Hydrogen Production Cost with Anion Exchange Membrane Electrolysis

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Prepared By:

Strategic Analysis, Inc.

Brian D. James (PI), Yaset M. Acevedo, Kevin R. McNamara,
Jacob H. Prosser, Jennie M. Huya-Kouadio

STRATEGIC ANALYSIS INC

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Throughout the entire project, SA has reached out to many professionals to obtain information on state-of-the-art manufacturing processes, system designs, electrolyzer efficiency, and performance/durability. SA strives to incorporate the best assumptions for each system analyzed to provide the most accurate cost results with appropriate transparency to the community. This would not be possible without the transfer of knowledge from leading companies in each field. The authors would like to particularly thank the following groups for their contributions to this 2024 report on AEM Water Electrolysis: NREL (Mark Ruth, Bryan Pivovar, Alex Badgett, Joe Brauch), EVOLOH (Scott Blanchet), Georgia Institute of Technology (Paul Kohl) and De Nora (Ed Revers, Andrew Smeltz, Chuck Schultz).

Authors Contact Information

Strategic Analysis, Inc. may be contacted at:

Strategic Analysis, Inc.
4075 Wilson Blvd, Suite 200
Arlington VA 22203
(703) 527-5410
www.sainc.com

The corresponding authors may be contacted at:

Brian D. James
Vice President, Energy Analysis Services
(703) 778-7114
BJames@sainc.com

Yaset Acevedo
Senior Engineer
(407) 719-6777
yacevedo@sainc.com

1 Executive Summary

Rigorous stakeholder-vetted techno-economic analysis was performed to assess the cost of hydrogen (H_2) produced using state-of-the-art Anion Exchange Membrane (AEM) electrolysis. Projected high-volume, untaxed and unsubsidized levelized cost of hydrogen (LCOH)[1] range from **2020 $1.78 to $3.68/kg H_2** depending on technology year, process design, and electrolyzer project scale, assuming an electricity price of $0.03/kWh and a capacity factor of 97% (Table 1).

Table 1. Hydrogen levelized cost for AEM KOH and AEM Water electrolyzer plants for a constant electricity price of $0.03/kWh and a 97% capacity factor.

Electrolyzer Case					
Technology Basis	-	Current		Future	
Nominal Year	year	2023	2023	2030	2030
Plant Scale	MTD	50	500	50	500
Plant Design	# of Modules	4	3	2	3
Levelized Cost of Hydrogen					
AEM KOH	2020 $ / kg H_2	$2.68	$2.32	$2.03	$1.78
AEM Water	2020 $ / kg H_2	$3.68	$3.29	$2.08	$1.83

The total installed capital cost for an AEM electrolysis plant was estimated from bottom-up stack and process plant cost models. The stack cost model accounts for manufacturing equipment, equipment maintenance, material, tooling, cycle time, yield, labor, utilities and general overhead. The process plant cost model accounts for purchased equipment, installation costs, site preparation, and general overhead costs. For this study, the AEM electrolysis plant is assumed to be a stick-built, greenfield project developed by an engineering, procurement, and construction (EPC) firm with electrolysis stacks purchased directly from an electrolysis stack manufacturer. The price of the electrolysis stacks is based on a bottom-up cost assessment with business markup for the electrolysis company fabricator. Two stack technologies bases are considered: Current and Future. Current represents 2023 near state-of-the-art stack design, materials, and performance but not necessarily available commercially in that year. Future technology correspondingly represents stacks using 2030 projected state-of-the-art design, materials, and performance. Both are based on a 1 GW/year factory stack manufacturing rate. Methods from the Hydrogen Analysis (H2A) production model, a peer-reviewed national laboratory-developed discounted cash flow (DCF) model, were used to calculate the production LCOH in 2020 $/kg H_2.[2] The baseline electricity price case ($0.03/kWh) corresponds to average wholesale electricity prices currently possible in U.S. markets with plentiful wind.[3] Similar low-cost electricity pricing is possible from solar

[1] Production cost only. Cost of hydrogen delivery, storage, and dispensing excluded from current assessment
[2] Hydrogen Analysis (H2A) Production Models. https://www.nrel.gov/hydrogen/h2a-production-models.html
[3] Seel, J.; Millstein, D.; Mills, A.; Bolinger, M.; Wiser, R. Plentiful Electricity Turns Wholesale Prices Negative. Advances in Applied Energy 2021, 4, 100073. https://doi.org/10.1016/j.adapen.2021.100073.

Power Purchase Agreements (PPA)[4] although these prices are typically limited by renewable energy capacity factors.

[4] M. Bolinger, J. Seel, C. Warner, and D. Robson, Utility-Scale Solar, 2022 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States, (2022), p. None, 1888246, ark:/13030/qt7496x1pc https://www.osti.gov/servlets/purl/1888246/.

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2 Analysis Summary

This Program Record documents projected LCOH for H_2 production from Anion Exchange Membrane electrolyzers based on techno-economic analysis of current and future technology. Results for the LCOH represent untaxed and unsubsidized costs associated solely with H_2 production and compression to 30 bar (delivery, storage, and dispensing not included). Clean H_2 production tax credits are not considered in this analysis.

This study focused on centralized AEM plants with production corresponding to nominal 100 MW to 1 GW input power. For an AEM plant, the 100 MW base case was sized to deliver 50,000 kg/day (50 MTD[5]) of H_2, whereas a 1 GW plant was sized to deliver 500,000 kg/day (500 MTD). The LCOH was evaluated in this report for two technology cases: Current (2023) Central plant and Future (2030) Central plant H2A cases. The Current (2023) technology basis is associated with an AEM stack using technology that is near state-of-the-art stack design, materials, and performance and assumed to be manufactured at a scale of 1 GW/year. The Future (2030) technology basis is associated with an AEM stack projected to be available in the lab by 2030 in terms of catalyst materials, construction, and performance. This case also assumes a manufacturing scale of 1 GW/year. Two competing stack and associated process designs were considered for the AEM plant: AEM KOH which assumes 1M KOH electrolyte electrolysis and AEM Water which assumes pure water electrolysis.

2.1 System Definition

The project cost and LCOH were modeled for two competing AEM technologies, AEM KOH and AEM Water. The project cost includes both the installed direct costs for the hydrogen plant and the overhead costs associated with developing and deploying the plant. Each hydrogen plant is assumed to be divided into separate and standalone H_2 production modules, supported by common high voltage infrastructure that supports the whole plant. Each module is assumed to be a fully independent electrolysis system including water supply and purification, electrolysis stacks including electrical energy supply and conditioning, heat management, liquid electrolyte/gas separation, and H_2 processing. See Figure 1 for a visual representation of the plant terminology and the scope of supply included within this project cost model.

[5] MTD – metric tonnes per day

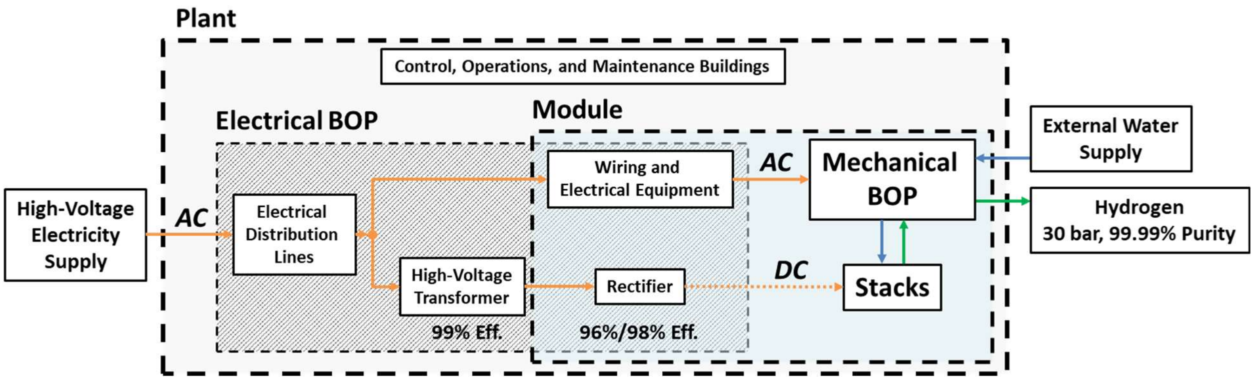

Figure 1. Plant terminology and scope of supply for modelled hydrogen production project

For both AEM technologies, the project cost and LCOH were calculated for four total base cases: 50 MTD Current Central, 500 MTD Current Central, 50 MTD Future Central, and 500 MTD Future Central. The Current 50 MTD cases are divided into 4 separate and standalone H_2 production modules (12.5 MTD/module) while the Future 50 MTD cases are divided into 2 modules (25 MTD/module). Large-scale 500 MTD plants are divided into 3 separate and standalone H_2 production modules (167 MTD/module), which are based on the maximum sizing for hydrogen compressors and water purification systems currently commercially available. Selection of module size is meant to balance a reasonable level of redundancy (to improve reliability and partial operation during module repair or maintenance) and the desire for large module size (to lower cost). The system definition for an AEM KOH electrolysis system is shown in Table 2 while the system definition for AEM Water electrolysis system is shown in Table 3.

For all cases, the plant lifetime is set for 40 years. The stack is assumed to operate at 60 °C. The plant output hydrogen is delivered at 99.99% purity and 30 bar, with water being the only expected impurity.

Table 2. System definition for AEM KOH.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	107	1,070	104	1,040
Number of Modules per Plant	#	4	3	2	3
Plant Power per Module (BOL Rated)	MW_AC	26.8	357	52.1	347
Number of Stacks per Module	#	112	1,499	24	158
DC Power per Stack (BOL Rated)	MW_DC	0.22	0.22	2.1	2.1
Current Density (BOL Rated)	A/cm^2	0.8	0.8	3.0	3.0
Cell Voltage (BOL Rated)	V	1.8	1.8	1.8	1.8
Stack Degradation Rate (at BOL Rated Current Density)	mV/kh	10.0	10.0	1.0	1.0
Stack Lifetime	year	4	4	10	10
Anode Pressure	bar	1.3	1.3	1.3	1.3
Cathode Pressure	bar	31	31	31	31
Stack Electrical Usage (BOL Rated)	kWh_DC/kg	47.8	47.8	47.8	47.8
Plant Electrical Usage (BOL Rated)	kWh_AC/kg	51.5	51.4	50.0	49.9
KOH Concentration	wt% / M	4.3 / 1	4.3 / 1	4.3 / 1	4.3 / 1

Table 3. System definition for AEM Water.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,099	104	1,036
Number of Modules per Plant	#	4	3	2	3
Plant Power per Module (BOL Rated)	MW_AC	27.6	366	51.9	345
Number of Stacks per Module	#	155	2,078	25	162
DC Power per Stack (BOL Rated)	MW_DC	0.16	0.16	2.0	2.1
Current Density (BOL Rated)	A/cm2	0.5	0.5	2.0	2.0
Cell Voltage (BOL Rated)	V	1.8	1.8	1.8	1.8
Stack Degradation Rate	mV/kh	48.6	48.6	1.5	1.5
Stack Lifetime	year	1	1	7	7
Anode Pressure	bar	1.3	1.3	1.3	1.3
Cathode Pressure	bar	31	31	31	31
Stack Electrical Usage (BOL Rated)	kWh_DC/kg	47.8	47.8	47.8	47.8
Plant Electrical Usage (BOL Rated)	kWh_AC/kg	52.9	52.8	49.8	49.7
KOH Concentration	wt% / M	-	-	-	-

The system is modeled assuming constant H_2 production (constant current), thus the energy consumption varies over the stack lifetime due to voltage degradation. Rated voltage and current density are listed in Table 2 and Table 3 to provide a reference point for the reader to assess general polarization performance. Balance of plant (BOP) equipment energy demand is calculated from Aspen simulations of the BOP and assumed electrical rectifier and high-voltage transformer efficiencies from public information.[6] A modest efficiency improvement is assumed for the balance of plant as the module size increases leading a slight reduction in the balance of plant equipment energy going from the 50 MTD to the 500 MTD systems. Multiple sizes of modules for each case were evaluated to measure the impact on the cost of H_2. These modules are categorized by the module input power and number of stacks. Conventional AEM systems operate using a 4.3 wt% KOH concentration (~1 M KOH) as represented by the AEM KOH cases. However, there is significant interest in pure water systems as represented by AEM Water cases due to enhanced process equipment durability, simplification of maintenance activities, and elimination of KOH water waste stream.

2.2 AEM Operating Point Optimization

The rated stack operating point[7] on the polarization curve can differ from the cost-optimal operating point, due to the effect of electricity price on the LCOH. A trade-off exists between stack size and capital cost versus system electrical usage and total electricity cost while maintaining the same net hydrogen production rate. SA performed an iterative calculation to determine the cost-optimal operating point (i.e., operating point that achieves minimum LCOH for each AEM case).

Based on the expected performance of Current and Future AEM systems, electrolysis cell polarization curves were postulated based on a simple first-principals electrolysis model (previously developed by SA) that enables a realistically-shaped curve to be fit to a specified rated operating point (cell voltage and current density). In this manner, full polarization curves can be generated for future systems using only a single hypothesized future performance point.

AEM stack design is similar to Proton Exchange Membrane (PEM) stack, which informs the potential for future AEM stacks to achieve high polarization curve performance. Similarly to PEM, AEM stacks use a dry cathode with water permeating though the membrane and a cathode outlet consisting primarily of gaseous hydrogen. In addition, AEM uses a lower ~1M KOH concentration compared to Alkaline which typically uses ~7M KOH. The associated ionic conductivity is ~5x less for an AEM stack compared to an Alkaline stack at electrolysis temperatures of 60 to 90 ℃.[8] Therefore, the voltage losses associated with shunt currents will be minimized for AEM stacks.

The rated operating point selected for the AEM KOH Current case is based on a composite of publicly available performance data for both commercial stacks and lab-scale demonstrations (1.8 V/cell at 0.8 A/cm^2). Examples of higher current densities at similar voltages, up to 3 A/cm^2, have been seen in small-scale demonstrations, especially when Pt catalyst is included. To be conservative, this study limits the

[6] Current rectifier efficiency assumed to be 96% while Future rectifier efficiency assumed to be 98%. Transformer efficiency assumed to 99% for all cases.
[7] Operating point refers to the cell voltage and current of the electrolyzer stack.
[8] Gilliam, R.; Graydon, J.; Kirk, D.; Thorpe, S. A Review of Specific Conductivities of Potassium Hydroxide Solutions for Various Concentrations and Temperatures. International Journal of Hydrogen Energy 2007, 32 (3), 359–364. https://doi.org/10.1016/j.ijhydene.2006.10.062.

rated current density to 0.8 A/cm^2, since this has been shown commercially and a primary advantage of AEM over PEM electrolysis is the minimization of precious metal catalysts. In addition, there is presently uncertainty about how much degradation will affect AEM performance at higher current densities. Commercial offerings for AEM KOH will continue to increase in current density over the next decade. The rated operating point selected for the AEM KOH Future case (1.8 V/cell at 3.0 A/cm^2) is based on the assumption that AEM KOH stacks can reach the same performance achieved by Proton Exchange Membrane (PEM) stacks due to similarities in stack design and operation (although the PEM membrane conducts H^+ ions and the AEM membrane conducts OH^- ions). This assumption for Future case performance is useful from the perspective of understanding the potential of AEM technology but has not been validated by experimental results. Stack degradation in the Current scenarios is derived from publicly available AEM degradation data. Future stack degradation is assumed to match the general performance of Future PEM stacks. For cost estimation purposes, the stack lifetime is assumed to be 4 years for the Current case and 10 years for the Future case.

AEM Water membranes suffer from far lower performance during lab-scale tests and is reflected in the assumed rated polarization point for the Current case (1.8V/cell at 0.5 A/cm^2). While performance is expected to improve over time, current experimental data suggests that AEM Water systems will always perform worse than their AEM KOH counterparts. This is reflected in the assumed rated polarization point for the Future case (1.8 V/cell at 2.0 A/cm^2). In addition to lower performance, AEM Water stacks have significantly more rapid degradation. Commercially relevant AEM Water stack lifetimes have not yet been demonstrated so conservative estimates of 1 year for the Current case and 7 years for the Future case were selected for cost estimation.[9]

The Current and Future polarization curves were combined with the assumed degradation rate for each case to establish the stack beginning of life (BOL) and end of life (EOL) polarization curves (Figure 1 for AEM KOH and Figure 3 for AEM Water). The degradation rate is assumed to scale linearly with current density. The lifetime was derived from the degradation rate and a practical nominal operating window of 1.8 to 2.2V/cell for the rated operating point. The Current case shows lower performance and higher degradation assumptions compared to the Future system. In other words, for the same current density, the Current case assumes a higher voltage than the Future system. The performance model assumes a constant current operation (constant H_2 production) with varying voltage (varying efficiency) and uses the average voltage to determine the energy usage (kWh/kg) over the stack lifetime.

For a fixed production rate, the stack operating point and stack capital cost are interdependent; therefore, these must be co-optimized. Results from the performance model and the AEM stack costs are used in the H2A LCOH model to estimate the resulting levelized cost of H_2 for a range of current densities. Further details of levelized cost of hydrogen calculation are provided in Section 5.1. The optimization of this LCOH model determines the constant stack current density that results in the lowest

[9] Much AEM Water research is focused on improving membrane durability (at high levels of performance) and researchers anticipate achievement of 1+ years of durability in the short future. Consequently, we select a 1 year lifetime (48.6 mV/kh degradation rate) for Current technology although this is on the optimistic side of current capabilities.

H_2 cost ($/kgH$_2$). Note that the stack lifetime is assumed to be constant, regardless of the selected current density. Since the estimated degradation rate scales with current density, operating points at lower current densities may be able to have longer stack lifetimes and have additional capex savings at the expense of a higher average stack electrical usage. This additional layer of optimization is not considered in this study.

