Hydrogen Production Cost and Performance Analysis

DOE Hydrogen Program

2022 Annual Merit Review and Peer Evaluation Meeting

PI: Brian D. James, Strategic Analysis (SA)
Jennie M. Huya-Kouadio (SA)
Cassidy Houchins (SA)
Yaset Acevedo (SA)
Kevin McNamara (SA)
Genevieve Saur (NREL)

Project ID: P204
Award No. DE-EE0009629
June 2022

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 **distributed and central production facilities** (1.5-50 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: ~20% 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
  - ~$121K SA (though Mar 2022)
- 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

Progress Toward DOE Targets or Milestones

On-track to achieve 2025 DOE electrolysis targets at an electricity price of $0.03/kWh
Continued improvements needed to achieve $1/kg H_2 by 2031

Levelized Cost of H2 Production ($/kg)	**SA H2A Current Status** ($0.03/kWh electricity)	**SA H2A Future Status** ($0.03/kWh electricity)	**DOE 2025 Target**	**DOE 2031/Ultimate Target**
Distributed Water Electrolysis Cost (1.5 Tons/Day)	2.54 (2019 PEM Tech) (2019 Record) 3.76 (2025 AEM Pure Water Tech) 2.59 (2025 AEM KOH Tech)	1.92 (2035 PEM Tech) (2019 Record) 2.18 (2035 AEM Pure Water Tech) 2.02 (2035 AEM KOH Tech)	2.30	1
Central Water Electrolysis Cost (50 Tons/Day)	2.31 (2019 PEM Tech) (2019 Record) 2.36 (2019 SOEC Tech) (2020 Record) 2.41 (Alkaline – optimized oper. cond.)	1.86 (2035 PEM Tech) (2019 Record) 2.00 (2035 SOEC Tech) (2020 Record) 1.79 (Alkaline – optimized oper. cond.)	2.00	1
Solar Thermochemical (STCH) (100 Tons/day)	NA	2.54 (2022 Journal Article, NREL)	3.70	1

- All electrolysis H2A status values assume **$0.03/kWh** in current and future
- Although the cost of H_2 for liquid alkaline water electrolysis is preliminarily estimated to be higher cost than PEM for the current case and lower cost than PEM for the future case, **the PEM 2019 case was not based on optimized operating conditions at BOL and EOL. Re-evaluation at optimized conditions for PEM are planned for future work.**

Values in Green are preliminary and from 2021/2022 analysis

Project Objective and Approach

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)
- Determine the most optimal production pathway for specific end-uses
- 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

- Select H_2 production pathway to evaluate (in collaboration with DOE)
- Collect data from industry/researchers, assess data for consensus and trends
- Conduct system modeling (Design for Manufacture and Assembly (DFMA bottom-up cost modeling, Mass/Energy Balance modeling w/ Aspen Hysys)
- Evaluate the cost of H_2 using the H2A tool
- Document in public reports: detailed, transparent statement of assumptions and cost results

Task	Description	Completed for 2022 Analysis?
1	Technologies Identification, Review, and Selection of Pathway	Milestone 1.1 submitted in October 2021
2	System Definition and Bill of Materials	Milestone 2.1 submitted in March 2022
3	Techno-economic Analysis	In Progress: Milestone 3.1 to be submitted in June 2022
4	Case Study Documentation and Project Reporting	Planned: Milestone 4.1 to be submitted in September 2022 (Go/No-Go decision metric)

Selection of H_2 Production & Delivery Cases

- DOE selects cases that support the HFCTO development mission
  - Advanced Water Splitting
  - Biomass-based processes
  - Waste recovery to H_2 processes

- Cases selected based on:
  - Highest priority cases with direct application to HFCTO mission
  - Data availability
  - Ability to assist studies in providing relevant cost estimates
    - Beneficial for cases without cost estimates
    - Provide assistance for proper development of H2A cases

Types of H2 Production Cases:

- 1,500 kg H_2/day distributed sites
- 50,000 kg H_2/day central production sites (sometime larger systems)
- Typically two technology levels analyzed
  - Current or Near Term: current technology at high-manufacturing rate
  - Future: future technology at high-manufacturing rate

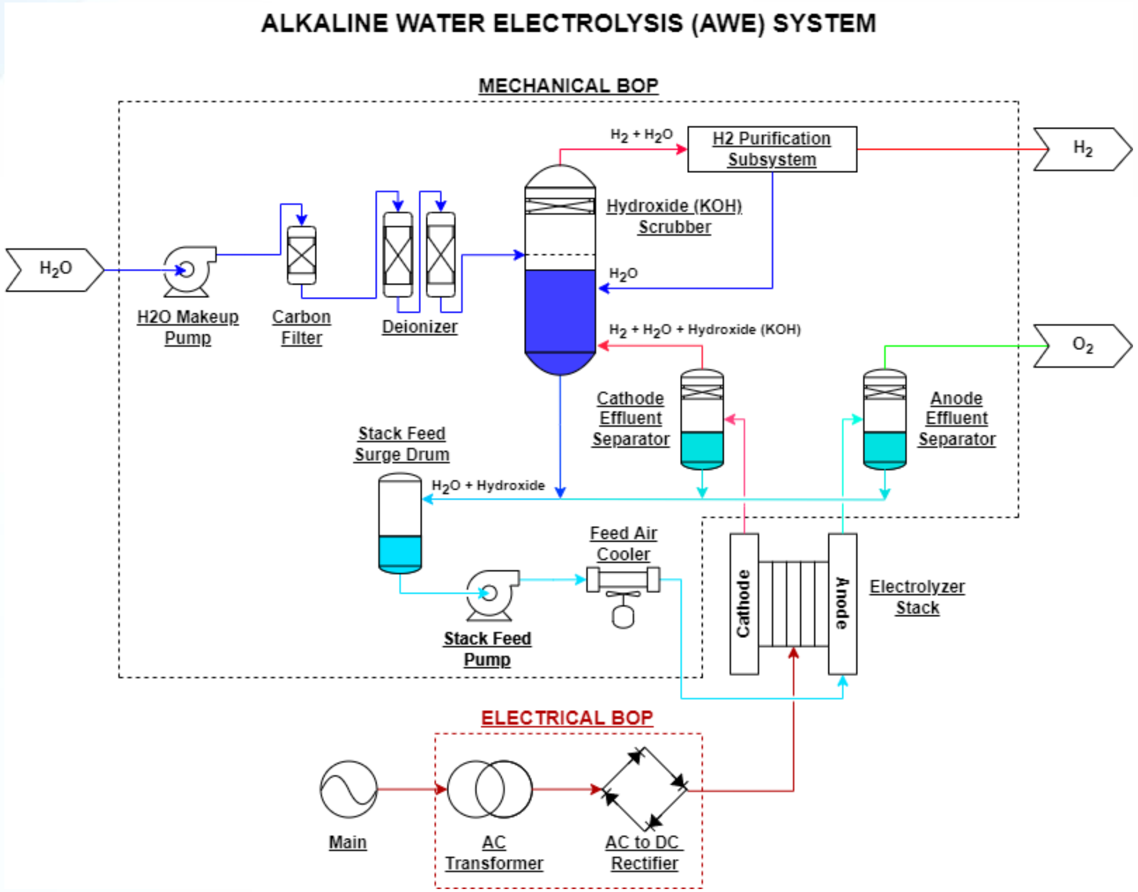
Cases Currently Under Development

- Liquid Alkaline Water Electrolysis (LAWE)
  - Current and Future Central Cases

- Anion Exchange Membrane (AEM) electrolysis
  - Near Term and Future Distributed Cases for pure water and KOH/water feeds

Liquid Alkaline Water Electrolysis (LAWE) System Definition

Process Flow Diagram



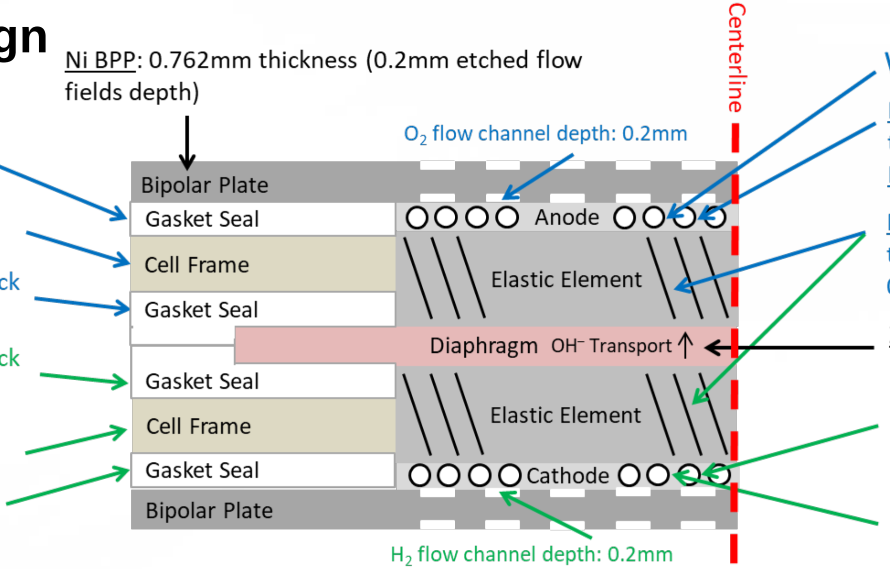
Strategic Analysis 2022

Table of System Design Parameters

		SA 2022 Cases	
	Unit	**2021**	**2031**
Plant Capacity (Rated)	MW_AC	118	97
Module Power	MW_AC	30	49
Rated Stack Input Power	MW_DC	3.9	3.8
Number of Stacks	#	7	12
# of Cells	#	450	450
Cell Area	cm^2	10,000	10,000
Rated Current Density	**A/cm^2**	**0.7**	**1**
Rated Cell Voltage (BoL)	**V**	**2**	**1.7**
Degradation Rate	mV/1000 hrs	3.2	1.4
Pressure Cathode	bar	31	31
Temperature	degC	80	80
Specific Energy Demand (Stack)	**kWh_AC/kg**	**48.9**	**42.5**
Specific Energy Demand (System)	**kWh_AC/kg**	**53.7**	**44.9**
KOH Concentration	wt%	40	40
Output Pressure	bar	30	30
Gas Purity	%	99.99	99.99
Stack Lifetime	year	10	10

