 L/min flow rate
Deionizer tanks (3)	Quote	7 L capacity
Deionizer resin	Quote	22.3 kg
Water tank	Eq. 1	10 m^3 capacity
Demister pad	Eq. 1	1.5 m diameter
Polishing deionizer tanks (2)	Quote	7 L capacity
Polishing deionization loop pump	Quote	4 L/min flow rate
Recirculation pump	Eq. 2	141 gal/min flow rate
Motor for recirculation pump	Eq. 2	50 hp
Prestack filter	Quote	10 micrometers (μm), high flow
Water supply total cost (2020$)	**$61,057**	

Three pumps are included in the BOP: one for the inlet water feed, one for the polishing deionization loop in the water tank, and one to feed water into the electrolyzer stack. Pump sizing is based on flow and pump head estimates from Wang, Star, and Ahluwalia (2023). The feedwater pump and polishing deionization loop pump both drive relatively low flows and as such are costed based on quotes. Conversely, the pump that feeds the electrolyzer stack powers the recirculation loop of the stack inlet and outlet and drives much higher flows. We estimate the cost of this larger pump using Eq. (2, including a separate cost estimate for the motor used to drive the pump.

To estimate costs for demister pads (here and in other BOP subsystems), we use a cost of stainless steel structured packing from ChemCatBio (2021) with a similar surface-area-to-volume ratio as demister pads described in a commercially available demister pad (i.e., assuming that material costs are the primary driver of costs for demisters) (ChemCatBio 2021). We assume a demister pad volume defined by the diameter of the tank/pad and a thickness of 0.1 m.

To size and cost the deionization systems including tank and resin costs, we estimate the amount of resin needed based on an assumed 24-hr operating time before resin regeneration. Using water quality estimates, we determine how much ion exchange capacity is needed for a 24-hr cycle. This determines the quantity of resin that must be purchased and the tank sizes required to hold that volume of resin plus a 20% buffer. For simplicity, we assume that the polishing deionizer loop functions similarly and uses similar equipment to the main deionization system. In reality, because the polishing deionization occurs at a higher temperature (~80˚C), that resin may not be regenerable and may need to be replaced for each use. However, this resin should have a much longer lifetime than the initial deionization resin because it removes only trace contaminants not removed earlier. These assumptions may over- or underestimate costs slightly because more resin could be required for practical lifetimes or because only one tank could be needed. Any resulting error should be well within the precision of estimates in this report, especially given the low costs for deionizer tanks and resin.

In this analysis, we consider the cost of the initial resin purchase only. Any resin replacements for the polishing deionization loop or resin replacements for the main loop as it loses capacity over time are treated as electrolyzer system operating costs rather than manufactured costs and are outside the scope of this work.

2.2.2 Thermal Management

Providing heat to and removing heat from BOP components is crucial to operating the electrolyzer at appropriate conditions and controlling temperature-based separation steps. These components exist upstream and downstream of the electrolyzer itself, managing temperatures and phases of process streams.

In the electrolyzer stack, unconverted water gains thermal energy from inherent inefficiencies, resulting in a 5–10˚C temperature rise in the stack (Wang, Star, and Ahluwalia 2023). An air-cooled fin-fan radiator is used to cool water from the feedwater tank to the desired stack input temperature (80˚C) before the water enters the electrolyzer stack.

Other thermal management equipment includes a cooler for hydrogen and water separation following the stack and a heater and cooler for the TSA system that removes trace water from the outlet hydrogen. Systems to heat and cool flows are needed because TSA separation is driven by temperature changes. Table 4 shows the sizing, cost methods, and estimated costs for heating and cooling equipment in the BOP. The separation steps and TSA design are discussed in more detail in Section 2.2.3.

Table 4. Thermal Management Equipment and Costs

Component	Costing Method	Sizing Parameter or Criteria
Air-cooled radiator	Eq. 1	154 ft^2 heat transfer area
Chiller for high-pressure water separation (HPWS) system	Eq. 1	206 ft^2 heat transfer area
Chiller for TSA dryer	Eq. 1	916 ft^2 heat transfer area
Electric heater for TSA dryer	Quote	5 kilowatts (kW)
Thermal management total cost ($2020)	**$72,661**	

Aside from the air-cooled radiator, the two coolers on the hydrogen output side are assumed to be plate-and-frame heat exchangers because these yield the lowest costs for the system size. (A higher nameplate capacity, alternative designs/operating conditions, or more detailed design considerations for a specific electrolyzer system could warrant different types of heat exchangers, which could increase costs.) The heater for the TSA system is assumed to be an electric circulation heater. To size each heater and cooler within the balance of plant, we estimate the required heat flux for each unit based on inlet and output temperatures, stream compositions, and heat capacities of stream components. For the heater, we use the heat flux to inform the heater wattage needed to provide the necessary heating. For coolers, we calculate an approximate heat transfer area based on principles of heat exchange described in Eq. (4 and (5:

$$Q = UA\Delta T_{lm} \tag{4}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1 - \ln \Delta T_2}, \tag{5}$$

where Q is the heat flux, U is the heat transfer coefficient of the heat exchanger, A is the heat transfer area, and ΔT_{lm} is the log-mean temperature difference, determined by the temperature differentials at each end of the heat exchanger ΔT_1 and ΔT_2. The heat transfer coefficients for each heat exchanger are estimated from Sinnott and Towler based on the process fluids, shown in Table 5 (Sinnott and Towler 2020b). For conservative estimates, we assume that the process fluid for both chillers is a gas because both streams contain significant gaseous hydrogen.

Table 5. Estimated Heat Transfer Coefficients Used in This Work

Component	Process Fluid	Cold Fluid	Coefficient Range Identified by Sinnott and Towler (2020b) (watt [W]/m^2 ˚C)	Coefficient Used in This Work (W/m^2 ˚C)
Air-cooled radiator	Inlet water	Air	300–450	375
Chillers for HPWS and TSA dryer	Hydrogen plus water vapor at 30 bar	Cooling water	20–300	160

For heat exchanger sizing, we add a 50% contingency to the heat transfer area to account for design considerations, such as fouling, temperature correction factors, and differing heat exchange coefficients that are not otherwise captured in this high-level analysis. We assume a conservative ambient air temperature of 40˚C for the air-cooled radiator and a cooling water temperature of 25˚C. Though the cooling water would likely see a small temperature rise in the chillers, we assume that the impact of this on heat exchanger sizing is negligible.

2.2.3 Hydrogen-Side BOP and Hydrogen Processing

Outlet processing subsystems are designed to separate hydrogen produced from the electrolyzer from water and trace oxygen with a target hydrogen purity of 99.97%. The hydrogen-side BOP contains a high-pressure and low-pressure separation step. A high-pressure water separation (HPWS) system, consisting of a cyclone separator and downstream chiller, immediately follows the electrolyzer outlet and is designed to separate water and hydrogen at the electrolyzer outlet pressure of 30 bar. Subsequently, a low-pressure hydrogen separation (LPHS) comprising a flash tank with a demister pad removes hydrogen from the water stream. This work assumes that any oxygen in the electrolyzer stack outlet is considered negligible.

Hydrogen exiting the hydrogen-side BOP still contains some water vapor and is sent to hydrogen processing for final purification via TSA. TSA operates using adsorbent with a higher affinity for water at lower temperatures. Two tanks with adsorbent are used: in one, a cold hydrogen stream flows through the adsorbent, which captures any remaining water in the hydrogen stream—creating a high-purity outlet stream. In the other, a reheated stream removes water from the adsorbent to regenerate it. This water is separated in a demister/flash separation and fed to the LPHS. The two TSA columns operate on a roughly 3-hr cycle; i.e., one column removes water while the other is regenerated for ~3 hours before the process streams are switched to the opposite column. This work also includes costs for a third backup TSA column. For TSA column and tank design and costing, we assume that the TSA operates at the outlet pressure of 30 bar (though in reality there may be pressure drops in components that may reduce the pressure below the electrolyzer stack outlet pressure). Table 6 shows the sizing, cost methods, and estimated costs for the hydrogen-side BOP and hydrogen processing equipment.

Table 6. Outlet Processing Equipment and Costs

Component	Costing Method	Sizing Parameter or Criteria
HPWS cyclone	Eq. 2	35 ft^3/min gas flow
LPHS column	Quote	50 gal capacity
LPHS demister	Eq. 1	0.5 m diameter
Hydrogen-side BOP total cost ($2020)	**$5,158**	
TSA adsorbent material	Quote	224 kg
TSA dryer columns (3)	Eq. 1	62.4 kg shell mass
TSA flash tank	Eq. 1	62.7 kg shell mass
TSA flash tank demister	Eq. 1	0.25 m diameter
Recirculation blower	Eq. 2	1 hp
Hydrogen processing total ($2020)	**$118,632**	

The cyclone separator and flash tanks are sized based on material flow rates from process modeling (Wang, Star, and Ahluwalia 2023). For the cyclone separator, we use a cost correlation for ambient pressure and adjust based on an estimated wall thickness to accommodate 30-bar pressure. We scale up costs according to additional material amounts needed for extra wall thickness, assuming that material costs will account for most of the cyclone cost. To size the TSA units, we estimate the volume of adsorbent needed to hold the amount of water removed from the hydrogen stream over the course of a TSA cycle (about 3 hours). We then size the tanks accordingly, accounting for needed packing and void space.

2.2.4 Piping, Instrumentation, and Housing

Costs for the purchase and assembly of piping are included as part of the BOP to account for connections between the various BOP components of the electrolyzer. This piping represents the prepackaged design of the electrolyzer, which requires that the system is ready to operate when delivered and installed. This work assumes that a total of 30 meters (m) of piping is needed for the electrolyzer. For simplicity and to develop a conservative estimate of total piping costs, we assume that half of the piping (15 m) is 4-inch piping on the water/inlet side and half of the piping is 1-inch piping on the hydrogen/outlet side (NREL 2022).

We also estimate costs for valves and instrumentation for the electrolyzer system. We assume a given number of valves of various types based on the process flow diagram (Figure 2), plus additional check valves and pressure relief valves for handling pressurized flow. This is likely not a comprehensive estimate of valves needed for the system, so a 25% contingency on valve costs is included.

Instrumentation costs include costs for thermocouples, pressure sensors, a flow meter for inlet water, and a control system. We also include two hydrogen sensors for safety, ensuring that the presence of hydrogen outside of process streams results in system shutdown or corrective action. See Appendix B for additional detail on assumed piping, valve, and instrumentation requirements. Piping, valves, and instrumentation costs are based primarily on vendor quotes. For the control system, we use an estimate designed to capture the cost of a computer and a control software.

Finally, we include a cost estimate for assembly of the electrolyzer stack and BOP, in accordance with a preassembled, “plug-and-play” electrolyzer system concept. To include specific assembly costs while excluding other soft costs that are often captured in general chemical plant costing rules, this work adopts a more specific estimation framework based on assembly steps such as welding or attaching flanges. Based on the system configuration and estimates for valves and instrumentation, we assume several assembly steps and calculate an associated amount of labor using Page’s *Estimator’s Piping Man-hour Manual* (Page 1999). We use this to estimate assembly costs, based on $50/hr cost of labor (Baldea et al. 2017). An additional 50% contingency for assembly costs is included in this estimate. See Appendix B for detailed documentation on assembly assumptions. Note, however, that we do not include costs of containerization or other additional costs that an electrolyzer operator may see, such as engineering and site preparation (see Section 2.4). Table 7 shows sizing and quantity assumptions and resulting estimated costs for piping, instrumentation, and housing equipment and assembly.

Table 7. Piping, Instrumentation, and Housing Equipment and Costs

Component	Costing Method	Sizing Parameter or Criteria
Water-side piping (4 inch)	Quote	15 m
Hydrogen-side piping (1 inch)	Quote	15 m
Solenoid valves (15)	Quote	1-inch connections
Proportional valves (5)	Quote	1-inch connections
Water-side valve (1)	Quote	4-inch connections
Three-way valve (1)	Quote	4-inch connections
Check valves (10)	Quote	1-inch connections
Relief valves (5)	Quote	1-inch connections
Valve contingency	Estimate	25% of valve costs
Piping and valves total cost ($2020)	**$74,150**	
Thermocouples (13)	Quote	n/a
Pressure sensors (10)	Quote	n/a
Hydrogen sensors (2)	Quote	n/a
Flow meter (1)	Quote	3-inch connections
Control system	Estimate	n/a
Sensors and control total cost ($2020)	**$21,500**	
Assembly cost ($2020)	**$23,598**	
Piping, instrumentation, and housing total ($2020)	**$119,248**	

2.2.5 Electrical Balance of Plant

Power electronics take high-voltage alternating current (AC) energy (e.g., from the grid) and convert it to direct current (DC) at a voltage and current suitable for powering the electrolyzer. A rectifier is used to produce DC electricity from AC line voltages, and a DC-DC converter is used to change the DC voltage and current to suitable levels for the electrolyzer.

This work adopts power electronics costs developed by Mayyas et al. (2019), which are based on quotes from power supply manufacturers and suppliers. Power electronics costs are assumed constant at $199/kW for low manufacturing rates and include both the transformer and rectifier for a 1 MW electrolyzer (Mayyas et al. 2019). Given the low adoption rates of PEM electrolyzers, suppliers of power electronics for these systems generally operate at small manufacturing rates and do not leverage significant economies of scale.

Optimizing power electronics for electrolyzers is a key opportunity for cost reduction and is the focus of ongoing research. Opportunities to reduce power electronics costs include directly coupling electrolyzers with variable renewable power generation such as wind and solar photovoltaics (PV) (Yodwong et al. 2020). Power supplies can also be optimized to better match voltages and currents of the electrolyzer, leveraging production of existing systems, and increasing cost reductions through scale-up.

2.3 Reductions in Balance-of-Plant Costs at Scale

The BOP cost analysis methods presented here estimate electrolyzer system costs for a single, 1 MW nameplate electrolyzer with current or near-term technologies. However, electrolyzer deployment is projected to increase dramatically, which could drive significant cost reductions from research, development, and manufacturing supply chain buildout. It is important to consider these cost reductions at higher production scales, particularly for planning and capacity expansion modeling. Unlike the electrolyzer stack, the BOP cost estimation framework in this analysis is mostly based in purchase costs of commoditized components and cannot capture potential cost reductions at higher manufacturing scales via throughput and utilization implications. Still, scale-up of manufacturing rates has the potential to drive cost reduction in the BOP using a variety of mechanisms, including cost reductions through bulk purchasing, *manufacturing* economies of scale, increased utilization for assembly processes, and process or technology improvements based on experience. Note that increasing the scale of BOP through larger nameplate capacities or BOP sharing among stacks—i.e., *process* economies of scale—is not considered in this analysis, though it is a promising area for BOP cost reduction and will be considered in future work.

Estimating BOP costs at future increased production scales is particularly challenging because of the many potential avenues for cost reduction, many of which are difficult to estimate and highly uncertain in and of themselves. Fully capturing each of these mechanisms properly would require complex supply chain and economic analyses, detailed manufacturing/assembly process analysis, and consideration of technology improvements from learning that are far beyond the scope of this analysis. Still, we suggest that there is value in implementing some form of cost reduction analysis—not to predict future costs but to consider potential, if uncertain, trajectories for costs.

In literature, many of these cost reduction pathways are considered to follow exponential cost reduction with respect to some measure of the volume of technology manufactured or deployed. Changes in cost because of economies of scale are often modeled based on a scaling exponent n:

$$C = C_0 \left(\frac{S}{S_0}\right)^n \tag{6}$$

where C is the total cost at some production scale S and C_0 is the initial total cost at scale S_0. The exponent n is process specific (for chemical industries, it averages around 0.6, so Eq. (6 is often called the "six-tenths rule"). This is often used regarding *process* economies of scale, but we consider it here for *manufacturing* economies of scale, for lack of a better correlation, to capture bulk purchasing, increased utilization and efficiency, and so on. In their analysis of BOP cost scaling, Mayyas et al. (2019) consider similar exponential scaling using a 20% cost reduction for 10x increase in purchase quantity for BOP parts (mathematically equivalent to Eq. (6) (Mayyas et al. 2019).