Figure 4 for AEM KOH and Figure 5 for AEM Water graphically illustrate the optimal LCOH for each technology basis assuming an electricity price of $0.03/kWh. A summary of the optimized operating points is shown in Table 4. The cost optimization for AEM KOH finds that a low current density (~0.6A/cm^2) is the cost-optimal operating point for the Current case whereas the Future case optimizes to a higher current density (~0.8 A/cm^2). The cost optimization for AEM Water suggests the cost-optimal operating point is ~0.9 A/cm^2 for both the Current case and the Future case. Note that these cost-optimized current densities are based on $0.03/kWh electricity and a specified stack cost (~$0.17/cm^2 for Current, ~$0.11/cm^2 for Future, see section 3.1). If these parameters change significantly, the optimized current density is also expected to change.

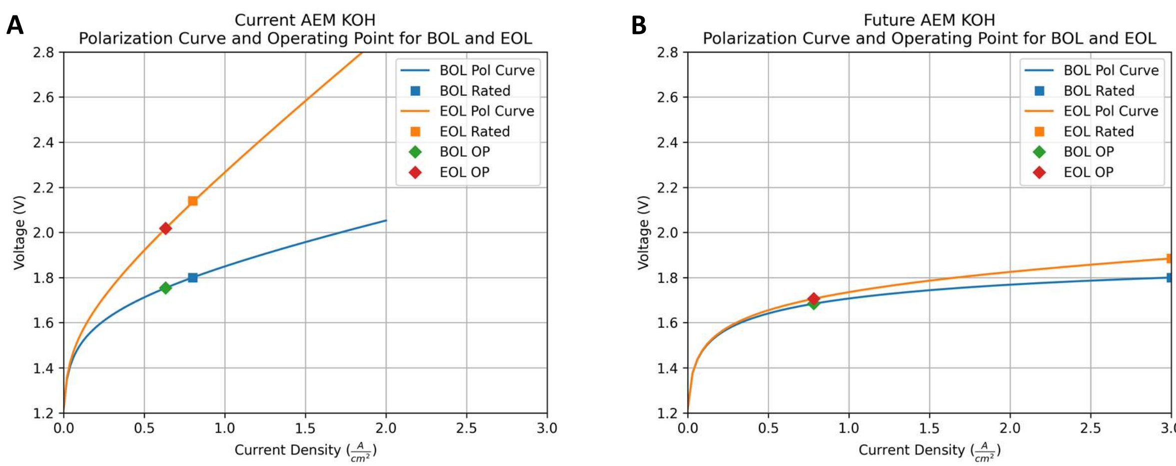

Figure 2. Graphs of rated and optimized (OP) polarization (Pol) curves for AEM KOH at BOL and EOL for (A) Current and (B) Future technology bases. Assumes 4 year stack lifetime for Current case and 10 year stack lifetime for Future case.

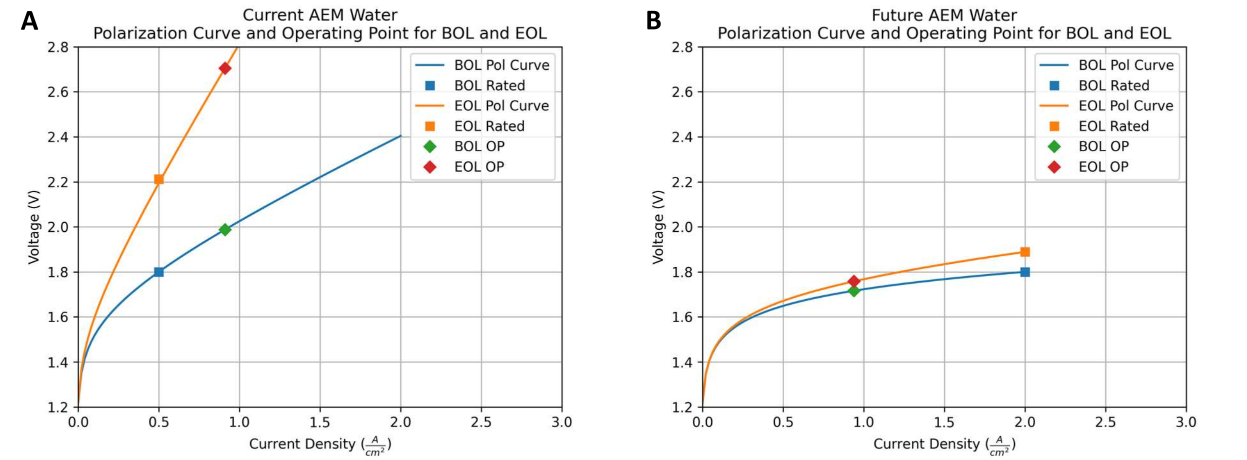

Figure 3. Graphs of rated and optimized (OP) polarization (Pol) curves for AEM Water at BOL and EOL for (A) Current and (B) Future technology bases. Assumes 1 year stack lifetime for Current case and 7 year stack lifetime for Future case.

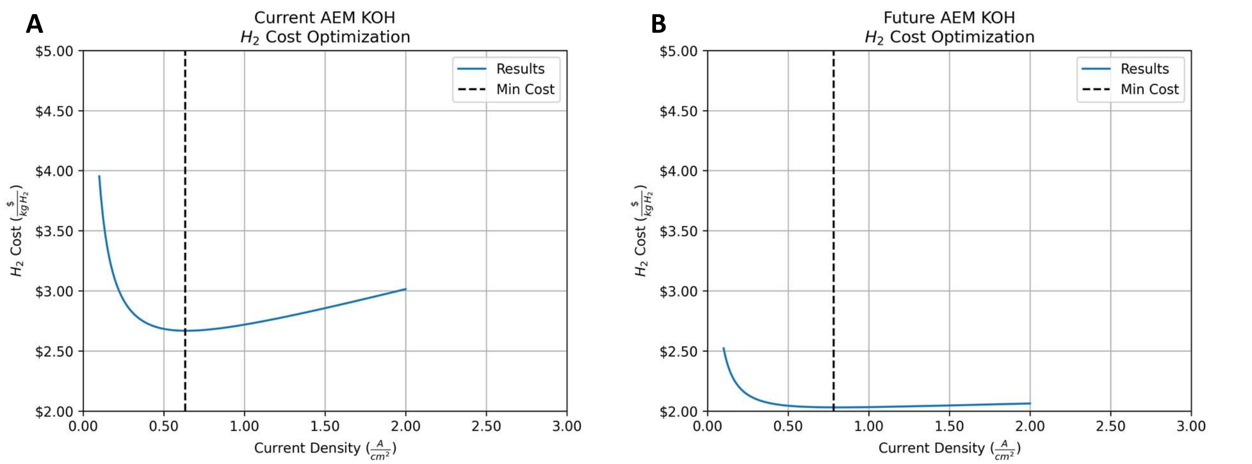

Figure 4. Projected levelized cost of hydrogen (LCOH) across a range of operating points for AEM KOH for (A) Current and (B) Future technology bases. Minimum LCOH is indicated by a vertical dashed line and defines the optimized operating point assuming a constant current density during operation. Modelled plant has a capacity of 50 MTD at an electricity price of \$0.03/kWh and a 97% capacity factor.

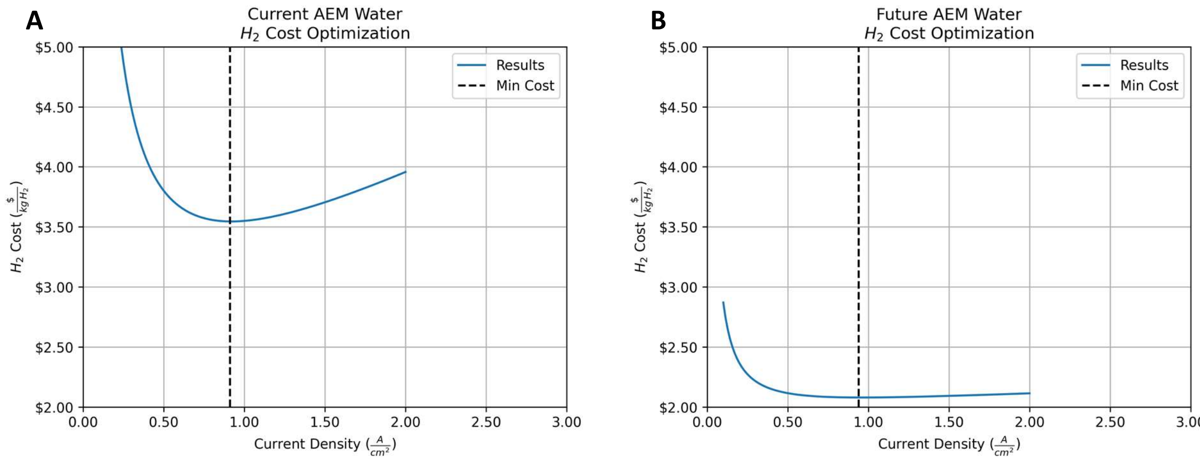

Figure 5. Projected levelized cost of hydrogen (LCOH) across a range of operating points for AEM Water for (A) Current and (B) Future technology bases. Minimum LCOH is indicated by a vertical dashed line and defines the optimized operating point assuming a constant current density during operation. Modelled plant has a capacity of 50 MTD at an electricity price of $0.03/kWh and 97% capacity factor.

Table 4. Optimized operating point compared to rated operating point for AEM KOH and AEM Water electrolyzers for an electricity price of $0.03/kWh and 97% capacity factor.

		AEM KOH	AEM KOH	AEM Water	AEM Water
Technology Basis	-	Current	Future	Current	Future
Plant Scale	MTD	50	50	50	50
Plant Design	# of Modules	4	2	4	2
Current Density (BOL Rated)	A/cm^2	0.80	3.00	0.50	2.00
Cell Voltage (BOL Rated)	V	1.80	1.80	1.80	1.80
Current Density (BOL Optimized)	A/cm^2	0.63	0.79	0.95	0.92
Cell Voltage (BOL Optimized)	V	1.75	1.68	2.01	1.71

2.3 AEM Stack Design

An extensive literature and patent review was conducted, in addition to discussions with electrolyzer suppliers on current AEM cell design, performance, and potential technology advances. Current and Future cell designs, component material selections, and performance levels were postulated to serve as the basis for cost estimation. In general, AEM stack designs share many similarities with PEM stack designs and similar manufacturing methods were assumed. While there are commercial AEM stacks, we expect AEM stack design to continue to evolve as more AEM companies enter the marketplace.

Figure 6 show a cross-sectional view of a single electrolysis cell for an AEM stack with annotations describing each component material, thickness, and manufacturing process. Both the Current and

Future cells are assumed to use a zero-gap design between the electrodes and the membrane. All stacks were modeled with rectangular cells with Current stacks having an active area size of 800 cm^2/cell and Future stacks having an active area size of 3,000 cm^2/cell.

Both the AEM KOH and AEM Water stacks assume the anode (OER) catalyst is FeNiOOH and the cathode (HER) catalyst is Pt. Current commercial AEM stacks commonly use an iridium-free anode and are able to achieve acceptable performance, which is replicated in the cost model. While the cathode could use a PGM-free catalyst, platinum offers a significant performance improvement, leading to a significantly reduced levelized cost of hydrogen despite the increased stack cost due to use of Pt. We opted to include platinum as the cathode catalyst for both the Current and Future cases, although future research and development may lead to cathode catalysts without platinum group metals that achieve both long durability and high performance. Future cathode Pt loading is reduced (from 0.4mgPt/cm^2 to 0.1mgPt/cm^2) to reflect advances in catalyst utilization and in recognition that PEM-based fuel cells can achieve good performance with very low HER loadings (~0.05mgPt/cm^2): this offers hope for significantly reduced future AEM loading.

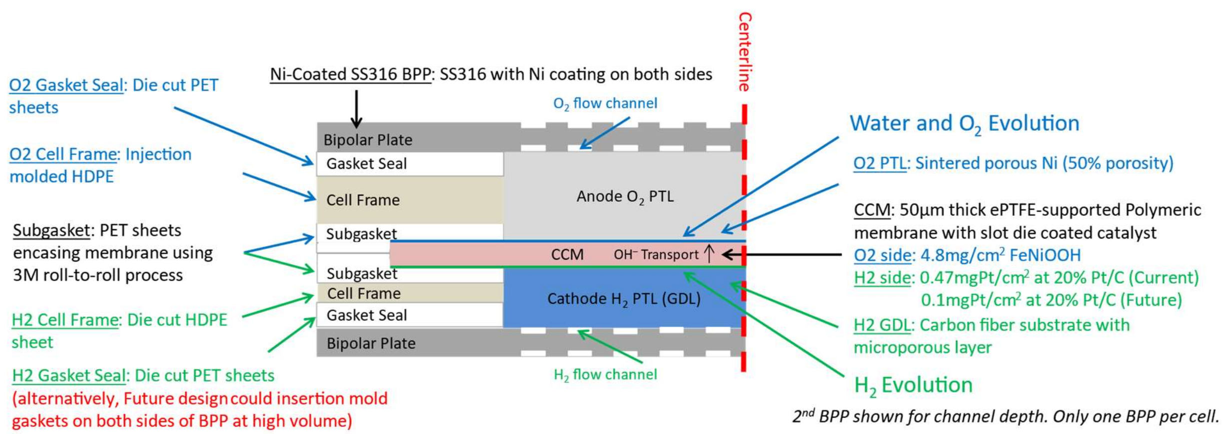

Figure 6. Cross-sectional view of a single AEM electrolysis cell for the Current and Future design with descriptions of all modeled components.

Table 5 shows a comparison between the AEM KOH stack design parameters for the Current vs. Future designs.

Table 6 shows a comparison between the AEM Water stack design parameters for the Current vs. Future designs. The parameters were determined from various sources (in addition to internal analysis and estimates), including journal publications and price quotes from component material suppliers.

Table 5. Comparison of AEM KOH stack design parameters for the Current vs. Future designs.

Parameter	Unit	AEM KOH Current	AEM KOH Future
OER Catalyst	-	FeNiOOH	
OER Catalyst Loading	$mg_{catalyst}$ / cm^2	4.8 mg/cm^2	
OER Catalyst Cost	$/kg	~$3 @ 500MW/yr	
HER Catalyst	-	Pt/C	
HER Catalyst Loading	$mg_{catalyst}$ / cm^2	0.47 mgPt/cm^2	0.1 mgPt/cm^2
HER Catalyst Cost	$/kg	~$49,191/kg @ 500MW/yr	
Membrane	-	ePTFE-supported Polymeric membrane	
Membrane Thickness	µm	50	
Membrane Cost	$/$m^2$	~$40 @ 1GW/yr	~$42 @ 1GW/yr
Stack Pressure (Cathode / Anode)	bar	31 / 1.3	
Voltage Degradation	mV/kh	10.0 @0.8 A/cm^2	1.0 @3.0A/cm^2
Anode Porous Transport Layer		Sintered Porous Ni (50% porosity)	
Cathode Porous Transport Layer		Carbon fiber substrate with microporous layer	
Bipolar Plate		Etched, Nickel-Coated Stainless Steel 316	
Current Distributor		Stamped, Copper Plate	
End Plate		Machined, Stainless Steel	
Compression System		Tie Rods	

Table 6. Comparison of AEM Water stack design parameters for the Current vs. Future designs.

Parameter	Unit	AEM Water Current	AEM Water Future
OER Catalyst	-	FeNiOOH	
OER Catalyst Loading	$mg_{catalyst}$ / cm^2	4.8 mg/cm^2	
OER Catalyst Cost	$/kg	~$3 @ 500MW/yr	
HER Catalyst	-	Pt/C	
HER Catalyst Loading	$mg_{catalyst}$ / cm^2	0.47 mgPt/cm^2	0.1 mgPt/cm^2
HER Catalyst Cost	$/kg	~$49,191/kg @ 500MW/yr	
Membrane	-	ePTFE-supported Polymeric membrane	
Membrane Thickness	µm	50	
Membrane Cost	$/$m^2$	~$58 @ 1GW/yr	~$46 @ 1GW/yr
Stack Pressure (Cathode / Anode)	bar	31 / 1.3	
Voltage Degradation	mV/kh	48.6 @0.5 A/cm^2	1.5 @2.0A/cm^2
Anode Porous Transport Layer		Sintered Porous Ni (50% porosity)	
Cathode Porous Transport Layer		Carbon fiber substrate with microporous layer	
Bipolar Plate		Etched, Nickel-Coated Stainless Steel 316	
Current Distributor		Stamped, Copper Plate	
End Plate		Machined, Stainless Steel	
Compression System		Tie Rods	

2.4 AEM Balance of Plant Design

Process design for AEM KOH and AEM Water plants are quite similar, with the exception of KOH being present in specific streams within the AEM KOH system. Simplified process flow diagrams for the AEM

KOH and AEM Water systems are shown in Figure 7 and Figure 8, respectively. Similar to PEM stacks, the AEM stacks are assumed to operate in differential pressure mode where the anode is near-atmospheric (~1.3 bar) and the cathode is pressurized (~31 bar). The primary water loop (which includes the anode, the anode effluent separator / stack feed surge drum, stack feed pump, and feed air cooler) is assumed to be held at near-atmospheric pressure. Similar to PEM systems, to maintain water purity and preserve stack durability and performance, AEM Water assumes an additional circulation water deionizer. Pure water feeds can lead to instability of the electrode and the membrane is more susceptible to contaminant poisoning and subsequent performance losses.[10] Because the stack cathode operates at an elevated pressure of ~31 bar, there is no need for an H_2 gas compressor before the H_2 purification stage. The H_2 purification subsystem utilizes a Temperature Swing Adsorption (TSA) subsystem to remove saturated water from the H_2 gas stream. Two TSA adsorption beds are used to provide continuous water removal producing an H_2 product stream with 99.99 mol% H_2 purity. Water removed from the H_2 stream is fed back into the stack feed surge drum.

