Hydrogen Production Cost and Performance Analysis

DOE Hydrogen Program
2024 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: ~80% 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
  - ~$590K SA (though Feb 2024)
- 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)

Coordination

- Phillips 66 DOE Project (Reversible SOFC)

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 H_2 Shot goal of $1 for 1 kg hydrogen by 2031

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

Project Objective

- Support HFTO 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 current DOE focus is on Central cases)
- Update H2A model with new values to obtain updated $/kg H_2 projections

Selected Pathway: Proton-Conducting Solid Oxide Electrolysis (P-SOEC)

Task	Description	Completed for 2023-2024 Analysis
1	Technologies Identification, Review, and Selection of Pathway	Milestone 1.3 submitted in October 2023
2	System Definition and Bill of Materials	In Progress: Milestone 2.3 to be submitted in March 2024
3	Techno-economic Analysis	In Progress: Milestone 3.3 to be submitted in June 2024
4	Case Study Documentation and Project Reporting	Planned: Milestone 4.3 to be submitted in September 2024 (Go/No-Go decision metric)

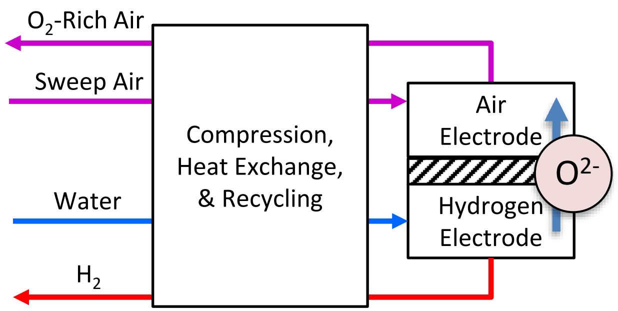
Approach: Safety Planning and Culture

This analysis-type project is exempt from submitting a safety plan to Hydrogen Safety Panel

Proton vs. Oxygen Conducting SOEC

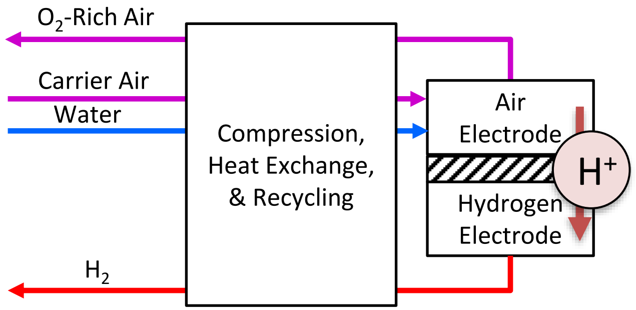
(P-SOEC is expected to have a higher current density than conventional O-SOEC)

Oxygen-Conducting SOEC
[O-SOEC]



Operating at 1.285 V/Cell, 1.50 A/cm^2, 800°C

Proton-Conducting SOEC
[P-SOEC]



Operating at 1.285 V/Cell, 1.75 A/cm^2, 600°C

O-SOEC	P-SOEC
Oxygen ion conducting	**Hydrogen ion** conducting
800°C Stack	**600°C** Stack
Higher degradation expected due to higher temperature	**Lower degradation** expected due to lower temperature
Degradation of H_2 electrode due to water/steam	**Degradation of air electrode** due to water/steam
Uses Air as Sweep Gas on O_2 side	Uses excess Air as Sweep/Carrier Gas on O_2 side
	Higher current density reduces number of stacks and equipment needed

		O-SOEC	P-SOEC
BOL Rated			
Current Density (BOL Rated)	A/cm^2	1.5	1.75
Voltage (BOL Rated)	V/cell	1.285	1.285
Stack Degradation	mV/khrs	6.4	6.4
Stack Degradation	%/khrs	0.54%	0.54%
Stack Lifetime	years	4	4
Operating Point			
Current Density (BOL)	A/cm^2	0.99	1.16
Voltage (BOL)	V/cell	1.176	1.176
Current Density (EOL)	A/cm^2	0.99	1.16
Voltage (EOL)	V/cell	1.394	1.394
Voltage (Average)	V/cell	1.285	1.285
Power Density (BOL)	W/cm^2	1.16	1.36

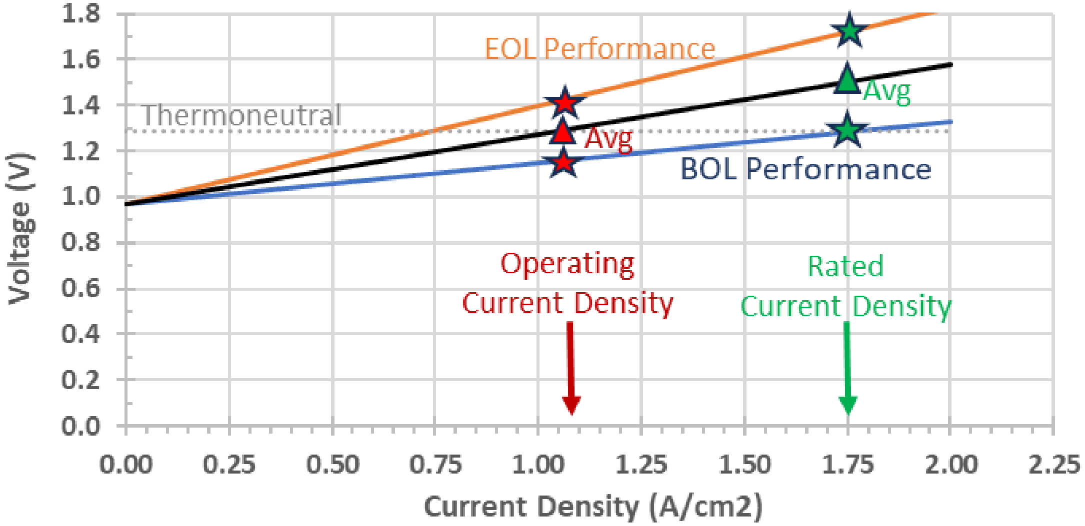
P-SOEC Stack Operation

(Operate with Constant Current for Constant Hydrogen Production)