Liquid Alkaline Water Electrolysis Stack DFMA

Current Design



Ni BPP: 0.762mm thickness (0.2mm etched flow fields depth)

O2 Gasket Seal: 1mm thick die cut EPDM sheets

O2 Cell Frame: 2mm thick injection molded PEEK

O2 Gasket Seal: 1.25mm thick die cut EPDM sheets

H2 Gasket Seal: 1.25mm thick die cut EPDM sheets

H2 Cell Frame: 2mm thick injection molded PEEK

H2 Gasket Seal: 1mm thick die cut EPDM sheets

O_2 flow channel depth: 0.2mm

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

Water and O_2 Evolution

Perforated Ni plate anode substrate: 0.5mm thickness, 700 micron hole diameter
NiFe(OH)2 catalyst: 7 mg/cm^2

Ni wire elastic element: 3.5mm compressed thickness, 7mm uncompressed thickness, 0.15mm wire diameter

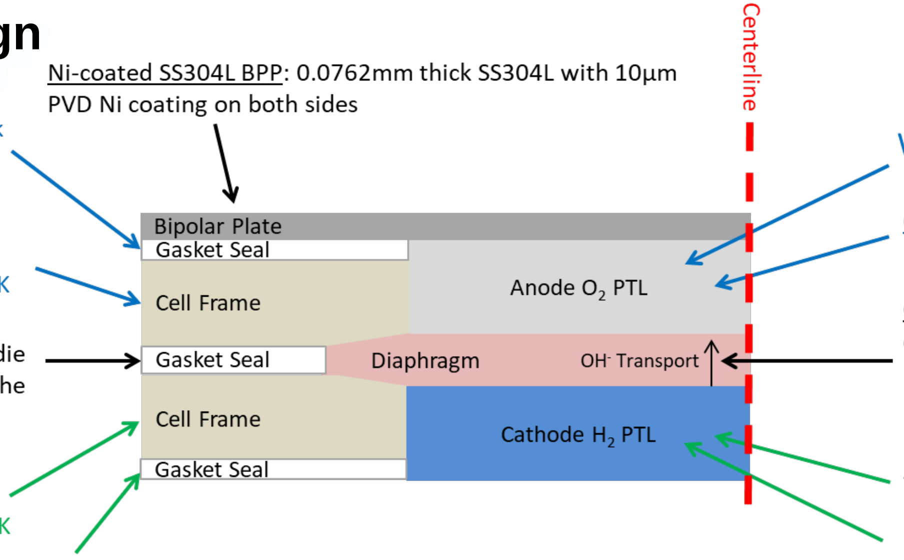
Zirfon (ZrO2/polysulfone) diaphragm: 500 micron thickness

Perforated Ni plate cathode substrate: 0.5mm thickness, 700 micron hole diameter
NiMo catalyst: 7 mg/cm^2

H_2 Evolution

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

Future Design



Ni-coated SS304L BPP: 0.0762mm thick SS304L with 10µm PVD Ni coating on both sides

O2 Gasket Seal: 50µm thick die cut EPDM sheets

O2 Cell Frame: 1.605mm thick injection molded PEEK

Gasket Seal: 110µm thick die cut EPDM sheet abutting the diaphragm

H2 Cell Frame: 1.605mm thick injection molded PEEK

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

Water and O_2 Evolution

O2 PTL anode: 1.6mm thick sintered porous Ni (95% porosity)

CCM: 220µm thick Zirfon (ZrO_2/polysulfone) diaphragm membrane with decal-transfer
- anode (NiFe(OH)2 catalyst: 7 mg/cm^2)
- cathode (NiMo catalyst: 7 mg/cm^2)

H2 PTL cathode: 1.6mm thick sintered porous Ni (95% porosity)

H_2 Evolution

Changes between Current and Future Designs

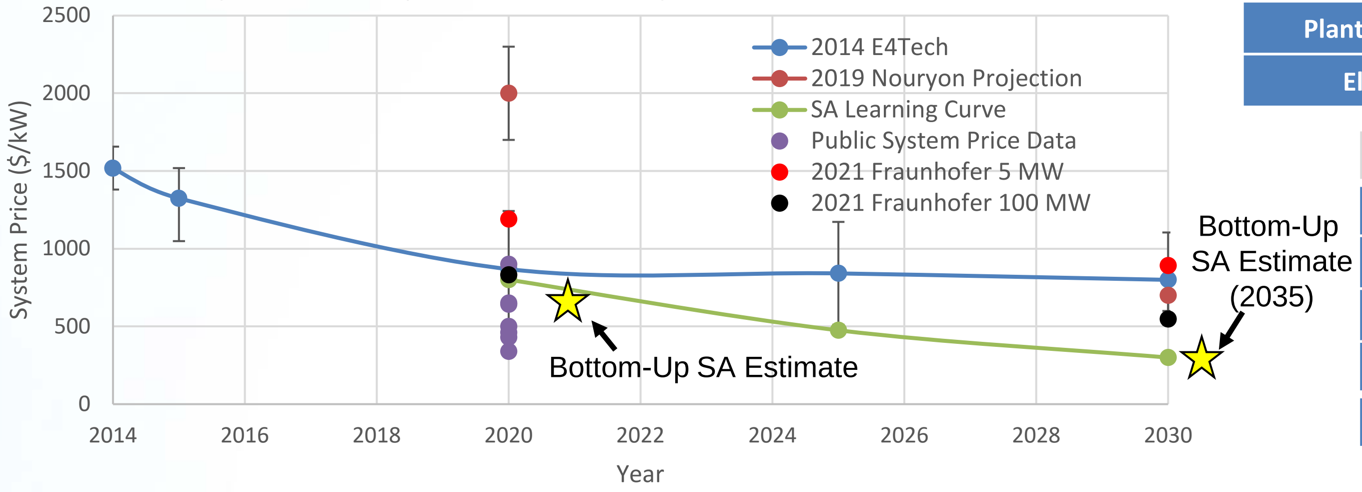
- Finite Gap for Current and Zero Gap for Future
- Reduction of diaphragm thickness (500 to 220microns)
- Remove elastic elements and reduce number of components in the future design
- Anode/Cathode switch from perforated Ni plates to sintered porous Ni in future
- Bipolar Separator Plate switch from nickel plates to Ni-coated SS plates in future

Preliminary Liquid Alkaline Water Electrolysis H2A Modeling Assumptions/Results

Current and Future Central LAWE H2A Cases

- SA DFMA-based System cost is ~$610/kW (Current) and ~$340/kW (Future).
  - This is in range of recent public system prices and towards low-end of public future projections.
  - Cost in $/kW$_{stack\text{-}Input}$ excl. installation
- H2A-based H2 cost projections are $2.41/kgH$_2$ (Current) and $1.79/kgH$_2$ (Future) based on:
  - $0.03/kWh electricity)
  - Large Central (50 TPD) plants

System Price Projections for this Analysis and Other Published Sources



	Unit	Current Central	Future Central
Avg. System Electrical Usage	kWh/kg H_2	**53.7**	**44.9**
Avg. Stack Electrical Usage	kWh/kg H_2	**48.9**	**42.5**
Thermal Energy Usage	kWh/kg H2	**0.0**	**0.0**
BoP Electrical Usage	kWh/kg H_2	**4.8**	**2.4**
Total System Price	$/kWstack_input	$610	$344
Stack Price*	$/kWstack_input	$353	$148
Total BoP Price*	$/kWstack_input	$257	$195
Mechanical BoP	$/kWstack_input	$158	$97
Electrical BoP	$/kWstack_input	$99	$99
Operating Capacity Factor	(%)	97%	97%
Plant Design Capacity	kg of H_2/day	56,500	59,500
Electricity Cost	($2016)/kWh	$0.03	$0.03