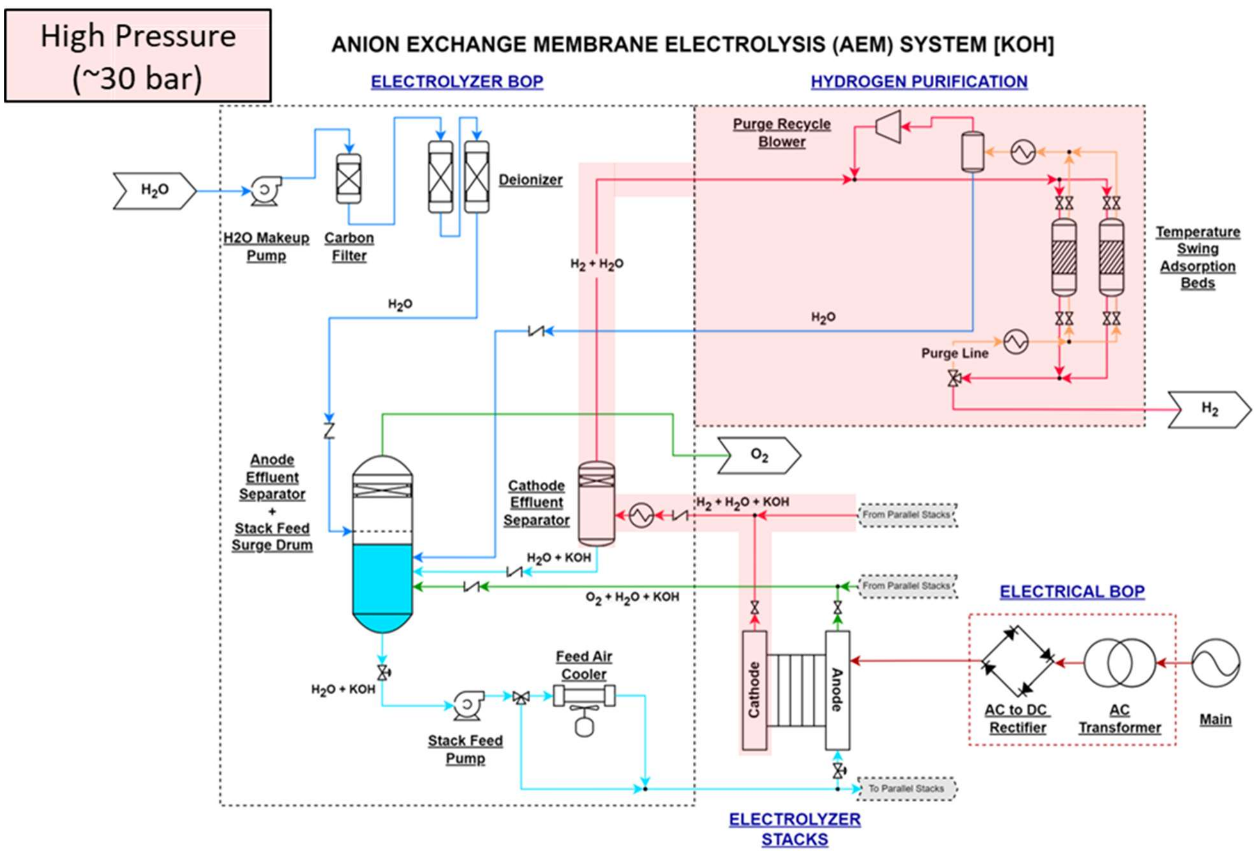

Figure 7. System Diagram for Current and Future AEM KOH Electrolysis Systems.

[10] Miller, H. A.; Bouzek, K.; Hnat, J.; Loos, S.; Bernäcker, C. I.; Weißgärber, T.; Röntzsch, L.; Meier-Haack, J. Green Hydrogen from Anion Exchange Membrane Water Electrolysis: A Review of Recent Developments in Critical Materials and Operating Conditions. Sustainable Energy Fuels 2020, 4 (5), 2114–2133. https://doi.org/10.1039/C9SE01240K.

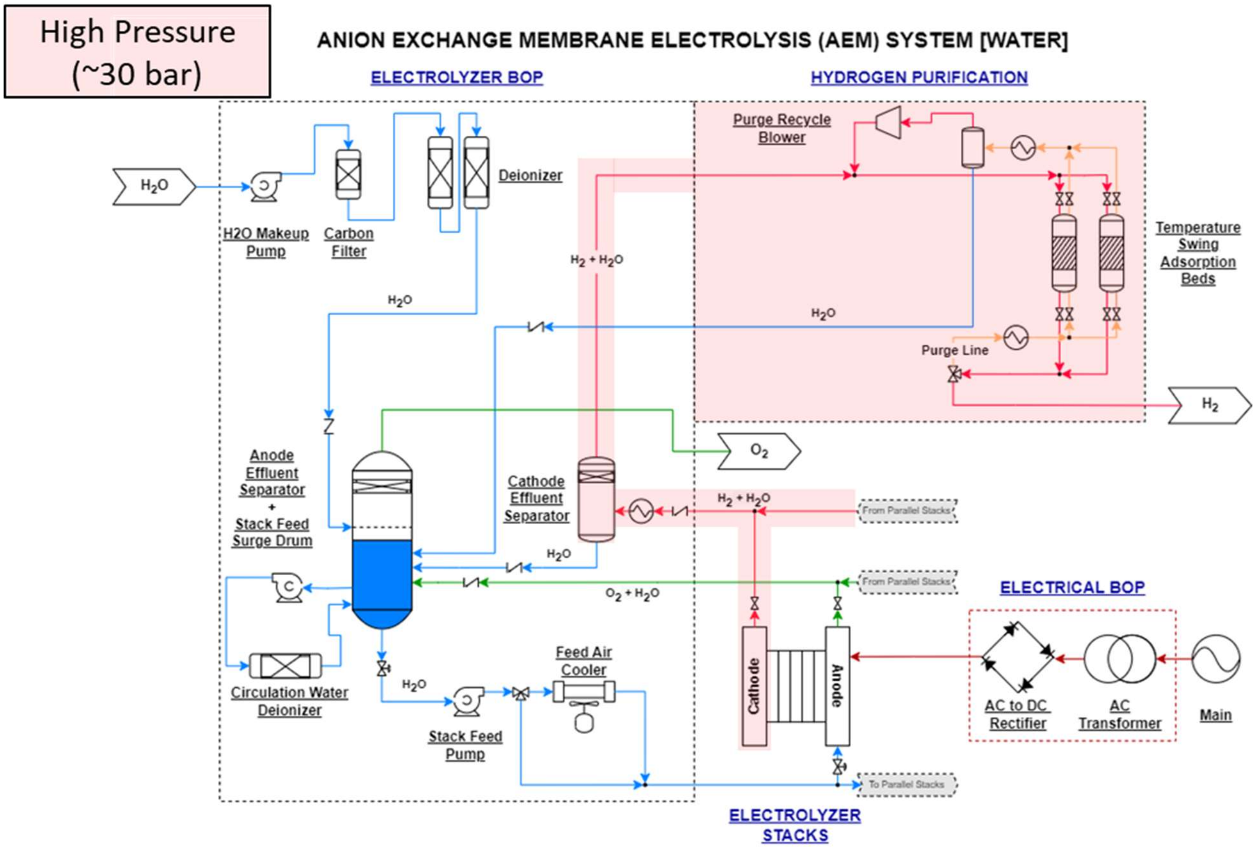

Figure 8. System Diagram for Current and Future AEM Water Electrolysis Systems.

3 Project Capital Cost

3.1 AEM Stack Cost

Design for Manufacture and Assembly® (DFMA®)[11] cost analysis of AEM stacks was performed at multiple production rates, system sizes, and stack sizes. Although the stack cost was evaluated for a range of production rates (MW/yr), the project cost results for the Current Central cases and Future Central cases were constrained to a nominal stack size of 0.25 MW for Current cases and 2 MW for Future cases at a manufacturing rate of 1 GW/year and 5 GW/year. The 0.25 MW stack size used for the Current case was inspired by commercially available AEM stack sizes available at the time of model development. Current innovations in the market will likely case stack sizes to increase in the near-term. The stack manufacturing cases used in this report for AEM KOH and AEM Water systems are shown in Table 7 and Table 8, respectively. Stack cost is reported in units of $\$/cm^2$ active area as this costing metric is independent of the stack operating point and power supply. In general, a higher cell manufacturing rate is associated with a lower stack cost per cell due to better manufacturing equipment utilization and economies of scale for material costs. Additionally, stack cost in $/kW at the BOL power operating point is shown to allow for comparison to other stack technologies. The stack cost in $/kW is highly sensitive to the operating point and a common power basis should be used when compared to other technologies. To understand the impact of the stack manufacturing rate, the stack cost per active area is shown as a function of stack manufacturing rate in Figure 9 and the stack cost normalized by optimized BOL input power is shown as a function of stack manufacturing rate in Figure 10. The manufacturing rate on the low end is limited to 100 MW/year, which is the likely lower limit of highly automated manufacturing methods assumed in the cost model, whereas the high end of the manufacturing rate is set to 5 GW/year, which is a reasonable upper limit of manufacturing rate in a single manufacturing facility.

The uninstalled costs for the stacks as shown in Table 9 and Table 10 include a 30% manufacturer's markup.[12] The installation costs for the stack include a bottom-up estimate for shipping and installation of stacks.

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[11] Boothroyd, G., P. Dewhurst, and W. Knight. "Product Design for Manufacture and Assembly, Second Edition," 2002.

[12] A 30% markup for the electrolyzer manufacturer corresponds to a 23% gross margin. A gross margin between 20% and 30% is considered reasonable for a manufacturing company in a competitive market, although the value can vary significantly between companies depending on their stage of development, growth rate, and target market. For example, among electrolyzer companies, recent gross margins are ~17% for Thyssenkrup, ~20% for Bloom Energy, ~55% for NEL, a negative ~90% for Plug Power, and a negative ~345% for ITM Power.

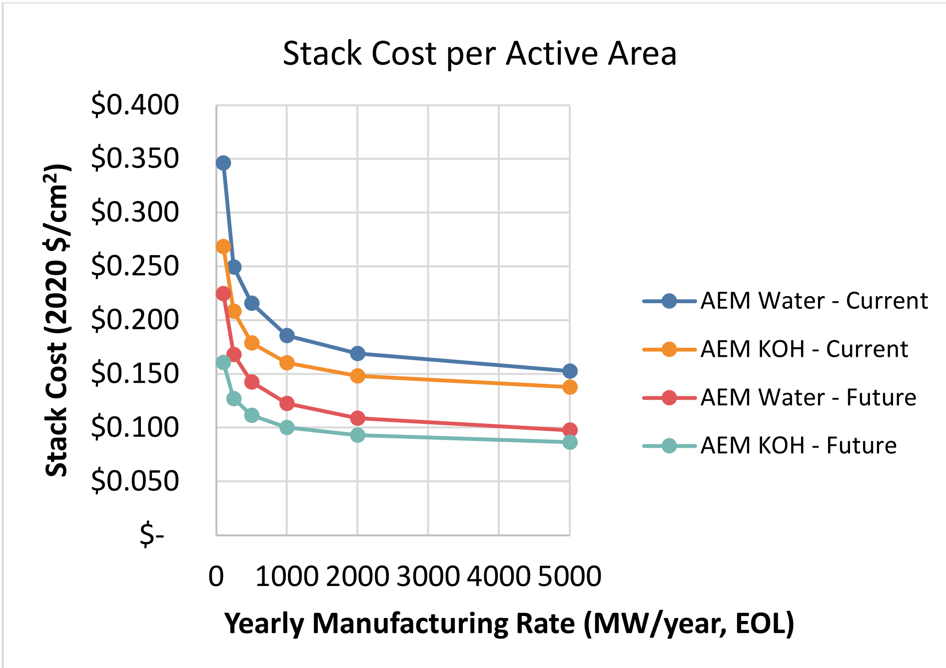

Figure 9. Stack cost per active area as a function of annual manufacturing rate. The manufacturing rate in MW/year is based on EOL power which is 0.25 MW/stack for the Current cases and 2.0 MW/stack for the Future cases.

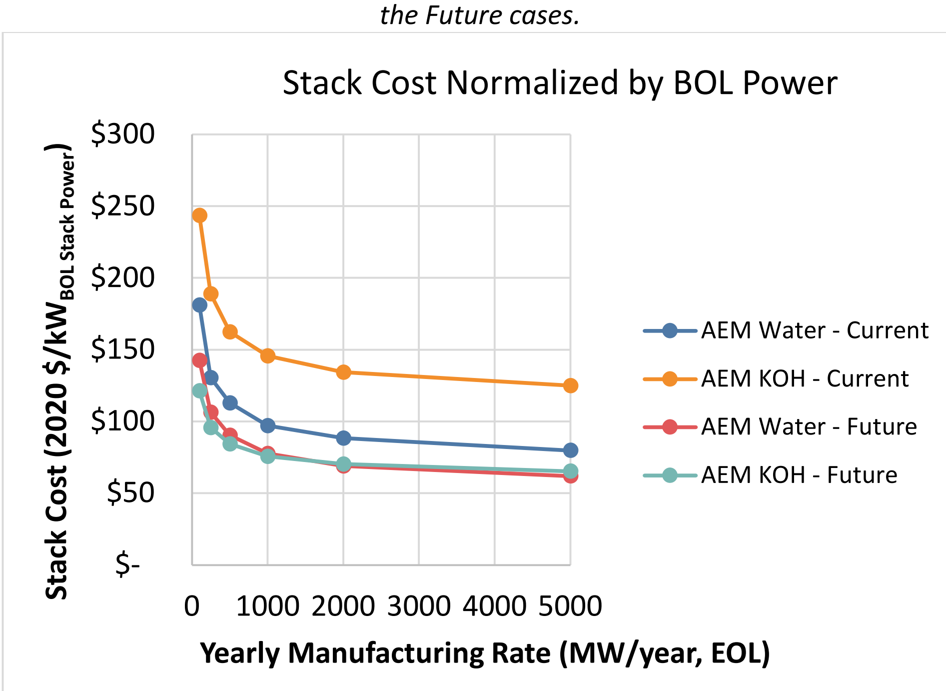

Figure 10. Stack cost normalized by beginning of life power as a function of annual manufacturing rate. The manufacturing rate in MW/year is based on EOL power which is 0.25 MW for the Current cases and 2.0 MW for the Future cases.

The results suggest that for the Current design, AEM Water stacks are less expensive than AEM KOH stacks. However, this is primarily caused by the higher BOL current density selected for AEM Water operation (0.87 A/cm^2) compared to the current density selected for AEM KOH operation (0.60 A/cm^2). This increases the power density of the stack at the cost of a higher operating voltage and lower electrical efficiency.

Table 7. Selected of AEM KOH Stack Design for Manufacture and Assembly® (DFMA®) Cost for Current vs. Future Designs.

Technology Basis	-	Current	Future
Nominal Year	year	2023	2030
Stack Power (BOL Rated)	MW_DC	0.22	2.1
Stack Power (BOL)	MW_DC	0.22	1.9
Stack Power (EOL)	MW_DC	0.25	2.0
Nominal Stack Production Rate (Assuming EOL Power)	GW/year	1	1
Cells per Stack	cells/stack	246	489
Nominal Cell Production Rate	cells/year	1,000,000	251,500
Stack Cost (Excludes markup and installation)	2020 $/kW (BOL)	$146	$76
Stack Cost (Excludes markup and installation)	2020 $/cm^2	$0.160	$0.100

Table 8. Selected of AEM Water Stack Design for Manufacture and Assembly® (DFMA®) Cost for Current vs. Future Designs.

Technology Basis	-	Current	Future
Nominal Year	year	2023	2030
Stack Power (BOL Rated)	MW_DC	0.16	2.0
Stack Power (BOL)	MW_DC	0.18	1.9
Stack Power (EOL)	MW_DC	0.25	1.9
Nominal Stack Production Rate (Assuming EOL Power)	GW/year	1	1
Cells per Stack	cells/stack	117	401
Nominal Cell Production Rate	cells/year	476,000	209,000
Stack Cost (Excludes markup and installation)	2020 $/kW (BOL)	$97	$78
Stack Cost (Excludes markup and installation)	2020 $/cm^2	$0.186	$0.122

3.2 AEM Balance of Plant Cost

The BOP can be divided into two broad categories: the mechanical BOP and the electrical BOP. The mechanical BOP is composed of four primary elements: process equipment, piping, valves, and instrumentation including temperature, pressure, flow, and level indicators. The cost model used the Aspen Process Economic Analyzer™ for preliminary cost estimates of the process equipment. Piping and valve costs are derived from Aspen Capital Cost Estimator ™. Based on industry heuristics, instrumentation is assumed to be 20% of installed equipment costs, and would be inclusive of fire detection systems, hydrogen detection systems, and any early warning systems required for hydrogen safety. [13] [14]

While the system diagram is similar for both AEM KOH and AEM Water, the increased durability assumed by AEM Water is represented by changes to certain elements of the mechanical BOP. AEM KOH uses duplex steel[15] for the high temperature water loop piping to protect against hydrogen, oxygen, high temperatures, and KOH. AEM Water does not have KOH electrolyte and high temperature water loop components are assumed to use 316 stainless steel. Other equipment, such as pumps and tanks, are already assumed to be stainless steel so no changes are needed to differentiate AEM KOH and AEM Water. Finally, KOH specific equipment is excluded from the AEM Water case. No other elements of hypothetical cost improvements are modeled in the capital cost or in the operations and maintenance costs. The electrical BOP consists of 4 primary elements: rectifier, transformer, power substation, and electrical wiring. The cost model used vendor quotes for the rectifier and an estimate from a 2013 engineering study for the high-voltage transformer.[16] The electrical wiring was estimated from the 2020 National Electrical Estimator published by Craftsman.[17] The power substation and overhead power lines for external transmission were derived from publicly available price estimates.[18] Where necessary, cost values in this study were adjusted to 2020$ using the Chemical Engineering Plant Cost Index (CEPCI), the standard index used by chemical process industries.

