Hydrogen Production Cost and Performance Analysis

DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

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Strategic Analysis

AMR Project ID: P204
DOE Project Award No. DE-EE0009629
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Project Goal

- **Conduct technoeconomic analysis** to evaluate the cost to produce H_2 ($/kg) through **various technological production pathways** (i.e., electrolysis, PEC, others) using
  - Design for Manufacture and Assembly (DFMA) capital cost estimation techniques,
  - Heat & mass balances, and
  - H2 Analysis (H2A) discounted cash flow models.

- **Estimate the cost of H_2** based on state-of-the-art technology at **central production facilities** (50-500 tons per day) and **measure the cost impact** of technological improvements in H_2 production technologies.

- Evaluate the **cost drivers** and **recommend** to DOE the **technical areas needing improvement** for each technology.

Overview

Timeline

- Project start date: 10/1/2021
- Project end date: 9/30/2024
- Percent complete: ~50% of project

Barriers

- Hydrogen (H_2) Generation by Water Electrolysis
  - F: Capital Cost
  - G: System Efficiency and Electricity Cost
  - K: Manufacturing

Budget

- Total Funding Spent
  - ~$392K SA (though Mar 2023)
- Total DOE Project Value:
  - ~$775k SA
- Cost Share Percentage: 0%
  (not required for analysis projects)

Partners

- National Renewable Energy Laboratory (NREL)
- Idaho National Laboratory (INL)

Collaborators (unpaid)

- 4 Electrolyzer companies and research groups

Relevance and Impact

- Investigates production and delivery pathways selected/suggested by DOE that are relevant, timely, and of value to HFCTO.
- Supports selection of portfolio priorities through evaluations of technical progress and hydrogen cost status.
- Provides complete pathway definition, performance, and economic analysis not elsewhere available.
- Provides analysis that is transparent, detailed, and made publicly available to the technical community.
- Results of analysis:
  - Identifies cost drivers
  - Assesses technology status
  - Provides information to DOE to help guide R&D direction
  - Highlight real world scenarios that can achieve the Hydrogen Shot goal of $1 for 1 kg hydrogen in 1 decade

Approach: Bottom-Up Project Cost Model for Low-Temperature Electrolysis

Project Objective

- Support HFCTO in their selection of portfolio priorities by evaluating technical progress of H_2 production pathways
- Assess the potential to meet H_2 production cost targets (H2 Shot: $1/kg of H_2 by 2031)
- Evaluate the uncertainty and show the potential for H_2 cost reduction for each pathway through single and multi-variable sensitivity analyses
- Perform rigorous review of system design and assumptions, confirm the validity of assumptions with experts external to the project, and document results in reports and presentations

Approach

- Collect data via published journal articles, patents, and report
- Conduct DFMA analysis to estimate cost of electrolysis stack
- Obtain review of DFMA cost results and compare with other studies
- Conduct system modeling to estimate sizing of balance of plant components
- Plant and equipment sizing are based on end-of-life (EOL) operating conditions
  - Central: 50 Tons/Day (nominally)
  - (Distributed cases at 1.5 Tons/Day have been considered in past SA analyses. But DOE has directed us to solely assess the Central case)
- Update H2A model with new values to obtain updated $/kg H_2 projections

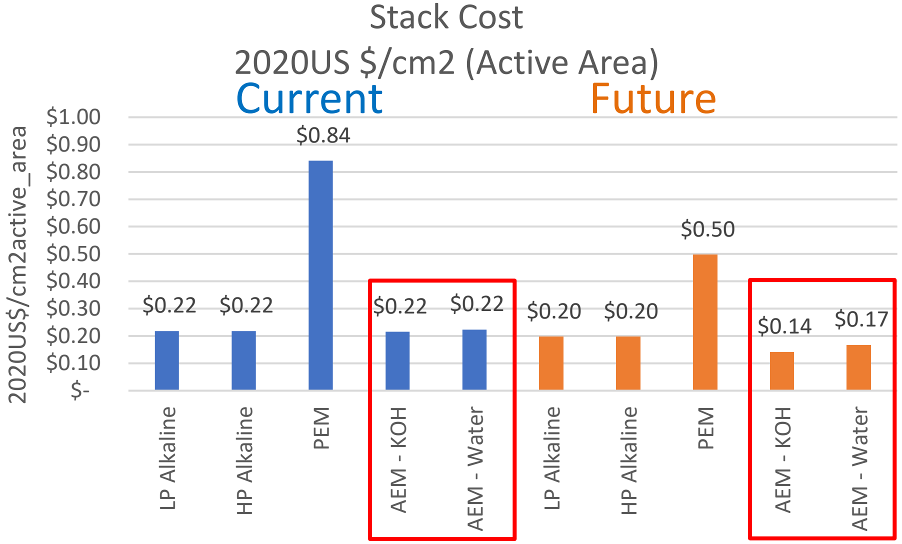
Selected Pathway: Anion Exchange Membrane (AEM) using KOH solution [AEM KOH] and AEM using pure water solution [AEM Water]

Task	Description	Completed for 2023 Analysis
1	Technologies Identification, Review, and Selection of Pathway	Milestone 1.2 submitted in October 2022
2	System Definition and Bill of Materials	Milestone 2.2 submitted in March 2023
3	Techno-economic Analysis	In Progress: Milestone 3.2 to be submitted in June 2023
4	Case Study Documentation and Project Reporting	Planned: Milestone 4.2 to be submitted in September 2023 (Go/No-Go decision metric)

System definition developed for AEM KOH and AEM Water electrolysis systems

(Optimized operating points shown in table. Polarization curves shown on future slide.)

		AEM KOH		AEM Water	
Parameter	**Units**	**Current**	**Future**	**Current**	**Future**
Performance					
Current Density (BOL Rated)	**A/cm^2**	*0.8*	*3.0*	*0.5*	*2.0*
Voltage (BOL Rated)	**V/cell**	*1.8*	*1.8*	*1.8*	*1.8*
Current Density (BOL, optimal)	**A/cm^2**	0.47	0.72	0.45	0.74
Voltage (BOL, optimal)	**V/cell**	1.70	1.68	1.77	1.69
Current Density (EOL, optimal)	**A/cm^2**	0.47	0.72	0.45	0.74
Voltage (EOL, optimal)	**V/cell**	1.90	1.70	2.15	1.72
Degradation Rate	**mV/khrs**	10.0	1.0	48.6	1.0
Stack Durability	**years**	4	10	1	7
Specifications					
Cell Active Area	**cm^2/cell**	800	3,000	800	3,000
Nominal Pressure (Anode/Cathode)	**bar / bar**	1 / 30	1 / 30	1 / 30	1 / 30
Operating Temperature	**°C**	70	70	70	70
KOH Concentration	**M**	1	1	1	1
Nominal Stack					
EOL Power (DC)	**MW**	0.24	2.0	0.24	2.0
Hydrogen Production	**kgH$_2$/day**	119	1,042	104	1,042
# of cells	**#**	373	532	320	520



- Stack Cost from SA DFMA analysis
- Assumes 1 GW/year manufacturing rate
- Includes 30% stack manufacturing markup

Current Technology assumption of a low active area cell (800cm^2) results in a low power stack (240kW EOL). (This will lead to relatively high LCOH as shown on a future slide.)