When considering technology and cost improvements because of experience—e.g., a new piping layout that minimizes costs rather than a decrease in pipe costs because of bulk purchasing—it is common to see cost reduction referred to as "learning-by-doing." In practice, this cost reduction often follows a pattern of a constant percentage reduction for each doubling of cumulative production. Mathematically, this is expressed as:

$$C^* = C_0^* \left(\frac{P}{P_0}\right)^{-\epsilon}, \tag{7}$$

where C^* is the cost per unit at a cumulative production P, C_0^* is the cost per unit at an earlier (typically initial) cumulative production P_0, and ϵ is the learning parameter. The learning parameter is specific to the industry/technology (much like n for economies of scale) and indirectly expresses the percentage of cost reduction for each doubling in cumulative production, called the learning rate (LR):

$$LR = 1 - 2^{-\epsilon}. \tag{8}$$

Learning rates are often estimated for specific industries or technologies based on empirical data for those or similar industries. Bohm et al. estimate a learning rate of 13% for electrolyzer BOP, though they estimate 7% as a learning rate for gas conditioning, which could comprise some of the processes we consider BOP, such as TSA (Böhm, Goers, and Zauner 2019). Staffell and Green present learning rates from literature for PEM fuel cells (and general energy technologies) ranging from approximately 10% to 40% and clustered around 15%–20% (Staffell and Green 2013). One might expect PEM electrolyzer learning rates to be similar, with BOP-specific rates slightly lower because BOP comprises more developed chemical equipment. The Hydrogen Council also estimates a 13% learning rate for PEM electrolyzer systems (Hydrogen Council 2020). Specific drivers of learning-by-doing are inherently vague: For example, cost reductions because of *process* economies of scale could be captured by a learning rate depending on the scope and considerations of the analysis in which the learning rate is based. Learning is also difficult to correlate with manufacturing scale because cumulative deployments of electrolyzers is connected but not directly related to the manufacturing scale of any given electrolyzer plant.

Still, it can be shown that the mathematical correlations for economies of scale and learning-by-doing take the same form of exponential cost decay with respect to some measure of scale. Rearranging Eq. (6 to express cost per unit of scale instead of total cost, we obtain the following:

$$C^* = \frac{C}{S} = \frac{C_0}{S_0}\left(\frac{S}{S_0}\right)^{-(1-n)} = C_0^*\left(\frac{S}{S_0}\right)^{-(1-n)}. \tag{9}$$

In this case, $1 - n$ is analogous to the learning parameter ϵ. Based on this, we consider similar exponential cost scaling for the BOP with respect to annual manufacturing capacity in MW/yr to capture potential cost reductions for the BOP at higher scales. We also estimate that cost improvements from economies of scale, bulk purchasing, learning, and so on will require some amount of manufacturing scale before pronounced reductions are achieved. To account for this, we hold costs constant below the manufacturing threshold Q_0 and apply exponential cost reduction with respect to this threshold as the "initial value":

$$C^* = \begin{cases} C_0^*, Q \leq Q_0 \\ C_0^*(Q/Q_0)^{-\alpha}, Q > Q_0, \end{cases} \quad (10)$$

where Q is the manufacturing rate of electrolyzers (MW/yr) and α is a parameter specific to the component or subsystem that captures the speed of cost reduction. We apply individual cost reductions to BOP components (or in some cases, subsystems) to better capture specific cost factors for different equipment and examine potential evolution in cost over time. We select 50 MW/yr as our value for Q_0 based on engineering judgment and industry feedback.

The challenge of this analysis then becomes selecting appropriate values for α. Given the nascency of electrolyzers and resultant lack of data, it is impossible to eliminate the high degree of uncertainty. Still, we believe that there is value in considering a potential cost trajectory for the BOP. For a conceptual basis, we consider values of α regarding their resultant cost reductions from a doubling in manufacturing scale, analogous to learning rates. Mathematically, then, we are considering what we dub "improvement rates" (IR), expressed as

$$IR = 1 - 2^{-\alpha}. \quad (11)$$

For example, a component with a 10% improvement rate would see a 10% cost reduction with a doubling of the manufacturing scale. We discuss our selection of improvement rates next, which can be converted to values for α using Eqn. (11 for use in Eq. (10.

To estimate improvement rates for each component or subsystem, we reference primarily Design For Manufacture and Assembly analyses performed by James et al. for hydrogen fuel cells and hydrogen storage systems (James et al. 2017; James, Moton, and Colella 2014). These analyses estimate costs of fuel cell BOP and hydrogen storage components at various system manufacturing scales. For each electrolyzer BOP component/subsystem considered in this analysis, we select an appropriate analog from the James et al. analyses and fit the cost estimates at varying production scales to an improvement rate for that component. (At the time of publication, we are unaware of analyses for electrolyzer BOP with similar cost detail for such estimations.) Details of improvement rates and their references are shown in Table 8. For some components, we adjusted the rates based on engineering judgment or used an alternative source if there was not an appropriate analog:

- For the feedwater tank, filters, demister pads, hydrogen-side BOP, and TSA systems, we estimate an improvement rate of 6.5% based on Mayyas et al. (2019) (a 6.5% improvement rate is equivalent to a 20% cost reduction for a 10x increase in production scale). Bohm et al. (2019) also estimate a 7% learning rate for gas conditioning, similar to our assumption of 6.5% for TSA.

- For the system assembly, we increase the improvement rate estimate yielded from James et al. (2017) for assembly and testing (5.8%) to 9.5% to account for reduction of contingency costs over time. This increase roughly eliminates our 50% contingency on assembly costs by a gigawatt (GW)/yr production scale. We assume that piping costs follow a similar improvement rate, combining cost improvements from bulk purchasing and economies of scale (e.g., 6.5% improvement rate based on Mayyas et al. [2019]) with minor improvements from experience such as reduction of pipe length needed.

- For electrical BOP, we assume an improvement rate of 12% based on the learning rate for power electronics estimated by Bohm et al. (2019), given the lack of a better basis. This is a key and highly uncertain assumption given that our improvement rates are fundamentally different from learning rates: Basing an improvement rate on a learning rate essentially uses manufacturing scale as a proxy for cumulative deployment. In reality, cumulative deployment may increase faster than manufacturing scale (i.e., causing more rapid cost reduction), but a learning rate may also decrease over time as the technology becomes more established (i.e., causing less rapid reduction). How these factors would combine and play out, along with other considerations, is unclear. However, we believe 12% to be a reasonable, if somewhat uncertain, estimate; similar to piping, this estimate could also capture some economies-of-scale improvements along with some level of improvement from learning, such as increased rectifier efficiency.

Table 8. BOP Component Improvement Rate Assumptions

Component	Improvement Rate	Reference
Pumps and blowers	10.2%	James et al. (2017), based on compressor, expander, and motor unit for a fuel cell system
Filters	6.5%	Mayyas et al. (2019)
Feedwater tank	6.5%	Mayyas et al. (2019)
Demister pads	6.5%	Mayyas et al. (2019)
Water deionization	7.0%	James et al. (2017), based on resin deionizer filter in coolant loop
Heat exchangers	3.9%	James et al. (2017), based on radiator system in coolant loop
Electric heater for TSA	6.5%	Mayyas et al. (2019)
Hydrogen-side BOP	6.5%	Mayyas et al. (2019), Bohm et al. (2019), learning rate for gas conditioning
TSA tanks and adsorbent	6.5%	Mayyas et al. (2019), Bohm et al. (2019), learning rate for gas conditioning
Piping	9.5%	Assumed same as assembly
Flow control valves	14.5%	James et al. (2014), based on solenoid valves for a hydrogen storage system
Check valves	24.7%	James et al. (2014), based on check valves for a hydrogen storage system
Relief valves	7.0%	James et al. (2017), based on overpressure cutoff valves for a fuel cell system
Thermocouples	6.6%	James et al. (2017), based on air temperature sensor for a fuel cell system

Component	Improvement Rate	Reference
Pressure sensors	24.8%	James et al. (2014), based on pressure transducer for a hydrogen storage system
Hydrogen sensors	16.4%	James et al. (2017), based on a hydrogen sensor for a fuel cell system
Flow meter	6.7%	James et al. (2017), based on an air mass flow sensor for a fuel cell system
Control system	6.9%	James et al. (2017), based on system controller for a fuel cell system
BOP assembly	9.5%	James et al. (2017), based on BOP assembly plus an increase to effectively eliminate contingency at high production scales
Electrical BOP	12%	Bohm et al. (2019) learning rate for power electronics

2.4 Hydrogen Levelized Cost

The H2A and H2A-Lite analysis platforms were used to estimate potential resulting hydrogen levelized cost (HLC) from the system capital costs developed in this analysis (NREL 2020; 2023). The current central hydrogen production from the PEM electrolysis H2A model was used as a basis for additional costs for installation, site preparation, etc. while the H2A-Lite platform was used to estimate HLC for the various assumptions shown in Table 9. HLC is calculated for a range of electricity prices and capacity factors, accounting for recent work that investigated operating electrolyzers in wholesale power markets with hourly variable pricing (Badgett, Ruth, and Pivovar 2022).

Table 9. H2A-Lite Cost Analysis Assumptions

Assumption	Value	Units
Electricity price	\$0.01, \$0.03, or \$0.06	\$/kilowatt-hour (kWh)
Capacity factor	40, 60, or 90%	%
Stack efficiency	51.1[1]	kWh/kg H_2
BOP efficiency	4.2[1]	kWh/kg H_2
Fixed operational costs	5%	% of direct capital investment
Variable operational costs	\$0.024	\$/kg H_2
Plant life	40	Years
Annualized stack replacement costs	15%	% of direct capital investment
Debt-to-equity ratio	1.5	N/A
Debt interest rate	3.7%	%
Real return on equity	8%	%
Income tax rate	25.74%	%

Assumption	Value	Units
Inflation rate	1.9%	%
Depreciation type	MACRS	n/a
Depreciation period	20	years
Cash on hand	1	Month of opex
Dollar basis	2020	n/a

[1] (Ruth and Ahluwalia 2022)

In addition to performance input values in Table 9 and capital cost estimates, these results include a series of fixed costs to approximate the cost of constructing and operating an electrolyzer (Figure 11). This analysis uses the default H2A current central PEM electrolysis case study as a basis for installation factors and other indirect capital costs, with marked-up manufactured costs as an approximation for electrolyzer purchase costs.

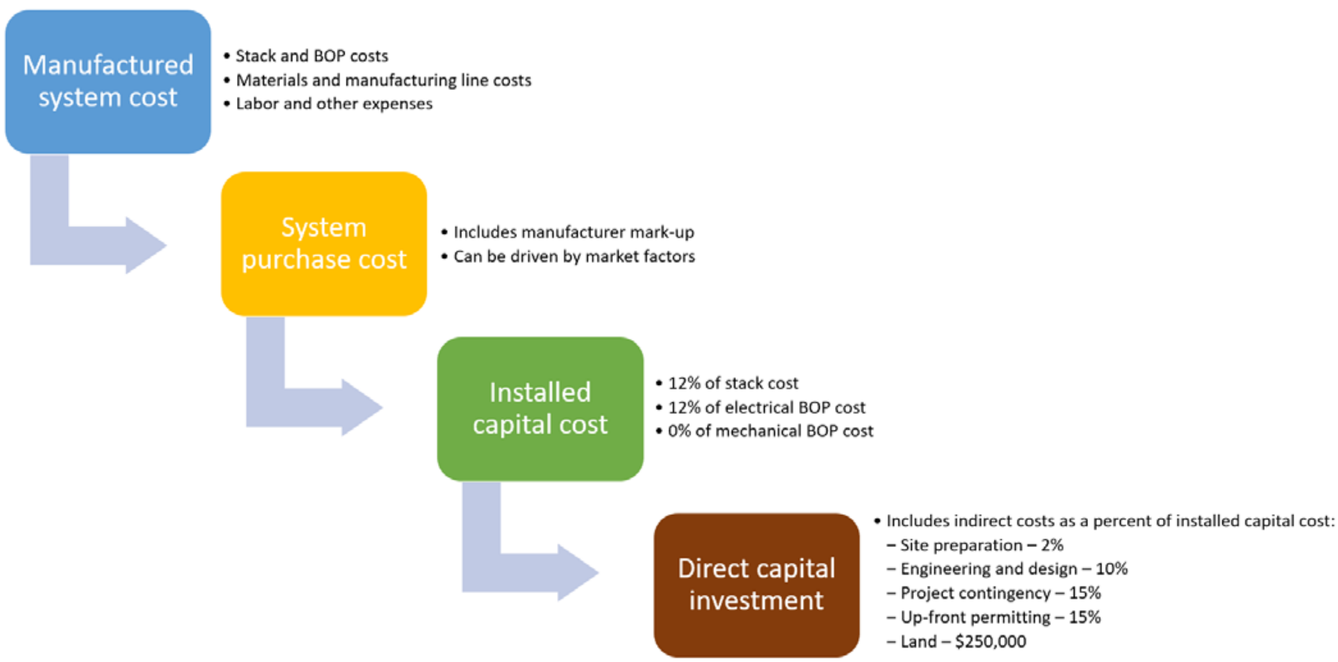


Figure 11. Additional cost factors included in hydrogen levelized cost analysis

The current central PEM electrolysis H2A case study includes additional installation factors for the electrolyzer stack and electrical BOP components. One-time indirect capital expenses are included in the total capital investment for the system, which includes expenses such as site preparation, engineering and design, and land purchase costs.

3 Results and Discussion

This section presents results of the stack and BOP cost analysis based on the methodologies outlined in Section 2, aggregating stack and BOP costs into total system costs and estimating the levelized cost of hydrogen production for these systems. The results shown throughout this section are expressed in units of 2020 dollars per kW ($/kW), which requires incorporation of the power density of the electrolyzer. This work uses the beginning of life cell voltage (1.9 volts [V]), operating current density (2 amperes per square centimeter [A/cm^2]), and corresponding power density (3.8 watts [W]/cm^2) to determine the $/kW costs shown.

3.1 Stack Cost Analysis

A 1 MW PEM electrolyzer stack is considered in this work, where each 1 MW stack has a dedicated BOP system to enable operation of the electrolyzer. This section focuses on the manufactured costs of components of the electrolyzer stack.

The CCM comprises an ion exchange membrane (Nafion® 117 in this case) coated with catalysts on either side. The method of depositing these catalysts can be either ultrasonic spray coating or slot die coating. Costs in $/kW for slot die manufacturing techniques are shown in Figure 12, including both capital expenses and material costs.

At production rates greater than 100 MW/yr, material costs dominate the total cost of manufacturing CCMs for slot die manufacturing systems (Figure 12). Largest among material costs is the anode catalyst, which is iridium in this case. Historically, iridium prices have represented a smaller share of total costs (Mayyas et al. 2019); however, the recent spike in prices in early 2020 has led to sustained price increases. Although recent iridium costs have dipped slightly in 2022, annual averages remain significantly higher than in previous years (Badgett et al. 2021). As such, the high material cost for iridium (an average of $142,238/kg iridium in 2022) (Umicore 2022) drives the high price of the anode catalyst shown here, making reducing iridium loadings a key opportunity to decrease manufactured CCM costs.

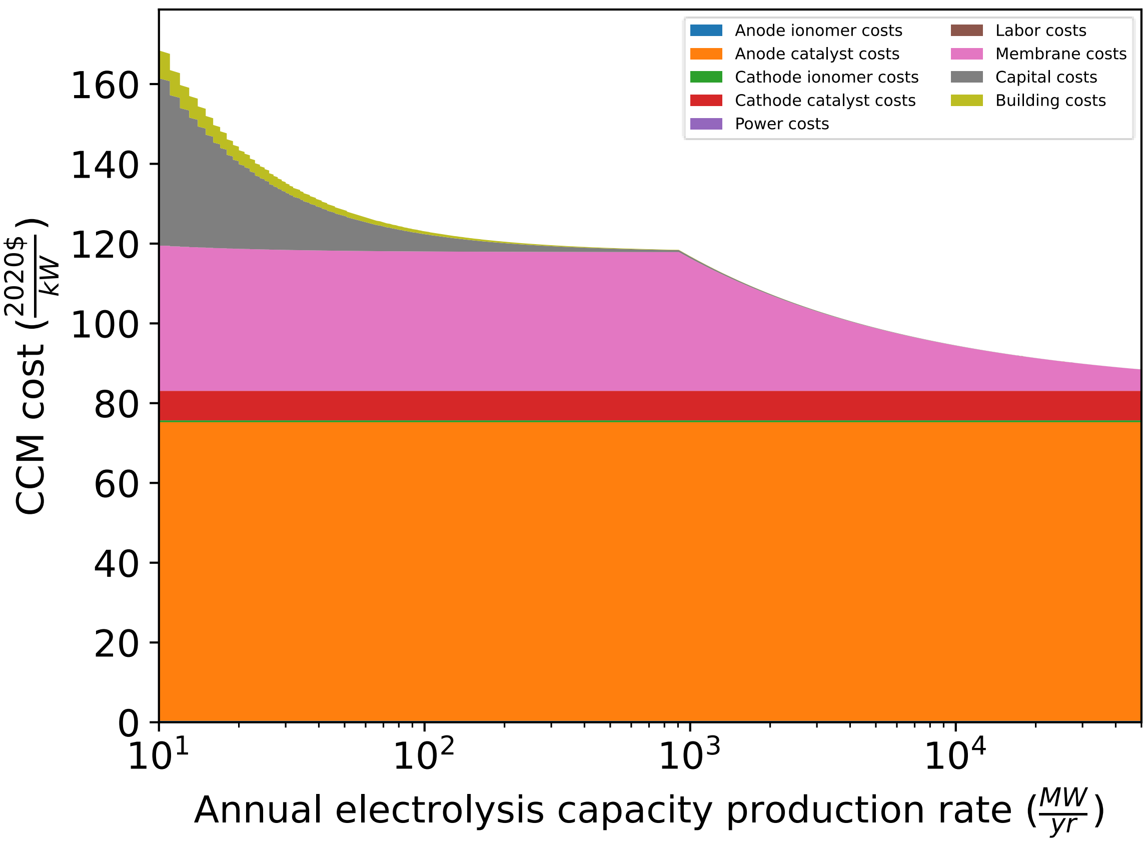


Figure 12. Manufactured cost estimates for CCM production, assuming slot die coating methods

Membrane costs represent the second largest component of CCM costs for slot die manufacturing lines. This work assumes that current retail prices for ion exchange membranes in $/m^2 are constant until approximately 700 MW/yr of production, based on work by Mathias et al., assuming that membrane costs are likely to scale as large amounts are manufactured (Mathias et al. 2005). This analysis assumes that these systems are manufactured in isolation without other competing manufacturers, but a larger annual manufacturing rate of electrolyzers might speed up the onset of this cost decrease.