3.3 Uninstalled and Direct Capital Costs for AEM Electrolyzer System

A rigorous bill of materials was developed for 4 reference cases: (1) 50 MTD Current Central with 4 modules (AEM KOH); (2) 50 MTD Future Central with 2 modules (AEM KOH); (3) 50 MTD Current Central with 4 modules (AEM Water); and (4) 50 MTD Future Central with 2 modules (AEM Water). These cases were selected to understand the cost impact of increasing module size and changing electrolysis performance. The BOP equipment costs were then extrapolated from the reference cases by extrapolating the process design and using conventional power-law[19] based industry scaling factors. The uninstalled capital costs only include the cost of purchasing the equipment whereas the direct cost include installation of the stacks, equipment, piping, power electronics, wiring, and electrical

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[13] Aspen Technology, Inc. Aspen Process Economic Analyzer. Version 12 (40.0.0.4267).

[14] Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003

[15] Duplex steel is a family of stainless steels whose name is derived from a roughly equal mix of austenitic and ferritic phase metallurgical structure. It is designed for superior strength and corrosion resistance (particularly stress corrosion) compared to 316 stainless steel.

[16] $7.5M for 290 MW high temperature steam electrolysis (HTSE) from Krull, P. Roll, J. Varrin, Jr.R.D. "HTSE Plant Cost Model for the INL HTSE Optimization Study," R-6828-00-01, Revision 1, Dominion Engineering, Inc. March 2013.

[17] Tyler, M. C. (2019). 2020 National Electrical Estimator. Craftsman Book Company.

[18] Cost of the transmission line is set at $390,000/mile. https://www.power-grid.com/td/underground-vs-overhead-power-line-installation-cost-comparison/

[19] Power law cost relationships for chemical plants typically take the form of {Variant Cost/Base Cost} = {Variant Sizing/Base Sizing}^p where p is often assumed to be 6/10th. Specific exponential factors were tailored to each equipment based on industry best practices and estimates based on Aspen Process Economic Analyzer™.

infrastructure. Summarized uninstalled and direct capital costs for AEM KOH and AEM Pure Water are shown in Table 9 and Table 10, respectively. Note that all $/kW values are scaled using BOL Rated plant power input.

Table 9. Uninstalled and direct capital costs for AEM KOH. The cost in $ / kW is normalized by BOL Rated plant power. [a]

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	107	1,070	104	1,040
Uninstalled Capital Costs					
Stack Capital Cost	2020 $k / plant	$18,365	$179,825	$9,178	$89,873
Mechanical BOP	2020 $k / plant	$20,146	$147,221	$7,616	$54,425
Electrical BOP	2020 $k / plant	$20,498	$158,457	$15,311	$131,739
Total Uninstalled Capital Costs	**2020 $k / plant**	**$59,010**	**$485,503**	**$32,106**	**$276,037**
Stack Capital Cost	2020 $ / kW	$171	$168	$88	$86
Mechanical BOP	2020 $ / kW	$188	$138	$73	$52
Electrical BOP	2020 $ / kW	$191	$148	$147	$127
Total Uninstalled Capital Costs	**2020 $ / kW**	**$550**	**$454**	**$308**	**$265**
Direct Capital Costs					
Stack Capital Cost	2020 $k / plant	$19,904	$195,273	$9,910	$97,097
Mechanical BOP	2020 $k / plant	$33,195	$202,678	$13,076	$75,298
Electrical BOP	2020 $k / plant	$23,293	$168,925	$17,849	$139,461
Total Direct Capital Costs	**2020 $k / plant**	**$76,393**	**$566,876**	**$40,834**	**$311,855**
Stack Capital Cost	2020 $ / kW	$186	$182	$95	$93
Mechanical BOP	2020 $ / kW	$310	$189	$126	$72
Electrical BOP	2020 $ / kW	$217	$158	$171	$134
Total Direct Capital Costs	**2020 $ / kW**	**$712**	**$530**	**$392**	**$300**

[a] Electrolyzer systems are assumed to be manufactured and assembled at a rate of ~1 GW/year (~500 MTD/year). These manufacturing rates have not yet been demonstrated by any AEM stack manufacturer and no GW-scale factories have been announced as of the publication of this report. Therefore, current commercially available prices are likely to be significantly higher than what is presented here.

Table 10. Uninstalled and direct capital costs for AEM Water. The cost in $ / kW is normalized by BOL Rated plant power. [a]

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,099	104	1,036
Uninstalled Capital Costs					
Stack Capital Cost	2020 $k / plant	$14,016	$137,740	$9,584	$95,838
Mechanical BOP	2020 $k / plant	$21,793	$152,244	$7,301	$47,609
Electrical BOP	2020 $k / plant	$27,450	$218,292	$15,888	$136,258
Total Uninstalled Capital Costs	**2020 $k / plant**	**$63,258**	**$508,275**	**$32,773**	**$279,705**
Stack Capital Cost	2020 $ / kW	$127	$125	$92	$93
Mechanical BOP	2020 $ / kW	$198	$138	$70	$46
Electrical BOP	2020 $ / kW	$249	$199	$153	$132
Total Uninstalled Capital Costs	**2020 $ / kW**	**$574**	**$462**	**$316**	**$270**
Direct Capital Costs					
Stack Capital Cost	2020 $k / plant	$16,145	$159,153	$10,346	$103,244
Mechanical BOP	2020 $k / plant	$34,551	$204,254	$12,349	$65,981
Electrical BOP	2020 $k / plant	$30,501	$231,378	$18,437	$144,045
Total Direct Capital Costs	**2020 $k / plant**	**$81,197**	**$594,785**	**$41,132**	**$313,270**
Stack Capital Cost	2020 $ / kW	$146	$145	$100	$100
Mechanical BOP	2020 $ / kW	$313	$186	$119	$64
Electrical BOP	2020 $ / kW	$277	$210	$178	$139
Total Direct Capital Costs	**2020 $ / kW**	**$737**	**$541**	**$397**	**$302**

[a] Electrolyzer systems are assumed to be manufactured and assembled at a rate of ~1 GW/year (~500 MTD/year). There are no commercial scale manufacturers of AEM Water stacks. The listed stack costs primarily show what may be possible in the future as more AEM stacks manufacturing is deployed.

3.4 AEM Plant Site Preparation and Construction Overhead

In addition to the direct capital cost of an AEM plant (including installed stacks and equipment), the construction of a greenfield electrolysis plant includes two additional cost elements: site preparation and construction overhead (which includes engineering and design, up-front permitting costs, and project contingency). The site preparation and construction overhead costs are alternatively known as indirect capital costs. The site preparation cost model is based on the equipment and plant site plans and uses labor hour, material cost, and equipment cost data from the Craftsman National Construction Estimator cost data books.[20] The construction overhead cost model is an empirical exponential scaling model based on publicly available estimates for engineering and design[21] (inclusive of procurement and construction activities), and legal and permitting expenses.[22] Project contingency is budgeted as a constant 15% of installed capital cost regardless of project scale. Summarized plant site preparation and

[20] "National Construction Estimator" online cost estimating database by Craftsman Book Company. Free Software download available online at: http://craftsman-book.com

[21] Derived from Fraunhofer estimate of $7.5M for a 100 MW AEL facility. Marius Holst; Stefan Aschbrenner; Tom Smolinka; Christopher Voglstätter; Gunter Grimm. Cost Forecast for Low-Temperature Electrolysis - Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems. 2021.

[22] Permitting costs anchored by a $4.3M cost for a 100 MW facility derived from the most recent DOE H2A ~100 MW SOE case. https://www.nrel.gov/hydrogen/h2a-production-models.html

construction overhead results are reported for AEM KOH and AEM Water in Table 11 and Table 12, respectively. Total site preparation and construction overhead costs (as a percentage of total direct capital costs) range from 40-57% for 50 MTD H_2 plants and 21-25% for the 500 MTD H_2 plants.

In general, the construction overhead costs assumed in this cost model are best understood to be representative of costs after multiple repeat deployments, also known as Nth-of-a-kind (NOAK) costs. This is reflected in the relatively low ratio of overhead costs compared to the installed capital costs (20-60% of installed capital costs). As a general heuristic, based on industry commentary, we would expect a first-of-a-kind (FOAK) electrolyzer plant to have indirect costs that approximately match installed capital costs (i.e. 100% of direct capital costs). This reflects a higher FOAK cost of procurement for deployment of new technologies that have yet to be commoditized, higher labor costs for installation of new technology, additional engineering costs and procurement costs to account for unexpected design changes during construction, and higher project contingency due to higher uncertainty. Overhead costs are expected to decrease as project sizes increase, EPC companies gain experience, and hydrogen technologies achieve performance and cost maturity.

Table 11. Site preparation and construction overhead for AEM KOH. The cost in $ / kW is normalized by BOL Rated plant power.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	107	1,070	104	1,040
Indirect Capital Costs					
Site Preparation	2020 $k / plant	$6,644	$14,202	$5,095	$10,864
Engineering and Design	2020 $k / plant	$7,937	$14,107	$7,880	$14,007
Up-Front Permitting Costs	2020 $k / plant	$4,395	$6,962	$4,369	$6,923
Project Contingency	2020 $k / plant	$11,459	$85,031	$6,125	$46,778
Total Indirect Capital Costs	**2020 $k / plant**	**$30,435**	**$120,303**	**$23,469**	**$78,572**
Site Preparation	2020 $ / kW	$62	$13	$49	$10
Engineering and Design	2020 $ / kW	$74	$13	$76	$13
Up-Front Permitting Costs	2020 $ / kW	$41	$7	$42	$7
Project Contingency	2020 $ / kW	$107	$79	$59	$45
Total Indirect Capital Costs	**2020 $ / kW**	**$284**	**$112**	**$225**	**$76**
Total Indirect Capital Costs	**% of Direct Capital Cost**	**40%**	**21%**	**57%**	**25%**

Table 12. Site preparation and construction overhead for AEM Water. The cost in $ / kW is normalized by BOL Rated plant power.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,097	104	1,036
Indirect Capital Costs					
Site Preparation	2020 $k / plant	$7,429	$16,540	$5,195	$11,317
Engineering and Design	2020 $k / plant	$7,992	$14,203	$7,871	$13,994
Up-Front Permitting Costs	2020 $k / plant	$4,419	$7,000	$4,366	$6,917

Project Contingency	2020 $k / plant	$12,180	$89,218	$6,170	$46,990
Total Indirect Capital Costs	**2020 $k / plant**	**$32,019**	**$126,960**	**$23,601**	**$79,219**
Site Preparation	2020 $ / kW	$67	$15	$50	$11
Engineering and Design	2020 $ / kW	$73	$13	$76	$14
Up-Front Permitting Costs	2020 $ / kW	$40	$6	$42	$7
Project Contingency	2020 $ / kW	$110	$81	$59	$45
Total Indirect Capital Costs	**2020 $ / kW**	**$290**	**$115**	**$228**	**$76**
Total Indirect Capital Costs	**% of Direct Capital Cost**	**39%**	**21%**	**57%**	**25%**

3.5 Total Installed Capital Cost

The total installed capital (TIC) cost is the sum of both the direct capital costs and the indirect capital costs associated with building an AEM plant. This investment scales with plant size and is expected to decrease in the future as module sizes increase and plant efficiency improves. The total installed capital cost is summarized for the KOH and Pure Water Current Central and Future Central AEM technology cases in Figure 11. Numerical tabulation of TIC is shown in Appendix A.

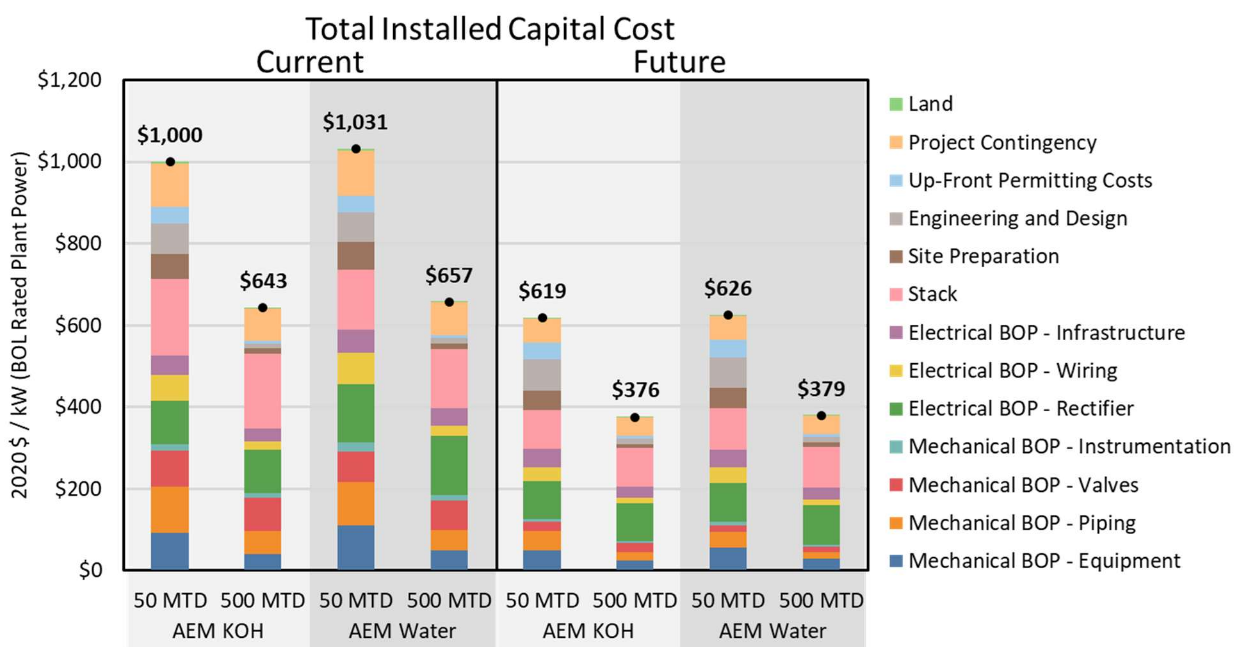

Figure 11. Total installed capital cost scaled by BOL Rated plant power and summarized by cost element for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD assuming a baseline electricity price of $0.03/kWh and 97% capacity factor.

4 Operating Cost

The operating costs for an AEM plant are composed of utility costs (electricity), feedstock costs (water and KOH solution), maintenance costs (periodic replacement of stacks, additional annual costs for all other maintenance activities), and operating labor costs.

4.1 Utility Cost

The utilities for an AEM plant are primarily electricity. Previous LCOH calculations performed using the H2A model used default values to define these utility costs. In particular, the electricity was assumed to follow Annual Energy Outlook (AEO) cost projections for grid-based industrial electricity prices.[23,24] However, for this study and based on DOE guidance, a reduced price of 2020 $0.03/kWh was assumed to represent a nominal low-cost electricity price currently possible in specific favorable U.S. markets. Specifically, the baseline electricity price case ($0.03/kWh) corresponds to average wholesale electricity prices currently possible in U.S. markets with plentiful wind.[25] Similar low-cost electricity pricing is possible via solar Power Purchase Agreements (PPA)[26] although the extent of electricity available at these favorable prices is typically limited by renewable energy capacity factors. In this model, 100% availability was assumed to simplify the analysis. If conventional grid-based electricity was used, the cost of electricity would be almost two-times greater and would make the LCOH significantly higher than the DOE HFTO untaxed cost target of $1/kg H_2. Future studies will explore the effect of availability and electricity price on the LCOH, along with the integration of battery intermediaries to regulate fluctuations in electricity supply.

4.2 Feedstock Cost

The feedstock for an AEM plant is assumed to be water and KOH solution.[27] Water consumption is estimated at 3.78 gallons per kg H_2 inclusive of water converted to H_2 and O_2 and water lost from the system due to purging during water purification, O_2 gas venting, and as an impurity in the H_2 product. No cooling water is assumed in the current process model. The H2A model default water price of ~2020 $ 0.00237/gal is used. Different process configurations will likely consume different amounts of water, thus, water consumption may differ from that reported here. However, likely alternative values for water consumption and price are not expected to appreciably change the LCOH. Compared to the cost of water, KOH material cost and solution mixing cost are not appreciable. Therefore, the cost of KOH is excluded from this cost model.

4.3 Maintenance Cost

Default H2A model values for the total unplanned replacement capital costs are used in the analysis and are set at 0.5% of the total direct depreciable costs per year. In addition to the annual replacement costs, the cost model assumes the stack must be refurbished or replaced after the specified stack lifetime has elapsed. Based on the DFMA® stack cost model for AEM KOH, the replacement cost per

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[23] Annual Energy Outlook 2017, U.S. Energy Information Administration (EIA), (2017). Available at: https://www.eia.gov/outlooks/archive/aeo17/index.php

[24] While the DOE Annual Energy Outlook (AEO) is updated annually, the 2017 AEO estimate has been used by many past H2A cost analyses to provide a common utility price basis and facilitate comparisons.

[25] Seel, J.; Millstein, D.; Mills, A.; Bolinger, M.; Wiser, R. Plentiful Electricity Turns Wholesale Prices Negative. Advances in Applied Energy 2021, 4, 100073. https://doi.org/10.1016/j.adapen.2021.100073.

[26] M. Bolinger, J. Seel, C. Warner, and D. Robson, Utility-Scale Solar, 2022 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States, (2022), p. None, 1888246, ark:/13030/qt7496x1pc https://www.osti.gov/servlets/purl/1888246/.