Operation Philosophy

- Thermoneutral operating point represents a compromise between thermal demand and electrical demand
- For constant hydrogen production, current density must remain constant over the life of the plant
- With stack degradation, voltage will increase over time.
  - Current Case: 6.4 mV/1000 h (0.54%/kh) degradation (US DOE 2022 O-SOEC Current State)
  - Future Case: 3.2 mV/1000 h (0.26%/kh) degradation

- To maintain an average voltage that matches thermoneutral voltage, the current density must be reduced from rated current density
- Lower current density better for OPEX, but worse for CAPEX



Technology Basis		Current	Future
BOL Rated			
Current Density (BOL Rated)	A/cm^2	1.75	1.75
Voltage (BOL Rated)	V/cell	1.285	1.285
Stack Degradation	mV/khrs	6.4	3.2
Stack Degradation	%/khrs	0.54%	0.26%
Stack Lifetime	years	4	8
Operating Point			
Current Density (BOL)	A/cm^2	1.16	1.16
Voltage (BOL)	V/cell	1.176	1.176
Current Density (EOL)	A/cm^2	1.16	1.16
Voltage (EOL)	V/cell	1.394	1.394
Voltage (Average)	V/cell	1.285	1.285
Power Density (BOL)	W/cm^2	1.61	1.61

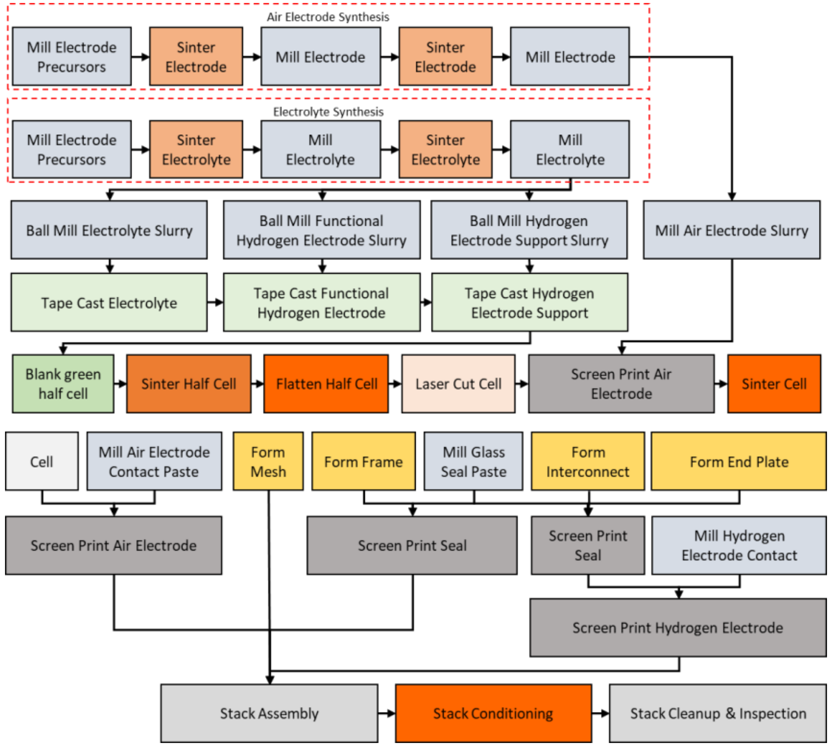
Currently assuming Future case has half the degradation and double the stack lifetime

Luo et al. “Durable and High-Performance SOECs Based on Proton Conductors for H2 Production”. The 23rd Annual SOFC Project Review Meeting. 2022.

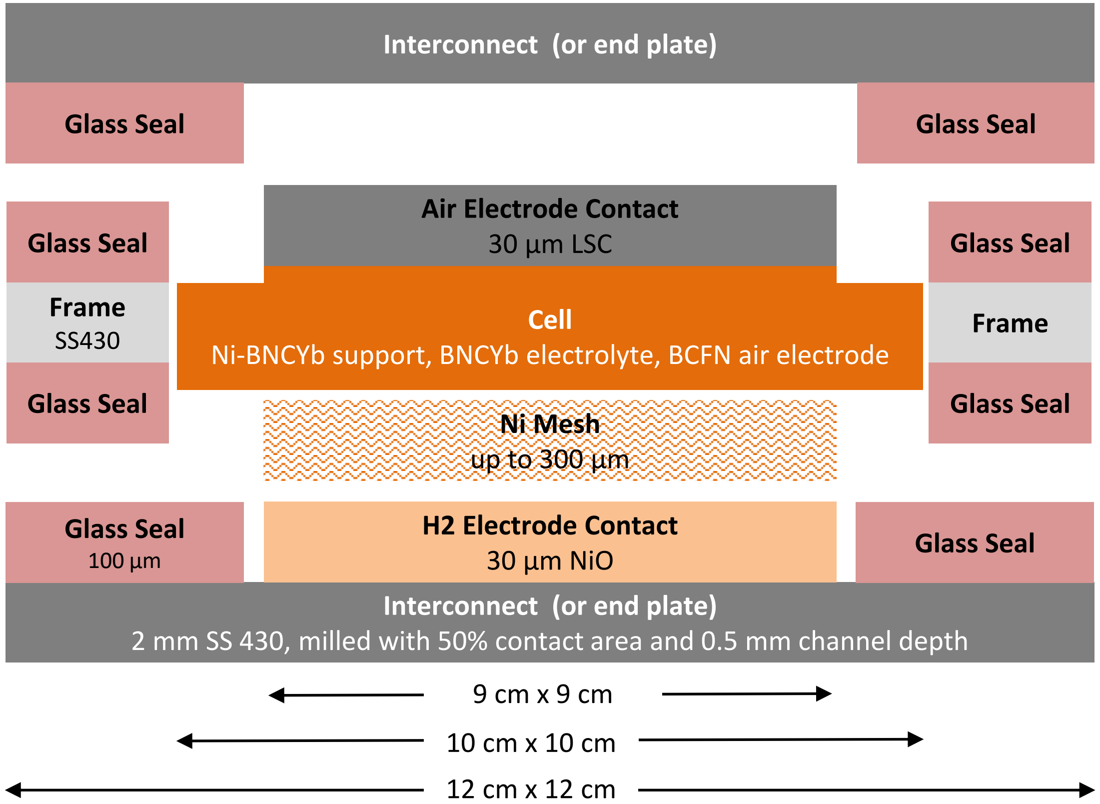
Modeled P-SOEC Cell Design and Manufacturing