The manufactured cost of frames for the electrolyzer stack are low relative to those of other components, with systems achieving manufacturing economies of scale at rates of about 1,000 MW/yr (Figure 13). Costs at scale are dominated by sealant materials (polyphenylen sulfide resin or other thermoplastics) used to construct the frame as well as employee labor to operate the frame construction and integration.

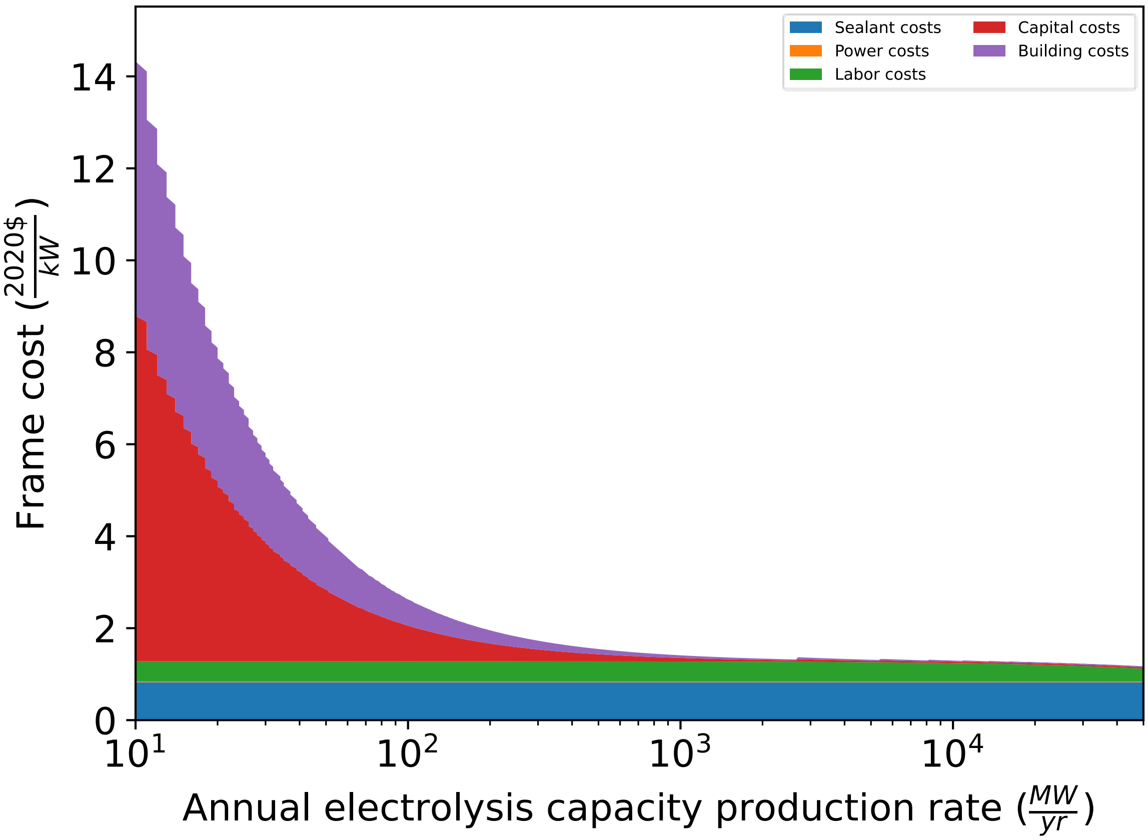


Figure 13. Manufactured cost estimates for electrolyzer frame

The anode PTL is a porous sintered titanium felt, with manufactured costs estimated using a bottom-up manufacturing process model. The felt is coated in a thin layer of platinum using PVD. Costs for this part are dominated by the cost of platinum for the coating layer even though the layer itself is thin (0.1 micrometer [µm]) (Figure 14). The cost of this part has decreased from previous estimates in Mayyas et al. (2019) because of changes in the assumed thickness of the GDL. A smaller thickness decreases the total amount of titanium required to produce it, driving the material costs lower.

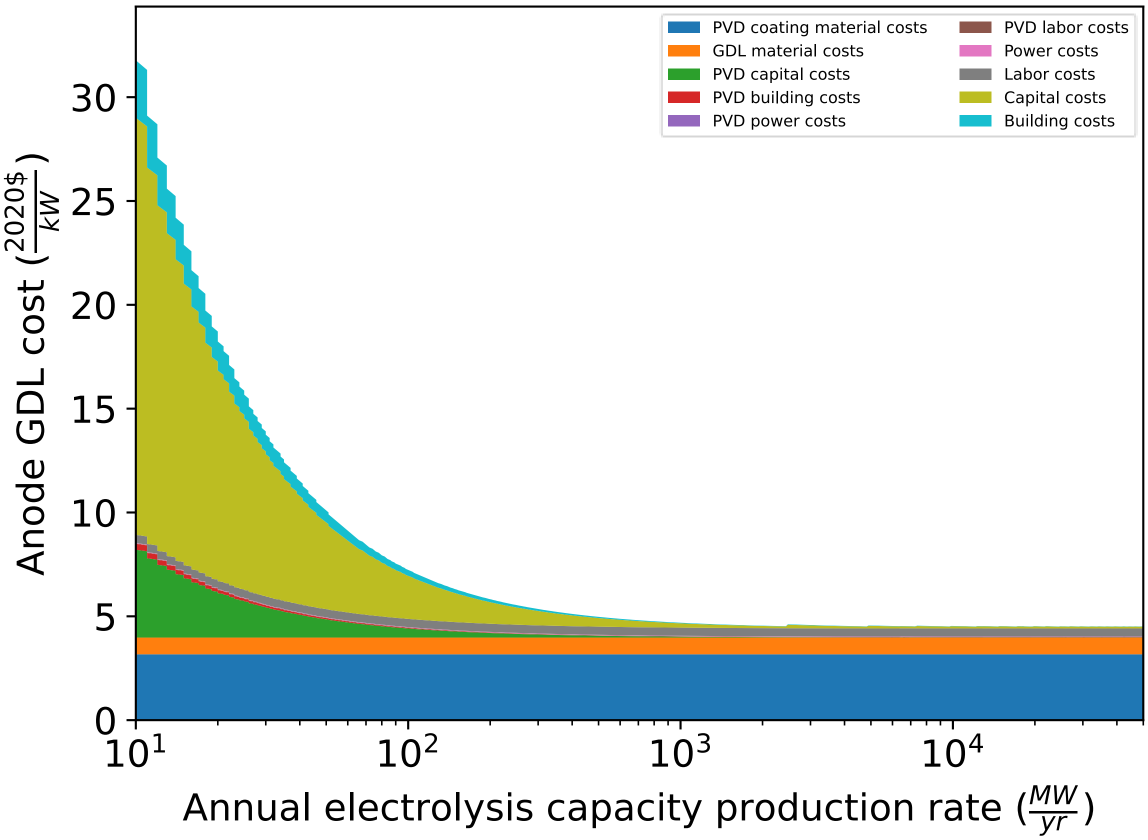


Figure 14. Manufactured cost estimates for anode GDL

Like the anode PTL, bipolar plates are made from titanium metal with a thin layer of platinum deposited through PVD. Rather than a sintered felt, the bipolar plate is manufactured from sheet titanium using a stamping process. Use of nonporous titanium and a thicker overall part drive a higher titanium material cost (Figure 15). The use of platinum also represents a significant portion of manufactured costs for this component. Although thinner plates reduce material costs, they could be more difficult to manufacture, requiring alternative techniques that could increase per-unit manufacturing costs.

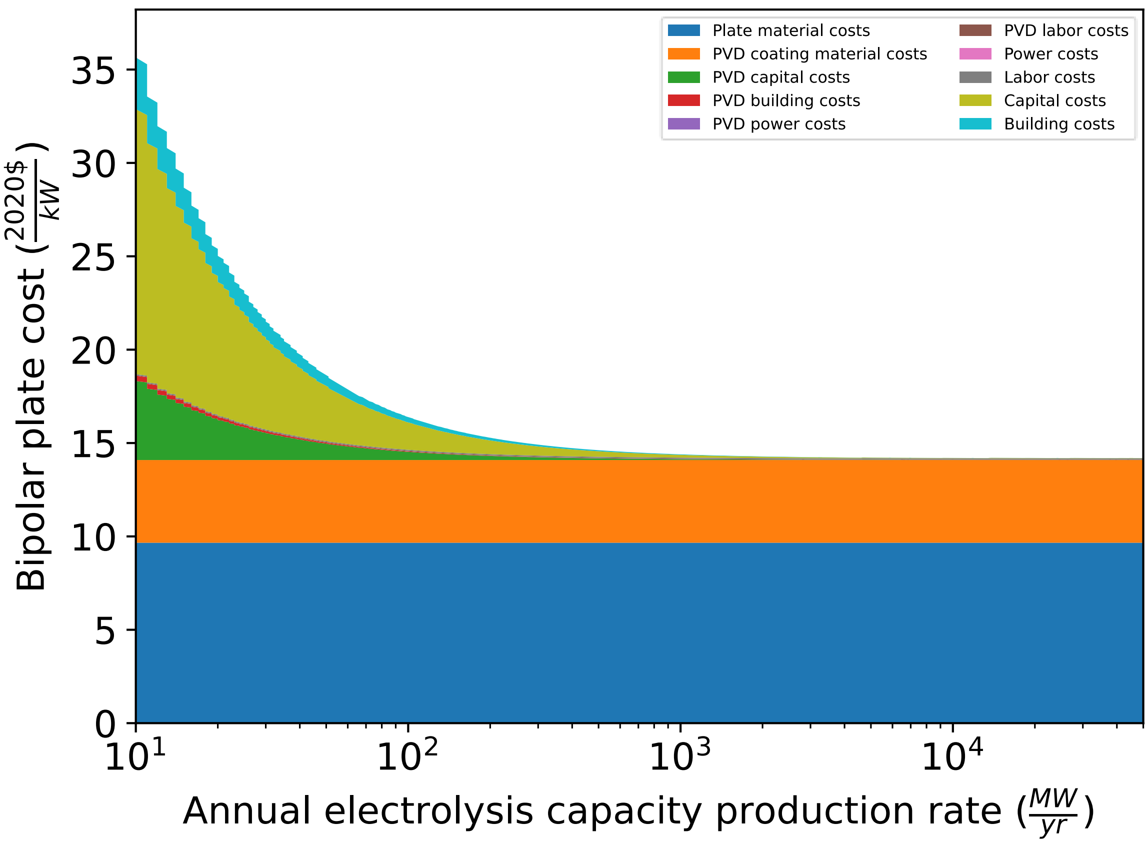


Figure 15. Manufactured cost estimates for bipolar plates

Figure 16 shows the cost distribution for components assembled into a completed stack at various scales. As assumed in Mayyas et al. (2019), a fully manual stack assembly process is used at small production rates, progressing to fully automated at high throughput. Manual assembly processes require significantly more labor and exhibit higher labor costs than fully automated assembly processes. Adhesive costs and capital costs are the second largest cost drivers of the assembly process. Capital costs for assembly increase as systems move toward more automated processes, representing slight increases but impacting costs less than labor cost changes.

System production rates of 100 and 250 systems per year were selected as the points when the model switches to semi and fully automated assembly processes, respectively (Mayyas et al. 2019). Switching to these systems at different rates could change the economics of this process, offering additional opportunities for cost optimization.

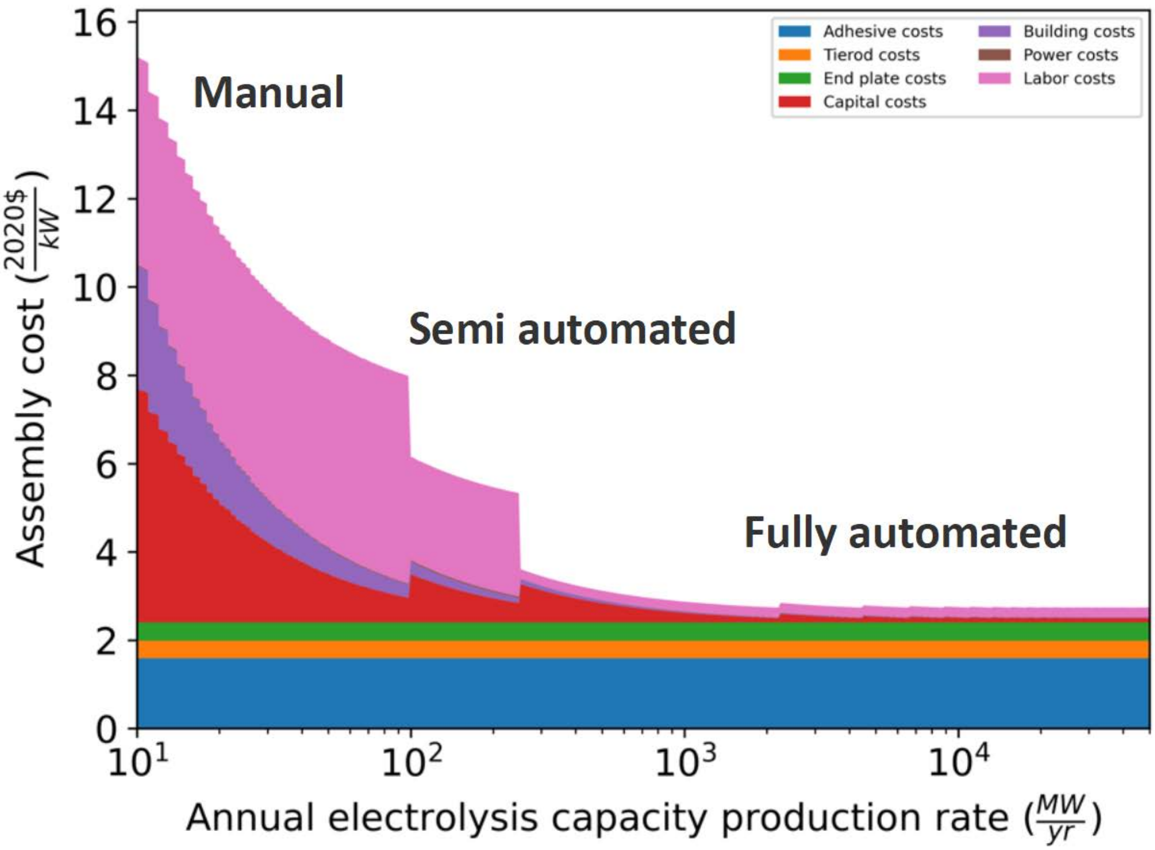


Figure 16. Manufactured cost estimates for stack assembly processes, with model adjustments for assembly processes at different throughputs. Labeled sections illustrate when the cost model switches between manual and automated stack assembly as production rates increase.

The total manufactured cost of the electrolyzer considered in this analysis is the sum of each part plus costs for stack assembly (Figure 17). Component costs are roughly aggregated by electrolyzer component. This illustrates the importance of the costs of catalysts in the electrolyzer stack and underscores the opportunities to lower manufactured costs through lower loadings. The loadings assumed in this work (Table 1) represent loadings for current PEM electrolyzers operating today, and future system designs target significantly lower loadings for both anode and cathode. Possible cost reductions associated with lower loadings are investigated in Section 3.3.