[27] KOH solution is not technically a feedstock as it is not consumed in the H_2 production process. However, it is classified as a feedstock for purposes of cost reporting within the H2A reporting format.

stack lifetime is estimated to be 60-70% of the initial stack cost.[28] This represents an average contribution of stack replacement, refurbishment, and salvage over the plant lifetime. The stack replacement is assumed to occur at the stack performance EOL, which varies for each technology case. Maintenance cost differences between AEO KOH and AEM Water are captured implicitly by the 0.5%/year maintenance factor being applied to each system's respective capital cost. No additional factors are modeled to capture any potential further maintenance cost difference between the two technologies.

4.4 Labor Cost

Labor cost includes charges for AEM plant operation, maintenance, and management. In general, the labor model assumes that labor increases with the number of stacks and major process equipment components and increases with plant size (due to increasing number of stacks). The number of AEM plant workers per shift is projected by an empirical labor model based on data from five major chemical companies.[29] This empirical relationship corresponds to the staffing used within a conventional chemical plant as opposed to an autonomous or semi-autonomous facility. The model scales with the number of process steps within the AEM plant (excluding process vessels and pumps) and counts each stack as one process step. The associated equation is:

$$N_{operators\ per\ shift} = (6.29 + 0.23N_{process\ steps})^{0.5}$$

The default H2A model assumes 2,080 hours per full-time equivalent (FTE) with 8,760 hours per year. While the original reference refers to only operators, this study assumes that this model is inclusive of operation and maintenance. Using this definition, the total number of FTE's (including operation and maintenance) is estimated as shown in Table 13. Note that the default H2A model assumes a 20% overhead cost markup on FTE labor, which is assumed to also include administrative and management labor.

The Current AEM Water cases are estimated to have higher labor personnel compared to the Current AEM KOH cases due to a higher number of stacks required for the AEM Water cases. This is due to the lower current density operating point assumed in the AEM Water stacks. The Future cases for AEM KOH and AEM Water have sufficiently similar cost-optimized operating points that the estimated labor needs are equal for both technologies.

Table 13. Number of full-time equivalents (including operation and maintenance) assumed for AEM KOH and AEM Water electrolyzers.

Electrolyzer Case					
Technology Basis	-	Current	Current	Future	Future
Nominal Year	year	2023	2023	2030	2030

[28] Future replacement cost may be affected by stack technology improvements during the life of the plant. Such technology changes are not modeled in the replacement cost estimate.
[29] Founding Principles in Chemical and Biological Engineering I. https://pressbooks.bccampus.ca/chbe220/chapter/cost-of-operating-labour/. Chapter 48. Cost of Operating Labour

Plant Scale	MTD	50	500	50	500
Plant Design	# of Modules	4	3	2	3
Annual Full-Time Equivalents					
AEM KOH	#	26	63	20	47
AEM Water	#	29	73	20	47

5 Levelized Cost of Hydrogen

5.1 LCOH Results for Base Current and Future Cases

An LCOH calculation (using the H2A model) was performed for the KOH and Pure Water Current Central and Future Central AEM technology cases. The H2A cases use the previously described DFMA® stack estimate with adjustment for OEM stack markup, and the BOP equipment lists. The operating point was determined from an optimization of the H2A cost as a function of BOL and EOL current density. The plant is assumed to operate at the H2A default capacity factor of 97% using an electricity price of $0.03/kWh. In other words, the plant will operate at the optimized operating point for 97% of the year. Additional financial parameters used within the discounted cash flow model are found in Appendix C. The performance and capital cost input parameters and H2A results are shown in Table 14 and Table 15 for AEM KOH and AEM Water, respectively. All capital costs listed in these tables include markup. The levelized cost of hydrogen for each case is summarized in Figure 12 broken down into capital costs, fixed operations and maintenance (primarily labor and maintenance costs), and utilities (primarily electricity costs).[30]

For the Future cases, AEM KOH has a slight advantage over AEM Water due to the increased stack lifetime and increased performance of AEM KOH. AEM KOH is estimated to have 0.8 kWh/kg less average plant electrical usage at the optimized operating point compared to AEM Water, which slightly lowers the net electricity cost (as part of the Utilities portion of the LCOH). In addition, AEM KOH is given a stack lifetime of 10 years, matching average alkaline electrolysis stack lifetime, whereas it is assumed that AEM Water would always have a slightly disadvantage of electrode and membrane stability and is given a 7 year stack lifetime. This leads to ~$0.03/kg H_2 increase in stack replacement costs (as part of Capital Costs portion of the LCOH).

[30] In keeping with H2A methodology, the H2A LCOH analysis includes an 8% real (i.e. after inflation) internal rate of return to compensate investors for the use of their investment capital. The LCOH is reported as a production "cost" rather than an H_2 "price" as it represents a baseline H_2 value that covers all business expenses but does not include "extra profit" that may result from dynamic pricing in a market governed by supply and demand economic forces.

Table 14. H2A Inputs and Results for Current and Future Cases for AEM KOH Electrolysis.

Technology Basis		Current Central	Current Central	Future Central	Future Central
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	107	1,070	104	1,040
Plant Electrical Usage (Average)	kWh/kg	53.8	53.8	47.2	47.2
Average Production Rate	kg H_2/day	48,500	485,000	48,500	485,000
Land	acres	7.4	11.3	3.3	7.4
System Performance					
Current Density (BOL)	A/cm²	0.63	0.64	0.79	0.80
Voltage (BOL)	V/cell	1.75	1.76	1.68	1.69
Current Density (EOL)	A/cm²	0.63	0.64	0.79	0.80
Voltage (EOL)	V/cell	2.02	2.03	1.71	1.71
BOP Electrical Usage	kWh/kg	3.6	3.5	2.1	2.1
Capital Cost					
Direct Capital Cost	2020 $k	$76,393	$566,876	$40,834	$311,855
Indirect Capital Cost	2020 $k	$30,435	$120,303	$23,469	$78,572
Non-Depreciable Capital Cost (Land)	2020 $k	$370	$566	$166	$372
Total Installed Capital Cost	**2020 $k**	**$107,198**	**$687,746**	**$64,469**	**$390,799**
Fixed Operating Cost					
Total Plant Staff	H2A FTE	26	63	20	47
Total Fixed Operating Cost	2020 $k / year	$7,681	$38,624	$5,010	$23,037
H2A Output					
Capital Costs	2020 $ / kg H_2	$0.58	$0.44	$0.28	$0.19
Fixed O&M	2020 $ / kg H_2	$0.44	$0.22	$0.29	$0.13
Utilities	2020 $ / kg H_2	$1.66	$1.66	$1.45	$1.45
Total	**2020 $ / kg H_2**	**$2.68**	**$2.32**	**$2.03**	**$1.78**

Table 15. H2A Inputs and Results for Current and Future Cases for AEM Water Electrolysis.

Technology Basis		Current Central	Current Central	Future Central	Future Central
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,097	104	1,036
Total Electrical Usage (Average)	kWh/kg	68.8	69.1	48.0	48.0
Average Production Rate	kg H_2/day	48,500	485,000	48,500	485,000
Land	acres	8.6	13.9	3.6	8.3
System Performance					
Current Density (BOL)	A/cm²	0.95	0.97	0.92	0.92
Voltage (BOL)	V/cell	2.01	2.01	1.71	1.71
Current Density (EOL)	A/cm²	0.95	0.97	0.92	0.92
Voltage (EOL)	V/cell	2.79	2.81	1.75	1.75
BOP Electrical Usage	kWh/kg	5.1	4.9	1.9	1.9
Capital Cost					
Direct Capital Cost	2020 $k	$81,197	$594,785	$41,132	$313,270
Indirect Capital Cost	2020 $k	$32,019	$126,960	$23,601	$79,219
Non-Depreciable Capital Cost (Land)	2020 $k	$432	$694	$180	$413
Total Installed Capital Cost	**2020 $k**	**$113,648**	**$722,439**	**$64,913**	**$392,902**
Fixed Operating Cost					
Total Plant Staff	H2A FTE	29	73	20	47
Total Fixed Operating Cost	2020 $k / year	$8,328	$41,403	$5,028	$23,122
H2A Output					
Capital Costs	2020 $ / kg H_2	$1.08	$0.92	$0.31	$0.22
Fixed O&M	2020 $ / kg H_2	$0.48	$0.24	$0.29	$0.13
Utilities	2020 $ / kg H_2	$2.12	$2.12	$1.48	$1.48
Total	**2020 $ / kg H_2**	**$3.68**	**$3.29**	**$2.08**	**$1.83**

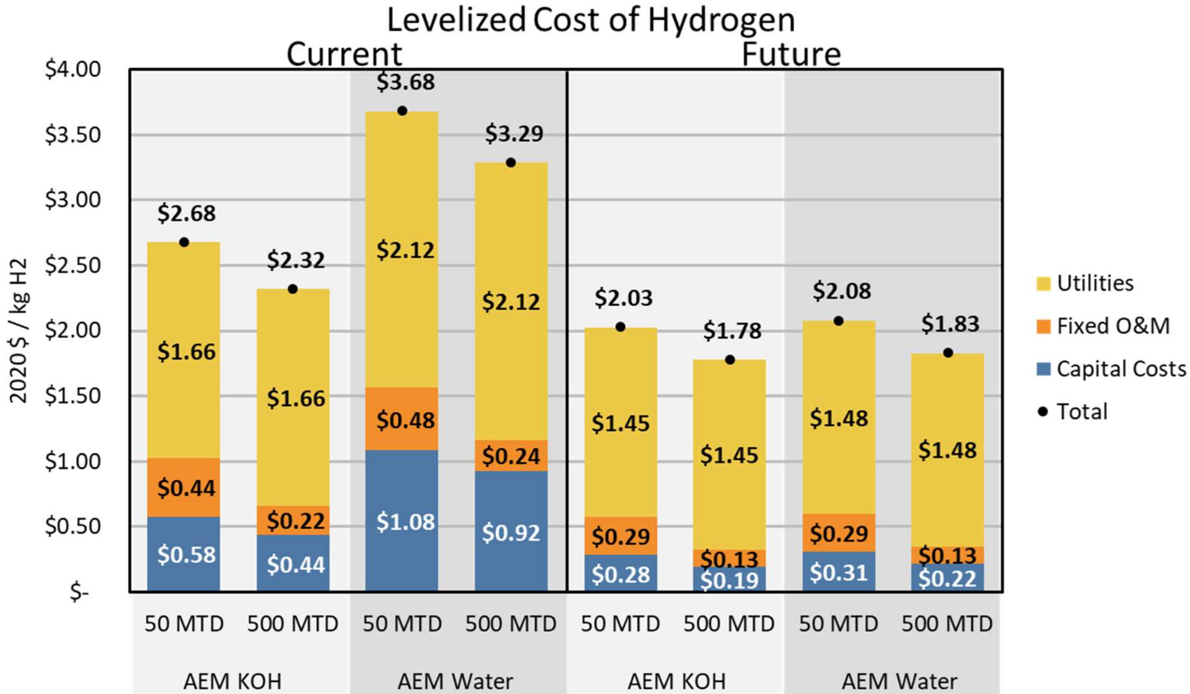

Figure 12. Projected levelized cost of hydrogen (LCOH) summarized by sub-component for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD assuming a baseline electricity price of $0.03/kWh and 97% capacity factor.

5.2 Sensitivity to Module Sizing and Plant Sizing

The levelized cost of hydrogen is affected by both the plant size and the size of the independent modules used to build up to the plant capacity. Each case assessed in *Figure* 12 is associated with a plant size and module size as described in the System Definition (Table 2 and Table 3). As a case study to understand the effect of plant size and module size, the levelized cost of hydrogen was calculated for key increments between the baseline 50 MTD case (which assumes 4 modules for the Current technology basis and 2 modules for the Future technology basis) and the baseline 500 MTD case (which assumes 3 modules). Results are shown in Figure 13 for AEM KOH and Figure 14 for AEM Water for both the Current and Future technology cases. The largest cost reduction for all sequences is the transition between the 50 MTD, 1 module cases and the 167 MTD, 1 module cases where the module size increases from 50 MTD to 167 MTD. This results in economies of size benefits which reduce the capital cost and the associated maintenance costs. This also significantly reduces the labor cost since the same number of non-stack process equipment is assumed for both the 50 and 167 MTD cases. Transitioning from 50 MTD, 4 module cases to 50 MTD, 1 module cases also increases the module size from 12.5/25 MTD (Current/Future) to 50 MTD and also achieves benefits from economies of size scaling. However, the impact is limited since the total plant capacity does not increase. Finally, transitioning from the 167 MTD, 1 module cases to the 500 MTD, 3 module cases involves replicating the 167 MTD module 3 times in a single plant which offers only modest LCOH savings associated with increasing plant size, particularly a reduction in expected labor costs and reductions in overhead costs.

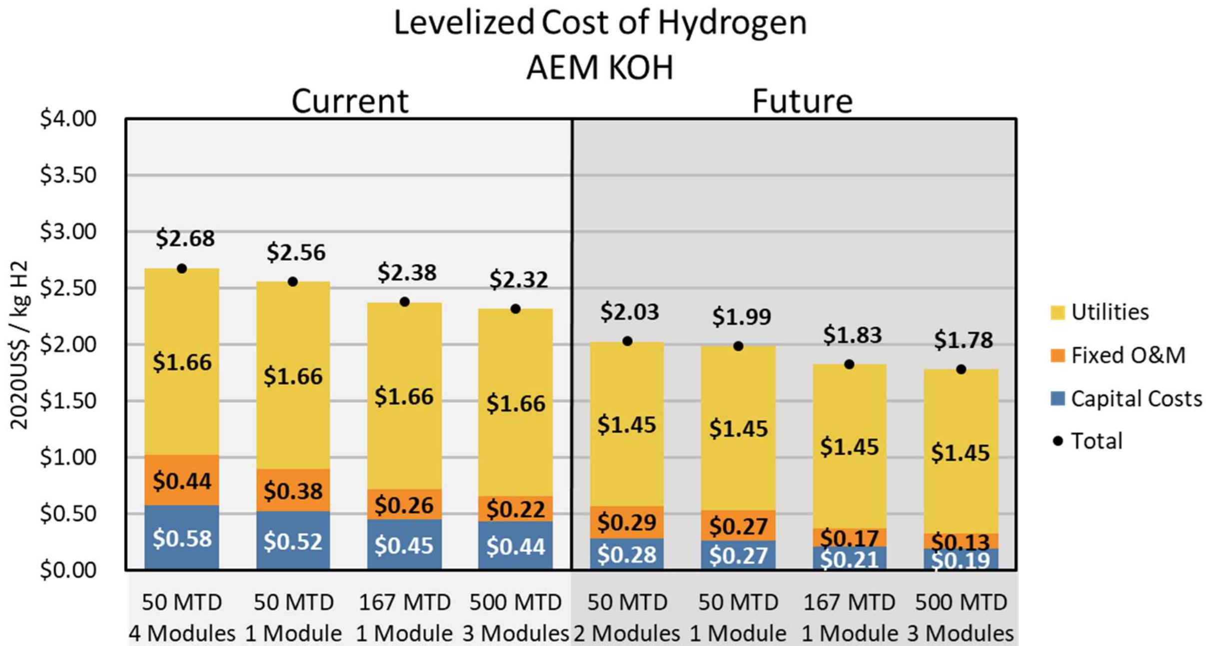

Figure 13. Projected levelized cost of hydrogen (LCOH) summarized by sub-component for AEM KOH transitioning from a plant capacity of 50 MTD using four 12.5 MTD modules to a plant capacity of 500 MTD using three 167 MTD modules assuming a baseline electricity price of $0.03/kWh and 97% capacity factor.

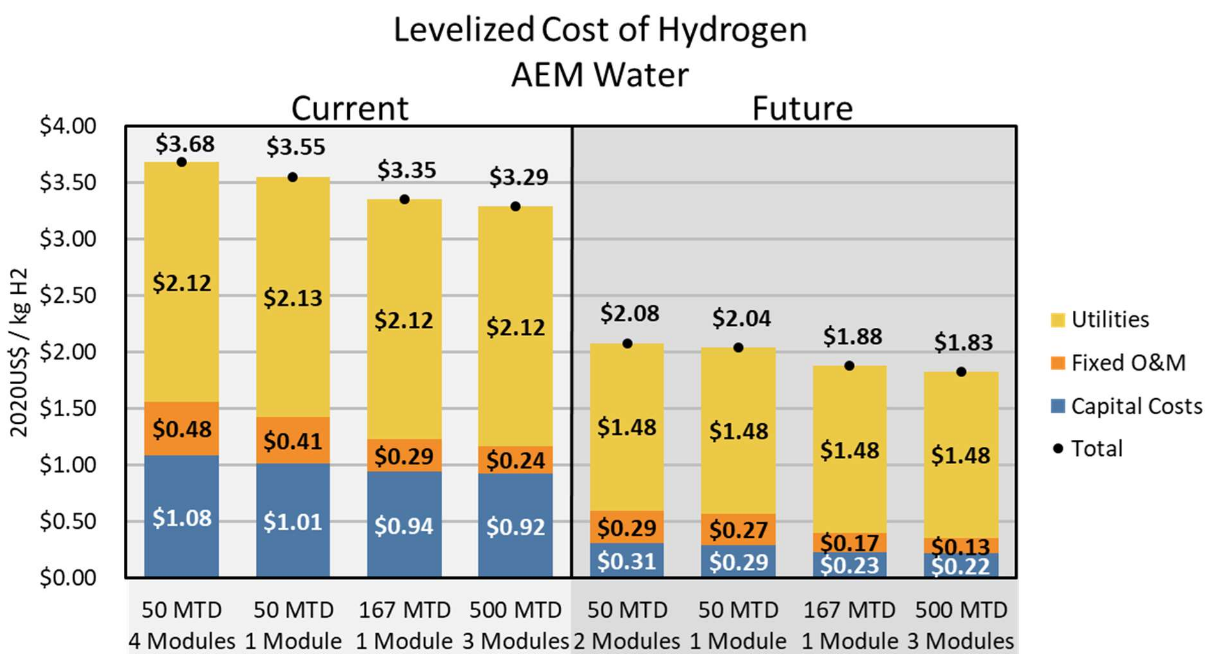

Figure 14. Projected levelized cost of hydrogen (LCOH) summarized by sub-component for AEM Water transitioning from a plant capacity of 50 MTD using four 12.5 MTD modules to a plant capacity of 500 MTD using three 167 MTD modules assuming a baseline electricity price of $0.03/kWh and 97% capacity factor.