(SA developed a bottom-up cost model for a P-SOEC stack)

Stack Manufacturing Steps



Exploded Cross-Section View of Stack Repeating Unit



Additional Notes

- Commercially available glass seal fired at 700°C
- Proton-conducting electrolyte discussed in WIPO Patent Application WO2022245710A2 and in https://doi.org/10.1021/acsenergylett.2c01544
- BCFN cathode discussed in https://doi.org/10.1016/j.ijhydene.2023.07.041
- Framed-cell stack design discussed in US Patent Application US20210249668A1
- Stainless steel tie-rods included for handling stacks post-conditioning

Improvements for "Future" design:

- Decrease the support layer thickness
- Increase cell active area to 15 cm x 15 cm

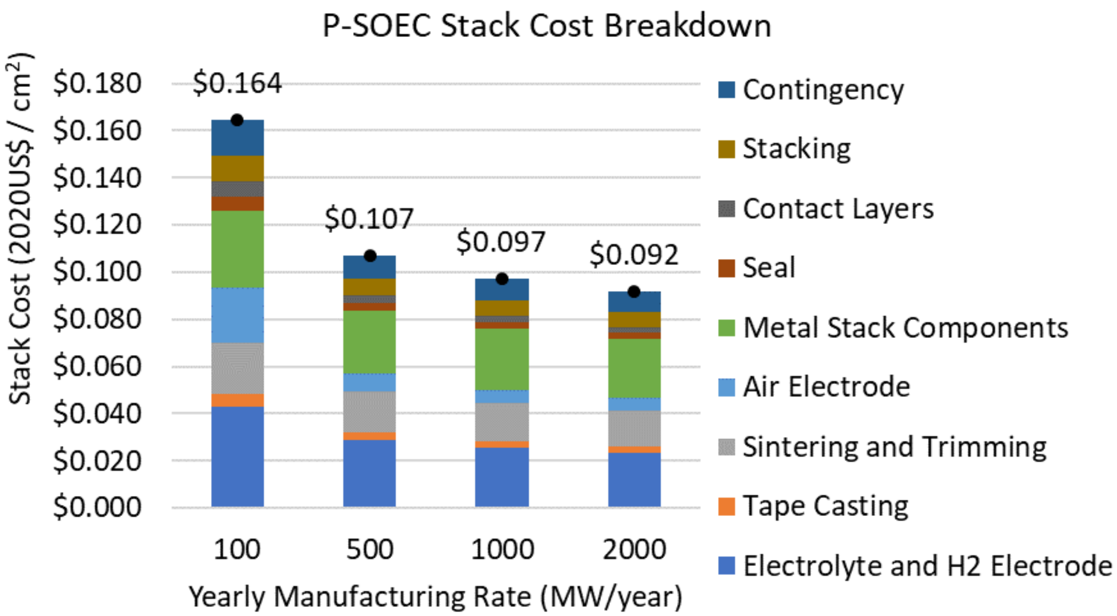
BCFN = $Ba_{0.9}Co_{0.7}Fe_{0.2}Nb_{0.1}O_3$
BHCYb = $Ba_1Hf_{0.1}Ce_{0.7}Yb_{0.2}O_3$