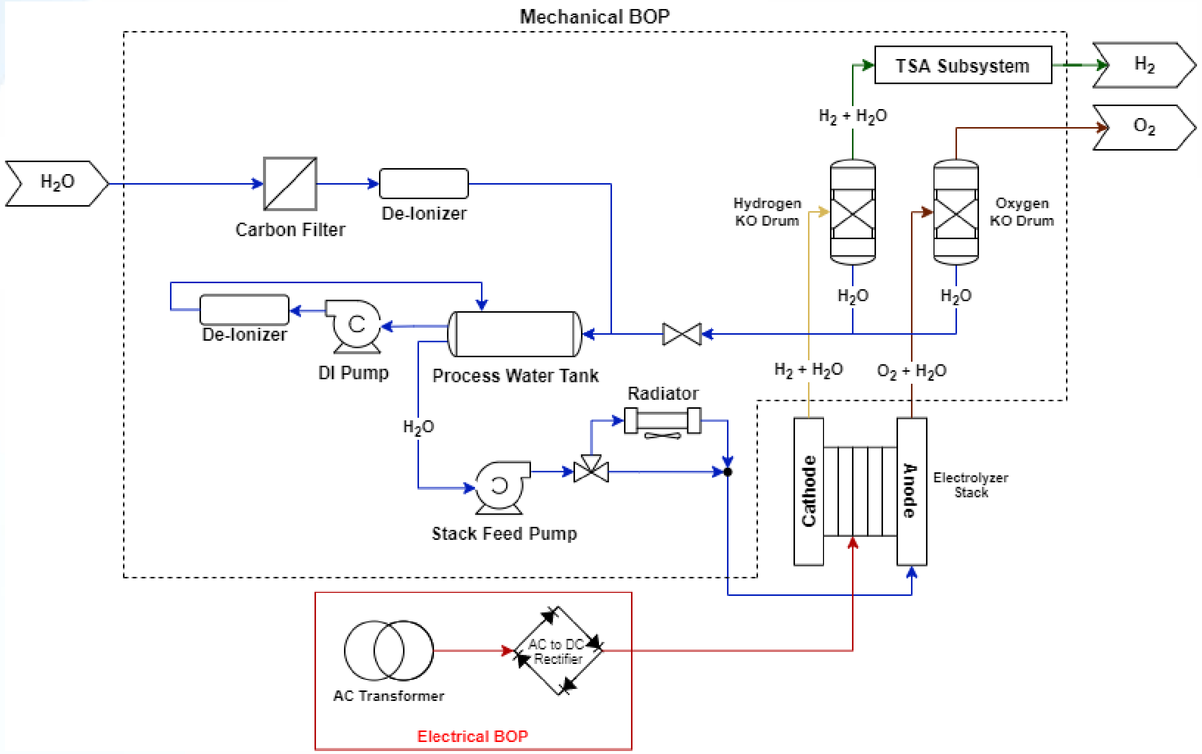
Preliminary	**Current Central**	**Future Central**
Cost Component	**Cost Contribution ($/kg)**	**Cost Contribution ($/kg)**
Capital Costs	$0.44	$0.22
Fixed O&M	$0.31	$0.19
Other Variable Costs (including utilities)	$1.65	$1.38
Total	**$2.41**	**$1.79**

*Includes manufacturer markup

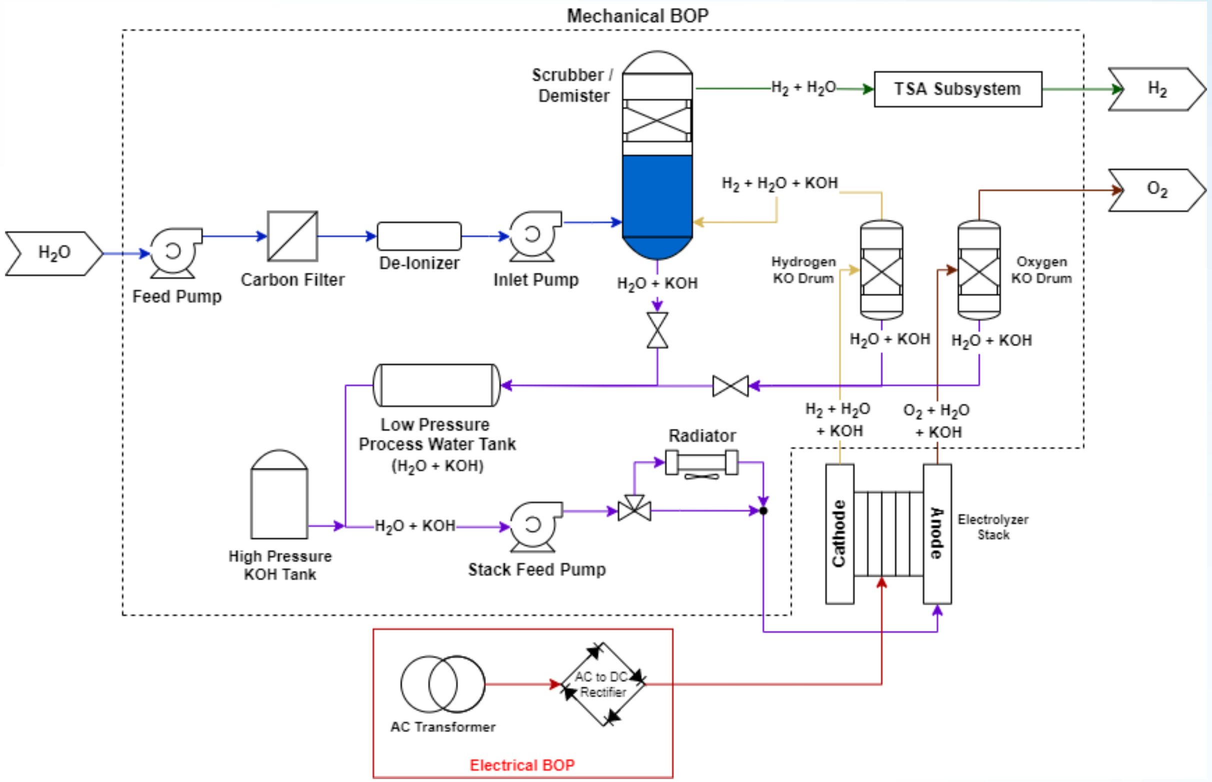
Anion Exchange Membrane (AEM) Electrolysis Systems

AEM Electrolysis Process Flow Diagrams

Pure Water

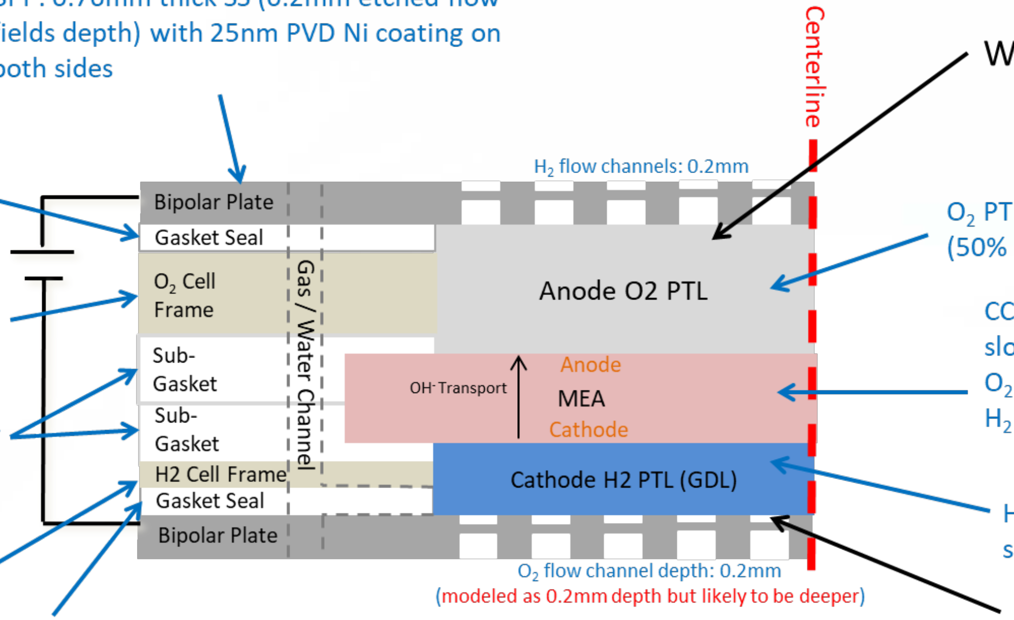


1M KOH



- Investigating both pure water and 1M KOH electrolyte system designs
- 1M KOH: Near-term demonstrated long life but complications of caustic KOH and low current density
- Pure Water: Active membrane research to eliminate KOH, improve durability, & deliver superior current density
- Both have potential for lower stack cost (than PEM or LA) due to inexpensive membrane, and low/no-PGM catalysts
- Both modeled at 20 bar operating pressure to eliminate need for additional mechanical compressor

Preliminary AEM Stack DFMA Cost Analysis



BPP: 0.76mm thick SS (0.2mm etched flow fields depth) with 25nm PVD Ni coating on both sides

O_2 Gasket Seal: 50µm thick die cut PET sheets

Electric current applied

O_2 Cell Frame: 925µm thick injection molded HDPE

Subgasket: 100µm thick PET sheets encasing membrane using 3M roll-to-roll process