5.3 Sensitivity to Electricity Pricing

As shown in Table 14 and Table 15 above, the largest portion of the LCOH is the electricity cost. The LCOH is highly sensitive to the price of electricity, regardless of the electrolyzer technology and timeframe. To assess the possible range of LCOH results for different low-temperature electrolysis (LTE) technologies, the LCOH was calculated for three different electricity prices at two different plant sizes: 50 MTD (~100 MW plant power) and 500 MTD (~1 GW plant power). Each LCOH case used the same operating expenditure (OPEX) and capital expenditure (CAPEX) co-optimization as described above to minimize the LCOH. Figure 15 shows the range of LCOH results as compared to the base case electricity price of $0.03/kWh. The intermediate electricity price case ($0.03/kWh) corresponds to the base case and to average wholesale electricity prices currently possible in U.S. markets with plentiful wind.[31] The high electricity price case ($0.074/kWh) corresponds to the average 2022 industrial electricity price estimated in the Annual Energy Outlook (AEO) 2022 published by the U.S. Energy Information Administration (EIA).[32] The low electricity price case ($0.01/kWh) was selected to show how low the average electricity price must be to achieve the US DOE HFTO 2031 target goal of $1/kg H_2. All cases assume a system capacity factor of 97%.

[31] Seel, J.; Millstein, D.; Mills, A.; Bolinger, M.; Wiser, R. Plentiful Electricity Turns Wholesale Prices Negative. Advances in Applied Energy 2021, 4, 100073. https://doi.org/10.1016/j.adapen.2021.100073.

[32] Annual Energy Outlook 2022, U.S. Energy Information Administration (EIA), (2022). Available at: https://www.eia.gov/outlooks/archive/aeo22/index.php

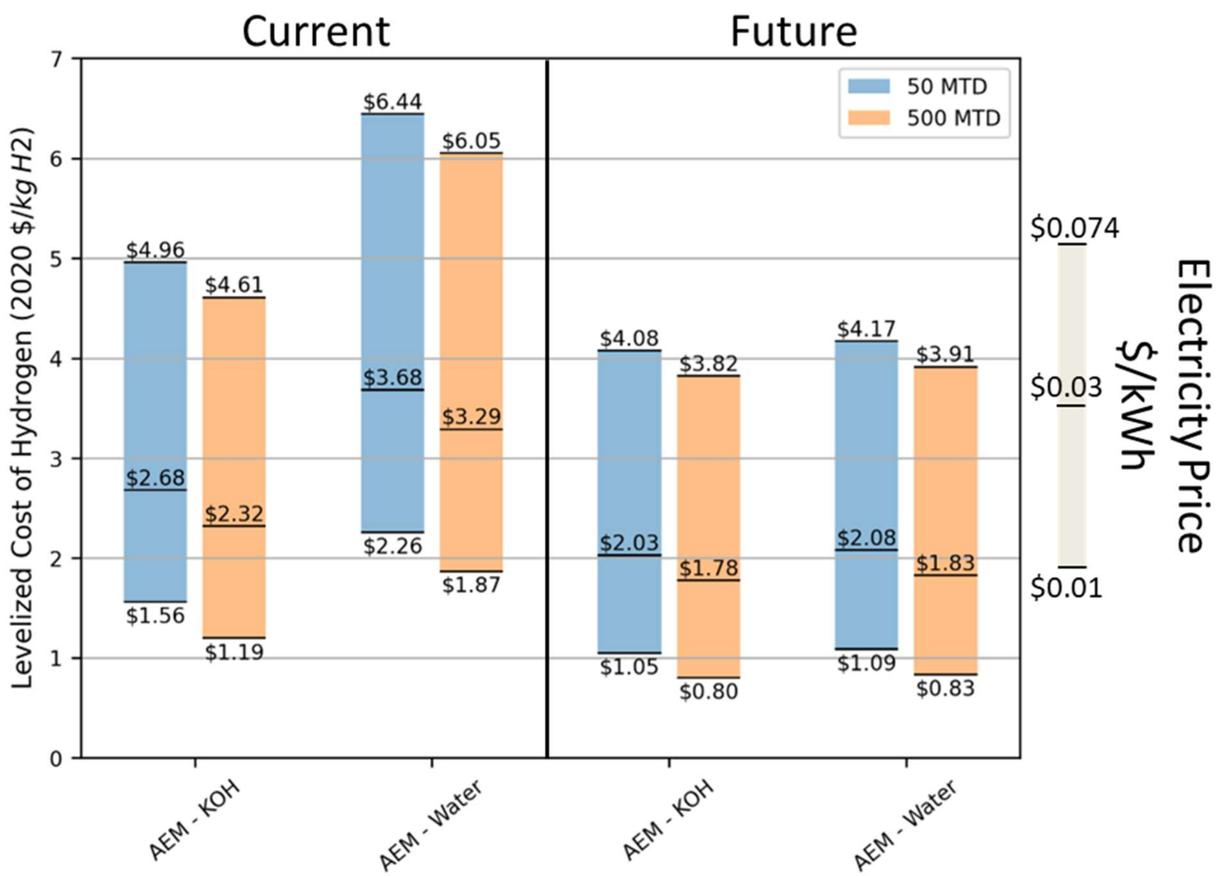

Figure 15. Projected levelized cost of hydrogen (LCOH) range for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD at 3 different electricity prices ($0.01/kWh, $0.03/kWh, and $0.074/kWh) and 97% capacity factor.

The results in Figure 15 suggest that a favorable electricity price has a more significant impact than electrolysis technology or plant size, both in the Current and Future cases. Scaling up the plant size from 50 MTD to 500 MTD leads to a significant and similar reduction in LCOH for all technologies. As the concept of transient electricity is explored in future studies, dynamic operating performance may lead to further distinguishment between LTE technologies.

5.4 Sensitivity to Electricity Pricing and Capacity Factor

Lower cost electricity sources such as wind and solar are associated with lower capacity factor, which can increase the relative cost of hydrogen produced from a renewable energy integrated electrolyzer. Understanding the relationship between electricity price, capacity factor, project cost, and levelized cost of hydrogen may provide a roadmap for unlocking lower cost hydrogen, especially in regions of high renewable energy penetration. To assess the possible range of LCOH results for different low-temperature electrolysis (LTE) technologies, the LCOH was calculated for multiple electricity prices ($0.00/kWh to $0.10/kWh) and capacity factors (10% to 100%) for a 50 MTD plant (assuming 4 modules for Current technology basis and 2 modules for Future technology basis). Each LCOH case used the same operating expenditure (OPEX) and capital expenditure (CAPEX) co-optimization as described above to minimize the LCOH. Sensitivity results for LCOH are shown in *Figure 16* and *Figure 17* for AEM KOH and

AEM Water, respectively. For legibility, cases that exceed $10/kg$H_2$ are omitted from the figures. Additional contour plots displaying associated total installed capital cost, plant power, scaled plant cost, optimized current density, and average plant electrical usage are shown in Appendix B.

The LCOH results suggest that a hydrogen price target of $2/kg$H_2$ is achievable across a wide range of capacity factors, as long as the net electricity price falls below $0.02/kWh. Lower capacity factors are associated with higher total project costs (and total electrolyzer capacity), which will be a barrier to feasibility in the short term. Lower hydrogen prices are only achievable with very low net electricity prices and high capacity factors, which will likely require a combination of high renewable energy penetration, dynamic electrolyzer operation, and tight integration with the grid.

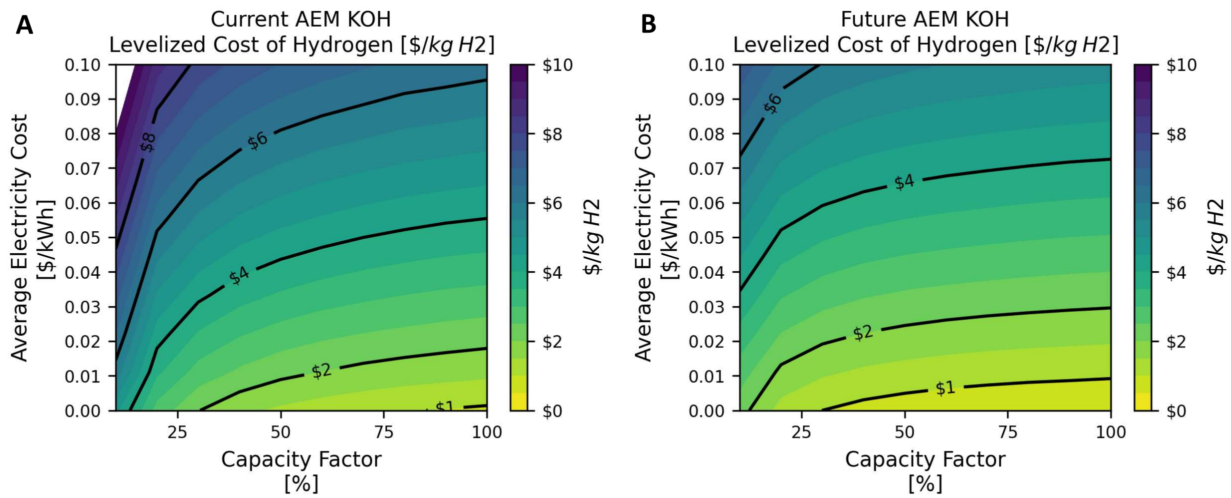

Figure 16. Projected levelized cost of hydrogen (LCOH) range for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

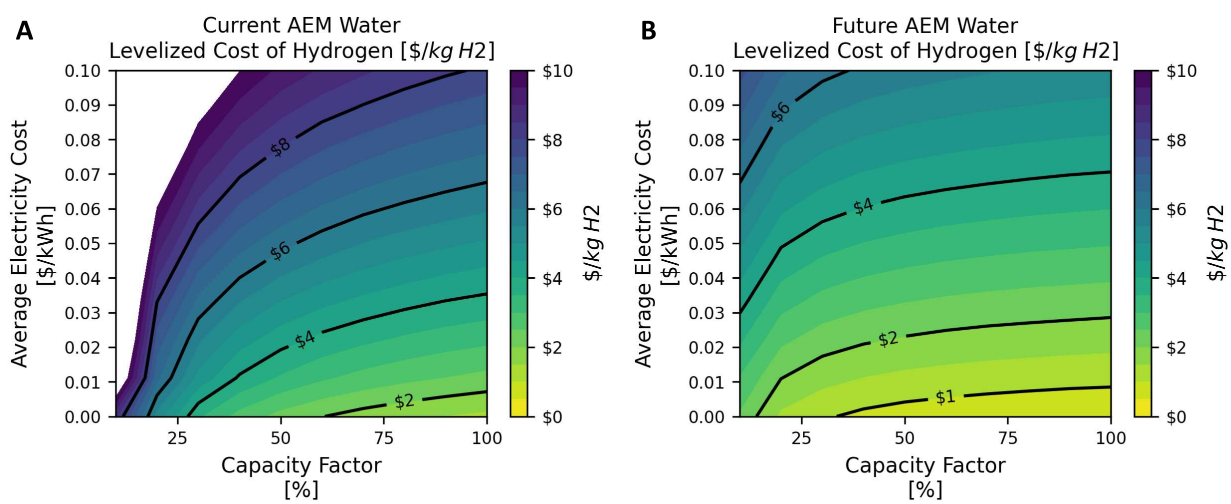

Figure 17. Projected levelized cost of hydrogen (LCOH) range for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

5.5 Sensitivity to Stack Costs

The H_2 production research community has been highly motivated to reduce stack costs in order to reduce the LCOH.[33] In order to assess the impact of stack price on the LCOH, the LCOH was calculated for two alternative stack prices for two different plant sizes (50 MTD and 500 MTD). The baseline stack costs (100% stack price multiplier) are listed in Table 7 above. The high stack price case doubles the stack cost on a $/cm^2 basis (200% stack price multiplier) while the low stack price case assumes half the stack cost on a $/cm^2 basis (50% stack price multiplier). The high-price case is useful in understanding the effect of catalyst metals price volatility. The low-price case explores the impact of lower metal loading in addition to reductions in cell pricing from cost optimization efforts. Each LCOH case used the same OPEX and CAPEX co-optimization methodology as described above to estimate a case-specific operating point to minimize the LCOH. Due to this optimization, the cost impact is similar for all electrolyzer cases. Figure 18 shows the range of LCOH results as compared to the base case stack price. The results suggest that reducing the stack price alone is insufficient to reach the US DOE HFTO 2031 $1/kg H_2 price target.

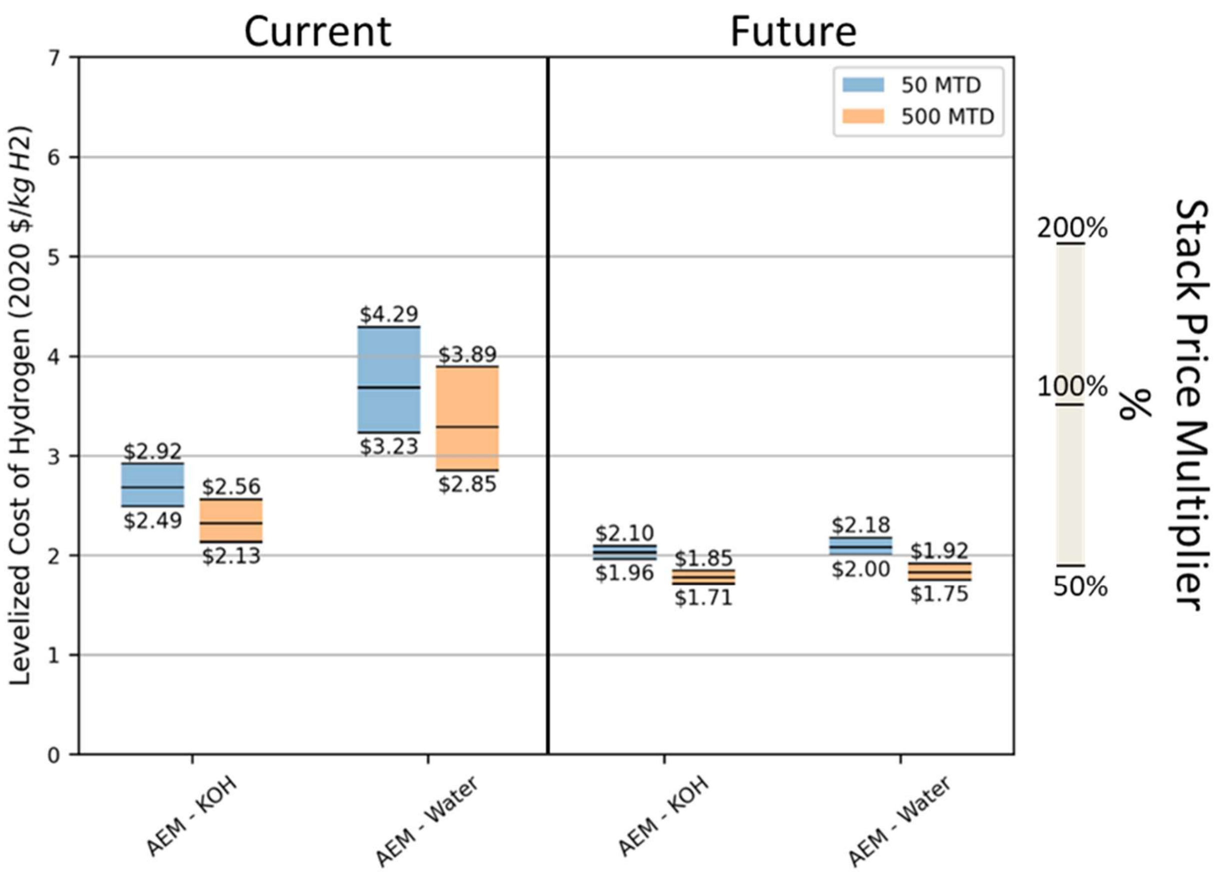

Figure 18. Projected levelized cost of hydrogen (LCOH) range for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD at 2 alternative stack prices (0.5x and 2x the base case price). The intermediate stack price case (100%) corresponds to the base case. The high stack price case (200%)

[33] Marius Holst, Stefan Aschbrenner, Tom Smolinka, Christopher Voglstätter, and Gunter Grimm, Fraunhofer Institute for Solar Energy Systems, (2021).

corresponds to double the base case cost on a \$/cm^2 basis. The low stack price case (50%) corresponds to half the base case cost on a \$/cm^2 basis.

5.6 Sensitivity to Number of Operation and Maintenance FTE's

Hydrogen production via water electrolysis requires industrial-scale chemical production equipment along with the associated operation and maintenance labor. Grid-connected electrolyzers with constant hydrogen production will run in steady-state operation and may be able to operate with reduced oversight and maintenance. To assess the impact of labor cost on the LCOH, the LCOH was calculated for a reduced operation and maintenance staffing scenario for the two different plant sizes (50 MTD and 500 MTD). The baseline labor FTE's (100% labor rate multiplier) are listed in the DOE Record. The low labor scenario assumed half the labor FTE's (50% labor rate multiplier). The low-price result explores the impact of reduced labor associated with an autonomous or semi-autonomous facility. Each LCOH case used the same OPEX and CAPEX co-optimization methodology as described above to estimate a case-specific operating point to minimize the LCOH. Figure 19 shows the range of LCOH results as compared to the base case labor. The results suggest that reducing the operation and maintenance FTE's will not significantly impact the expected LCOH, especially for larger 500 MTD plants.