BNCYb = $Ba_1Nb_{0.1}Ce_{0.7}Yb_{0.2}O_3$
Ni-BNCYb = 60 wt% NiO and 40wt% BNCYb

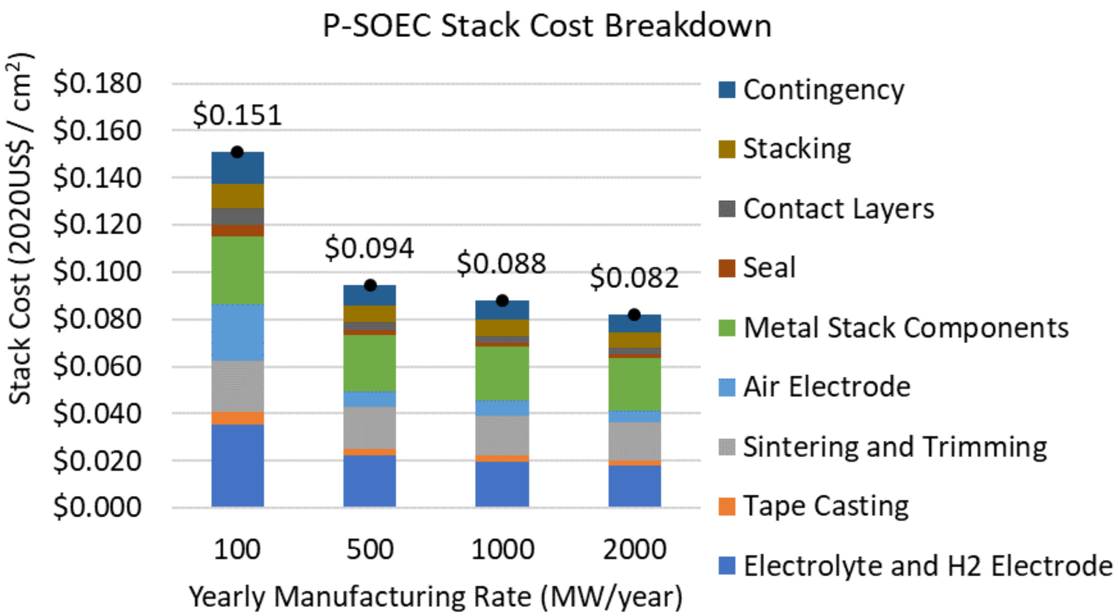
P-SOEC Cost per Active Area

~10% stack cost reduction between Current and Future (~$0.097/cm^2 vs ~$0.088/cm^2 at ~1GW/yr)

Current Central P-SOEC



Future Central P-SOEC

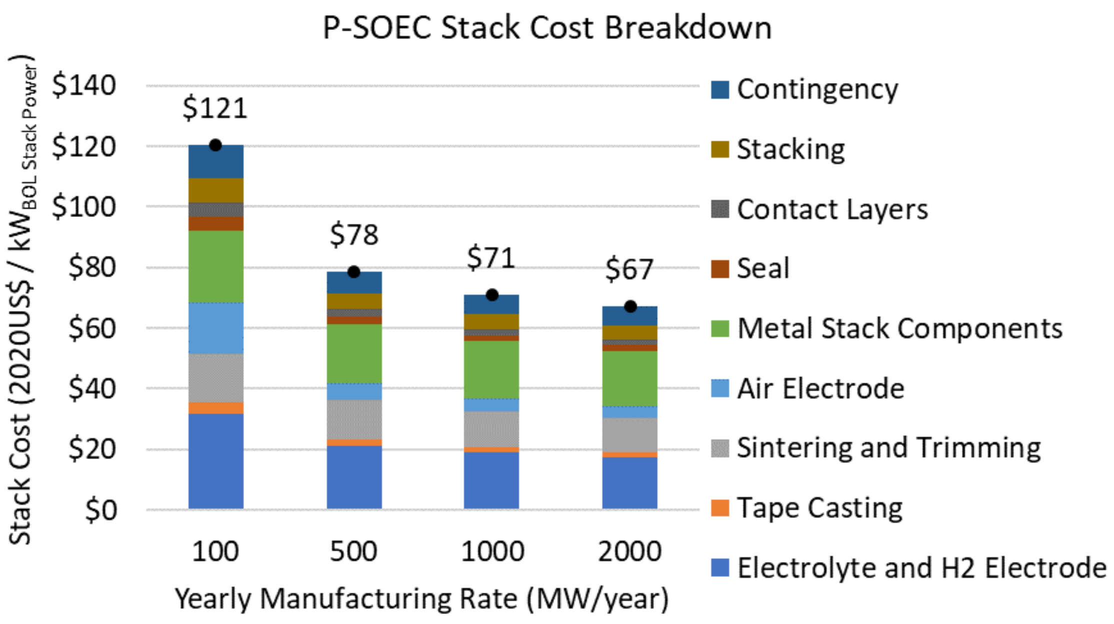


- **Values reported on this slide exclude markup and installation**
- Future system cost reduction due to:
  - increased stack size
  - reduction in support layer thickness
  - minor manufacturing improvements
  - (No power density improvement assumed & degrad. rate improvement doesn’t affect $/cm^2)