H_2 Cell Frame: 75µm thick die cut HDPE sheet

H_2 Gasket Seal: 50µm thick die cut PET sheets (alternatively, could insertion mold gaskets on both sides of BPP at high volume)

Water and O_2 Evolution

O_2 PTL: Sintered porous Ni foam 1.6mm thick (50% porosity) with no coating

CCM: 70µm thick PAP-TP-75 membrane with slot die coated catalyst
O_2 side: 4.8mg/cm^2 of FeNiOOH
H_2 side: 0.5mg Pt/cm^2 at 50% Pt/C

H_2 GDL: 150µm thick (105µm carbon fiber substrate with 45µm thick MPL)

H_2 Evolution

AEM Case Designs for Stacks

- Assumed no stack design changes between near term and future or between pure water and KOH
- Assumed improvement in stack performance between near term and current and pure water and KOH systems

DFMA model capable of exploring wide design space

Stack DFMA Model Values	Unit	SA PEM Model (for Reference)	SA 2022 AEM Model
Range in Manufacturing Capacity	**MW/year**	10-10,000	300 (based on Enapter)-600
Range in Cell Area (Active/Total)	**cm^2**	740-2981 / 1197-3900	740-1020 / 1196-1547
Stack Sizes	**MW**	1, 2, 2.5, 5	1, 1.5
System Sizes	**MW**	1, 4, 10, 100	3 (1.5 metric tons/day)

Preliminary AEM Electrolysis System Definition

AEM Key Technical and Cost Parameters (Distributed, 1,500kg H_2/day)

Parameter	Unit	AEM Near Term 2025, Pure Water	AEM Near Term 2025, 1M KOH	AEM Future 2035, Pure Water	AEM Future 2035, 1M KOH
Rated Operating Conditions					
Rated Current Density	A/cm^2	1	1.5	2	3
Rated Cell Voltage (BOL)	V	1.84	1.74	1.9	1.8
Stack Pressure	Bar	20	20	20	20
Stack Lifetime	years	1	3	7	10
Optimized Operating Conditions					
Current Density (BOL)	A/cm^2	1.64	1.43	1.09	1.37
Cell Voltage (BOL)	V	2.1	1.72	1.68	1.60
EOL System Power	MW	4.8	3.5	2.95	2.80
System Performance					
Degradation Rate	mV/khrs	50	13	1.5	1
Stack Lifetime	years	1.1	3.4	7	10
Avg. Stack Electrical Usage	kWh/kg	63.7	48.8	44.3	42.0
Avg. System Electrical Usage	kWh/kg	66.1	50.8	45.3	42.9
Capital Costs					
Total System Price	$/kW stack input	$457	$577	$615	$608
Stack Price	$/kW stack input	$87 (300MW/yr basis)	$110 (300 MW/yr basis)	$143 (600 MW/yr basis)	$116 (600 MW/yr basis)
Total BoP Price	$/kW stack input	$371	$467	$472	$493
Mechanical BoP	$/kW stack input	$272	$368	$373	$394
Electrical BoP	$/kW stack input	$99	$99	$99	$99

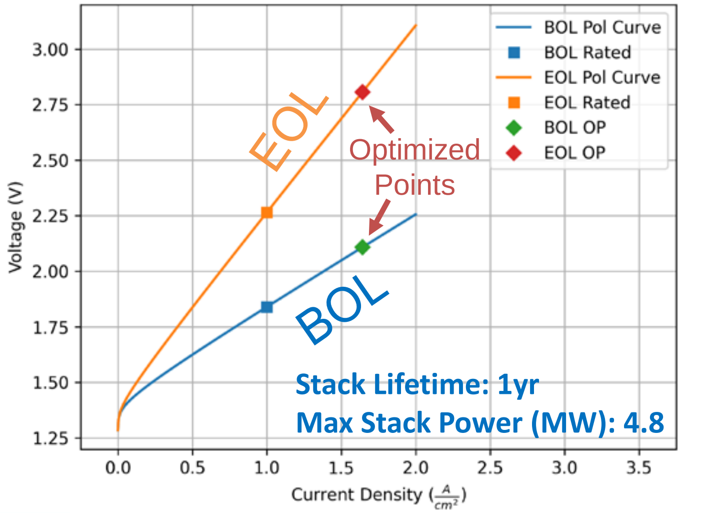
Stack costs are based on ground-up DFMA cost estimate. All dollar values are 2016$.

Current & Future Polarization Curves Developed Considering Voltage Degradation

Pure Water

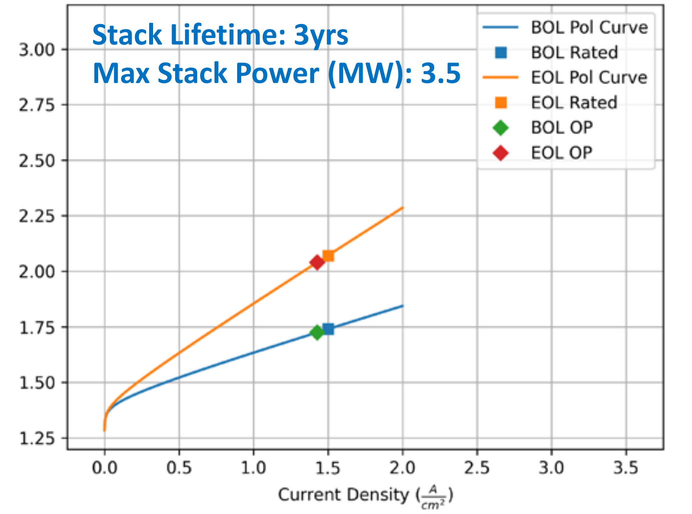
1M KOH

Near Term


Current Distributed AEM Water Case Pol Curves and Operating Points

Stack Lifetime: 1yr

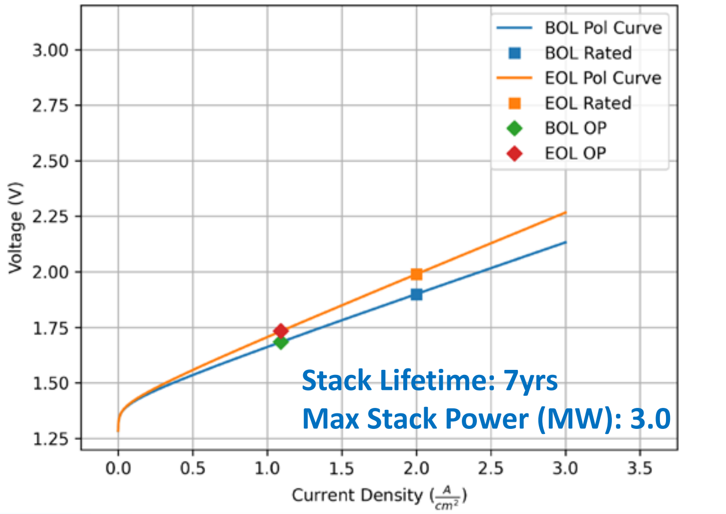
Max Stack Power (MW): 4.8


Current Distributed AEM Koh Case Pol Curves and Operating Points

Stack Lifetime: 3yrs

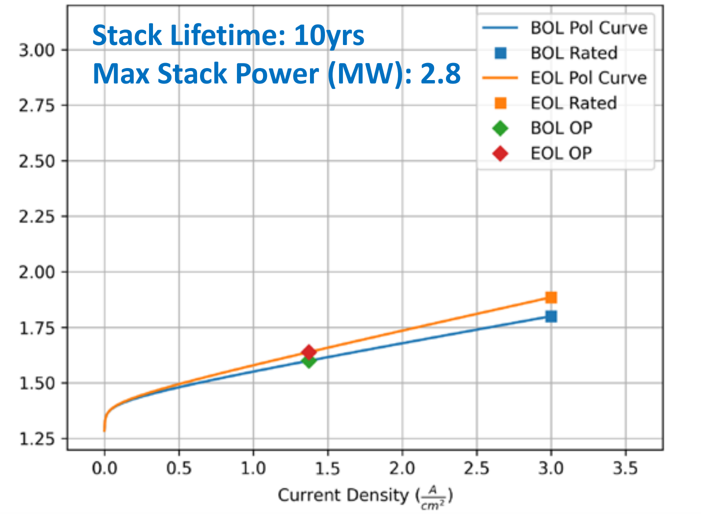
Max Stack Power (MW): 3.5

Future


Future Distributed AEM Water Case Pol Curves and Operating Points

Stack Lifetime: 7yrs

Max Stack Power (MW): 3.0


Future Distributed AEM Koh Case Pol Curves and Operating Points

Stack Lifetime: 10yrs

Max Stack Power (MW): 2.8

Pol. Curves used to determine Operating Point that leads to Lower H_2 Cost

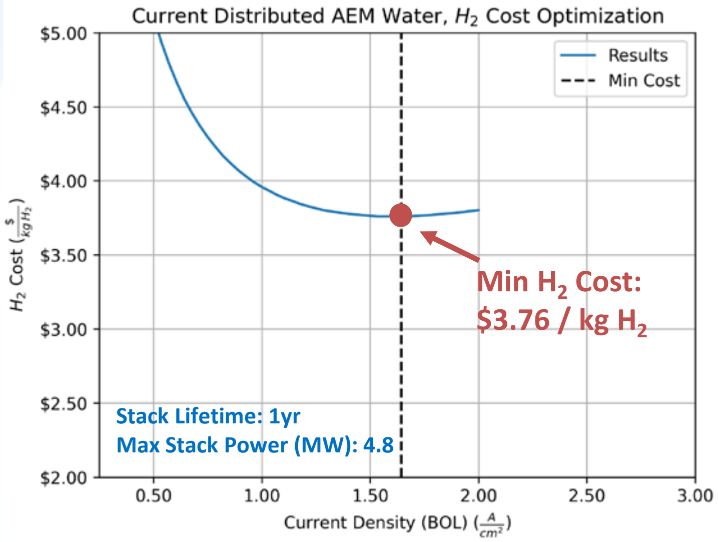
Optimization Model Approach

1. Specify BOL rated operating voltage, current density, and degradation (mv/1000hrs)
2. Determines EOL rated operating point
3. Estimates VI curve for BOL and EOL
4. Runs through each operating point along the curve to obtain cost of H_2
5. Returns the operating point with the lowest H_2 cost