Modeled AEM KOH and AEM Water Electrolysis Cell Design

SA design used for Current and Future Case Cost Analysis

- Generic AEM electrolysis cell design: does not exactly match any one company (but is meant to be representative of the key materials and design features of current, modern, commercial stacks)

O2 Gasket Seal: 50µm thick die cut PET sheets

O2 Cell Frame: 1.525mm thick injection molded HDPE

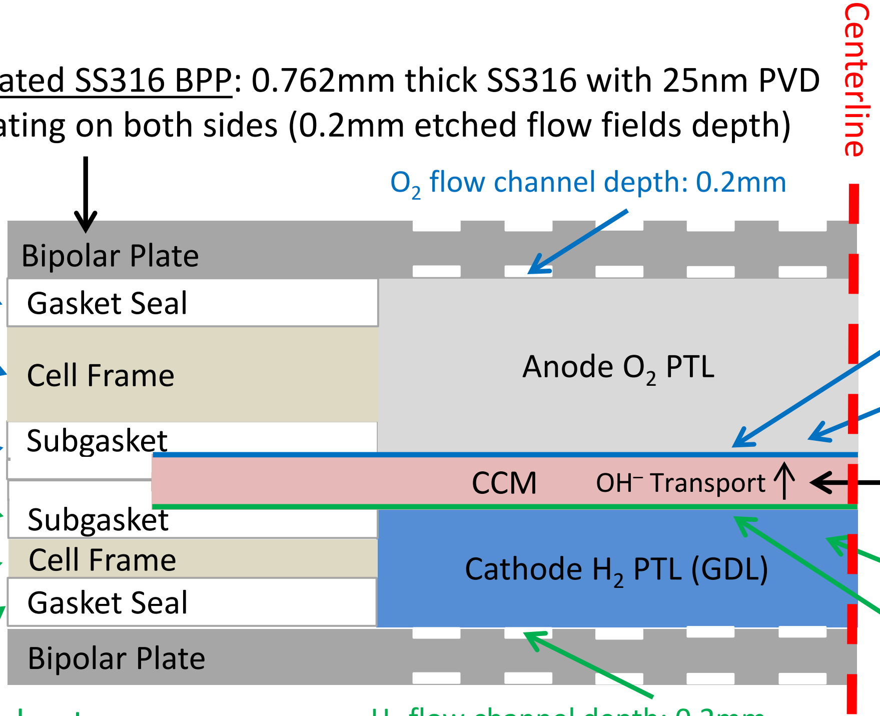
Subgasket: 50µm thick PET sheets encasing membrane using 3M roll-to-roll process

H2 Cell Frame: 75µm thick die cut HDPE sheet

H2 Gasket Seal: 50µm thick die cut PET sheets (alternatively, could insertion mold gaskets on both sides of BPP at high volume)

Ni-Coated SS316 BPP: 0.762mm thick SS316 with 25nm PVD Ni coating on both sides (0.2mm etched flow fields depth)

O_2 flow channel depth: 0.2mm



H_2 flow channel depth: 0.2mm
(modeled as 0.2mm depth but likely to be deeper)

☆ Future Case: Lower Pt loading ($0.1mgPt/cm^2$)

Water and O_2 Evolution

O2 PTL: Sintered porous Ni 1.6mm thick (50% porosity)

CCM: 50µm thick ePTFE-supported Polymeric membrane with slot die coated catalyst
O2 side: 4.8mg/cm^2 FeNiOOH
H2 side: 0.47mgPt/cm^2 at 20% Pt/C ☆

H2 GDL: 150µm thick (105µm carbon fiber substrate with 45µm thick MPL)

H_2 Evolution

2nd BPP shown for channel depth. Only one BPP per cell.

Cell Thickness = ~2.6mm

Distinguishing Features:

- Etched Ni-Coated SS BPP
- PTLs
- Catalyst Coated Membrane

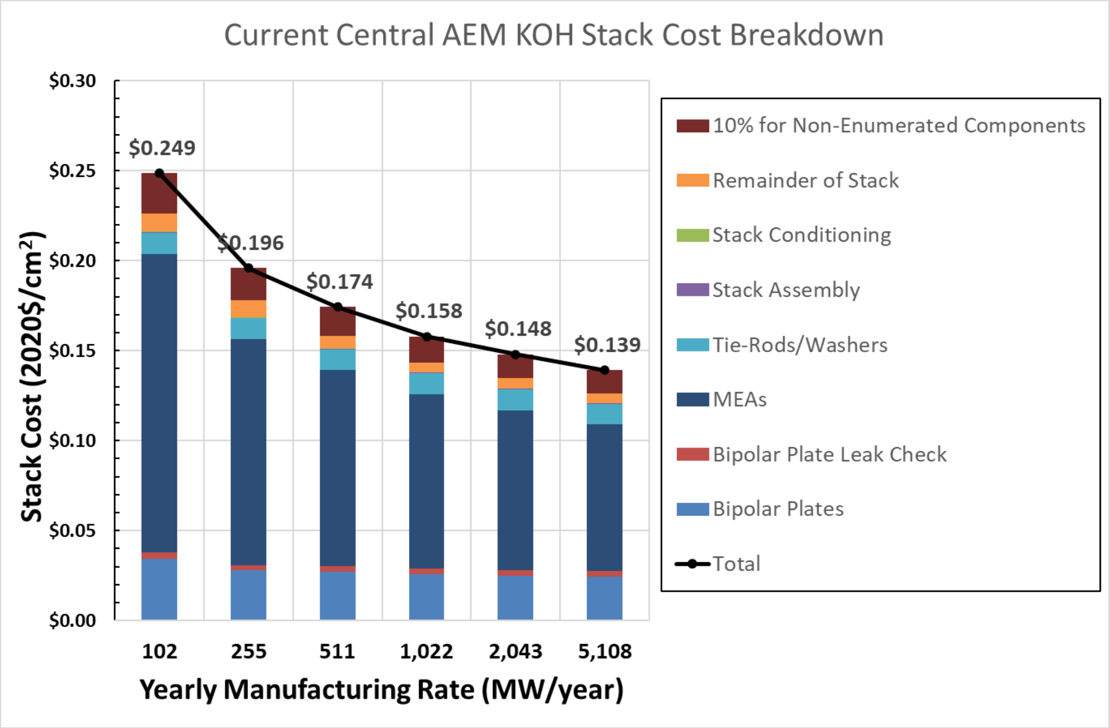
AEM Electrolyzer Stack Parameters

Parameter	Unit	AEM Current	AEM Future	Notes
OER Catalyst	-	FeNiOOH	FeNiOOH	
OER Loading	$\text{mg}_{\text{catalyst}}$/ cm^2	4.8mg/cm^2	4.8mg/cm^2	
OER Cost	$/kg	$3	$4	
HER Catalyst	-	Pt/C	Pt/C	
HER Loading	**$\text{mg}_{\text{catalyst}}$/ cm^2**	**0.47 mgPt/cm^2**	**0.1 mgPt/cm^2**	
HER Cost	$/kg	~$49,191	~$49,191	
Diaphragm/Membrane	-	Polymeric	Polymeric	
Diaphragm/ Membrane Thickness	µm	50	50	
BOL Cell Voltage	V	1.8	1.8	
Current Density (rated)	**A/cm^2**	**0.8 (KOH)** **0.5 (Water)**	**3.0 (KOH)** **2.0 (Water)**	AEM rated operating point modified from AMR 2022 based on literature review and feedback from reviewers
Stack Pressure (Cathode/Anode)	Bar	~30/~1	~30/~1	
Electrolyte		1M KOH	1M KOH	
Voltage Degradation	mV/1kh	**10.0 @0.8A/cm^2 (35kh life)**	**1.0 @3A/cm^2 (90kh life)**	
Anode Porous Transport Layer (PTL)		Sintered porous Ni 1.6mm thick (50% porosity)	Sintered porous Ni 1.6mm thick (50% porosity)	
Cathode Porous Transport Layer (PTL)		150µm thick (105µm carbon fiber substrate with 45µm thick MPL)	150µm thick (105µm carbon fiber substrate with 45µm thick MPL)	
Bipolar Plate		Etched, Ni coated Stainless Steel	Etched, Ni coated Stainless Steel	
Current Distributor		Stamped, Copper Plate	Stamped, Copper Plate	
End Plate		Machined, Stainless Steel	Machined, Stainless Steel	
Compression System		Tie Rods	Tie Rods	

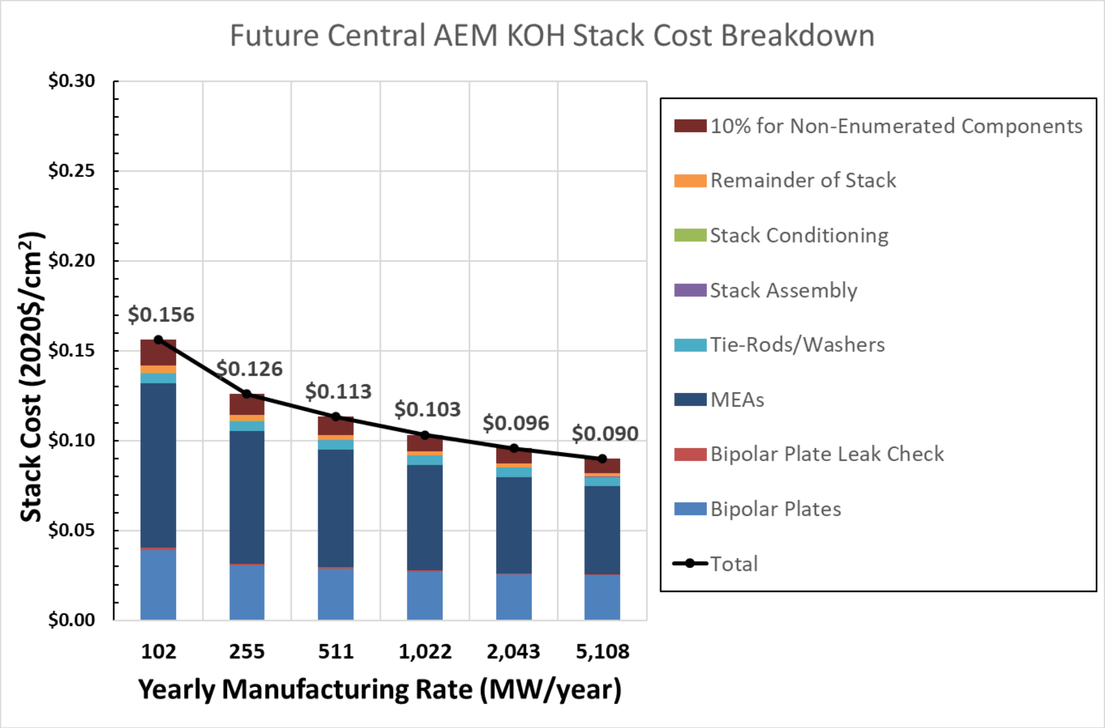
AEM KOH Electrolyzer Cost per Active Area

Current: ~$0.158/cm² compared to Future:~$0.103/cm² at ~1GW/yr

Current Central AEM KOH Electrolyzer



Future Central AEM KOH Electrolyzer

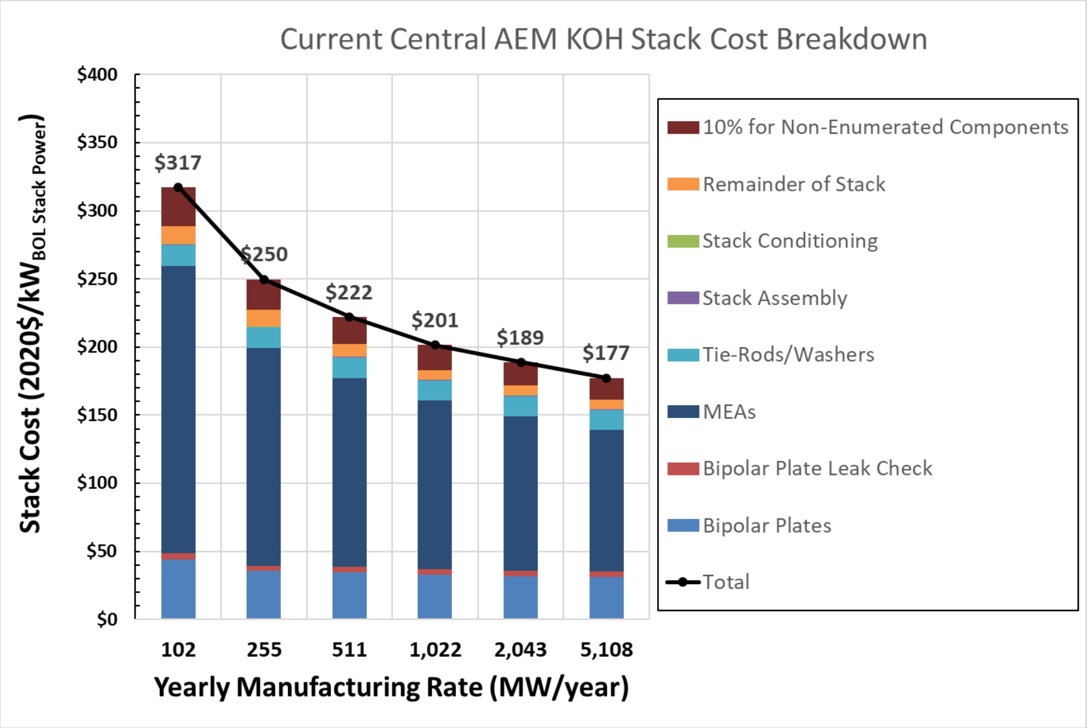


- **Values reported on this slide exclude markup and installation**
- Future system cost reduction due to omission of change of stack size and reduced Pt loading