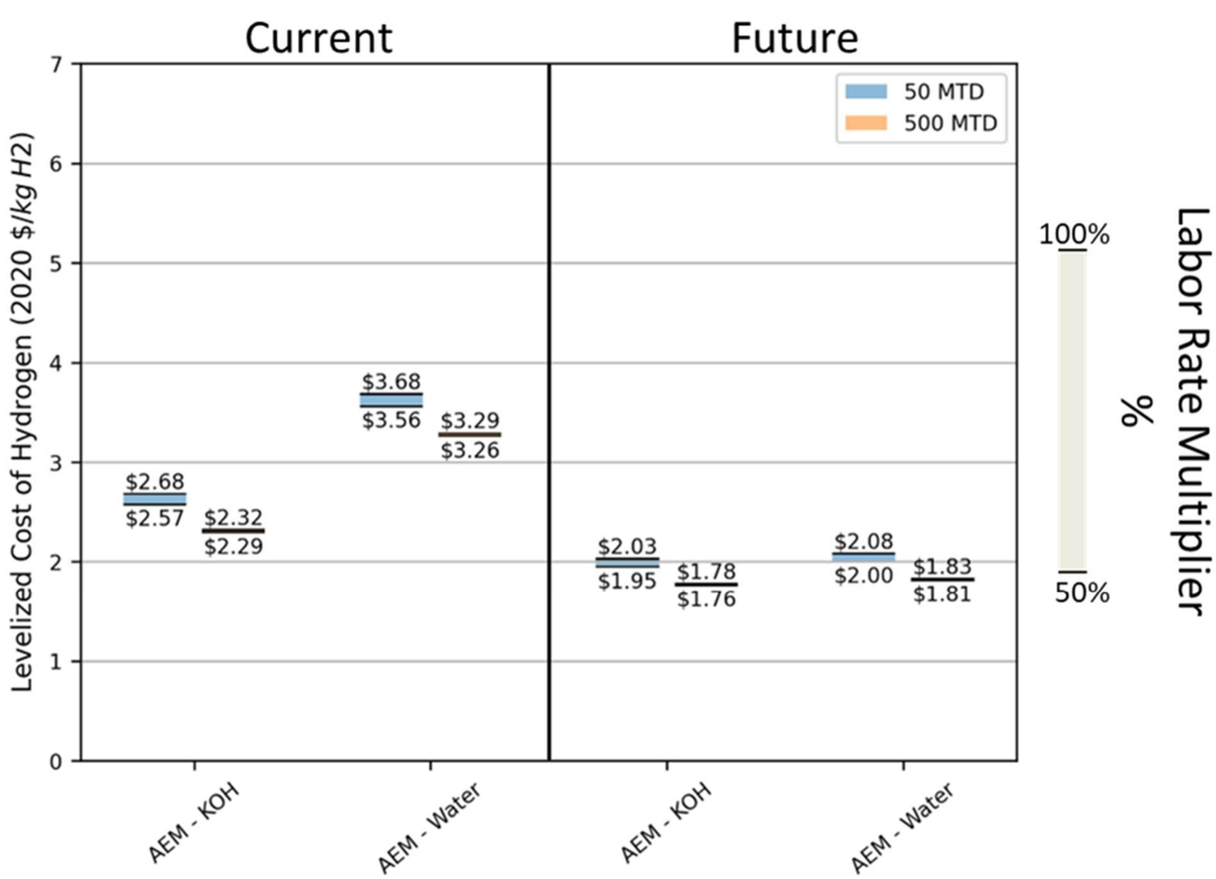

Figure 19. Projected levelized cost of hydrogen (LCOH) range for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD at 1 alternative labor (0.5x the base case labor rate). The higher labor case (100%) corresponds to the base case.

6 Appendix A. Summary of Total Installed Capital Cost

As described in Section 3.5, the total installed capital cost includes both direct costs and indirect costs and represents the total investment required to build an AEM plant. The total installed capital cost is summarized for the KOH and Pure Water Current Central and Future Central AEM technology cases in total cost (Table 16, Table 18) and scaled cost (Table 17 and Table 19). The percentage of total installed capital cost for each cost element is shown in *Figure* 20 for the KOH and Pure Water Current Central and Future Central AEM technology cases.

Table 16. Total installed capital cost for AEM KOH.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	107	1,070	104	1,040
Direct Capital Costs - Mechanical BOP					
Equipment	2020 $k / plant	$9,840	$43,230	$5,181	$25,720
Piping	2020 $k / plant	$12,226	$59,470	$4,866	$22,355
Valves	2020 $k / plant	$9,391	$88,614	$2,348	$23,287
Instrumentation	2020 $k / plant	$1,738	$11,365	$681	$3,937
Direct Capital Costs – Electrical BOP					
Rectifier	2020 $k / plant	$11,427	$114,810	$9,656	$96,699
Wiring	2020 $k / plant	$6,758	$19,714	$3,600	$14,319
Infrastructure	2020 $k / plant	$5,109	$34,401	$4,593	$28,442
Direct Capital Costs - Stacks					
Stacks	2020 $k / plant	$19,904	$195,273	$9,910	$97,097
Indirect Capital Costs					
Site Preparation	2020 $k / plant	$6,644	$14,202	$5,095	$10,864
Engineering and Design	2020 $k / plant	$7,937	$14,107	$7,880	$14,007
Up-Front Permitting Costs	2020 $k / plant	$4,395	$6,962	$4,369	$6,923
Project Contingency	2020 $k / plant	$11,459	$85,031	$6,125	$46,778
Land	2020 $k / plant	$370	$566	$166	$372
Total Installed Capital Costs	**2020 $k / plant**	**$107,198**	**$687,746**	**$64,469**	**$390,799**

Table 17. Total installed capital cost scaled by BOL rated plant power for AEM KOH.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,097	104	1,036
Direct Capital Costs - Mechanical BOP					
Equipment	2020 $ / kW	$92	$40	$50	$25
Piping	2020 $ / kW	$114	$56	$47	$21
Valves	2020 $ / kW	$88	$83	$23	$22
Instrumentation	2020 $ / kW	$16	$11	$7	$4
Direct Capital Costs – Electrical BOP					
Rectifier	2020 $ / kW	$107	$107	$93	$93
Wiring	2020 $ / kW	$63	$18	$35	$14
Infrastructure	2020 $ / kW	$48	$32	$44	$27
Direct Capital Costs - Stacks					
Stacks	2020 $ / kW	$186	$182	$95	$93
Indirect Capital Costs					
Site Preparation	2020 $ / kW	$62	$13	$49	$10
Engineering and Design	2020 $ / kW	$74	$13	$76	$13
Up-Front Permitting Costs	2020 $ / kW	$41	$7	$42	$7
Project Contingency	2020 $ / kW	$107	$79	$59	$45
Land	2020 $ / kW	$3	$1	$2	$0
Total Installed Capital Costs	**2020 $ / kW**	**$1,000**	**$643**	**$619**	**$376**

Table 18. Total installed capital cost for AEM Water.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1097	104	1036
Direct Capital Costs - Mechanical BOP					
Equipment	2020 $k / plant	$12,297	$54,210	$5,893	$29,899
Piping	2020 $k / plant	$11,496	$54,786	$4,026	$16,521
Valves	2020 $k / plant	$8,358	$79,772	$1,587	$14,786
Instrumentation	2020 $k / plant	$2,400	$15,487	$844	$4,776
Direct Capital Costs – Electrical BOP					
Rectifier	2020 $k / plant	$15,802	$159,191	$9,929	$99,285
Wiring	2020 $k / plant	$8,405	$25,620	$3,845	$15,683
Infrastructure	2020 $k / plant	$6,295	$46,567	$4,664	$29,076
Direct Capital Costs - Stacks					
Stacks	2020 $k / plant	$16,145	$159,153	$10,346	$103,244
Indirect Capital Costs					
Site Preparation	2020 $k / plant	$7,429	$16,540	$5,195	$11,317
Engineering and Design	2020 $k / plant	$7,992	$14,203	$7,871	$13,994
Up-Front Permitting Costs	2020 $k / plant	$4,419	$7,000	$4,366	$6,917
Project Contingency	2020 $k / plant	$12,180	$89,218	$6,170	$46,990
Land	2020 $k / plant	$432	$694	$180	$413
Total Installed Capital Costs	**2020 $k / plant**	**$113,648**	**$722,439**	**$64,913**	**$392,902**

Table 19. Total installed capital cost scaled by BOL rated plant power for AEM Water.

Technology Basis	-	Current	Current	Future	Future
Nominal Year	Year	2023	2023	2030	2030
Plant Capacity	MTD	50	500	50	500
Plant Power (BOL Rated)	MW_AC	110	1,097	104	1,036
Direct Capital Costs - Mechanical BOP					
Equipment	2020 $ / kW	$112	$49	$57	$29
Piping	2020 $ / kW	$104	$50	$39	$16
Valves	2020 $ / kW	$76	$73	$15	$14
Instrumentation	2020 $ / kW	$22	$14	$8	$5
Direct Capital Costs – Electrical BOP					
Rectifier	2020 $ / kW	$143	$145	$96	$96
Wiring	2020 $ / kW	$76	$23	$37	$15
Infrastructure	2020 $ / kW	$57	$42	$45	$28
Direct Capital Costs - Stacks					
Stacks	2020 $ / kW	$146	$145	$100	$100
Indirect Capital Costs					
Site Preparation	2020 $ / kW	$67	$15	$50	$11
Engineering and Design	2020 $ / kW	$73	$13	$76	$14
Up-Front Permitting Costs	2020 $ / kW	$40	$6	$42	$7
Project Contingency	2020 $ / kW	$110	$81	$59	$45
Land	2020 $ / kW	$4	$1	$2	$0
Total Installed Capital Costs	**2020 $ / kW**	**$1,031**	**$657**	**$626**	**$379**

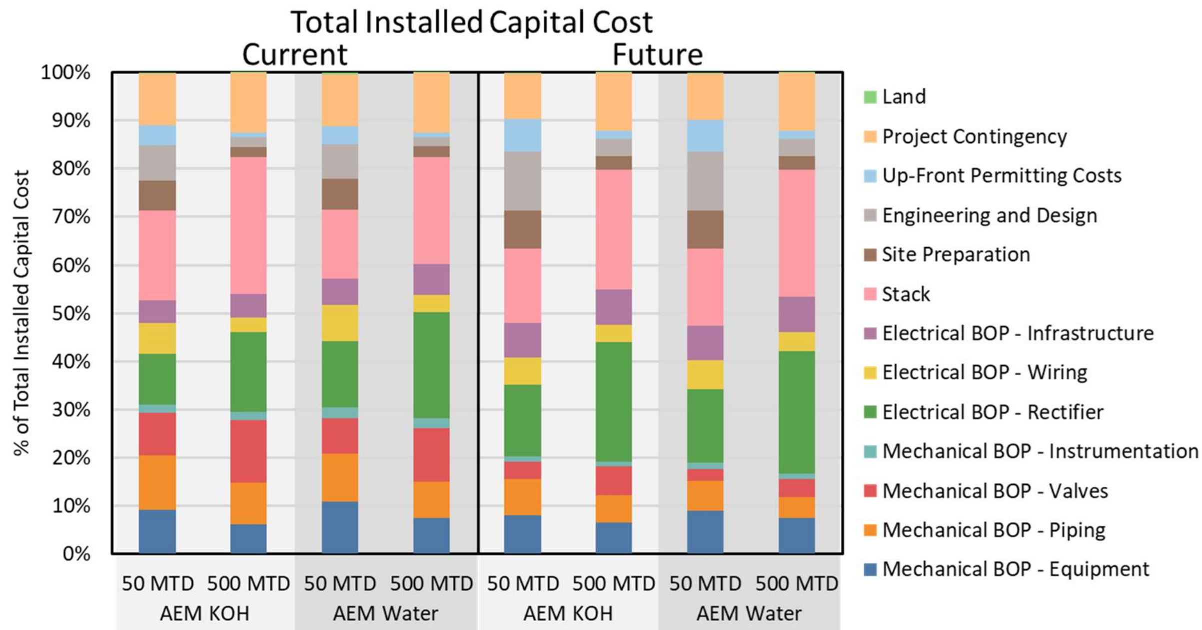

Figure 20. Percentage of total installed capital cost for each cost element for AEM KOH and AEM Water with a plant capacity of 50 MTD and 500 MTD assuming a baseline electricity price of $0.03/kWh and 97% capacity factor.

7 Appendix B. Sensitivity to Electricity Pricing and Capacity Factor: Additional Results

As described in Section 5.4, the levelized cost of hydrogen was calculated for multiple electricity prices ($0.00/kWh to $0.10/kWh) and capacity factors (10% to 100%) for a 50 MTD plant (assuming 4 modules for Current technology basis and 2 modules for Future technology basis). Additional results for each case are shown below.

7.1 Total Installed Capital Cost

Total installed capital cost for each case is shown in *Figure 21* and *Figure 22* for AEM KOH and AEM Water, respectively. Total installed capital cost is a complex mix of competing trends due to the effects of cost-optimization and normalization to 50 MTD. Since all of the cases are required to produce an average of 50 metric tonnes per day of hydrogen, a lower capacity factor electricity source would require a larger plant and subsequently incurs a higher total installed capital cost. Additionally, the higher installed capital cost results in the cost-optimized operating point to shift to a higher current density, which works to reduce stack count (or at least diminish the extent of overall stack count increase). Likewise, increasing the average electricity cost causes a shift in the cost-optimized operating point to a lower current density and, in turn, a corresponding increase in stacks and higher total installed capital cost. These trends compete against each other to create the tradeoff graphs shown below.

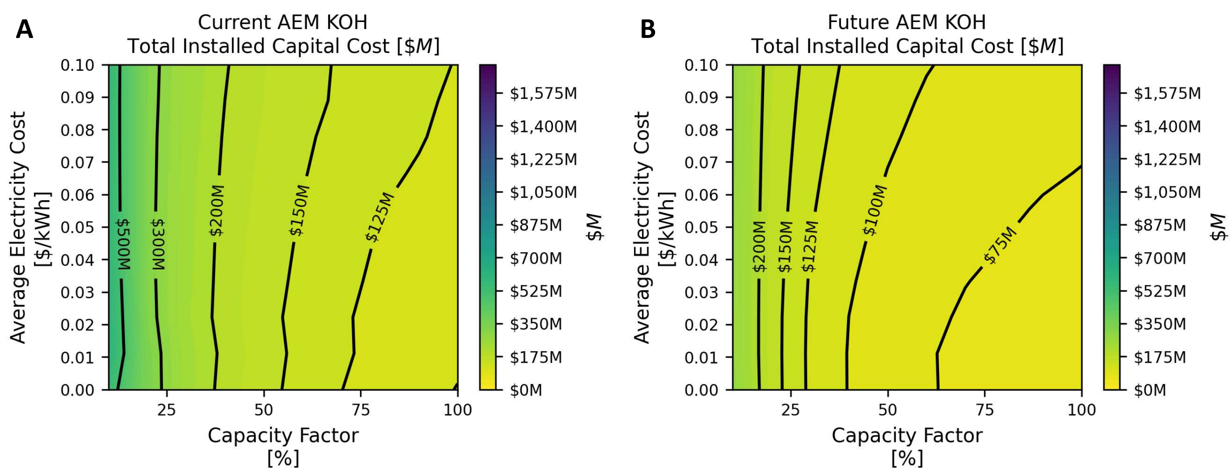

Figure 21. Total installed capital cost for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

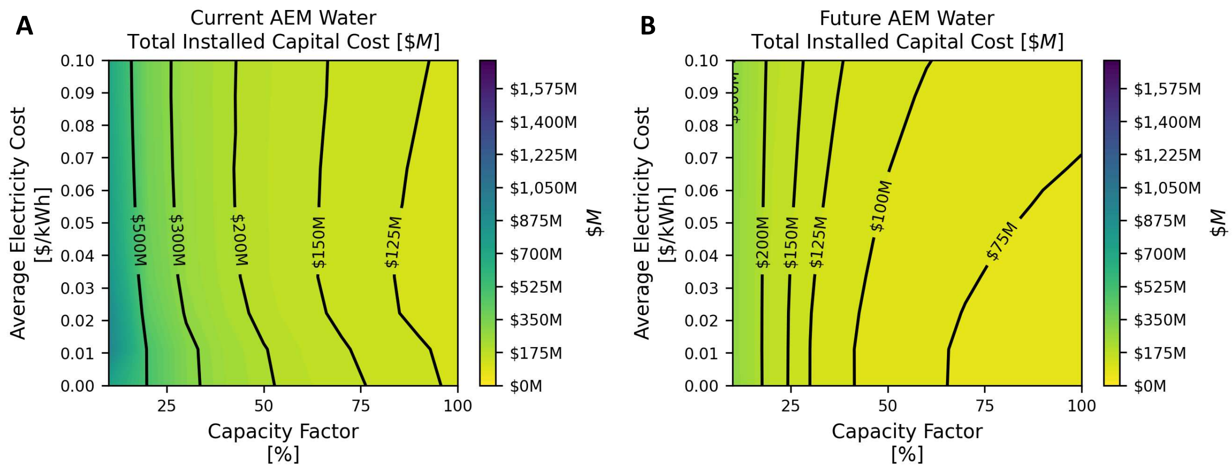

Figure 22. Total installed capital cost for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

7.2 Plant Power

Plant power (BOL Rated) for each case is shown in *Figure* 23 and *Figure* 24 for AEM KOH and AEM Water, respectively. The graphs indicate how BOL rated plant power increases with decreasing capacity factor for a constant 50 MTD production rate. Likewise, the graphs indicate there is essentially no correlation between average electricity cost and BOL rated plant power.