Cost Optimization of Stack Operating Point

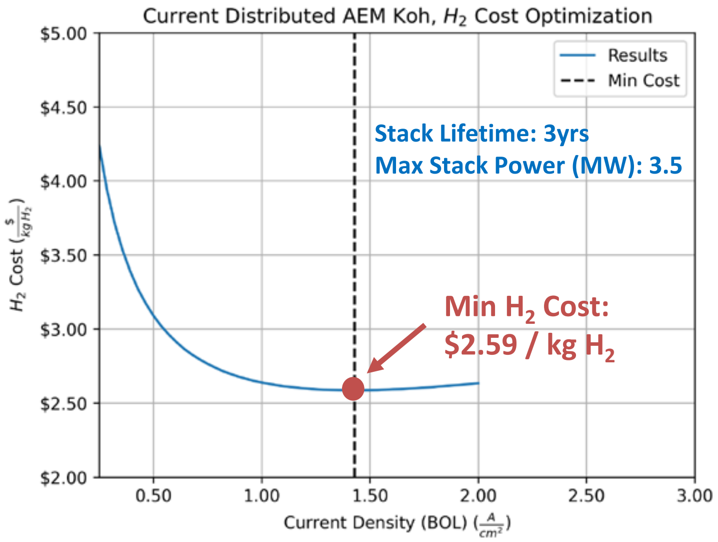
Pure Water **1M KOH**

Near Term



Min H_2 Cost: $3.76 / kg H_2

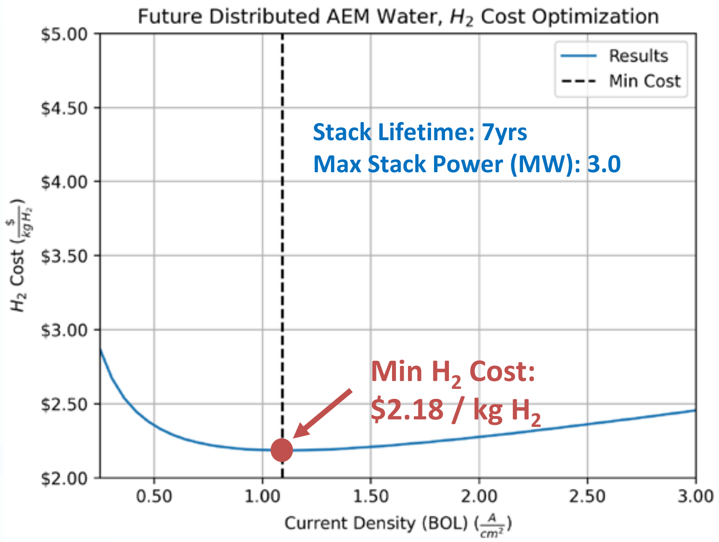
Stack Lifetime: 1yr
Max Stack Power (MW): 4.8



Stack Lifetime: 3yrs
Max Stack Power (MW): 3.5

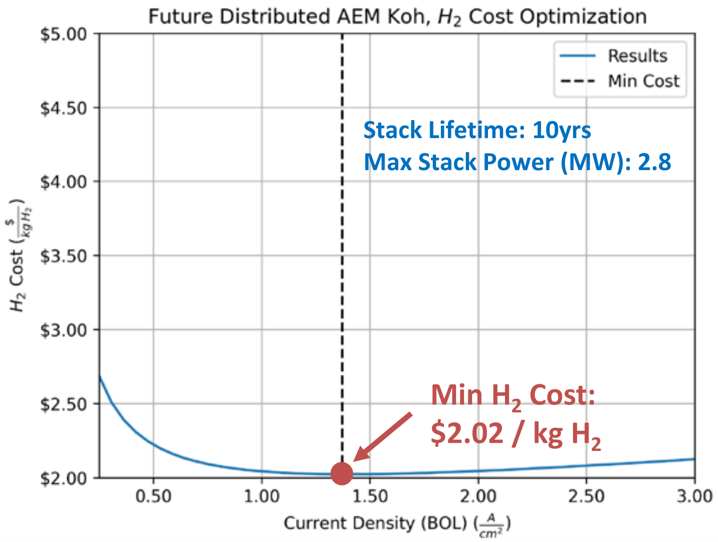
Min H_2 Cost: $2.59 / kg H_2

Future



Stack Lifetime: 7yrs
Max Stack Power (MW): 3.0

Min H_2 Cost: $2.18 / kg H_2



Stack Lifetime: 10yrs
Max Stack Power (MW): 2.8

Min H_2 Cost: $2.02 / kg H_2

Pol. Curves used to determine Operating Point that leads to Lower H_2 Cost

Optimization Model Approach

1. Specify BOL rated operating voltage, current density, and degradation (mv/1000hrs)
2. Determines EOL rated operating point
3. Estimates VI curve for BOL and EOL
4. Runs through each operating point along the curve to obtain cost of H_2
5. Returns the operating point with the lowest H_2 cost

Responses to Previous Year Reviewers' Comments

This is the first year of this project and thus was not reviewed during the 2021 Annual Merit Review Meeting

Collaborators

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur	Subcontractor	• Participated in weekly project calls • Assisted with H2A Production Model runs & sensitivity analyses • Drafted and reviewed reporting materials • Managed and arranged H2A Working Group activities
Idaho National Laboratory (INL) • Daniel Wendt	Subcontractor	• Participated in select project calls • Expert in Solid Oxide Electrolysis (which is not a current analysis focus in this year of the project)
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: • Nel • Versogen	Reviewer	• Nel provided feedback on Liquid Alkaline Water Electrolysis design • Versogen provided feedback on Anion Exchange Membrane design

Conclusions, Remaining Challenges and Barriers

- **Liquid Alkaline Water Electrolysis Systems**
  - LAWE systems can have a wide range of cell/stack designs and the chosen single baseline design modeled may not fully represent any one system (i.e., finite gap and zero gap design approaches both exist in current systems)
  - Design iterations have been somewhat stagnant for the last several decades with few present-day scientific research efforts addressing the durability of alternative materials and designs
  - A DFMA analysis confirms the current low cost of LAWE systems (~$600/kW) and shows a pathway to future cost of $300/kW.
  - The low cost of LAWE systems coupled with relatively high efficiency lend itself to a low near-term cost of hydrogen. While PEM, AEM, and SOE have the potential to beat LAWE on both capital cost and efficiency, LAWE remains a competitive option for near-termand long-term electrolyzer deployment

- **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 are not 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 $/kgH$_2$ cost basis

Proposed Future Work

- **Complete LAWE H2A Cases**
  - System Cost analysis
    - Finalize stack DFMA cost analysis
    - Re-evaluate BOP component costs (to ensure consistency with PEM and AEM cost assumptions)
    - Conduct sensitivity analysis
    - Vet cost results and sensitivity analysis with NREL and Nel collaborators
  - Publish H2A Results in a Case Study and DOE Record

- **Complete AEM H2A Cases**
  - System Cost analysis
    - Finalize BOP cost components
    - Conduct sensitivity analysis
    - Vet cost results and sensitivity analysis with NREL and Versogen
  - Publish H2A Results in Case Study DOE Record
- **\$1/kg H_2 Shot Scoping Study**
  - Investigate the ability of electrolysis to achieve the target by:
    - First estimating the cost with the lowest cost parameter values possible
    - Conducting a Monte Carlo multi-variable sensitivity analysis to determine successful parameter combinations

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

Summary

- **Overview**
  - Conducted technoeconomic analyses for LAWE and AEM Electrolyzer hydrogen production 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 SOA and future systems
    - Vet assumptions and results for correctness, completeness, and maximum transparency
- **Accomplishments**
  - (Planned) public distribution of H2A Model and Case Study Updates
  - Analysis of two H_2 electrolysis production systems (LAWE and AEM)

Technical Backup and Additional Information Slides

Technology Transfer Activities

Technology transfer does not apply to this analysis-type project

Publications and Presentations

1. James, B., "Liquid Alkaline Electrolysis Techno-Economic Review," Presentation at the US DOE Experts Meeting on Advanced Liquid Alkaline Water Electrolysis, January 2022.