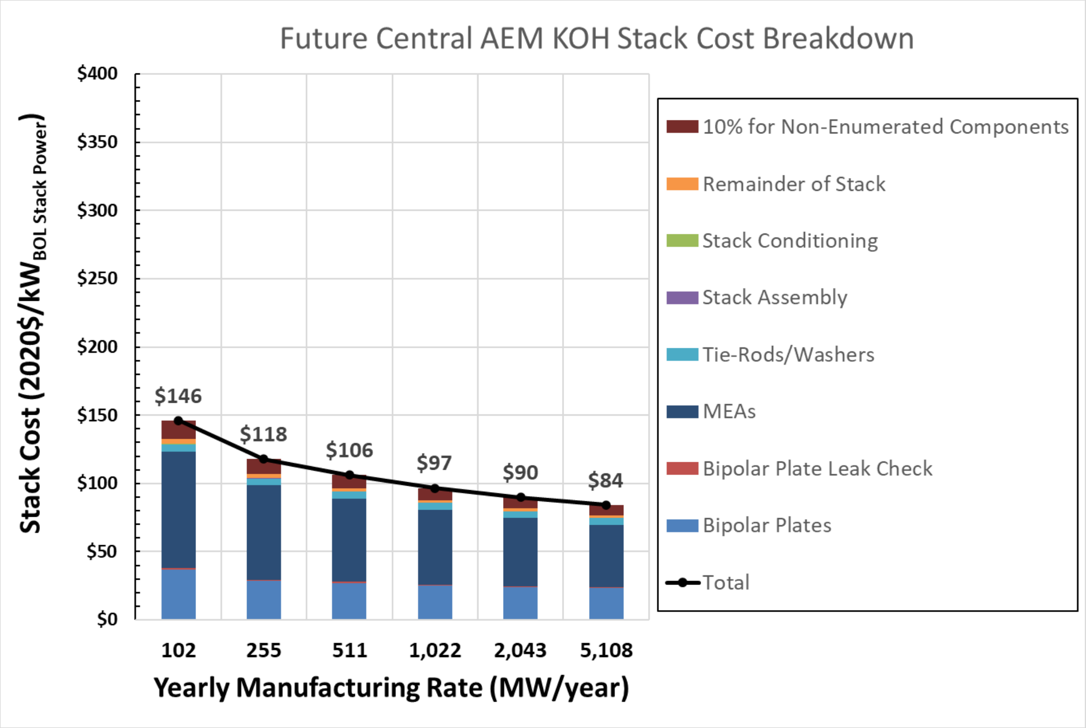
AEM KOH Electrolyzer Total Stack Cost

Current: ~$201/kW compared to Future:~$97/kW at ~1GW/yr

Current Central AEM KOH Electrolyzer



Future Central AEM KOH Electrolyzer

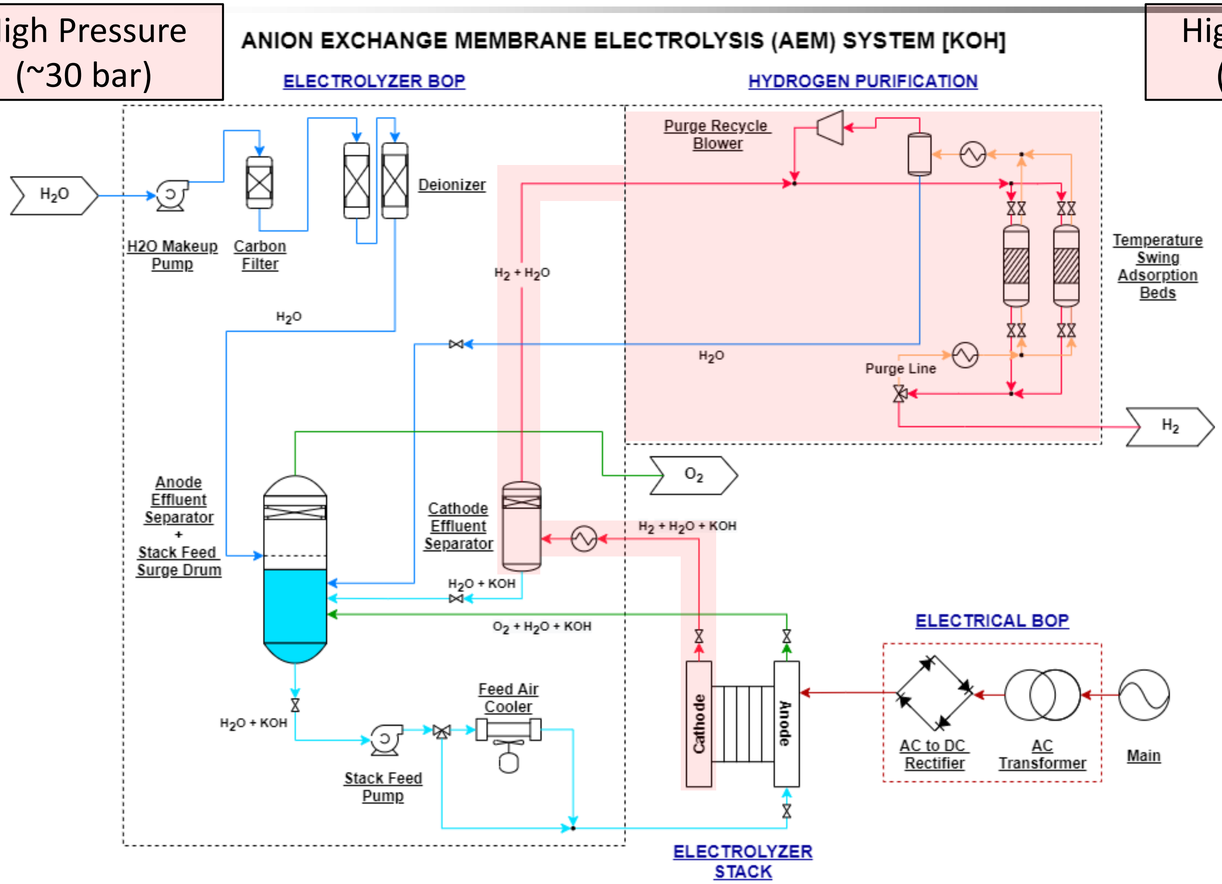


- **Values reported on this slide exclude markup and installation**
- $/kW costs are based on BOL stack power (optimized conditions)
- Future system cost reduction due to omission of change of stack size and reduced Pt loading