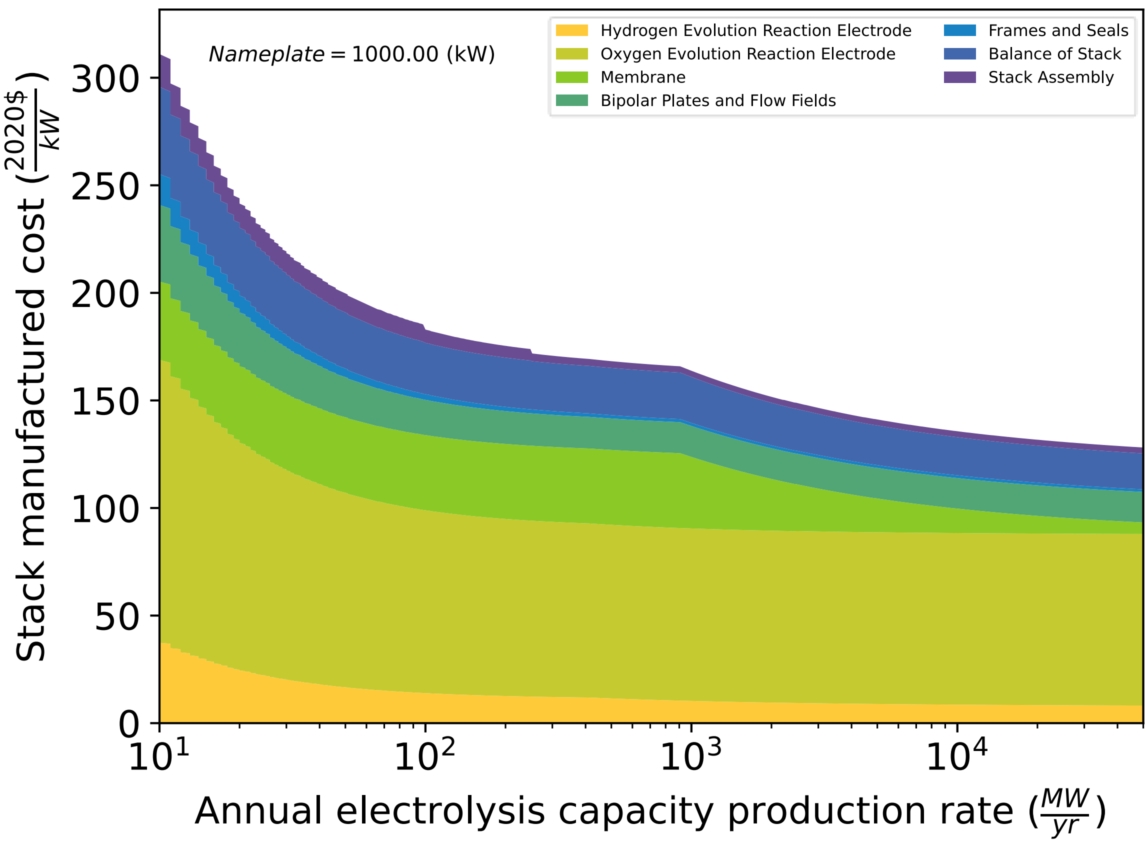


Figure 17. Electrolyzer stack manufactured costs at various production rates, illustrating the impact of manufacturing economies of scale on costs

Materials purchased from external suppliers such as the membrane and cathode GDL constitute a large portion of stack costs at scale. This work assumes modest purchase cost reductions of these components at scales near 700 MW/yr; however, at scales below this threshold, the costs of these components are significant. The evolution of costs for externally supplied components is a key uncertainty of this work because these costs are driven by external market factors, competing end uses, and manufacturing approaches.

For example, the cost of proton exchange membranes is likely to evolve and leverage greater economies of scale as electrolyzer manufacturers expand and increase throughputs, creating larger demand for these materials. In addition, the push toward thinner membranes to decrease ohmic resistances could result in lower materials costs associated with their manufacturing, a cost reduction that could be passed onto electrolyzer manufacturers. Finally, advanced production techniques designed to operate within a fully developed electrolyzer manufacturing supply chain could enable lower manufactured costs of various components. Detailed consideration of the cost drivers of externally supplied materials is beyond the scope of the present analysis but is an important opportunity for future work to address.

Given that the cost of materials used in manufacturing the stack comprise a large portion of total costs at production rates greater than 100 MW/yr, opportunities associated with recycling and salvaging the most expensive materials at the end of the stack lifetime is an emerging area of opportunity. For example, the intrinsic value of the iridium used in the anode catalyst is approximately $80/kW and is subject to change depending on loading rates and the market price for iridium. Recovering the value of this iridium and other high-cost materials when the stack has reached the end of life could increase the salvage value of the stack, favoring the overall economics of hydrogen production. Recovering materials, particularly PGMs from the stack, also represents an opportunity for developing circular domestic supply chains for these materials (Badgett, Brauch, et al. 2022).

Recovering the residual materials value from an electrolyzer stack requires the development and buildout of recycling systems to support these operations. This emerging area of research requires an understanding of how the design of an electrolyzer influences recyclability and degradation mechanisms occurring during operation that could preclude the recovery of certain materials.

3.2 Balance-of-Plant Costs

The baseline 1 MW BOP system consists of equipment upstream and downstream of the electrolyzer to handle water purification and thermal management, hydrogen/water separations, and supply of energy to the stack. At low production scales, we estimate a cost of $575/kW for the BOP of a 1 MW nameplate electrolyzer system. Figure 18 shows the breakdown of BOP cost by subsystem.

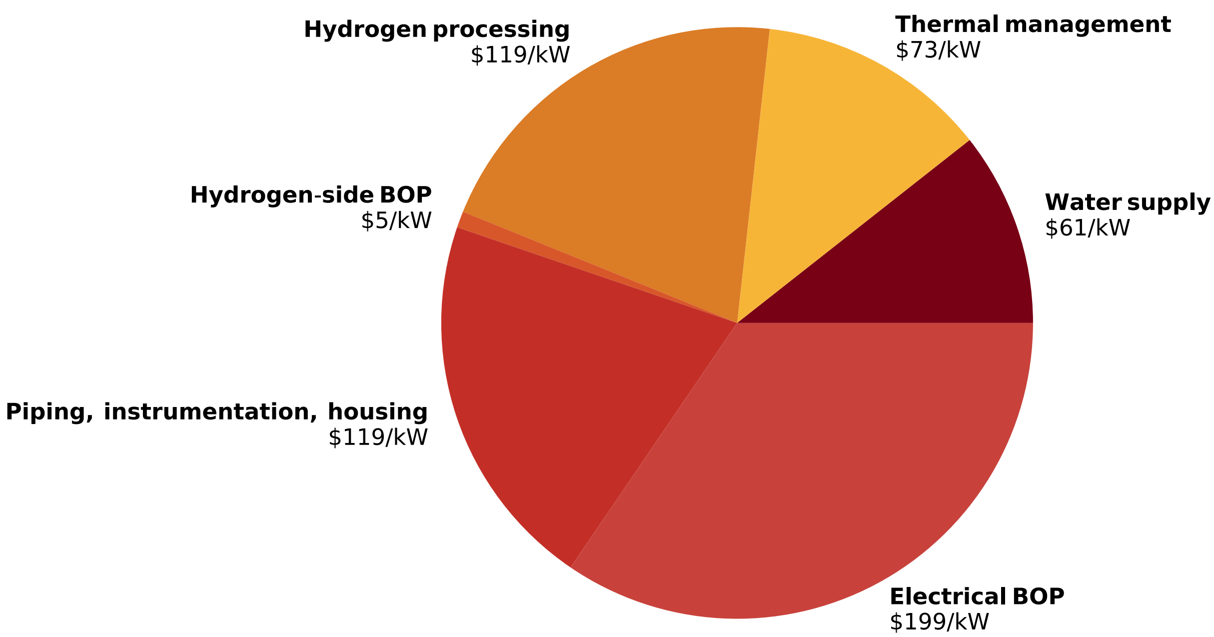


Figure 18. Balance-of-plant costs by subsystem at low production scales. Costs shown in 2020 dollars.

At $575/kW, BOP costs account for over half of estimated electrolyzer system costs at low manufacturing rates. Understanding possible opportunities to reduce BOP costs is therefore a critical objective of decreasing the capital costs of electrolyzers. Several key considerations might drive cost reductions, including manufacturing economies of scale, experience or learning-by-doing effects from increased electrolyzer production, optimization of subsystem design and integration, and optimization of electrolyzer/BOP integration.

Power electronics comprise the largest share of BOP costs and thus are a key area for reduction of system manufactured costs. Potential avenues for cost reduction of power electronics include direct improvement of power electronic technologies (e.g., increasing rectifier efficiency), optimization of stack voltage/current and power electronics design, scale-up of modularized power supplies specific to electrolysis stacks, and direct coupling with variable renewable power generation.

Other high-cost subsystems for BOP include hydrogen processing (which primarily encompasses the TSA for final hydrogen purification) and piping, instrumentation, and housing. As such, one potential avenue for BOP cost reduction could be reducing hydrogen purity requirements from the electrolyzer (e.g., by integration with a specific end use such as combustion). If output hydrogen could tolerate larger concentrations of water, TSA equipment could be made smaller or eliminated altogether. However, for a 1 MW system, the TSA tanks (the main driver of TSA costs) are small—perhaps toward a minimum practical size—and thus may not see significant cost reduction even at a smaller scale. Alternatively, operating the TSA at a lower pressure could also reduce costs by alleviating or eliminating the need for pressure vessels, which are more expensive than tanks or columns designed for ambient pressure. Operating at a lower pressure could have other implications, though, related to stack operation, BOP design, and integration with hydrogen offtake and use.

Piping, instrumentation, and housing have the potential to see cost reductions as more electrolyzers are deployed: R&D may yield alternative, more optimal system configurations. In addition, other components may see cost improvements with an increase in electrolyzer production, either from improvement to the component itself as demand increases or improvement in the integration with the electrolyzer system (e.g., system integration that combines a heater and cooler to remove a heat exchanger). As electrolyzer manufacturing scales, there may be opportunities to leverage expertise from other, high-scale industries (e.g., chemicals) on how to improve system designs and reduce costs at higher manufacturing scales.

To capture potential cost reductions as production scales increase, we apply exponential cost decay functions to BOP components as described in Section 2.3. This is intended to largely capture cost reductions because of *manufacturing* economies of scale—e.g., bulk purchasing discounts, improved use of equipment, and so on—and potentially some cost reductions because of BOP improvements from learning. Figure 19 shows the resulting BOP costs, broken down by subsystem, for a range of manufacturing scales.

Given that many of the BOP components are standard equipment (e.g., tanks and heat exchangers) that is purchased and assembled rather than manufactured in-house, BOP tends to see slower cost reduction with increasing scales compared to the stack, at least for a 1 MW system. Still, as scales increase exponentially, BOP cost reductions have the potential to be quite significant: At a production scale of 10 GW/yr, the entire BOP cost is only about $278/kW compared to an initial cost of $575/kW.

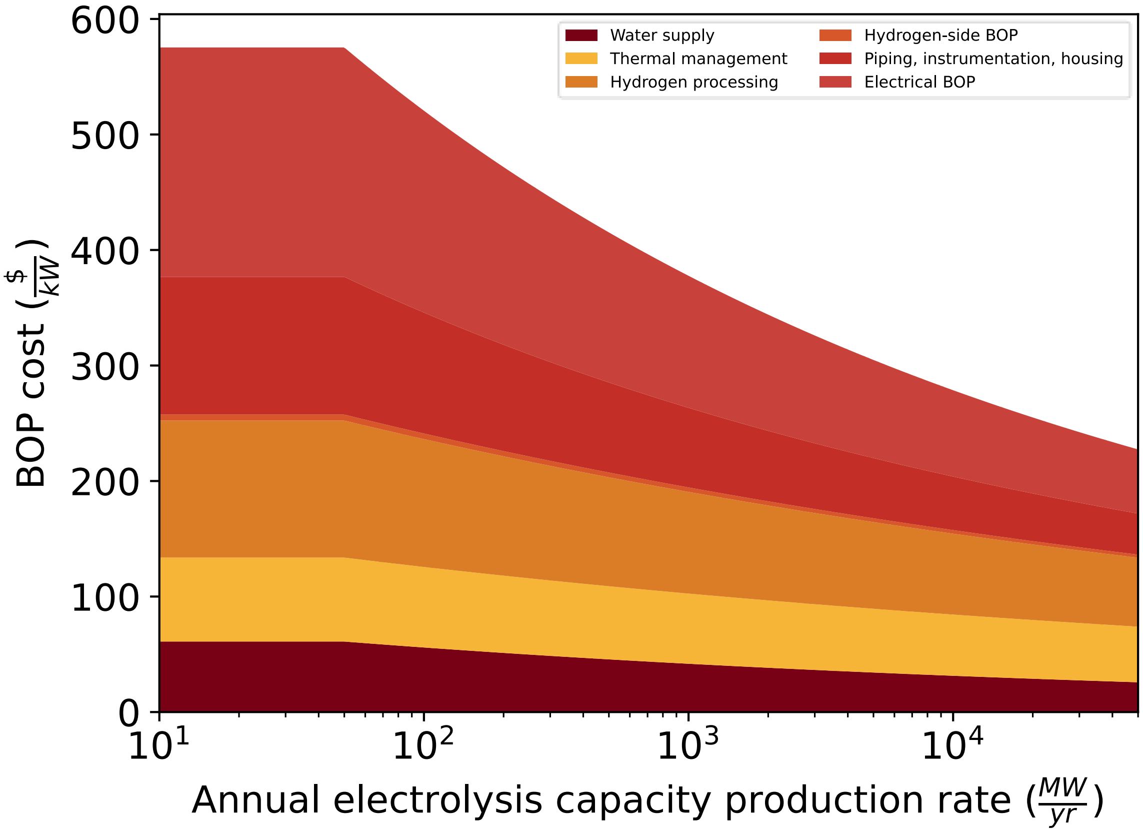


Figure 19. Balance of plant cost reductions at higher manufacturing rates. Note that the sharp "elbows" in this curve are an approximation as a result of the manufacturing threshold for cost improvement in our model; actual cost trajectories would likely be somewhat smoother.

These cost reductions are approximately equivalent to an average improvement rate of 9.1% applied to the entire BOP. Note that Figure 19 shows sharp "elbows" in the cost trajectory at the manufacturing threshold at which learning begins to be applied. This is an approximation based on our modeling approach. In reality, cost improvements would likely begin gradually *near* such a threshold, increase to more rapid improvements as learning and experience increases, and then level out as technologies mature (rather than show as a sharp drop in costs at a specific threshold).

It should be noted that factors influencing electrolyzer BOP cost reduction are highly complex and nuanced, and available data are limited at the component and subsystem level (see Section 2.3). As such, Figure 19 should not be taken as a prediction for electrolyzer cost but rather as a potential cost reduction trajectory for electrolyzer BOP as production scale increases. A particular value of this cost analysis is providing insight on how the evolution of major contributors to BOP change as production rates increase. Figure 20 shows the fraction of BOP cost each subsystem comprises over varying production scales for this potential cost reduction pathway.

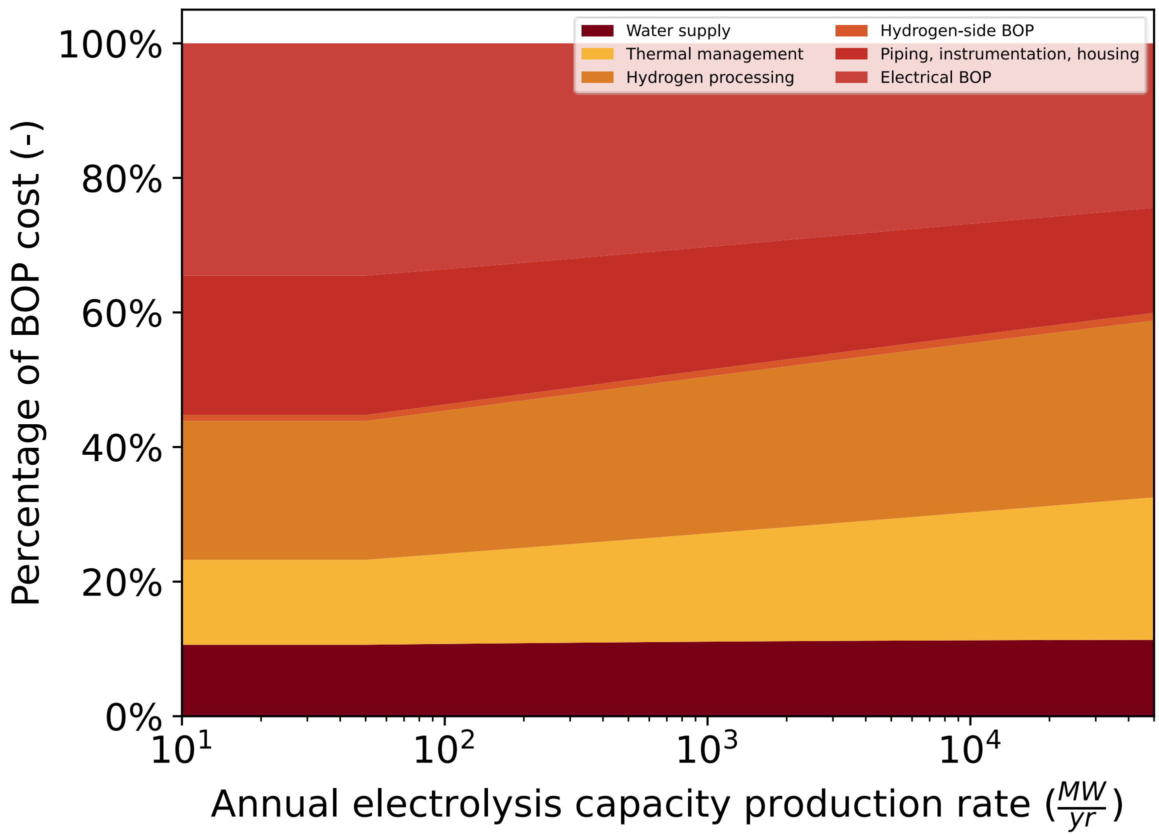


Figure 20. BOP costs by component as a percentage of total cost

Electrolyzer manufacturing may be able to exert a larger influence over the supply chain of components that are more nascent and specific to electrolyzers (e.g., hydrogen sensors, hydrogen-specific valves, piping and housing layouts, and electrolyzer power electronics), allowing for greater impacts of manufacturing economies of scale. These components may also see more rapid learning because they may be less developed. As such, as production scale increases, these nascent and specific components see more improvement and contribute less to system cost in our model. Conversely, subsystems based on more established technologies such as thermal management or hydrogen processing (TSA) comprise a larger portion of system cost at higher production scales. As production scales grow, shifting R&D efforts to some of these subsystems to look for major system and process improvements (rather than equipment/component cost reduction) could be impactful.