Photoelectrochemical (PEC) Water Splitting

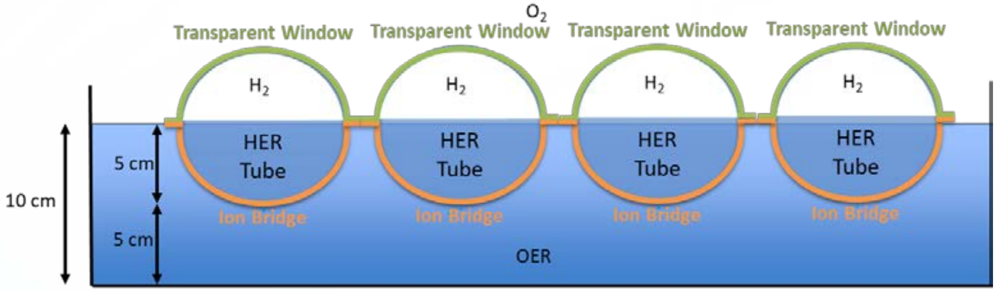
The following slides represent work conducted prior to the start of this project. Although this is a separate contract, the work conducted was on H_2 production pathway techno-economic analysis and these latest results have not yet been briefed to the public.

Collaboration with Shane Ardo (UC Irvine) and Rohini Bala Chandran (U of Michigan) on PEC catalysts and PEC type 2 raceway concepts

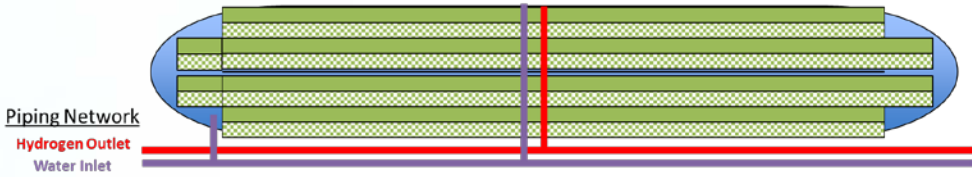
Photoelectrochemical Water Splitting

- Four Types of PEC Considered: Two selected for investigation by DOE
  - **Type II: Raceway System** - Nanoparticle catalysts contained in a separate aqueous systems
    - HER and OER reactions occur in separate aqueous systems connected via ion bridges
  - **Type IV: Concentrated PV Panel** – A PEC receiver contained in a water/electrolyte with concentrating solar panels

PEC Type II System: Raceway



Side View



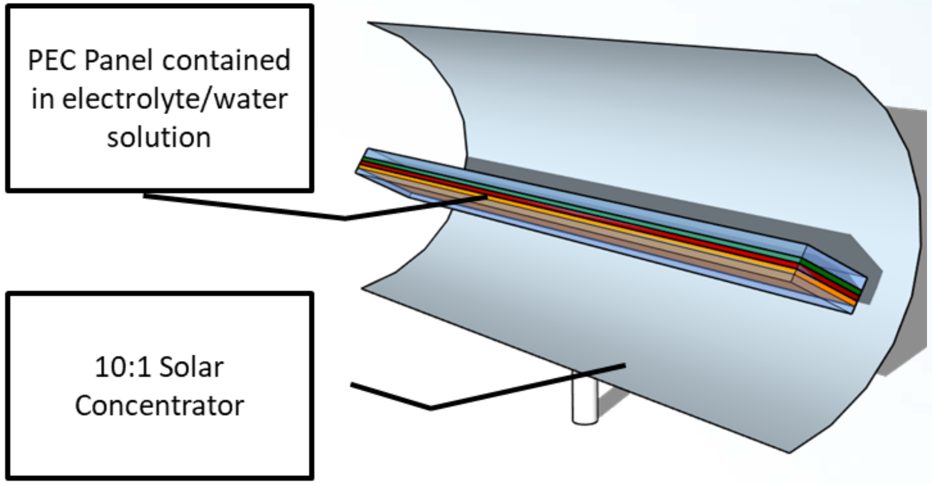
Top View

4000 m^2 Raceway:
~20m x ~200m

Top Bed: 4 photons + 4 D + 2 H_2O => 1 O_2 + 4H^+ + 4 D^-
Bottom Bed: 4 photons + 4H^+ + 4 D^- => 2 H_2 + 4 D

Intermediary reactant "D" (redox shuttle)

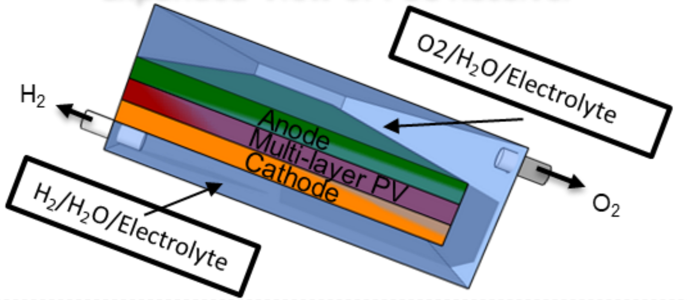
PEC Type IV System: Concentrated PV Panel