Process diagrams developed for AEM KOH and AEM Water

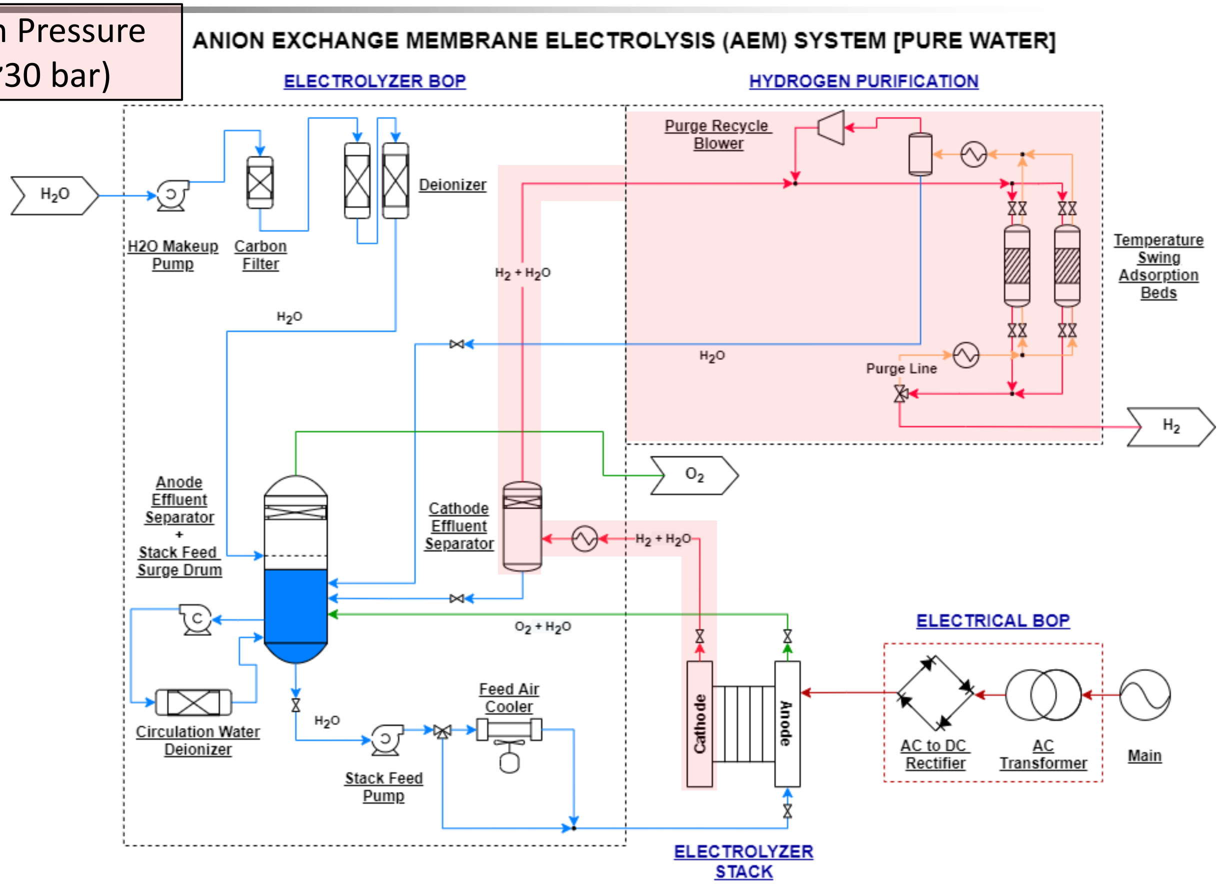
AEM KOH

High Pressure
(~30 bar)



AEM Water

High Pressure
(~30 bar)



AEM KOH Process Design Notes

- KOH solution only enters anode and diffuses to cathode. Cathode effluent separator only contains trace amounts of water
- Only Cathode assumed to be pressurized. No hydrogen compressor required

AEM Water Process Design Notes

- Water deionizer used to maintain inlet water purity
- Only Cathode assumed to be pressurized. No hydrogen compressor required

Mechanical and Electrical BOP Component Cost Overview

- Balance of Plant can be broken down into two sub-components:
  - **Mechanical BOP:**
    - Consists of **equipment, piping, valves, and instrumentation**
    - Cost basis
      - **Major BOP Equipment**: Aspen-generated cost estimates based on technical specifications
      - **Piping**: Aspen-generated cost estimates based on sizing and materials specifications
      - **Valves**: Published cost curves from Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003
      - **Instrumentation**: Published quotes from Plant Design and Economics for Chemical Engineers, Fifth Edition, 2003
        - Includes temperature, pressure, flow, and level indicators

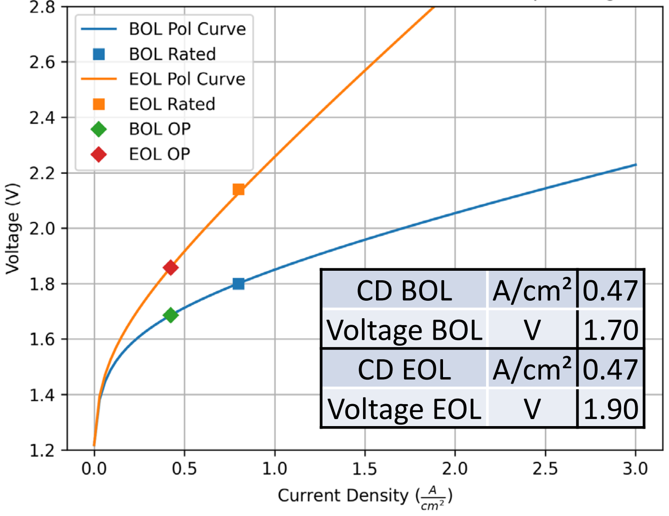
  - **Electrical BOP:**
    - Consists of **rectifier and housing; electrical wiring; and electrical infrastructure**
    - Cost basis
      - **Rectifier**: Quote from Rectifier vendor
      - **Transformer**: Estimate from 2013 engineering study
      - **Electrical Wiring**: Estimated using Craftsman methodology
      - **Electrical Infrastructure**: Estimated from publicly available price estimates

Polarization Curves – Cost Optimized Operating Point

Summary of Cost Optimization

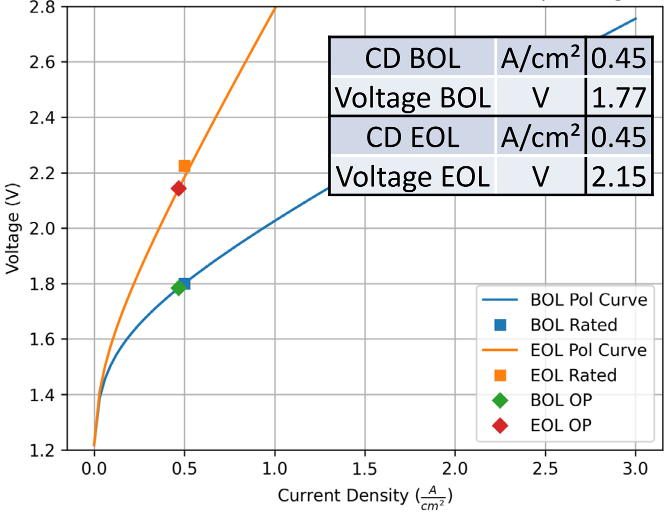
- Beginning of life (BOL) and end of life (EOL) polarization curve generated by assuming a constant degradation per year and a specific stack lifetime
- Cost optimized operating point selected by calculating a H2A hydrogen price for various current densities
- Operating point influences BOP capital cost, while BOP capital cost influences cost optimized operating point. **Therefore, operating point and capital cost must be co-optimized.**
  - 2nd iteration of H2A cost optimization procedure showed only minor changes between initial operating point and re-optimized operating point.