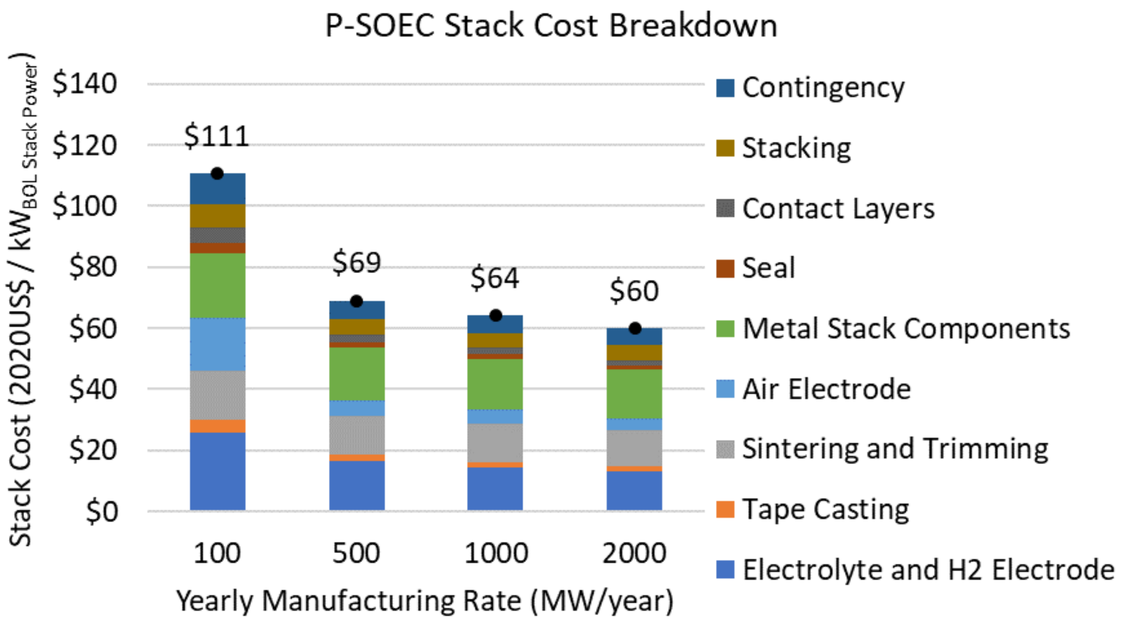
P-SOEC Cost per kW

~10% stack cost reduction between Current and Future (~$71/kW compared to ~$64/kW at ~1GW/yr)

Current Central P-SOEC



Future Central P-SOEC



- **Values reported on this slide exclude markup and installation**
- $/kW costs are based on BOL stack power (selected operating point)
- Future system cost reduction due to:
  - increased stack size
  - reduction in support layer thickness
  - minor manufacturing improvements

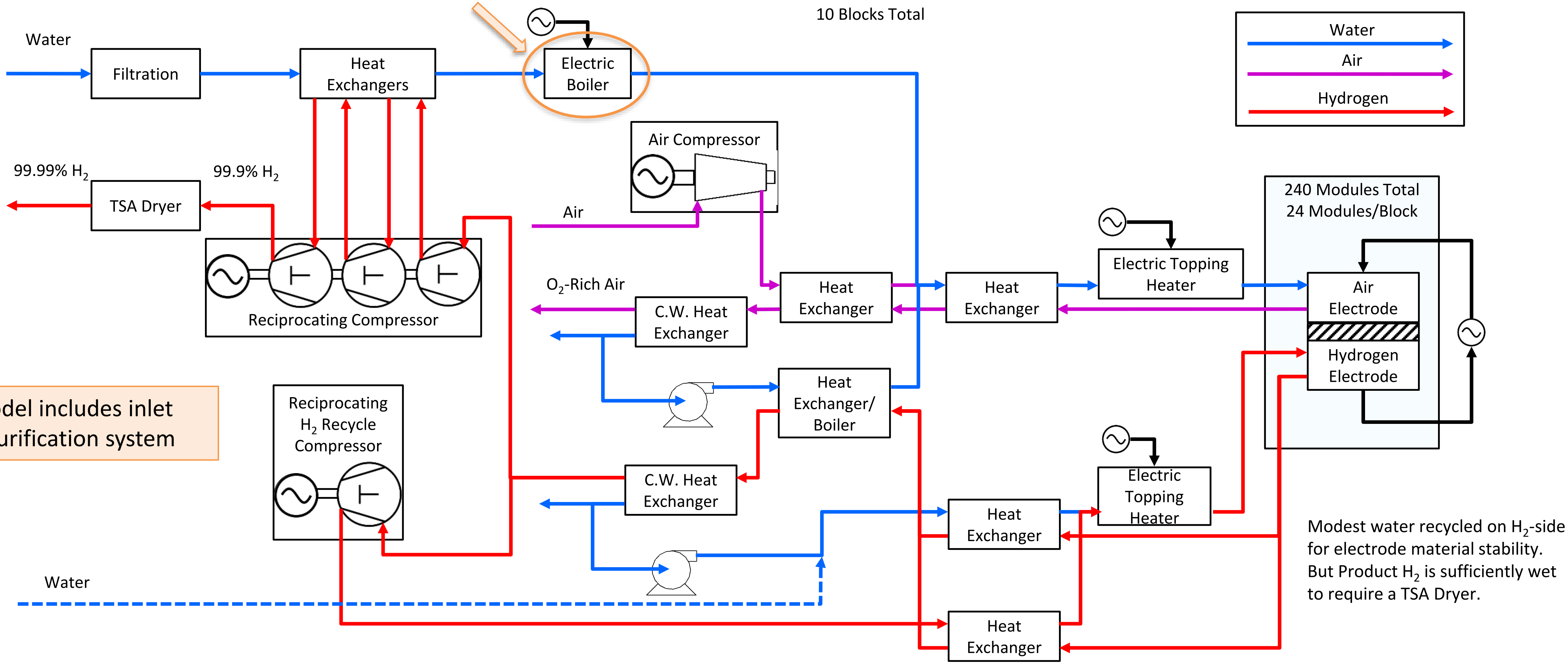
Process diagrams developed for P-SOEC

Accomplishment and Progress

(Similar components to O-SOEC, but re-arranged & slightly re-sized)

Current model assumes all-electric system. Electric boiler could be replaced with natural gas boiler

Cost model includes inlet water purification system



Modest water recycled on H_2-side for electrode material stability. But Product H_2 is sufficiently wet to require a TSA Dryer.