PEC Panel contained in electrolyte/water solution

10:1 Solar Concentrator

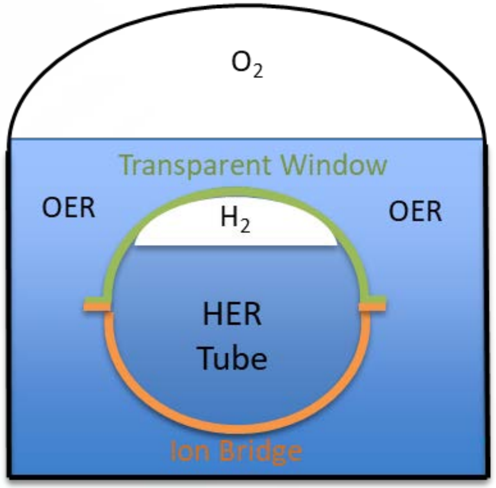
Expanded View of PEC Receiver

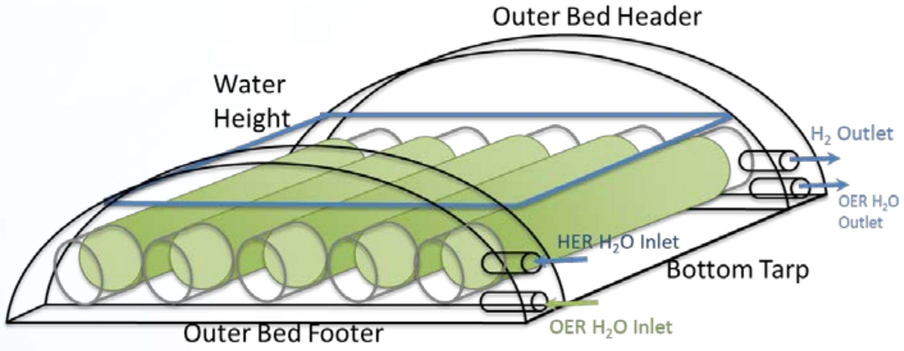


Progression of PEC Type 2 Designs

Baggie within Baggie

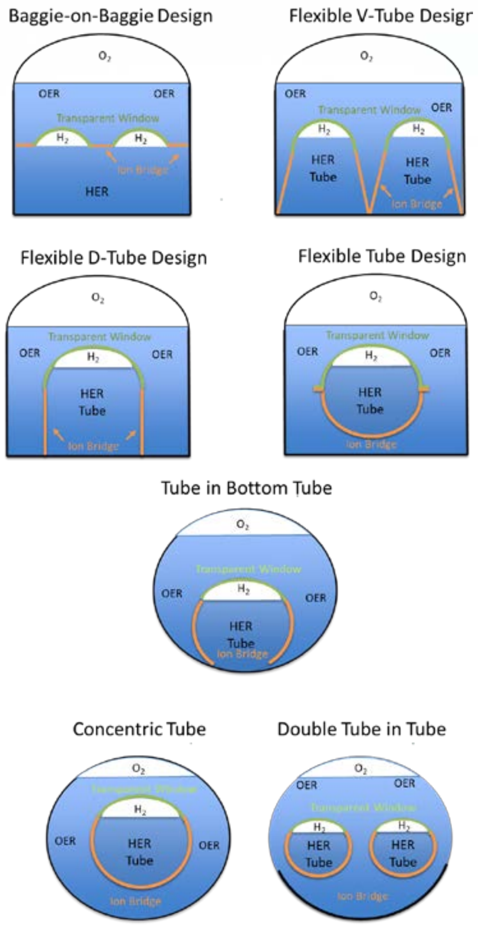
A





Alternative Baggie Geometries

B


Baggie-on-Baggie Design

Flexible V-Tube Desigr

Flexible D-Tube Design

Flexible Tube Design

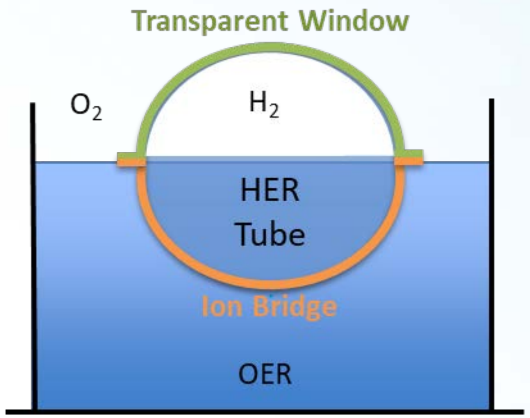
Tube in Bottom Tube

Concentric Tube

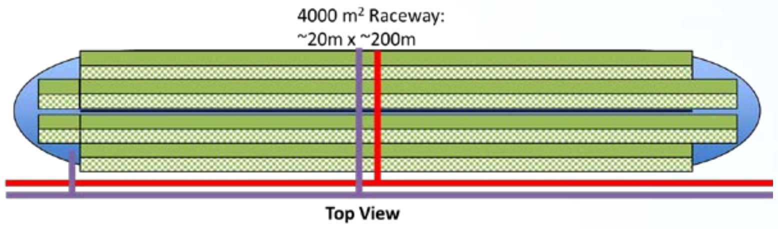
Double Tube in Tube

Raceway

C



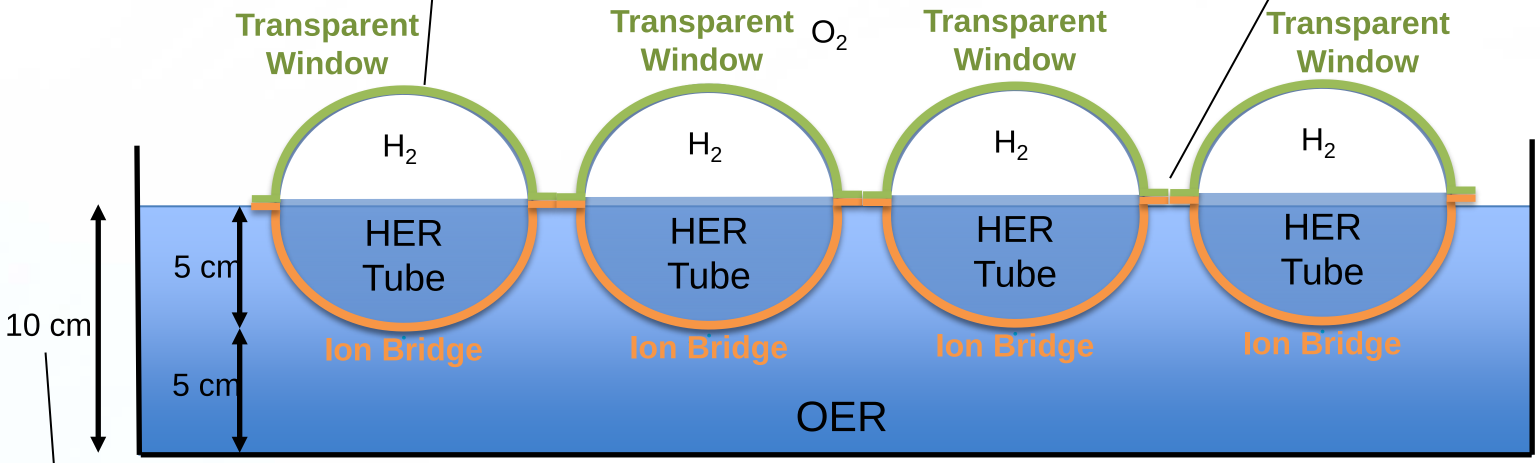
Side View



PEC Type 2: Flexible Tube Design *at Scale*

Continuous window and ion bridge sheet is relatively easy to manufacture

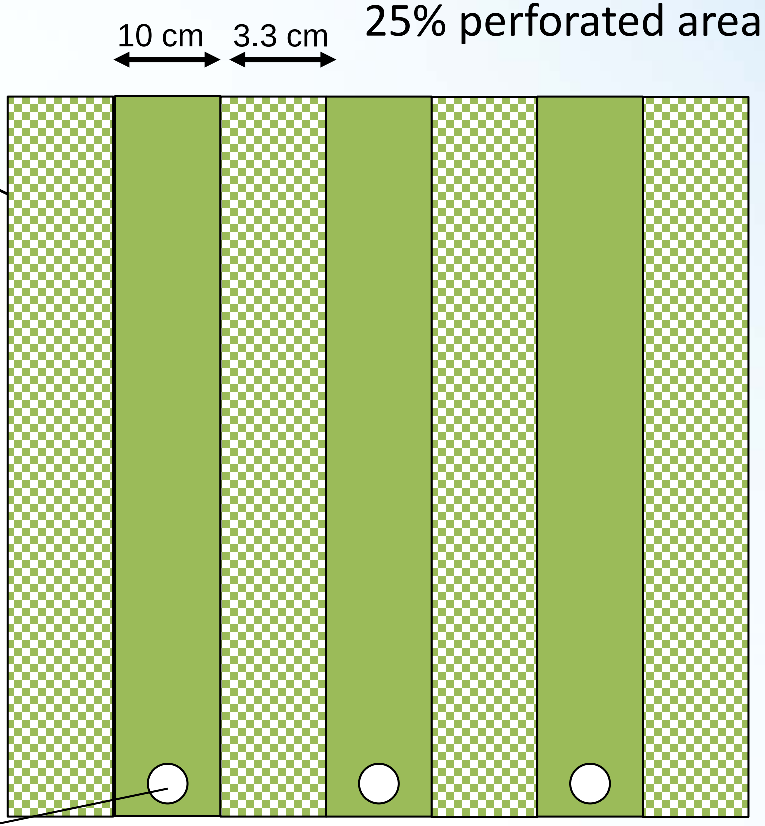
Sheet is perforated between tubes to allow oxygen to rise