AEM KOH


Current Central AEM KOH Case Pol Curves and Operating Points

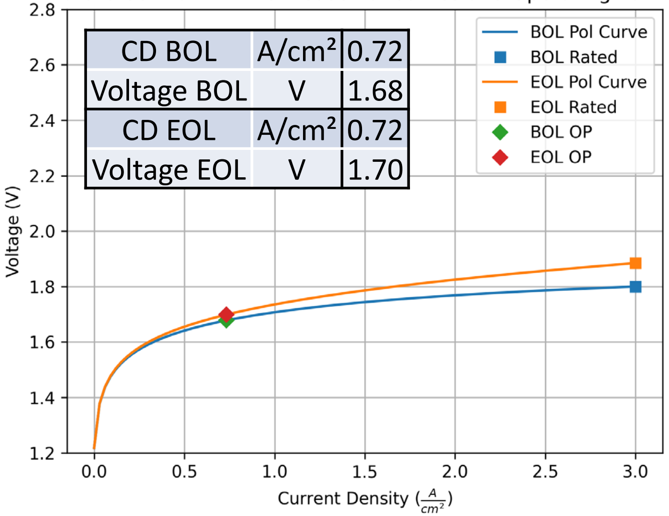
CD BOL	A/cm^2	0.47
Voltage BOL	V	1.70
CD EOL	A/cm^2	0.47
Voltage EOL	V	1.90

AEM Water

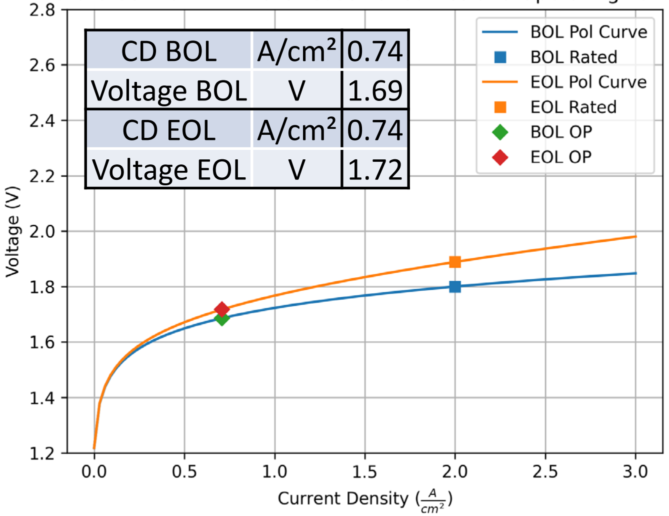

Current Central AEM Water Case Pol Curves and Operating Points

CD BOL	A/cm^2	0.45
Voltage BOL	V	1.77
CD EOL	A/cm^2	0.45
Voltage EOL	V	2.15

Current


Future Central AEM KOH Case Pol Curves and Operating Points

CD BOL	A/cm^2	0.72
Voltage BOL	V	1.68
CD EOL	A/cm^2	0.72
Voltage EOL	V	1.70


Future Central AEM Water Case Pol Curves and Operating Points

CD BOL	A/cm^2	0.74
Voltage BOL	V	1.69
CD EOL	A/cm^2	0.74
Voltage EOL	V	1.72

Future

Project Technical Parameters

		AEM KOH		AEM Water	
Parameter	**Units**	**Current**	**Future**	**Current**	**Future**
Plant Specifications					
Plant Capacity	kg H_2/day	50,000	50,000	50,000	50,000
Electrolyzer Power (System, BOL Rated)	MW	107	104	109	104
Number of Modules per Plant	#	4	2	4	2
Total Electrical Usage (BOL Rated)	kWh/kg	51.3	50.0	52.2	49.8
Stack Electrical Usage (BOL Rated)	kWh/kg	47.8	47.8	47.8	47.8
Total Electrical Usage (Average, optimal)	kWh/kg	51.4	47.0	59.3	47.2
Stack Electrical Usage (BOL, optimal)	kWh/kg	45.2	44.6	48.6	44.9
Stack Electrical Usage (EOL, optimal)	kWh/kg	50.5	45.1	61.1	45.7
BOP Electrical Usage	kWh/kg	3.4	2.2	4.4	1.9
Output Pressure	bar	30	30	30	30
Hydrogen Purity	%	99.99	99.99	99.99	99.99

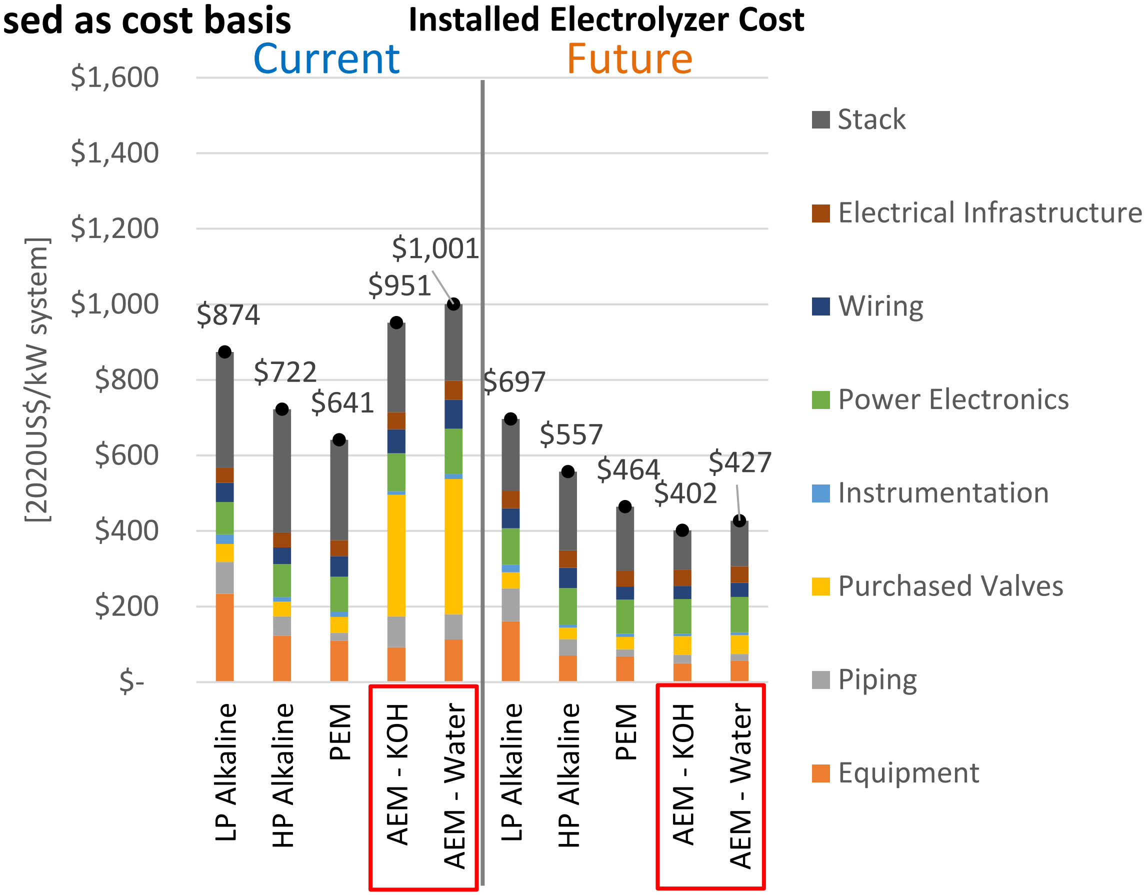
Project balance of plant equipment sized using EOL conditions, during which the most heat is generated
ΔT across low temperature stacks limited to 10 °C