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**: Aspen-generated cost estimates based on sizing and materials specifications
      - **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

System Definition and Project Technical Parameters

(Current & Future Systems have same capacity. But Future has larger cells, lower degradation)

Technology Basis	Units	Current	Future
Plant Capacity	**MTD**	**50**	**50**
Plant Design			
Electrolyzer Power (System, BOL Rated)	MW	96	96
Number of Systems	#	1	1
Number of Blocks per System	#	7	7
Number of Modules per Block	#	24	24
Number of Stacks per Module	#	16	16
Stack Operating Temperature	°C	600	600
Output Pressure	bar	30	30
Hydrogen Purity	%	99.99	99.99
Performance			
Total Electrical Usage (Average)	kWh/kg	45.1	45.1
Stack Electrical Usage (Average)	kWh/kg	34.2	34.2
BOP Electrical Usage	kWh/kg	11.0	11.0
Cell Active Area	cm^2/cell	83	196
Stack Degradation	mV/khr	6.4	3.2
Stack Durability	year	4	8
Operating Current Density	A/cm^2	1.16	1.16
Number of Cells per Stack	cells	216	91

- Project balance of plant equipment sized using average conditions, assuming thermoneutral operation
- ΔT across P-SOEC stacks limited to 100°C

- Active Area:
  Current case uses 10 cm x 10 cm
  Future case uses 15 cm x 15 cm

P-SOEC Electrolyzer and Project Capital Cost

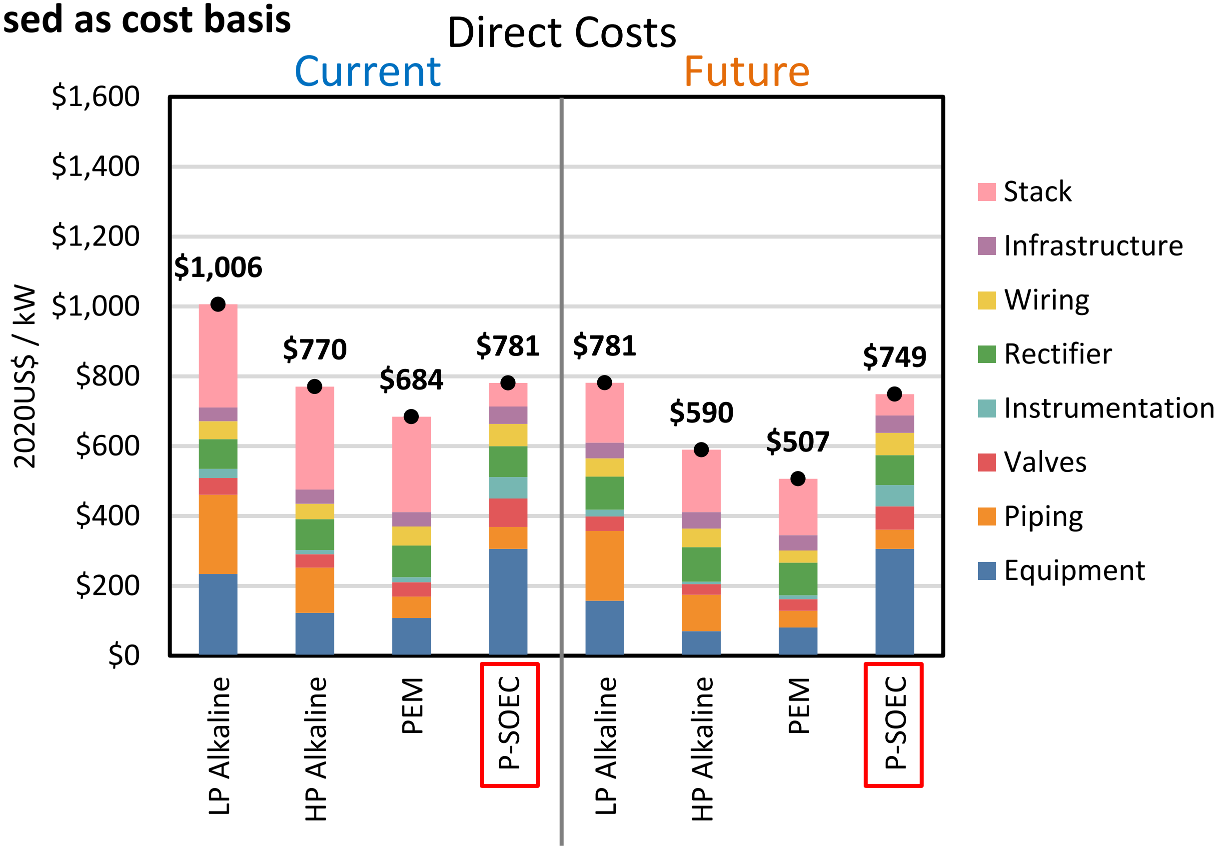
(Comparison to alternative low-temperature electrolyzers)