Further strategies for BOP cost reduction, such as alternative technologies (e.g., pressure swing absorption instead of TSA) and systems-level optimization of BOP and electrolyzer stacks, are outside the scope of this work but could represent critical pathways for achieving low electrolyzer costs. In particular, the use of larger BOP systems or subsystems (using larger nameplate capacities or BOP sharing among stacks) could allow for *process* economies of scale and may yield significantly lower BOP per-kilowatt costs.

To demonstrate this, we apply several different theoretical improvement rates and compare the resulting BOP costs to those in Figure 19. In Figure 21, we consider improvement rates based on BOP and gas conditioning learning rates in Bohm et al. (13% and 7%, respectively) (Böhm, Goers, and Zauner 2019) as well as an improvement rate roughly equivalent to the six-tenths rule of economies of scale (24%) . These three rates roughly capture the spread of improvement rates and learning rates we find in literature (see Section 2.3). As discussed in Section 2.3, these learning rates and the six-tenths rule are not equivalent to our improvement rate framework but are still shown in Figure 21 as function a of manufacturing capacity for high-level demonstration purposes. In reality, some of these cost reduction mechanisms would occur in relation to other scale parameters (e.g., cumulative deployment for learning and BOP system size for process economies of scale). Still, using them in this context can demonstrate the impact of larger cost reductions that may be enabled by BOP improvements outside the scope of this work. For example, a hypothetical cost of less than \$200/kW resulting from the six-tenths rule of economies of scale (24% improvement in Figure 21) may more likely be achieved by scaling up the BOP size to the GW scale, rather than by producing 1 GW/yr of total capacity via smaller BOP systems.

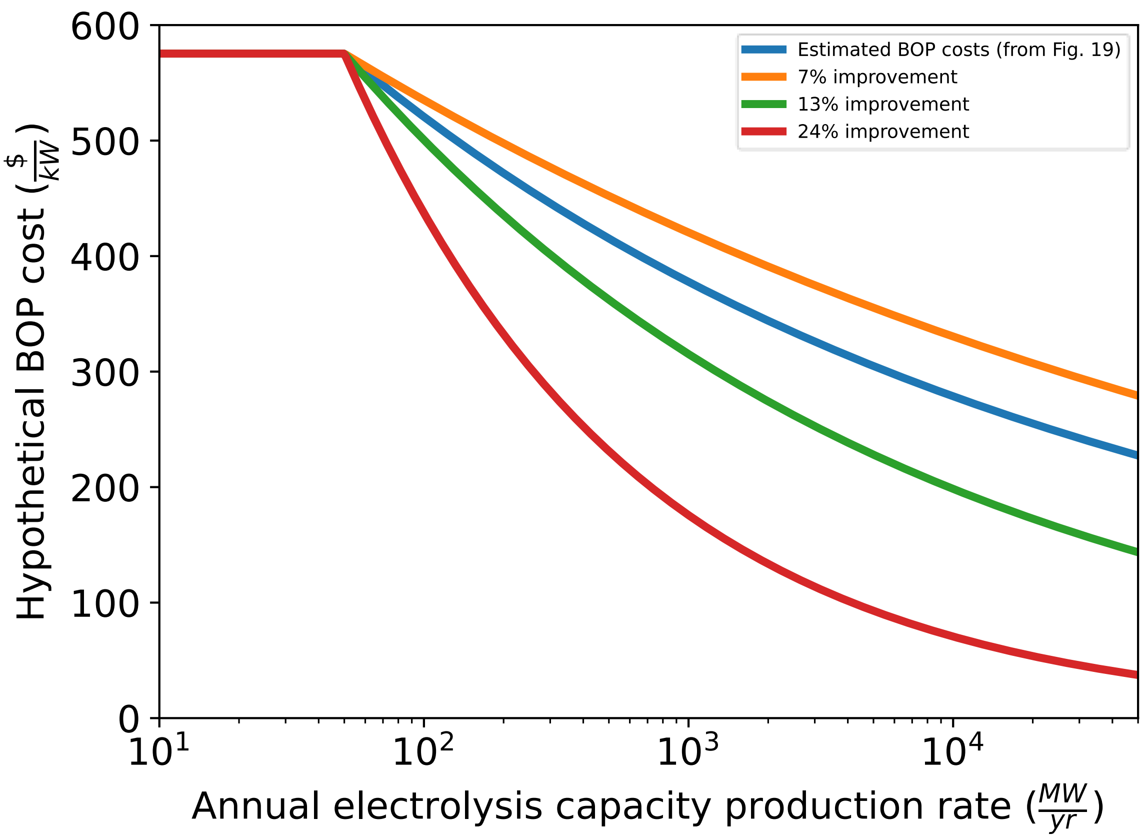


Figure 21. Alternative hypothetical cost trajectories for BOP cost reduction. These are based on high-level improvement assumptions and are intended to demonstrate potential impacts from BOP cost reduction strategies outside the scope of this work, including mechanisms that may scale with parameters other than manufacturing capacity (e.g., significant learning and BOP process scale-up). They do *not* indicate results founded in concrete analysis.

As shown in Figure 21, the costs for some of these trajectories are dramatically lower at higher production scales than costs in Figure 19. Note that these alternative trajectories are extremely high level and do not represent predictions or well-founded estimates of future costs. Still, they underscore the importance of considering additional BOP cost reductions strategies beyond manufacturing scale-up and show how the costs in Figure 19―although grounded in more detailed models for the scope of this analysis―may overestimate future BOP costs for practical installations.

3.3 Electrolyzer System Costs

Figure 22 shows comprehensive results for both the electrolyzer stack and BOP costs at varying production rates. On a high level, the electrolyzer stack and BOP both contribute significantly to total system costs, even at higher production rates. As such, improvements in both subsystems could be significant for electrolyzer cost reduction. The stack sees more dramatic cost reduction initially but levels out more quickly while the BOP shows slower but steadier cost reduction. This could correspond with rapid innovation for the electrolyzer stack—in general, a more nascent technology—compared to gradual improvements to more well-established BOP technology.

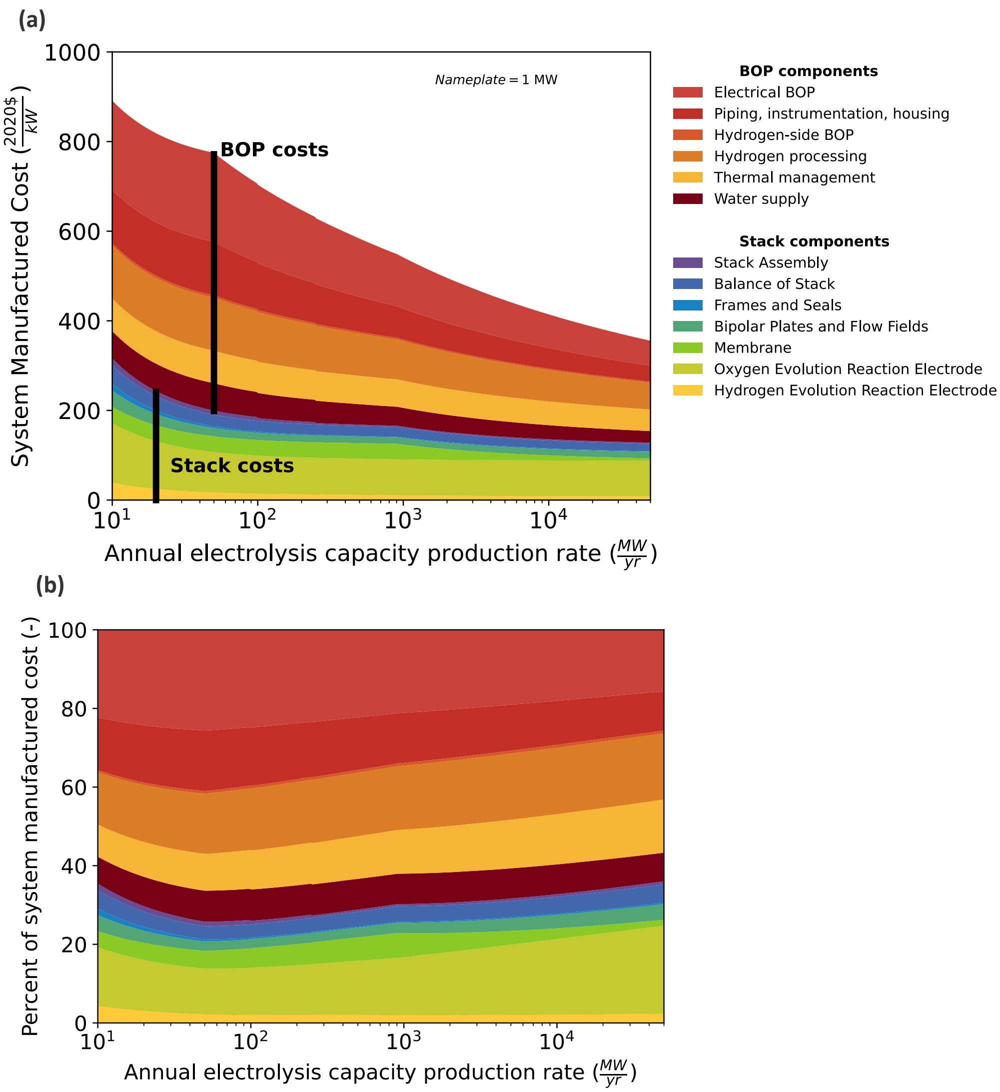


Figure 22. (a) Electrolyzer system manufactured costs at various production rates in $/kW; (b) electrolyzer system manufactured costs by component as a percentage of total manufactured cost. Projections for BOP use individual component improvement rates as discussed in Section 2.3. NOTE: These costs are in a 2020 dollar basis, and DO NOT include manufacturers mark-up, installation and soft cost, or inflation factors.

As manufacturing rates increase, stack costs could become dominated by OER electrode material costs, while BOP costs remain distributed among many components. Stack costs could thus see large reductions based on improvements only in the oxygen evolution reaction (OER) electrode, while BOP could require innovation in many components or subsystems to achieve large cost reductions. Electrolyzer manufactured costs at various scales are provided in Table 10 to estimate the impacts of economies of scale for stack manufacturing and the impact of BOP cost reductions on manufactured costs. Total manufactured costs for the stack and BOP are included in the rows following. These values represent the cost to manufacture the electrolyzer system but do not represent a market price for the system. A 50% markup on the manufactured cost is noted in the second-to-last row in Table 10 as a proxy adder onto the manufactured cost. The sum of manufactured cost and markup is shown in the final row of Table 10 and is used as a proxy for electrolyzer market price in the HLC calculations shown in Section 3.6.

Estimates of the marked-up manufactured cost for a PEM electrolyzer at various scales in the last row of Table 10 range from about $1,300/kW to $800/kW at manufacturing rates from 10 MW/yr to 1 GW/yr. These marked-up costs can be related to HFTO's definition for uninstalled capital costs; keeping in mind that the uninstalled capital cost for a PEM electrolyzer depends on the state of technology being manufactured, the manufacturing lines utilized, manufacturer markup, and other factors beyond the scope of this report. Additionally, the uninstalled capital cost will be different for different original equipment manufacturers (OEMs). Recently, the DOE "Pathways to Commercial Liftoff: Clean Hydrogen Report" has noted current ranges for electrolyzer uninstalled capital costs from $975 - $1200/kW (Murdoch et al. 2023), consistent with estimates in this report for production volumes in the range nearing 10 MW/yr to over 100 MW/yr.

Table 10. Manufactured Cost Estimates at Various Production Rates

Electrolyzer Component	10 MW/yr (2020$/kW)	100 MW/yr (2020$/kW)	1,000 MW/yr (2020$/kW)
Hydrogen Evolution Reaction electrode	38	14	10
Oxygen Evolution Reaction electrode	133	85	80
Membrane	36	35	33
Bipolar plates and flow fields	36	16	14
Frames and seals	15	3	1
Balance of stack	41	24	21
Stack assembly	16	6	3
Water supply	61	56	42
Thermal management	73	70	61
Hydrogen processing	119	111	88
Hydrogen-side BOP	5	5	4
Piping, instrumentation, housing	119	105	69
Electrical BOP	199	175	114
Total stack manufactured cost[a]	316	183	164
Total BOP manufactured cost[a]	575	520	377
Markup[b]	446	352	271
Marked-up manufactured cost[a]	1,337	1,055	812

[a] Totals may not sum because of rounding.
[b] 50% markup on total stack and BOP manufactured cost is assumed.

It is important to note that the costs shown in Table 10 show only the impacts of manufacturing economies of scale on costs. They do not include advances in system design such as lower catalyst loading rates, alternative materials, and improved cell performance. These cost drivers are discussed in detail in Sections 3.4 and 3.5.

3.4 Stack Sensitivity Analysis

This section outlines several sensitivity analyses conducted on various sections of the cost models developed in this work to identify key cost drivers at the manufacturing line and stack levels. These results underscore the important relationships between electrolyzer design, performance, and cost. Optimization across all these parameters is needed to ensure that commercial systems are low cost without sacrificing the performance or durability of the electrolyzer over its lifetime (Badgett, Ruth, et al. 2022).

Figure 23 considers cost trade-offs between slot die coating and ultrasonic spray coating for CCM production. Labor expenses for spray coating techniques are the most significant portion of manufactured costs because of the manual process operation and the low throughput of spray coating relative to faster R2R processes (Figure 23 [a]). As shown in Figure 23 (b), slot die costs are driven by the material costs of the CCM itself, primarily the PEM membrane and iridium catalysts.

The costs of CCM production via spray coating are sensitive to operating parameters of the manufacturing line (Figure 23 [c]). Because spray coating is a significantly lower throughput process than the R2R slot die alternative, significant capital and operating expenses are incurred to meet the throughput associated with mature electrolyzer manufacturing facilities. Line width and line speed are directly related to the rate of CCM production in m^2/yr and therefore significantly impact the capital and operating expenses. Labor is a significant portion of CCM costs when spray coating systems are used, making reductions in the number of employees per manufacturing line another key cost driver. Labor expenses for spray coating techniques are the most significant portion of manufactured costs because of the manual process operation and the low throughput of spray coating relative to faster R2R processes.

Conversely, because the slot die manufactured costs at scale consist primarily of material costs, parameters that impact the amount of material required to manufacture a component drive total costs. As such, manufacturing yield is the highest sensitivity for slot die systems considered here (Figure 23 [d]). Changes in yield significantly impact costs because a decreased yield both increases the amount of material used and reduces the output of the manufacturing line through higher rejection rates.