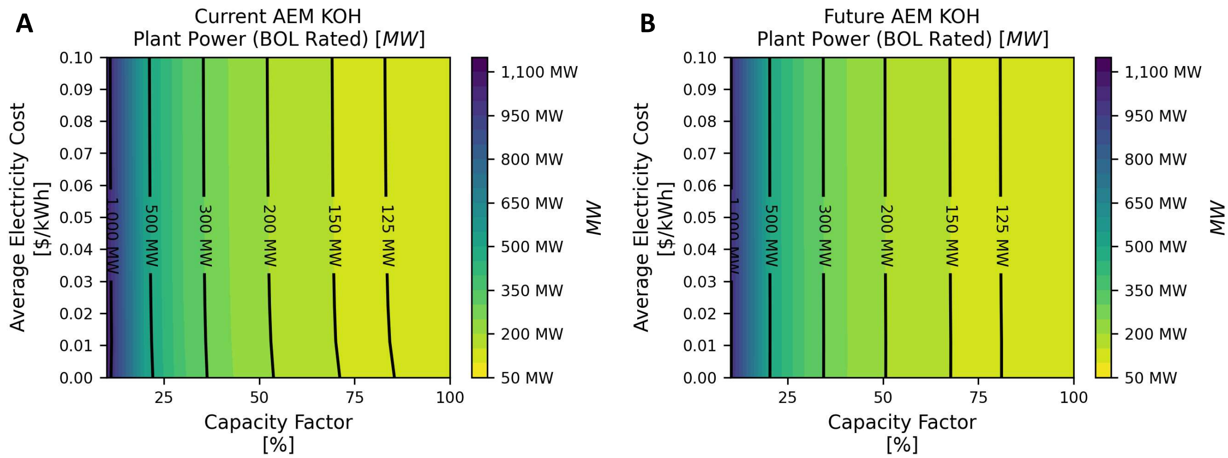

Figure 23. Plant power (BOL Rated) for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

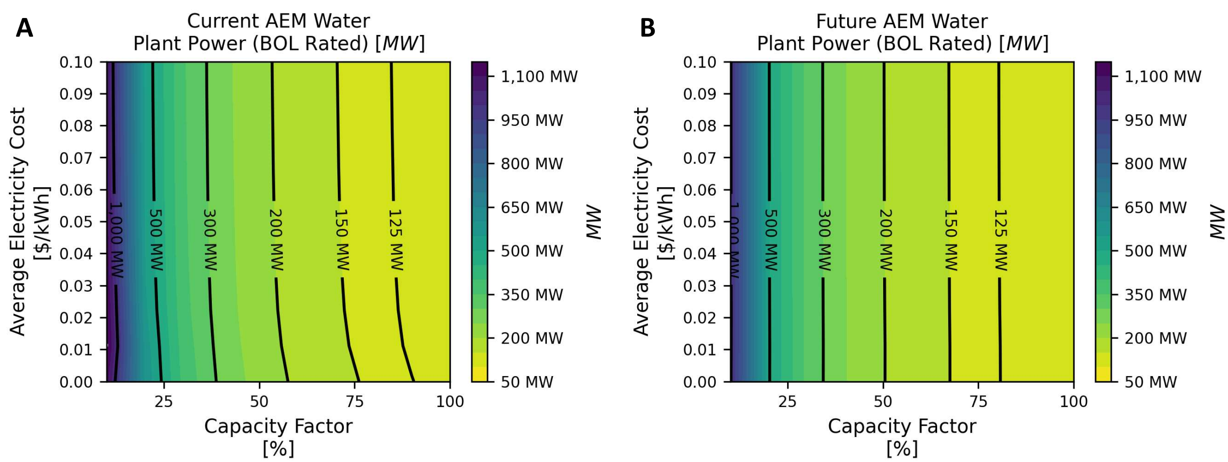

Figure 24. Plant power (BOL Rated) for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

7.3 Scaled Plant Cost

The scaled plant cost was calculated by dividing the total installed capital cost by the plant power (BOL Rated). Scaled plant cost for each case is shown in *Figure* 25 and *Figure* 26 for AEM KOH and AEM Water, respectively. Irregularities in the contours primarily stem from limitations of the plant cost model to smoothly transition between plant designs caused by different optimized operating points.

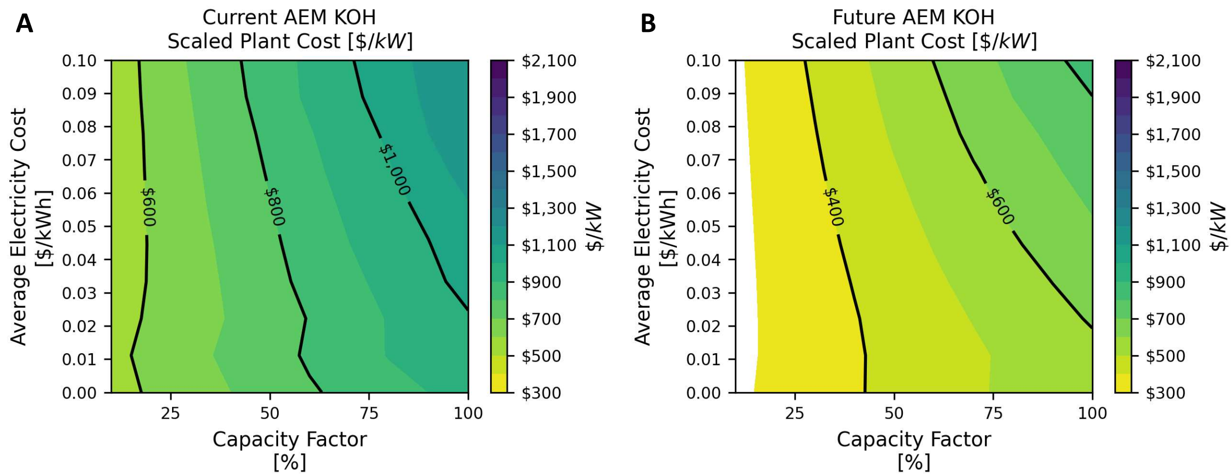

Figure 25. Scaled plant cost (2020 $ / kW, BOL Rated) for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

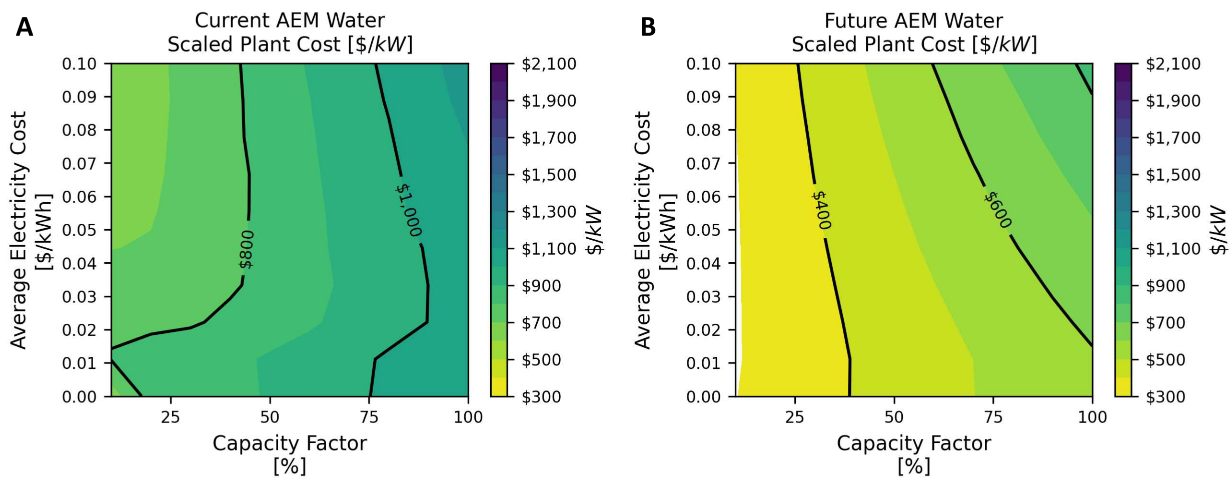

Figure 26. Scaled plant cost (2020 $ / kW, BOL Rated) for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

7.4 Current Density

The current density operating point (BOL Optimized) for each case is shown in *Figure* 27 and *Figure* 28 for AEM KOH and AEM Water, respectively. For legibility, cases that exceed 3 A/cm^2 are omitted from the figures. The graphs support the observation that both low electricity cost and low capacity factor drive the cost-optimized solutions to higher current density.

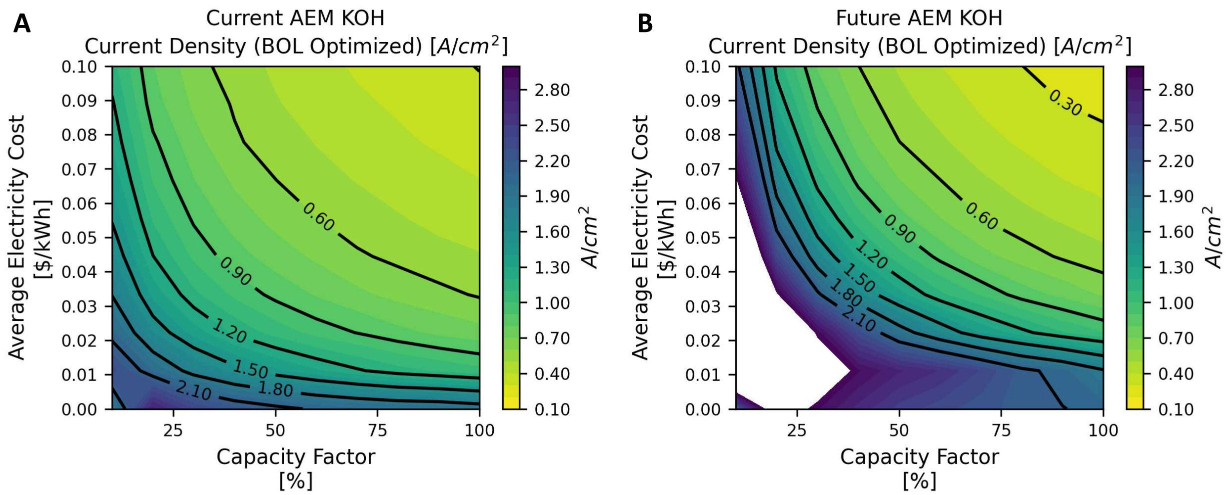

Figure 27. Current density operating point (BOL Optimized) for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

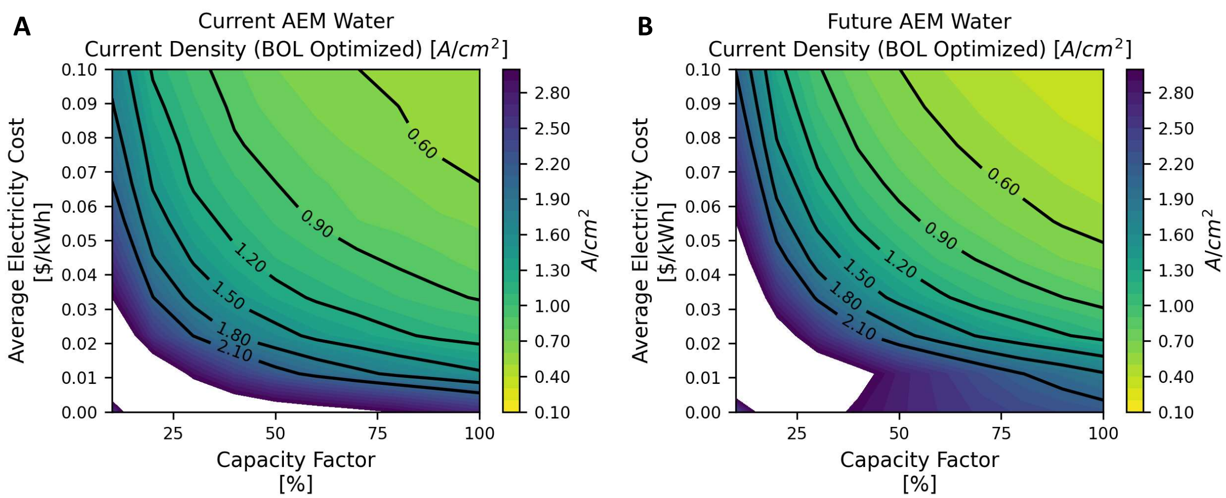

Figure 28. Current density operating point (BOL Optimized) for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

7.5 Average Plant Electrical Usage

The average plant electrical usage for each case is shown in *Figure* 29 and *Figure* 30 for AEM KOH and AEM Water, respectively. For legibility, cases that exceed 107.5 kWh/kg H_2 are omitted from the figures. The graphs support the observation that both low electricity cost and low capacity factor drive the cost-optimized solutions to higher average plant electrical usage.

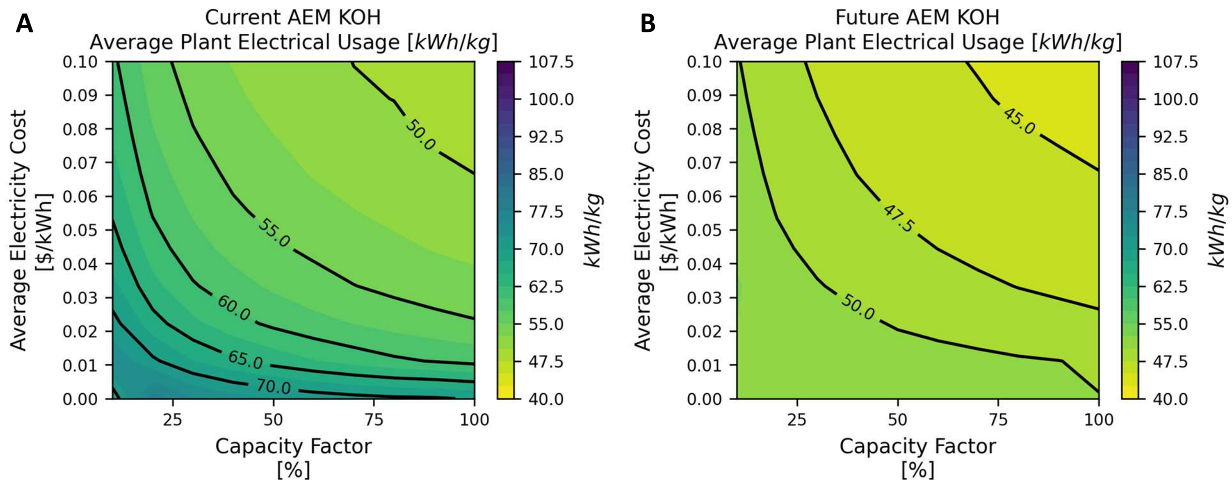

Figure 29. Average plant electrical usage for AEM KOH with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

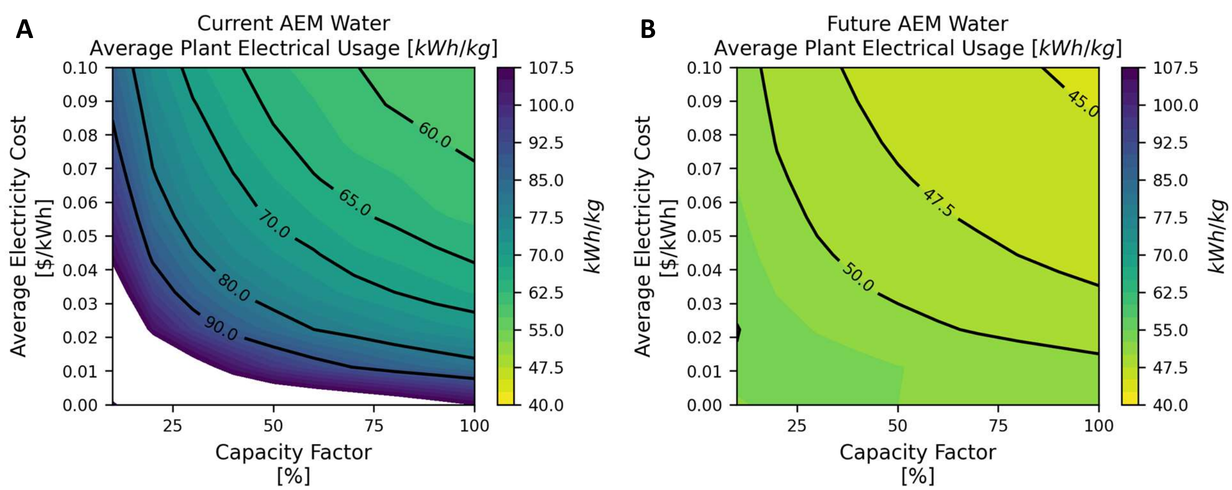

Figure 30. Average plant electrical usage for AEM Water with a plant capacity of 50 MTD for varying electricity prices and capacities for (A) Current and (B) Future technology bases.

8 Appendix C. H2A Model Financial Parameters

The levelized cost of hydrogen analysis primarily uses the default financial parameters for the H2A model. In general, the financial parameters are based on near-term deployment of an electrolyzer plant. Table 20 shows the key assumptions used within the discounted cash flow model, which feeds into the levelized cost of hydrogen calculation.

Table 20. H2A Financial Parameters

Parameter	Unit of Measure	Value
Reference year	year	2020
Assumed start-up year	year	2023
Basis year	year	2020
Length of Construction Period	years	1
Start-up Time	years	1
Plant life (years)	years	40
Depreciation Schedule Length	years	20
Depreciation Type	-	MACRS
% Equity Financing	%	40%
Interest rate on debt, if applicable	%	3.70%
Debt period	-	Constant debt
% of Fixed Operating Costs During Start-up	%	75%
% of Revenues During Start-up	%	50%
% of Variable Operating Costs During Start-up	%	75%
Decommissioning costs	% of depreciable capital investment	10%
Salvage value	% of total capital investment	10%
Inflation rate	%	1.9%
After-tax Real IRR	%	8.0%
State Taxes	%	6.0%
Federal Taxes	%	21.0%
Total Tax Rate	%	25.74%
Working Capital	% of yearly change in operating costs	15%