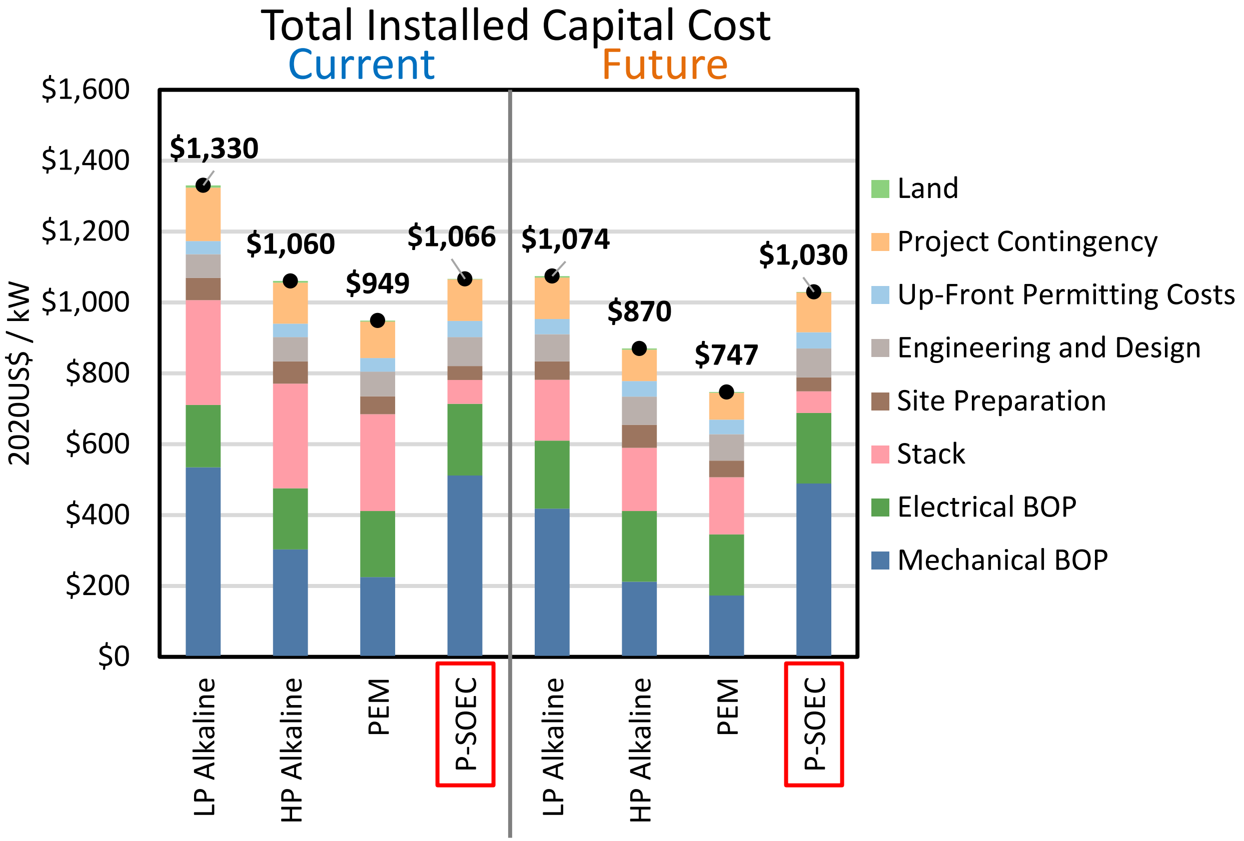
Accomplishment and Progress

1 GW/year annual electrolyzer manufacturing rate

BOL Rated power used as cost basis

Caveat: P-SOEC not fully BOP-size optimized





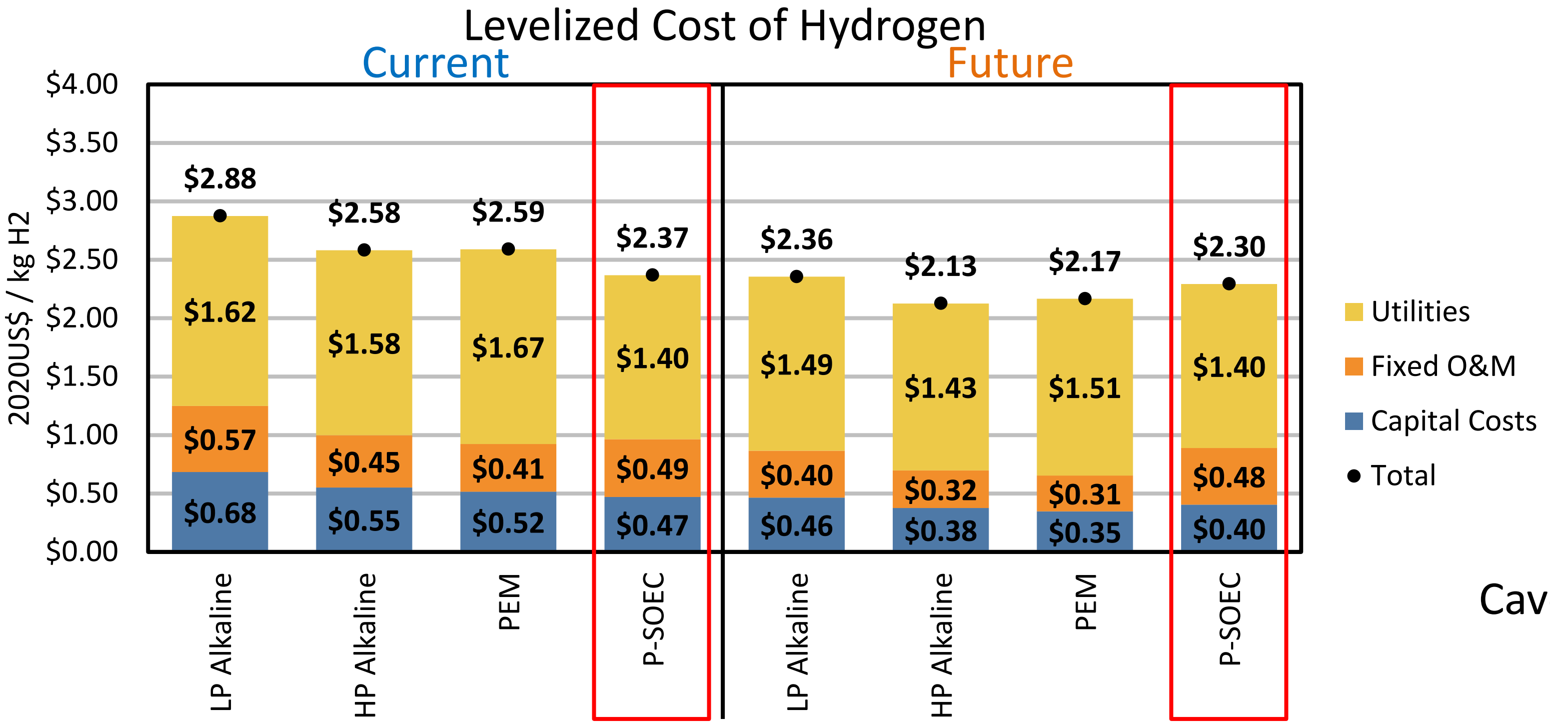
- Direct costs include both uninstalled costs and installation costs
- Low-temperature electrolysis cases use a cost optimized current density which balances capital costs and electricity costs
- P-SOEC trades off cheaper stack cost with more expensive equipment costs