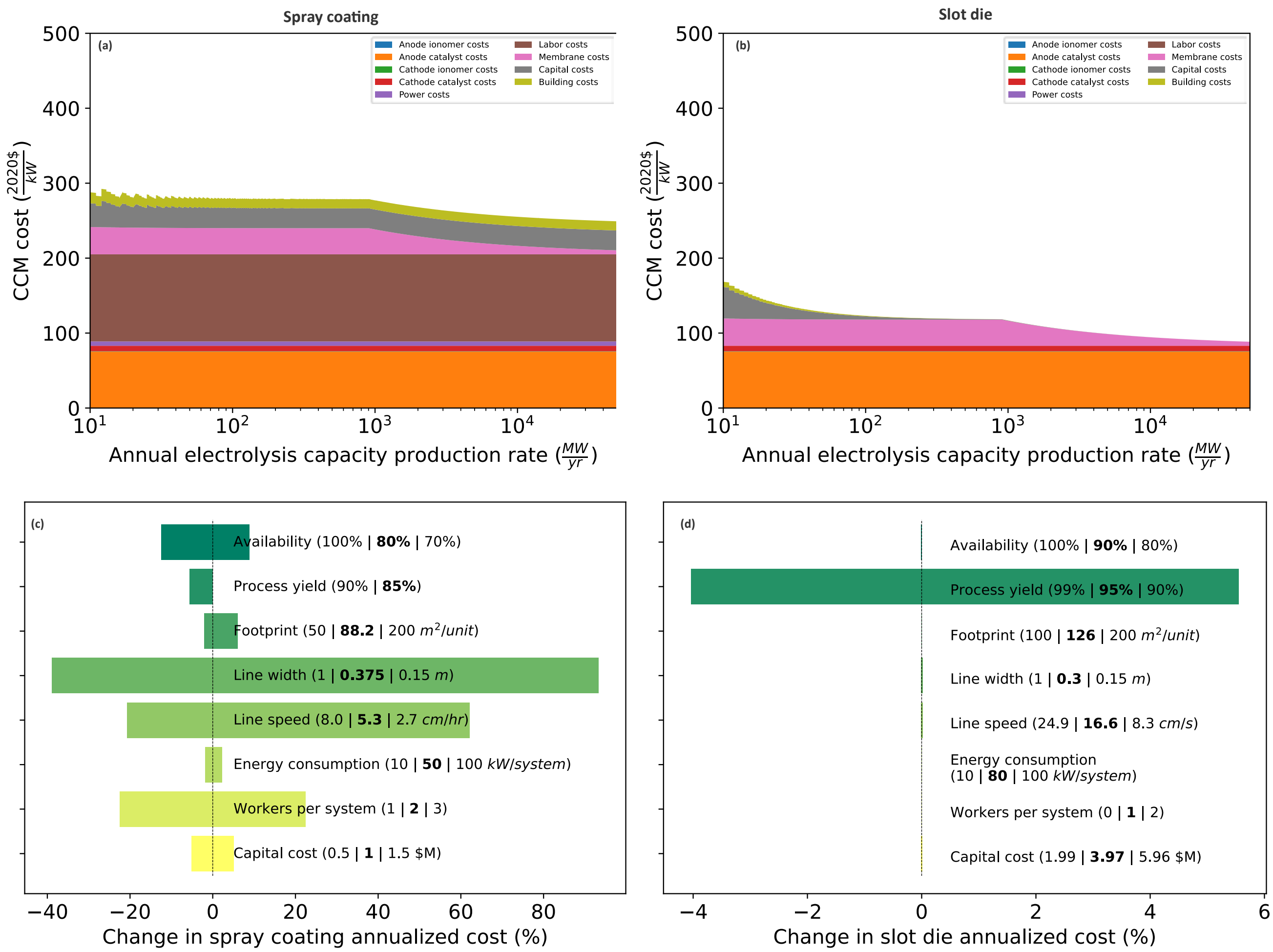


Figure 23. (a) Manufactured CCM costs for spray line production; (b) manufactured CCM costs for slot die production; (c) sensitivity analysis for spray line manufacturing systems; (d) sensitivity analysis for slot die manufacturing systems. Manufacturing rate for this sensitivity analysis shown in (c) and (d) is 1,000 MW/yr.

Although manufactured component costs are driven by yield and operating parameters, total stack production costs (on a $/kW basis) are driven by factors including system material usages and stack performance (Figure 24). While not shown in Figure 24, the rate of manufacturing is a large cost driver because it determines the utilization of manufacturing lines.

Operating current density of the electrolyzer stack is one of the most impactful parameters for total stack costs. Current density is a major cost driver because it directly determines the current flux through the stack and therefore the rate of hydrogen production. When capital costs are expressed in $/kW, a greater current density means that an electrolyzer can achieve a given nameplate power rating using fewer cells stacked together. Conversely, lower current density requires either larger individual cells or more cells in a stack. Because the CCM is one of the most expensive components in the stack, increasing the number of cells within a stack significantly increases material costs.

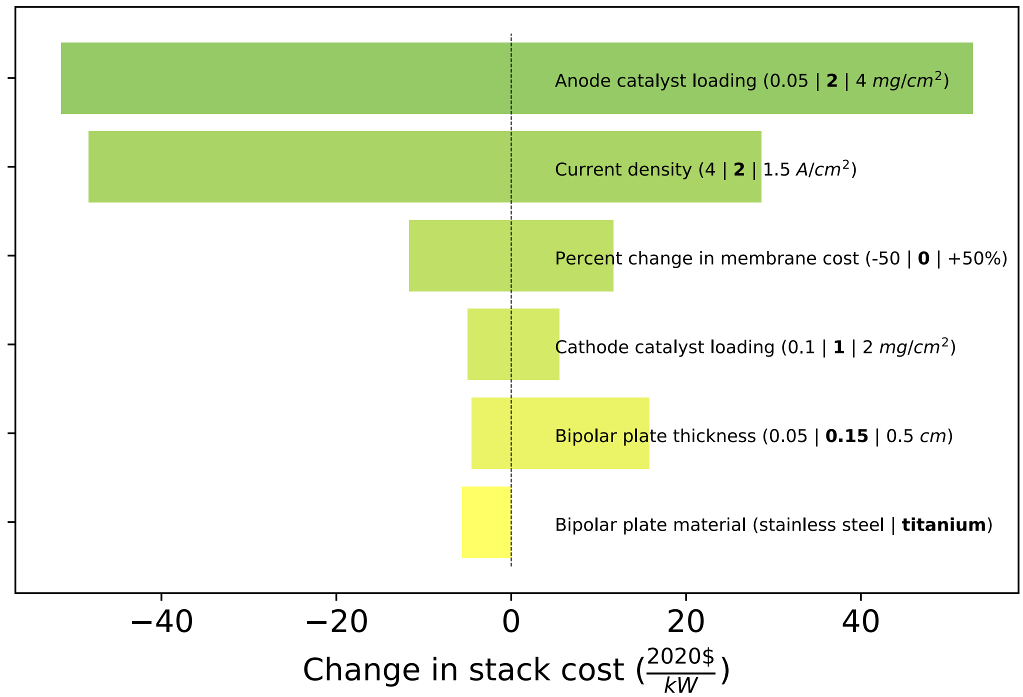


Figure 24. Electrolyzer stack sensitivity analysis. Baseline assumptions are listed in bold. 1,000 MW/yr stack production rate assumed.

Changing the usage rates of key materials is another opportunity for reducing stack production costs. High costs for iridium make anode catalyst loadings the largest opportunity for reduction in production costs, with bipolar plates and cathode catalysts comprising other important cost reduction opportunities.

The sensitivities identified can be used to guide strategies for manufacturing PEM electrolyzer stacks at the lowest possible cost. Achieving cost reductions requires combined advances in both manufacturing economies of scale and advances in system design and performance. Of the suite of strategies available for reducing stack costs, economies of scale, higher current density, and lower catalyst loadings are most likely to achieve significant reductions in the manufacturing of PEM stacks. It is important to note that the cost reduction strategies shown here vary in difficulty and can be interconnected. Some upper-end cost sensitivities might be possible to achieve using today's technology whereas others could require notable R&D advances. The "ease" of achieving these targets is not quantified in this analysis. In addition, driving anode iridium catalyst loadings lower while driving current density higher requires balancing system performance and durability. Low catalyst loadings can make electrolyzers more susceptible to performance degradation, especially those operating at high current densities (Alia, Stariha, and Borup 2019).

3.5 Cost Reduction Strategies and Pathways

There are numerous pathways to reducing the manufactured cost of a PEM electrolyzer system. This section discusses which pathways could yield the greatest impact as well as which pathways may face trade-offs between system design, cost, and performance. The impact of a given cost strategy on total manufactured costs depends on the given manufacturing rates and design parameters for the electrolyzer.

For example, if a stack uses extremely high loadings for catalysts, reducing those loadings is a significantly more relevant cost driver than a stack that is already using alternative catalyst materials or lower loadings.

Figure 25 shows modeled cost reductions from improvements to individual design variables at several manufacturing scales. At low manufacturing throughput, lowering PGM loadings and eliminating the costliest BOP components are likely to yield the largest cost reductions. However, cost reduction potential through BOP improvements may change at higher manufacturing scales. Because this analysis assumes some BOP cost reduction from production scale increases, the influence of eliminating BOP unit operations such as hydrogen processing and power electronics decreases at large manufacturing scales. Complete removal of these BOP components serves as a boundary case of possible cost reductions yielded from various systems integration strategies and is not intended to be predictive of real world costs. Comparatively, stack manufactured costs are dominated by capital costs for manufacturing lines at small scales but become almost entirely materials driven at large scales. Reductions in stack manufactured costs through thinner membranes or lower catalyst loadings are impactful across scales. Note that many of the design variables in Figure 25 are inherently connected (e.g., a thinner membrane may yield a higher current density), but here we consider only the effects of theoretical "isolated" changes in single variables for simplicity.

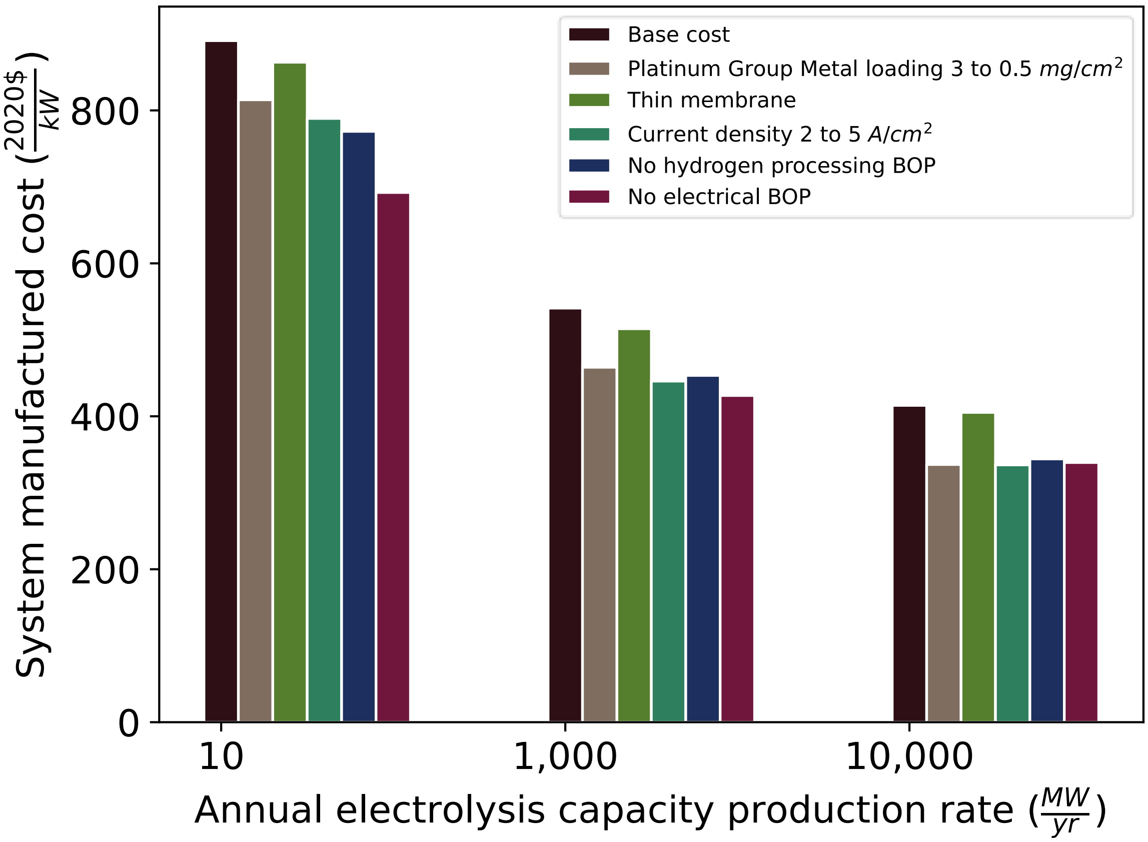


Figure 25. Cost reduction trajectories for several key technology advances, shown at three different manufacturing scales. Note that each trajectory (i.e., bar) represents a single change in only the specified variable. See Table A-7 for assumptions related to each trajectory shown.

Figure 26 shows the same cost trajectories as Figure 25 over a continuous range of manufacturing rates in addition to the cumulative impact of combining these trajectories, shown in gray. All the strategies discussed in this analysis yield incremental advances, but combining multiple strategies may be needed to achieve dramatic reductions in cost.

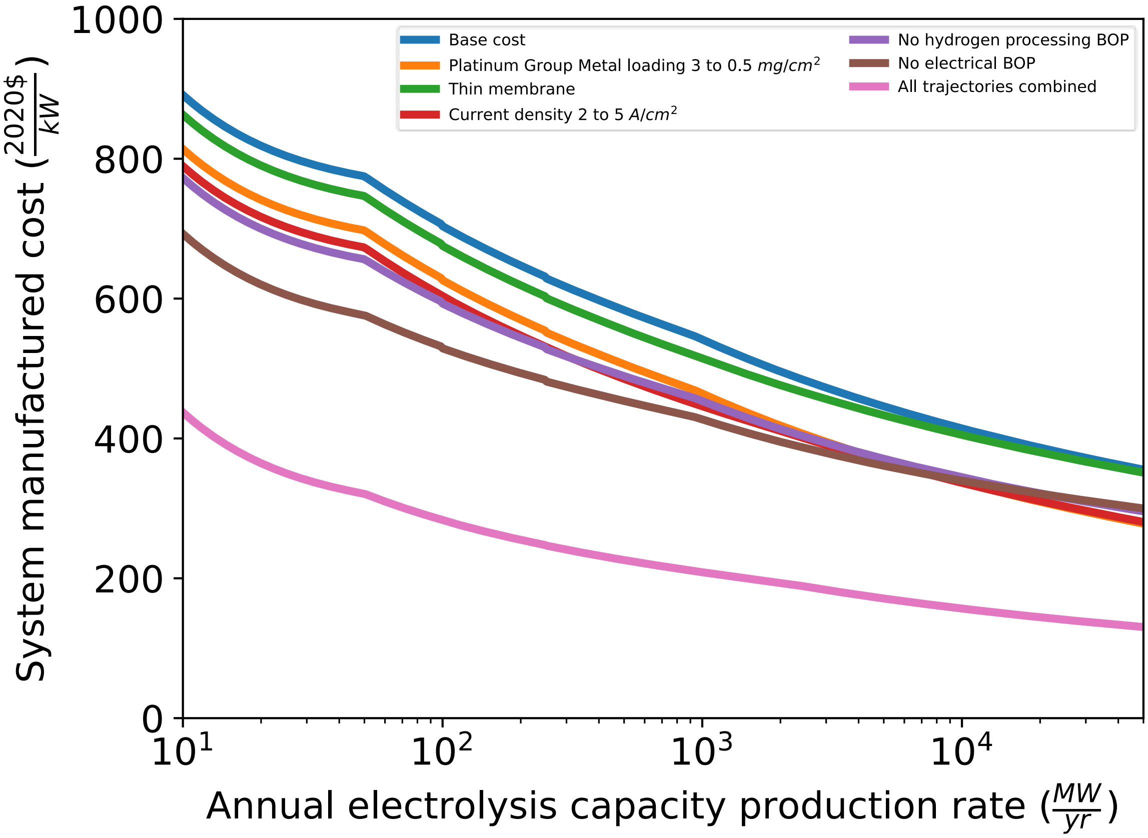


Figure 26. Electrolyzer cost trajectories at various manufacturing scales and all these cost trajectories combined (shown in pink). See Table A-7 for detailed assumptions associated with each cost trajectory.

We can expand the idea of the cumulative cost reductions from multiple advances to consider cost reduction trajectories. Figure 27 shows a waterfall chart considering a trajectory for stack advancements identified in Figure 25, with initial baseline costs on the left and reduced costs on the right. Each red step represents the impact of a given advance, including manufacturing economies of scale and improved performance. Although increased current density yields some of the largest cost reduction in Figure 27, it is important to note that the order in which advances occur impacts the magnitude of the change in costs. For example, current density is a significant cost driver of the baseline system defined here because we assumed high catalyst loadings for iridium and platinum relative to proposed target loadings. Increasing current density reduces the amount of catalyst used through higher stack current and increased hydrogen production. Reducing loadings prior to increasing current density would result in less of a cost impact because the system is already less expensive on a $\$/m^2$ basis. Because stack manufactured costs are driven by the capital expense of manufacturing equipment at low scales, increasing manufacturing throughput significantly reduces costs.