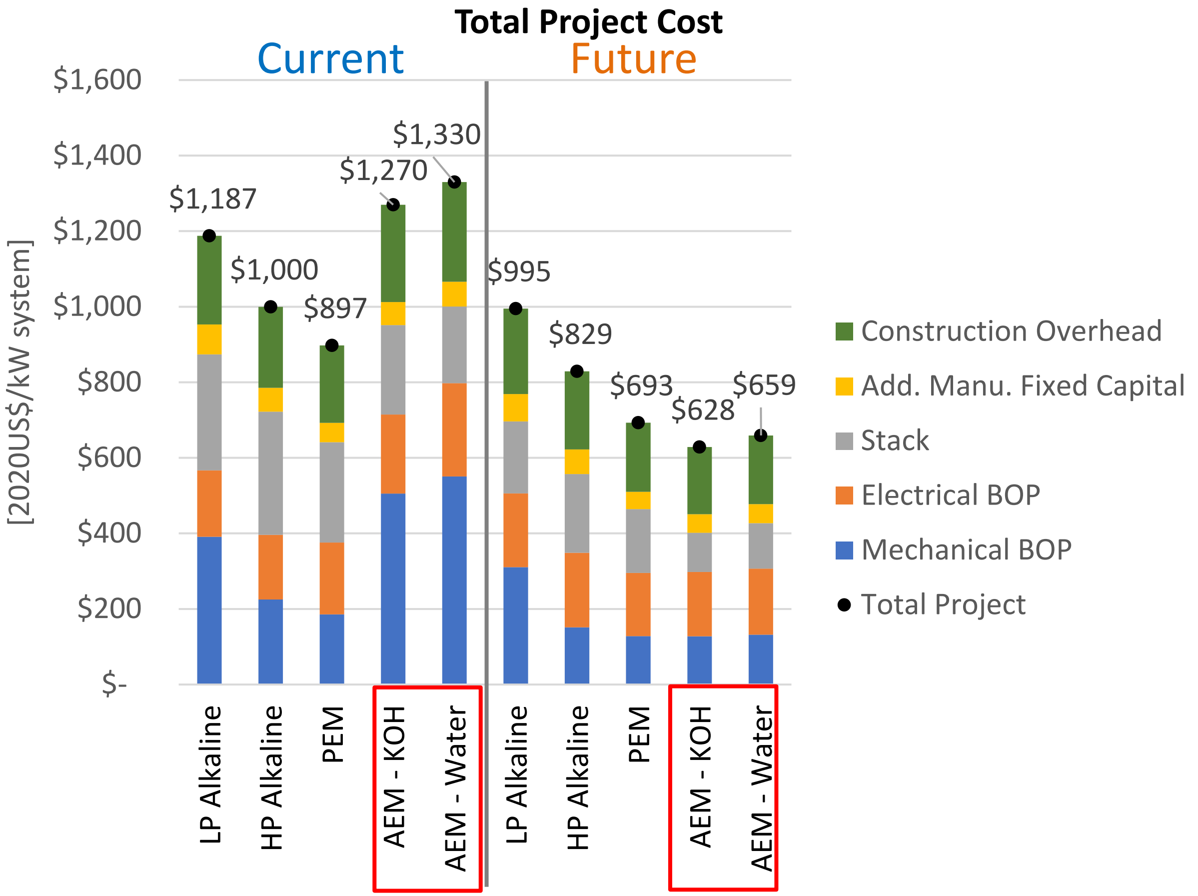
AEM Electrolyzer and Project Capital Cost
(Comparison to alternative low-temperature electrolyzers)