Site Preparation: Bottom-up cost estimate based on Craftsman cost methodology
Permitting costs: General project estimate based on historic data
Engineering & design: General project estimate assuming an Nth of a kind plant
Project contingency: 15% contingency assumed for an Nth of a kind plant

Low temperature electrolysis results revised from last year to reflect continued cost model improvements and cost optimization

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 low-temperature electrolysis assume 4 x 12.5 MTD modules
- Future low-temperature electrolysis assume 2 x 25 MTD modules

Caveat: P-SOEC not fully BOP-size optimized

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
- P-SOEC benefits from lower stack replacement cost coupled with lower total energy usage

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
- P-SOEC has a lower potential for cost reduction over time since total energy usage is not expected to significantly change and optimization to system design is limited

Low temperature electrolysis results revised from last year to reflect continued cost model improvements and cost optimization

Responses to Previous Year Reviewers' Comments

(Mostly in reference to our past Anion Exchange Membrane (AEM) electrolysis analysis)

Reviewer Comment	Response
-The current state of AEM performance seems optimistic, especially the AEM water scenario -Needs better documentation	• For early-stage commercialization, Strategic Analysis typically uses literature data as a starting point for system performance. • Guidance from industry experts, industry sentiment, and engineering judgement is used to define "current" and "future" performance. • Since performance values reported in literature might be uneconomical, we try to select what would be a reasonable first commercial implementation for the "current" case. • For the "future" case, we try to select an operating point that indicates what may be possible with the technology and highlights the potential to reduce levelized cost of hydrogen.
The reported solid oxide electrolysis cell (SOEC) current density is too low	• Current density for solid oxide systems are limited by the support layer used • We have elected to use higher current density technology for P-SOEC for better outlook to LCOH
Optimistic assumptions are made about EPC costs	• There are limited operating electrolyzer plants at the 100 MW scale. Therefore, we rely on EPC costs from literature and other technologies. • We are closely following reporting on electrolyzer suppliers to understand what near-term and long-term EPC costs will be (Plug Power being a key example with their operating 40 MW plant in Georgia).
Show the sensitivity of results to input assumptions	• Full AEM report will include several sensitivity studies including electricity price and capacity factor
Request industry input for other low temperature technologies, not just AEM	• Strategic Analysis frequently solicits information from Alkaline and PEM suppliers. While not all insights get incorporated into the AMR presentation, we continuously iterate on all cost models
Incorporate one-to-one CAPEX comparisons for deployed systems worldwide	• High quality public CAPEX estimates that clearly define scope of supply are limited • Where possible, SA will try to provide comparisons for mature technologies

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
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: • *Phillips 66*	DOE Prime on Adjacent Contract	• Provided data and peer review on stack design and performance for proprietary P-SOEC system.

Conclusions, Remaining Challenges and Barriers

Proton-Conducting Solid Oxide Electrolysis Systems

- P-SOEC systems are promising for their low-cost stacks and low total energy usage
- For current assumptions for electricity price and capacity, P-SOEC has a favorable LCOH outlook compared to alternative electrolyzer technologies

- Additional energy usage optimization may be possible by lowering average stack voltage
- While further process analysis is required to confirm, P-SOEC is unlikely to be able to operate under dynamic operating conditions associated with low capacity-factor environments without batteries or other mitigating factors (O-SOEC as similarly limited)

- Durability and performance are significant issues, with current academic and industrial research focused on materials science
  - Air electrode and electrolyte must be resilient to steam while also maintaining high current density
  - Long term durability data is generally not available for early-stage technology
- Pilots and scale-up activities are expensive and difficult due to the high temperature required to operate and the significant number of system components

Proposed Future Work

- **Complete P-SOEC Technoeconomic Analysis**
  - System Cost analysis
    - Conduct sensitivity analysis: stack lifetime, durability, electricity price, and capacity factor
    - Vet cost results and sensitivity analysis with DOE and Idaho National Laboratory
  - Publish technical report in OSTI repository (Office of Scientific and Technical Information)

- **General Cost Model Improvements**
  - Improve quality of piping & valve cost estimation
  - Improve quality of EPC cost estimation
  - Benchmark results against publicly available capital cost data

- **Conduct cost analysis of additional hydrogen production pathways**
  - Collaborate with DOE on system design and operation
  - Estimate total installed capital cost and resulting LCOH of system

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

Summary

- **Overview**
  - Conducted technoeconomic analyses for P-SOEC hydrogen production technologies and compared to other 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, INL, DOE, and tech experts to model alternative hydrogen production technologies
    - Vet assumptions and results for correctness, completeness, and maximum transparency
- **Accomplishments**
  - Published OSTI Technical Report for Alkaline Electrolysis:

    Acevedo, Yaset M., Prosser, Jacob H., Huya-Kouadio, Jennie M., McNamara, Kevin R., and James, Brian D., Hydrogen Production Cost with Alkaline Electrolysis. United States: N. p., 2023. Web. doi:10.2172/2203367.
  - (In Development) Public distribution of AEM-KOH and AEM-Water Electrolysis technoeconomic analysis