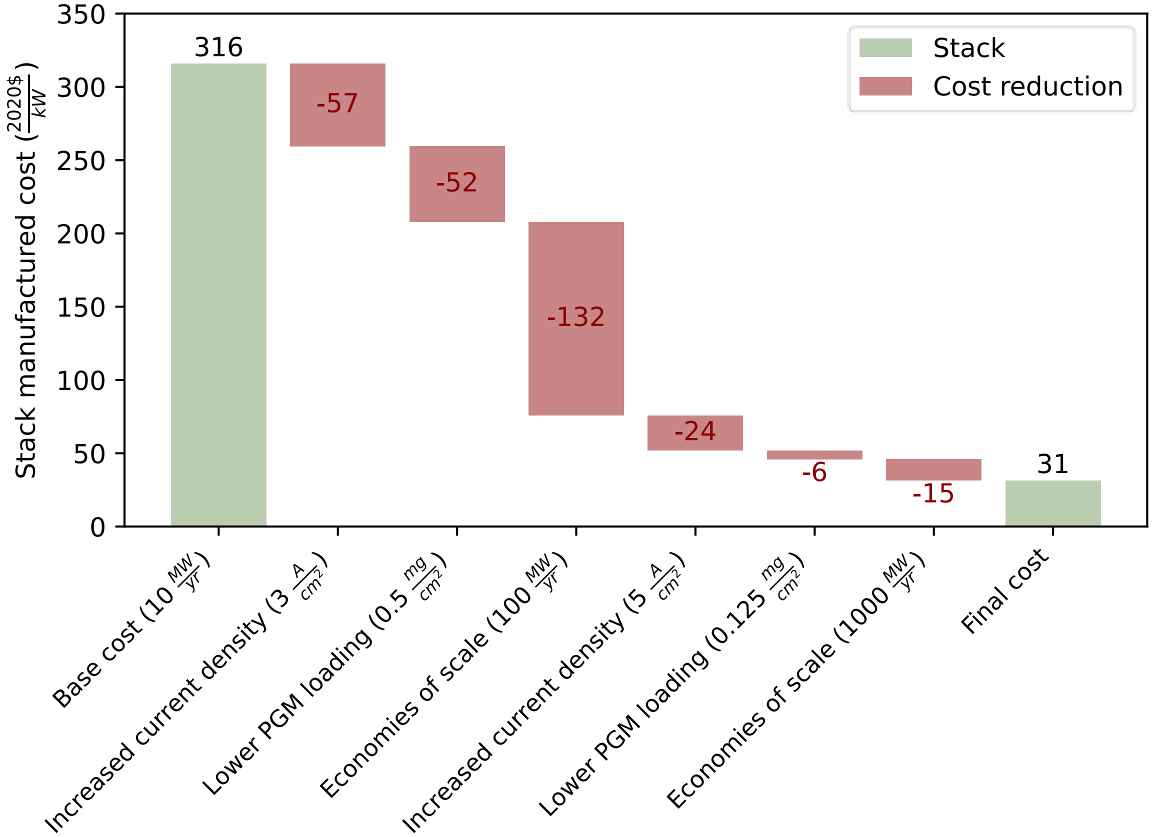


Figure 27. Waterfall chart showing cost reduction strategies for the PEM electrolyzer stack, including advances in system performance, lower catalyst loadings, and manufacturing economies of scale

These cost reduction strategies require careful consideration of trade-offs for electrolyzer manufacturing. It is important to operate manufacturing processes capable of supporting advanced electrolyzer designs that include alternative or reduced amounts of key materials. These systems must be capable of operating at high throughput and yield to minimize wasted materials. Figure 28 shows possible cost trajectories for the electrolyzer stack and BOP, which combine the stack cost reduction opportunities in Figure 27 with cost reductions from scale for BOP subsystems. "Stack-centric" cost drivers such as current density and catalyst loadings result in identical $/kW impacts for the system cost, but economies-of-scale steps result in larger cost reductions.

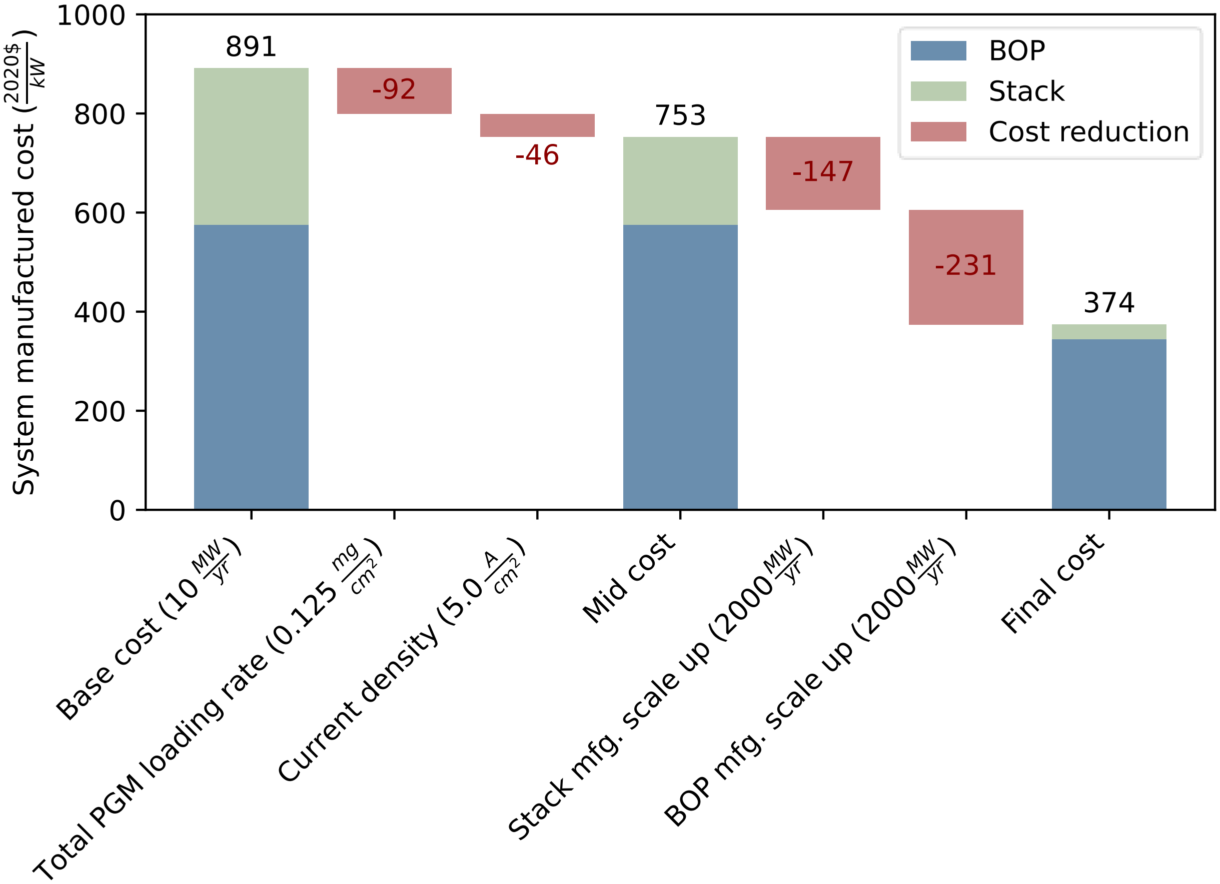


Figure 28. Electrolyzer system waterfall chart illustrating cost reduction strategies that include advances in stack performance and design and improvements to BOP costs from manufacturing scale increases

The cost reduction pathways shown in this analysis outline the importance of combining multiple advances to yield the greatest reduction in costs. However, some such advances could adversely affect other key cost factors and warrant consideration of the potential trade-offs. Several examples of these interdependencies are enumerated next:

- Lower catalyst loadings are a key opportunity for cost reduction; however, electrolyzers with extremely low loadings are more likely to experience reductions in performance through catalyst layer degradation. This effect is more pronounced for systems that are ramped up and down aggressively, making them less suited to dynamic operating profiles (Alia, Stariha, and Borup 2019). Minimizing catalyst loadings without sacrificing performance and lifetime is a key cost trade-off for PEM electrolyzers.

- Operating at very high current densities could reduce stack costs by reducing the amount of catalyst needed for a given amount of hydrogen production. However, high current densities may also drive higher voltages and lower efficiencies, requiring more electricity for hydrogen production. This could increase production costs, particularly in scenarios where electricity is expensive (e.g., a nonresponsive system that cannot ramp down during times of high-cost electricity).

- Advanced CCMs that use alternative or highly engineered materials must be able to be manufactured at scale. A highly efficient electrolyzer that requires the CCM to be manufactured in a manual spray coating line will not be able to achieve cost reductions through the economies of scale possible in slot die or other R2R processes.

- Opportunities to minimize the capital invested in BOP equipment depend on the end use for hydrogen produced and on the operating strategy for the electrolyzer. Using the hydrogen in a downstream biological or combustion process that is tolerant toward water and other trace impurities reduces the need for purification and associated costs. Conversely, water feeds with high levels of impurities will require more advanced treatment equipment and could increase costs. Directly connecting the electrolyzer to wind or solar generation could reduce the cost of power electronics but may be limited by the sizes of and transmission distance between the electrolyzer and power generator.

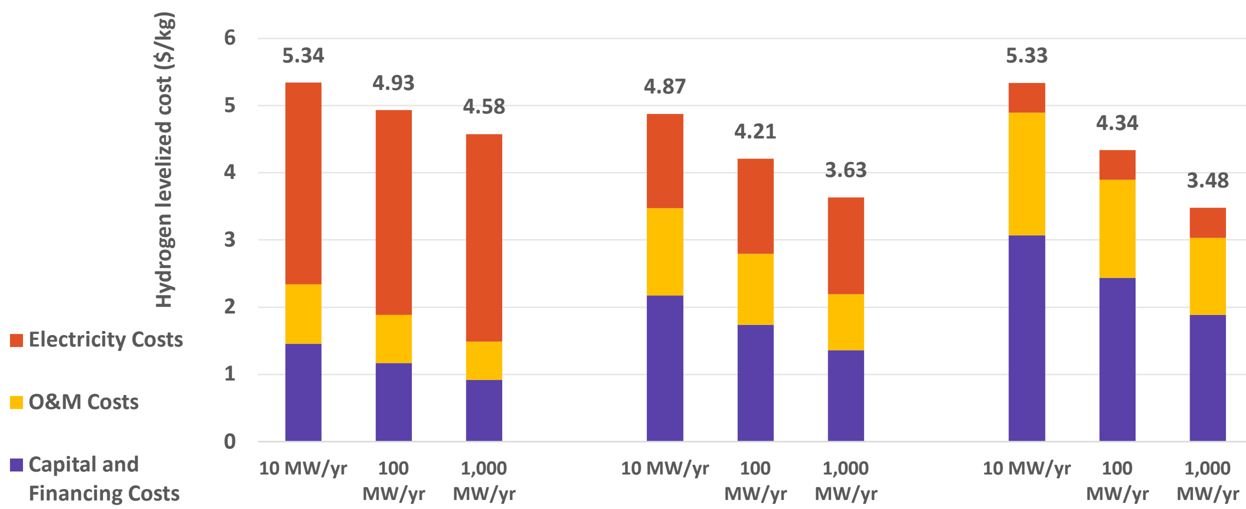
- Although this work does not focus on electrolyzer dynamic operating cycles, electrolyzers are likely to have a significant impact on system design and cost optimization. Electrolyzers that are cycled on/off frequently and ramped up and down aggressively are likely to experience faster performance degradation, potentially shortening the stack lifetime (Weiß et al. 2019; Alia, Stariha, and Borup 2019). Designing systems that operate without experiencing significant degradation while minimizing material costs is a key opportunity and area of ongoing work (Pivovar, Ruth, and Ahluwalia 2021).

3.6 Hydrogen Levelized Cost

Electrolyzer capital costs are only a portion of the levelized cost of hydrogen production, with electricity costs, installation, and other capital and operating costs impacting the cost of production. The relationship between total capital and operating and maintenance costs is captured in the hydrogen levelized cost (HLC), expressed in units of $/kg of hydrogen produced. This section uses some of the capital cost estimates from this analysis to estimate the HLC for an electrolyzer system in several scenarios. Here, capital costs realized by the hydrogen producer include a 50% markup rate for the electrolyzer on top of estimated manufactured costs, representing a proxy for the purchase price of the system (Table 10).

Figure 29 shows several scenarios for electricity price and capacity factor. These ranges reflect potential operating configurations possible for an electrolyzer: e.g., direct connection with renewable generation is likely to result in a lower capacity factor but less expensive electricity, while electrolyzers directly connected to the grid could operate at higher (e.g., 97%) capacity factors but may pay higher rates for electricity. As such, higher electricity costs are coupled with higher capacity factors, and lower costs are coupled with lower capacity factors. Three potential HLCs are calculated for each scenario given electrolyzer prices (estimated using a marked-up manufactured cost) of $1,337/kW, $1,055/kW, and $812/kW, corresponding to electrolyzer manufacturing rates of 10, 100, and 1,000 MW/yr.

At 10 MW/yr, the HLC ranges from ~$5.3 to $4.5/kg H_2, depending on the electricity price and capacity factor (Figure 29). For higher electricity prices and capacity factors, the cost of supplying electricity to the electrolyzer is the largest component of costs. However, as capacity factor decreases, the contribution of capital cost increases (because the cost is spread over fewer kilograms of hydrogen produced) to become the largest cost contributor for a 40% capacity factor. In this case the operational costs also increase as a proportion of total HLC since the default H2A assumption is that these costs are a fixed percentage of direct capital costs.



Electricity price	$0.06/kWh	$0.03/kWh	$0.01/kWh
Capacity factor	97%	60%	40%
Efficiency (kWh/kg)	55.3	55.3	55.3

Figure 29. HLC estimates using baseline electrolyzer capital cost assumptions.

O&M: operations and maintenance

Reducing the purchased system capital cost to $812/kW decreases the portion of production costs driven by capital costs and reduces the total levelized cost of hydrogen produced (Figure 29). Although the lower HLC from lower capital costs is clear, the lower capital cost also makes operation at lower capacity factors more economically feasible: At a high electrolyzer price ($1,337/kW), paying 3–6 times more for electricity to achieve higher capacity factors (60%–97%) generally yields a higher HLC than in the 40% capacity factor scenario, depending on the capital cost. Conversely, at a high electrolyzer price ($1,337/kW), operating at a 60% capacity factor yields a lower HLC compared to the 40% capacity factor scenario even with the lower electricity prices in the 40% scenario. This trend reverses at lower capital costs ($812/kW), where a lower capacity factor operation is favorable. This trend is important for emerging electrolyzer configurations such as wholesale power market integration or direct connection with renewable generation, both of which are likely to result in the system being operated at a lower capacity factor (Ruth and Ahluwalia 2022).

Note that in the analyses shown here, electricity prices are assumed fixed at the specified price for all hours that the electrolyzer operates. Although this assumption fits current operating strategies for electrolyzers, recent research has investigated opportunities for electrolyzers to operate in wholesale power markets in the United States, purchasing electricity at variable hourly rates (Badgett, Ruth, and Pivovar 2022). Doing so can reduce the cost of electricity to the system—perhaps at the expense of capacity factors if electrolyzers are shut down during times of high electricity prices, which makes the reductions in capital costs analyzed here even more critical. Such operation also implies that the electrolyzer must either cycle on/off to only buy electricity when prices are low or use battery energy storage to supply electricity during times when wholesale prices are high. Such strategies impact system designs and operation and will be considered in future work.

Just as nuances between the results of this analysis and DOE HFTO PEM electrolyzer cost targets were discussed in the Executive Summary and Section 3.3, we discuss the results of this Section in the context of HFTO targets for HLC. Specifically, HFTO HLC targets for 2026 and ultimate are $2/kg and $1/kg, respectively (DOE HFTO 2023). While lowering electrolyzer system costs is a key requirement for achieving low HLC, meeting cost targets also requires incorporating dynamic operation strategies similar to those discussed above. Dynamic operation that reduces the effective cost of electricity while the electrolyzer operates at a lower capacity factor is a key strategy likely to enable significant reduction in HLC. Dynamic electrolyzer operation introduces nuanced questions between performance degradation that results from numerous on/off cycles and the amounts of PGM used in the electrolyzer stack (Alia, Stariha, and Borup 2019), which directly influences the manufactured cost. While mapping and validating detailed pathways to achieve the $2/kg and $1/kg is not the focus of this work, we encourage readers to review other material more directly focused on strategies to minimize HLC while accounting for varying capital costs and operational strategies (Badgett, Ruth, and Pivovar 2022; Badgett et al. 2023).

4 Analysis Limitations

Understanding the assumptions of the results presented in this work is important to identifying the limitations of the values presented here and opportunities for future work. Of the assumptions made in the cost models analyzed here, several key assumptions used are listed and discussed in Table 11.