Accomplishment and Progress

1 GW/year annual electrolyzer manufacturing rate

BOL Rated power used as cost basis



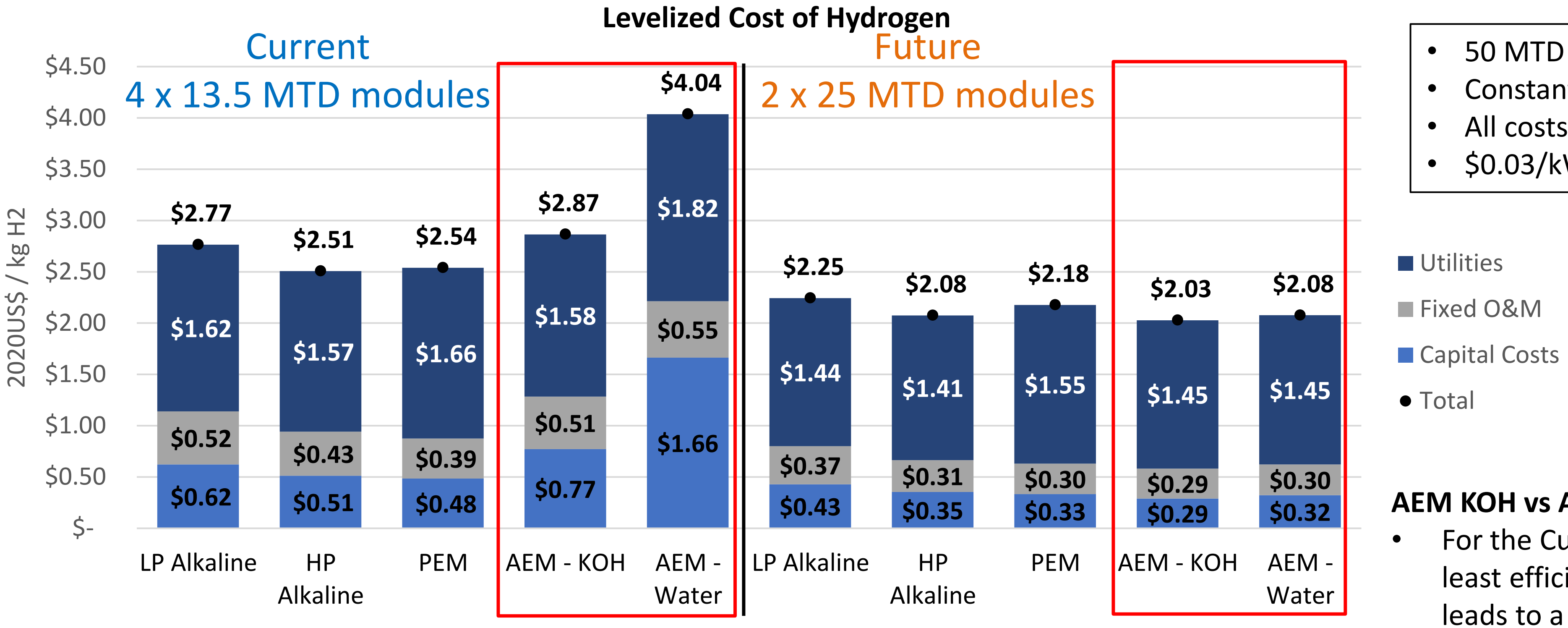


Cost optimization method adjusts the operating point and capital cost, resulting in balanced stack costs for different electrochemical technologies

Additional Manufacturing Costs (Site Preparation): Bottom-up cost estimate
Construction Overhead (Engineering & design, project contingency, and permitting costs): General project estimates

Levelized Cost of Hydrogen (using optimized operating conditions)

(Assumes $0.03/kWh electricity)



- 50 MTD Plant
- Constant electricity cost: $0.03/kWh
- All costs in 2020$
- $0.03/kWh electricity, 97% capacity factor

Current Technology

- HP Alkaline benefits from a simpler system (no compressor) and generally higher efficiency
- PEM limited by relatively lower efficiency compared to alkaline systems
- Small AEM stacks (240kW EOL) increase capital cost and introduce significant labor overhead
- Stack Replacement is a significant cost for near-term AEM water (1 year stack lifetime)

Future Technology

- Differences in LCOH between electrolyzer technologies shrink due to similar capital costs
- HP Alkaline is able to achieve a relatively high efficiency while keeping capital costs low
- AEM with 2 MW stacks is able to achieve low capital cost while maintaining a high efficiency

AEM KOH vs AEM Water

- For the Current Case, AEM Water has the least efficient polarization curve which leads to a higher electricity cost and CAPEX
- For the Future Case, AEM Water could have comparable cost to the other LTE systems if the performance can be improved.

Collaboration and Coordination

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur • Jamie Kee • Mark Chung	Subcontractor	• Participated in weekly project calls • Assisted with H2A Production Model runs & sensitivity analyses • Drafted and reviewed reporting materials
National Renewable Energy Laboratory (NREL) • Bryan Pivovar • Alex Badgett • Joe Brauch	Reviewer	• Provided guidance on electricity modeling and performance optimization • Review of assumptions for Alkaline and PEM electrolyzer performance
Idaho National Laboratory (INL) • Daniel Wendt	Subcontractor	• Participated in select project calls • Expert in Solid Oxide Electrolysis (which is planned for project analysis)
Department of Energy (DOE) • James Vickers (primary) • Ned Stetson • Dave Peterson	Sponsor	• Participated in biweekly project calls • Assisted with H2A Model and sensitivity parameters • Reviewed reporting materials
Companies: • Versogen • EvolOH • De Nora • AquaHydrex	Reviewer	• Versogen provided feedback on Anion Exchange Membrane design • EvolOH provided feedback on Anion Exchange Membrane design and performance • De Nora provided guidance on alkaline membrane performance and degradation • AquaHydrex provided feedback on Alkaline and PEM stack design and performance

Conclusions, Remaining Challenges and Barriers

- **Anion Exchange Membrane Electrolysis Systems**
  - AEM systems are promising for their potential for non-PGM catalysts, low membrane cost, and use of stainless components (i.e., Titanium or Nickel plates/plating may not be required)
  - Although pure water systems can have a simplified BOP system without a KOH scrubber, there are multiple advantages for operating with a supporting-electrolyte system (such as KOH) that include:
    - » improved durability over pure water systems
    - » improved current density over pure water systems
  - TEA analysis shows that due to lower $/cm^2 stack costs, AEM can be operated at lower cell voltages (than PEM) to achieve higher efficiency
  - Durability and performance remain significant issues, even with KOH electrolyte added
    - Although the understanding of degradation mechanisms are slowly being uncovered, AEM systems in a way are playing “catch-up” to PEM systems (which has had more intensive R&D in the last 20 years)
    - If AEM durability & performance can rise to the level of PEM systems, AEM systems may be quite competitive on a $/kg$H_2$ cost basis

- **Overview of Low Temperature Electrolysis**
  - By using a consistent cost basis and by using operating point optimization to minimize LCOH, the different LTE technologies can be compared on a fair basis
  - After operating point optimization, the difference in LCOH between LTE technologies is suppressed, especially for Future cases
  - Rigorous review of realistic future electricity costs needed for fair comparison of LTE technologies, especially with regards to dynamic operation

Proposed Future Work

- **Complete AEM H2A Cases**
  - System Cost analysis
    - Conduct sensitivity analysis
    - Vet cost results and sensitivity analysis with NREL, Versogen, EvolOH
  - Publish H2A Results in Case Study DOE Record

- **$1/kg Hydrogen-Shot Scoping Study**
  - Investigate the ability of electrolysis to achieve the target by:
    - Reducing stack cost
    - Reducing operating costs, including labor
    - Reducing cost of electricity through selective utilization of low-cost electricity generated from wind and solar
    - Co-optimize size of stack, operating point, capacity factor, and electricity price to minimize average LCOH
  - Investigate delivered cost of hydrogen depending on regional production and delivery

- **Conduct cost analysis of Proton-Conducting Solid Oxide Electrolysis**
  - Collaborate with INL for cell, stack, and system design and operation
  - Estimate stack cost and resulting LCOH of system

Any proposed future work is subject to change based on funding levels.

Summary

- **Overview**
  - Conducted technoeconomic analyses for AEM Electrolyzer hydrogen production technologies and compare to other low-temperature electrolysis technologies

- **Relevance**
  - Improve analysis models and increase understanding of areas demonstrating information deficiencies
  - Technoeconomic analysis for H_2 Production:
    - Defines a complete production and delivery pathway
    - Identifies key cost-drivers and helps focus research on topics that will lower cost
    - Generates transparent documentation available to the community with relevant data for improved collaboration

- **Approach**
    - Utilize various cost analysis methods for determining system cost: DFMA® and H2A
    - Collaborate with NREL, ANL, DOE, and tech experts to model alternative hydrogen production technologies
    - Vet assumptions and results for correctness, completeness, and maximum transparency

- **Accomplishments**
  - (In Development) Public distribution of Low-Pressure and High-Pressure Alkaline Electrolysis Case Study Report
  - (In Development) Public distribution of AEM KOH and AEM Water Electrolysis Case Study Report