Table 11. Key Limitations of This Analysis and Associated Opportunities for Future Work

Key Assumption Related to…	Discussion
PEM membrane manufacturing supply chains and costs	This work used membrane purchase costs from today's (2023) suppliers as a starting point for membrane costs. Once a certain purchase amount is reached, we assume that costs on a $/m^2 basis decrease as a function of the amount of membrane purchased. Data on what drives the cost of producing membranes and how their costs will evolve at scale are scarce and could be a key driver of future electrolyzer costs. Understanding the cost of membrane (both PEM and other ionic exchange membranes) is a key opportunity for future work and could better inform projections for what these components might cost in the future. In the context of regulations around per- and polyfluoroalkyl substances (PFAS) and other related compounds, understanding manufacturing supply chains and recycling of perfluorosulfonic acid (PFSA) compounds used in PEM membranes is another important area of investigation (US EPA 2021; Spendelow and Garland 2011).
Power electronics costs and integration opportunities	Power electronics, including the transformer and rectifier, are a key driver of BOP costs, so reducing the costs of power electronics is a significant opportunity for BOP cost reductions. The costs assumed in this work were taken from historical quotes and estimates for power electronics costs, but an improved understanding of cost drivers for these components is needed in future work. In addition, the cost implications of directly connecting electrolyzers with renewable generation such as wind or solar photovoltaics is another area of interest. Previous work (Yodwong et al. 2020) has analyzed limitations and opportunities for integration on a technical basis, but the cost implications of these configurations are not well understood at this time.
BOP optimization with multiple stacks	Optimizing BOP equipment with stack nameplate and more than one stack is a significant avenue for potential electrolyzer cost reduction that is not considered in this work. Integrating multiple stacks with a BOP system would increase flow levels and equipment sizes. Many BOP components would benefit from economies of scale and could be cheaper on a normalized basis than smaller equipment. For example, several pressurized tanks used for separation in the current BOP system are below the lower end of the cost correlation used to estimate their costs. As such, with the methodology used here, an approximate doubling in scale of those components would result in minimal cost increases. Integration of BOP with multiple stacks at a significant scale could require centralization of electrolyzer facilities, which would have its

Key Assumption Related to…	Discussion
	own costs and benefits. A centralized electrolyzer facility would see benefits of scale, but the need to move hydrogen to points of use may lead to higher transportation costs or logistical challenges (e.g., pipeline rights-of-way). If the trade-offs between centralization and modularization can be quantified, there may be potential for optimization of modularity vs. integration of electrolyzer systems to be considered in future work.
BOP improvement rates	There is a high degree of uncertainty around how electrolyzer BOP costs will improve as production scales increase. Because the BOP is largely assembled from purchased parts, it may not see cost improvements like the stack from improved throughput and utilization. However, higher production scales can lead to cheaper bulk purchasing, more influence over the supply chain, and other manufacturing economies of scale benefits that could reduce BOP costs, so we expect some cost reduction as scales increase. BOP costs may also see improvement because of learning-by-doing effects, which could be significant but are not inherently tied to production scale, making them challenging to incorporate in this analysis. In this analysis, we model some cost reductions for the BOP based on Design For Manufacture and Assembly analyses of fuel cell system parts with costs at different manufacturing scales. These are not perfect analogs to electrolyzer BOP components and carry significant uncertainty in their application here. Future costs described in this work should not be considered predictions for electrolyzer costs but rather a potential trajectory of costs as production scale increases.
Electrolyzer economies of scale vs. manufacturing economies of scale	The cost analysis presented here focuses on economies of manufacturing scale achieved through increasing manufacturing throughput of electrolyzer production. This work does not investigate the impacts of economies of scale in the electrolyzer system itself. For example, moving from the 1 MW system nameplate considered here to a nameplate of 5 MW could result in cost decreases through electrolyzer economies of scale. Electrolyzers are highly modular and can be constructed at various nameplate capacities to meet the demands of various end users of hydrogen. Future installations are likely to use systems larger than 1 MW and/or combinations of multiple 1 MW systems. Although not considered here, these impacts could be significant, both with respect to BOP design and integration and for total system manufactured cost. Opportunities for process optimization and cost reduction will be explored in future work.

5 Conclusions

Hydrogen production through water-splitting electrolysis is an emerging pathway to enabling long-duration energy storage and decarbonization of various heavy-duty transportation and industrial sectors. The capital costs of PEM electrolyzers are a large portion of today's levelized cost of hydrogen production, and reducing capital costs can enable dynamic, lower capacity factor operating profiles. This work estimates the manufactured cost of a 1 MW PEM electrolyzer stack and supporting BOP equipment, finding that manufactured electrolyzer costs with assumed markup are likely greater than $1,000/kW at low manufacturing rates between 10-100 MW/yr. Key opportunities to reduce this manufactured cost include the following:

- Reduced catalyst loadings, particularly iridium used on the anode
- Thinner (less material-intensive) ion exchange membranes
- Manufacturing economies of scale
- Cost reduction to power electronics and hydrogen purification systems, potentially through integration or optimization with power supplies and hydrogen end uses
- Improvement to BOP costs from manufacturing economies of scale and potential improvements from learning by doing
- Increases in stack performance (higher current density, lower overpotentials, longer lifetimes).

This work suggests that advances in stack design, reductions in catalyst loadings, and BOP cost improvements could yield significant reductions in the cost of manufacturing a PEM electrolyzer. Although any one of these strategies can yield reductions in the manufactured costs of PEM electrolyzers, achieving cost targets requires the incorporation of all these strategies. There are important connections between system design, manufacturing methods, and electrolyzer performance, and achieving cost reductions requires consideration of the interplay between these factors.

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Appendix A. Stack Manufacturing Process Model Parameters

The following equations outline the approach used to estimate the manufactured cost of an electrolyzer stack component. The production capacity of a single production line is estimated for a given scale to calculate the number of manufacturing lines required. This variable can either be expressed in terms of area produced (Eq. A-1) or parts produced (Eq. A-2).

$$L_{cap} = 8{,}760(a)(y)L_{speed}L_{width} \tag{A-1}$$

Where:

L_{cap} = capacity of a single manufacturing line	$(\frac{m^2}{yr})$
a = manufacturing line availability	$(-)$
y = manufacturing line yield	$(-)$
L_{speed} = manufacturing line speed	(m/s)
L_{width} = manufacturing line width	(m)

$$L_{cap} = 8{,}760(a)(y)L_{prod} \tag{A-2}$$

Where:

L_{cap} = capacity of a single manufacturing line	$(\frac{parts}{yr})$
a = manufacturing line availability	$(-)$
y = manufacturing line yield	$(-)$
L_{prod} = manufacturing line rate	$(parts/s)$

The number of manufacturing systems required is a function of the total annual systems manufactured and the maximum throughput of a single manufacturing line. Fractional results are rounded up.

$$S_{reqd} = \frac{A_{area}}{L_{cap}} \tag{A-3}$$

Where:

S_{reqd} = number of required manufacturing lines $(mfg\ lines)$

A_{area} = annual active area manufactured $(\frac{m^2}{yr})$

The capital cost of the equipment is a function of the cost per line, the lines required, and the installation factor.

$$C_{equipment} = S_{reqd}(C_{mfg\ line})(1 + R_{install}) \quad \text{(A-4)}$$

Where:

$C_{equipment}$ = cost of manufacturing equipment (\$)

$C_{mfg\ line}$ = cost of equipment for one manufacturing line $(\frac{\$}{mfg\ line})$

$R_{install}$ = installation factor $(-)$

The capital cost of buildings required to house manufacturing lines depends on the footprint per line and number of lines required.

$$C_{building} = S_{reqd}\left(R_{building}\right)M_{footprint} \quad \text{(A-5)}$$

Where:

$C_{building}$ = cost of buildings (\$)

$R_{building}$ = cost of building on a per area basis $(\frac{\$}{m^2})$

$M_{footprint}$ = footprint of one manufacturing line $(\frac{m^2}{mfg\ line})$

$$C_{energy} = S_{reqd}\left(R_{power}\right)M_{utilization}(8{,}760) \quad \text{(A-6)}$$

Where:

C_{energy} = annual cost of energy for the manufacturing system $(\frac{\$}{yr})$

R_{power} = power consumption for a single manufacturing line $(\frac{kW}{mfg\ line})$

$M_{utilization}$ = percent utilization of the manufacturing lines on an annualized basis $(-)$

$$C_{labor} = S_{reqd}(R_{workers})M_{utilization}(8{,}760)R_{labor} \quad \text{(A-7)}$$

Where:

C_{labor} = annual cost of labor $(\frac{\$}{yr})$

R_{labor} = employees required for a single manufacturing line $(\frac{kW}{mfg\ line})$

R_{labor} = labor rate $(\frac{\$}{hr})$

The total annualized cost of operating a manufacturing system is summarized in Eq. A-8, with annualized capital costs and operating costs summed together.

$$C_{anualized} = CRF_{equipment}(C_{equipment}) + CRF_{building}(C_{building}) + C_{energy} + C_{labor} + C_{material} \quad \text{(A-8)}$$

Where:

$C_{annualized}$ = annual capital and operating expenses for the manufacturing facility $(\frac{\$}{yr})$

$C_{material}$ = cost of material consumed in manufacturing process $(\frac{\$}{yr})$

CRF = capital recovery factor $(\frac{1}{yr})$

Table A-1. Catalyst-Coated Membrane (CCM) manufacturing process assumptions

	Slot Die Coating	Ultrasonic Spray Coating
Capital cost ($)	$3,970,000	$1,000,000
Workers (workers/system)	1	2
Energy consumption (kilowatts [kW])	80	50
Throughput (parts/hour [hr])	n/a	n/a
Line width (meters [m])	0.3	0.375
Line speed (m/second [s])	0.166	0.00001048
Footprint (square meters [m^2]/system)	126	88.2
Yield (%)	95%	85%
Availability (%)	90%	80%
Max production rate	179 (m^2/hr)	0.014 (m^2/hr)

Table A-2. Bipolar Plate Manufacturing Process Assumptions

	Metal Stamping	Physical Vapor Deposition
Capital cost ($)	$1,500,000	$400,000
Workers (workers/system)	3	1
Energy consumption (kW)	50	10
Throughput (parts/hr)	660	n/a
Coating rate (micrometers [μm]/hr)	n/a	250
Batch setup time (hr)	n/a	0.25
Batch coating area (m^2/batch)	n/a	12.4
Footprint (m^2/system)	150	15
Yield (%)	90%	90%
Availability (%)	85%	85%
Max production rate	660 (parts/hr)	12 (m^2/hr)

Table A-3. Stack Assembly Process Assumptions

	Manual	Semiautomated	Fully Automated
Capital cost ($)	$500,000	$1,000,000	$2,000,000
Workers (workers/system)	4	3	2
Energy consumption (kW)	10	20	30
Cell assembly time (hr/cell)	0.1	0.07	0.01
Footprint (m^2/system)	151.2	151.2	151.2
Yield (%)	90%	95%	98%
Availability (%)	85%	85%	85%

Table A-4. Anode GDL Manufacturing Process Assumptions

	Sintering	Physical Vapor Deposition
Capital cost ($)	$1,900,000	$400,000
Workers (workers/system)	4	1
Energy consumption (kW)	100	10
Throughput (parts/hr)	120	n/a
Coating rate (μm/hr)	n/a	250
Batch setup time (hr)	n/a	0.25
Batch coating area (m^2/batch)	n/a	12.4
Footprint (m^2/system)	150	15
Yield (%)	90%	90%
Availability (%)	85%	85%
Max production rate	120 (parts/hr)	12 (m^2/hr)

Table A-5. Die Cutting Process Assumptions

	Die Cutting System
Capital cost ($)	$110,000
Workers (workers/system)	1
Energy consumption (kW)	17.8
Throughput (parts/hr)	7,000
Line width (m)	1.09
Footprint (m^2/system)	30
Yield (%)	90%
Availability (%)	85%
Max production rate	7,000 (parts/hr)

Table A-6. Frame Process Assumptions

	Frame Manufacturing System
Capital cost ($)	$700,000
Workers (workers/system)	2
Energy consumption (kW)	100
Throughput (parts/hr)	120
Frame area (m^2)	0.209
Frame thickness (centimeters [cm])	0.5
Footprint (m^2/system)	100
Yield (%)	99%
Availability (%)	85%
Max production rate	120 (parts/hr)

Table A-7. Cost Reduction Trajectories Assumptions

Trajectory	Assumption
Very low PGM loadings	0.4 milligrams [mg]/cm^2 iridium on anode, 0.1 mg/cm^2 platinum (Pt) on cathode
Thin membrane	70% reduction in membrane purchase cost
Very high current density	5 amperes [A]/cm^2
No hydrogen processing balance of plant (BOP)	Hydrogen processing component costs set equal to zero
No electrical BOP	Power electronics component costs set equal to zero
All trajectories combined	All cost trajectories above combined

Table A-8. General Economic Assumptions for Stack Manufacturing Systems

Name	Value	Units
Labor rate	30	$/hour
Hours of operation	8000	hours/year
Discount rate	8%	%
Lifetime	15	years
Installation factor	10%	%
Salvage rate	2%	%
Income tax	40%	%
Electricity price	0.06	$/kWh
Manufacturing equipment capital recovery factor	0.117	--
Building cost	880 (Mayyas et al. 2019)	$/m^2
Cleanroom cost	2640 (Mayyas et al. 2019)	$/m^2
Building/cleanroom capital recovery factor	0.217 (Mayyas et al. 2019)	--

Appendix B. Balance-of-Plant Cost Modeling Assumptions

We estimate piping, valve, and instrumentation requirements for the electrolyzer balance of plant (BOP) based on the process flow diagram and engineering judgment. Details are shown in Table B-1.

Table B-1. Estimated Piping, Valves, and Instrumentation Requirements for BOP

System Component	Quantity	Justification
4-inch piping	15 meters (m)	Larger piping for water side (assumed half of 30-m total piping)
1-inch piping	15 m	Smaller piping for hydrogen side (assumed half of 30-m total piping)
Solenoid valves	15	Five valves per temperature swing adsorption (TSA) column to direct flow appropriately for purification and recharging
Proportional valves	5	Five valves for high-pressure water separation (HPWS) and low-pressure hydrogen separation (LPHS) to reduce pressure
Water-side valve	1	Valve to control flow out of water tank
Three-way valve	1	Valve to control flow for radiator cooling loop before stack inlet
Check valves	10	Used to prevent backflow of fluid; estimate based on engineering judgment
Relief valves	5	Used to prevent catastrophic failure in the event of pressure buildup; approximately one per pressurized subsystem (HPWS, 3 TSA columns, TSA flash tank)
Thermocouples	13	One for each heat exchanger/heater inlet and outlet (eight total) plus one for water feed and four for stack inlets and outlets
Pressure sensors	10	Two per proportional valve, i.e., one for each inlet and outlet of each pressure reduction
Hydrogen sensors	2	Engineering judgment
Flow meter	1	Measures inlet water flow for system control

To calculate BOP assembly costs, we estimate the needed assembly operations based on the BOP specifications. We then determine the labor requirements for these operations based on Page's *Estimator's Piping Man-hour Manual* (Page 1999). Page gives an estimate for both 4-inch and 1-inch piping; for simplicity, we use an average labor requirement from both pipe sizes. Table B-2 details our assembly assumptions.

Table B-2. Assumptions for Assembly Labor Requirements

Operation	Estimated Labor (4-inch pipe)	Estimated Labor (1-inch pipe)	Estimated Number for BOP	Labor Requirements (work-hours)
Shop handling pipe	0.045/feet [ft] of pipe	0.031/ft of pipe	98.4 ft	3.7
90-deg. pipe bend	4.4	1.6	20	60
Attaching flanges	2.5	1.5	11	22
Machine butt welds	0.65	0.4	11	5.8
Flame cutting plain ends	0.18	0.09	48	6.5
Threading pipe	0.36	0.17	74	20
Butt weld preheating	0.5	0.2	11	3.9
Field handling pipe	0.25/ft of pipe	0.17/ft of pipe	98.4 ft	21
Making on screwed fittings and valves	0.5	0.2	74	26
Field handling valves	2	0.3	37	43
Field erection bolt-ups	1.4	0.8	11	12
Hydrostatic testing	0.02/ft of pipe	0.014/ft of pipe	98.4 ft	1.7
Installing pressure instruments	5.1	5.1	10	51
Installing thermocouples	0.7	0.7	13	9.1
Installing relief valves	1	1	5	5
Installing flow controller	17.7	17.7	1	17.7
Installing control panel	1.5/ft of control panel	1.5/ft of control panel	5 ft	7.5
Total				**315**

Rows may not add exactly to totals because of rounding.

We estimate that the water-side valves and flow meter will be attached with flanges (seven) plus an additional four flanges for other pipe connections. We assume that a pipe cut will be needed for each flange and valve, and most valves are attached using threading. Other estimates for pipe bends and the control system are based on engineering judgment.

Given the large degree of uncertainty, we apply a 50% contingency to the calculated labor in Table B-2. At $50/hour, this yields an assembly cost of $23,598.