Side View

Height of OER fluid could be 1-10 cm

Current design assumes 25% perforated area

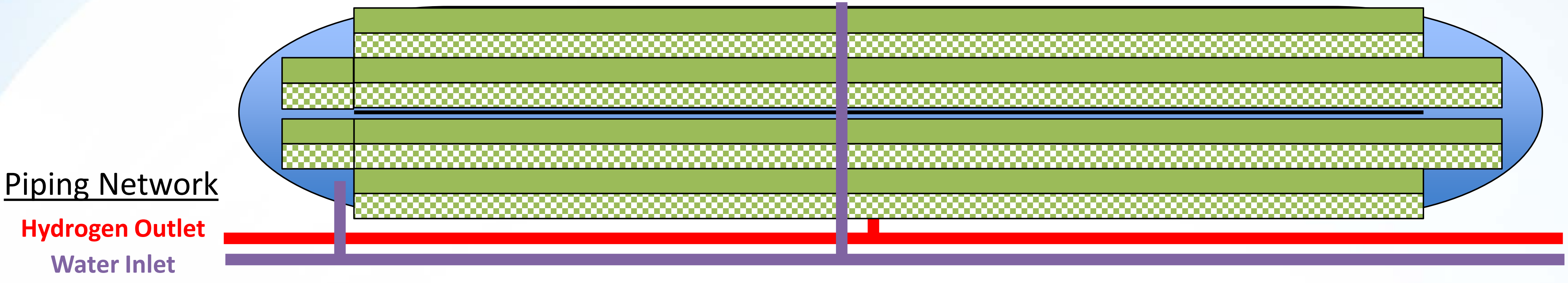


Port hole to collect H2 in central receiver

Top View

All dimensions are estimates only

PEC Type 2: Proposed "Open" Design



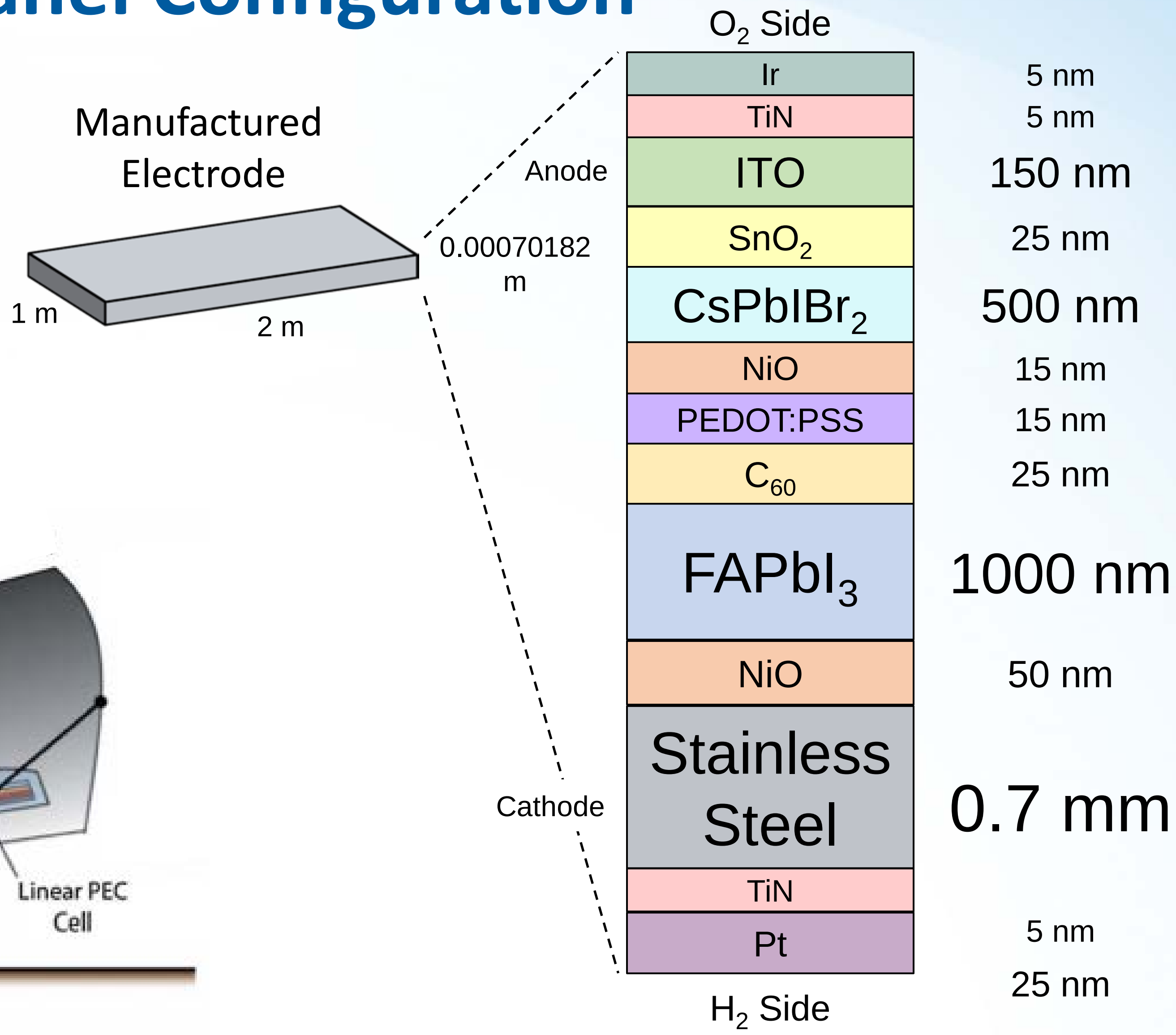
Top View
4000 m^2 Raceway:
~20m x ~200m

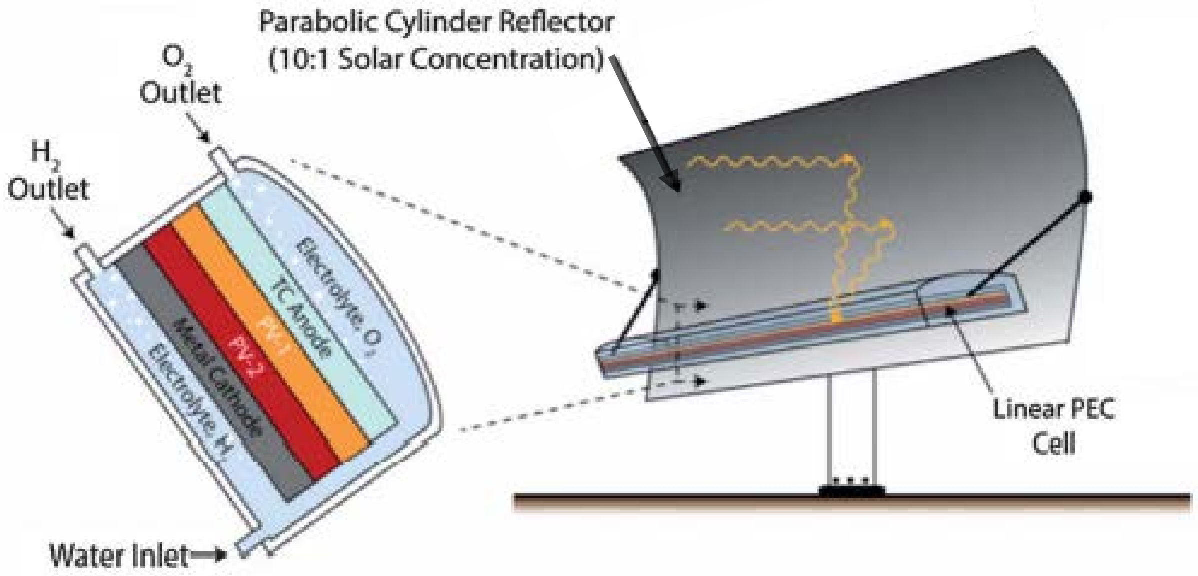
Design Notes:

- Conventional algae raceway uses a motor and paddle. However, due to shallow pool, no motor and paddle are assumed for PEC raceway
- ~1400 horizontal cylinders/raceway (10 cm diameter per cylinder)
- In addition to water conversion to hydrogen, water will be carried by both the hydrogen and oxygen outlets
  - Will need replacement water for OER pond and HER cylinders
- Port installation assumed for only cylinder inlets and outlets. Raceway inlets only use perforations

PEC Type 4: Panel Configuration

- Type IV Tracking Concentrator Array
  - Each concentrator array paired with a PEC panel encapsulating an electrode
  - Conducted DFMA model of panel manufacturing cost





Pinaud, Blaise A., et al. "Technical and economic feasibility of centralized facilities for solar hydrogen production via photocatalysis and photoelectrochemistry." *Energy & Environmental Science* 6.7 (2013): 1983-2002.

Construction and material selection is a modification of:
https://www.hydrogen.energy.gov/pdfs/review21/p191_yan_2021_o.pdf

PEC Type 4: DFMA Panel Cost Results

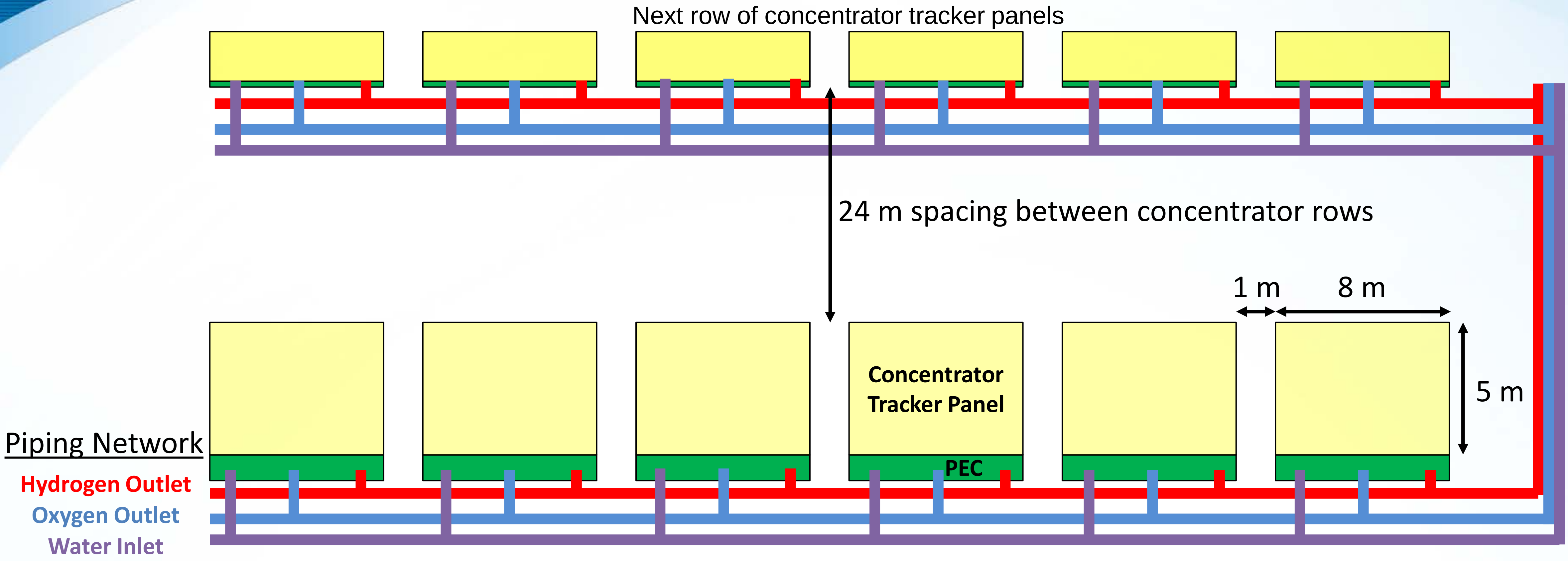
Annual Production Rate						
Area Per Year (m^2/year)	1,000	10,000	50,000	100,000	1,000,000	10,000,000
Panels Per Year (panels/year)	500	5,000	25,000	50,000	500,000	5,000,000

PEC Panel Results						
PEC Panel Cost Per Area (\$/m^2)	\$4,980	\$612	\$223	\$175	\$163	\$160
PEC Panel Material Cost Per Area (\$/m^2)	\$118	\$118	\$118	\$118	\$118	\$118
PEC Panel Manufacturing Cost Per Area (\$/m^2)	\$4,862	\$494	\$106	\$57	\$45	\$43
PEC Panel Cost (\$/panel)	\$9,960	\$1,223	\$447	\$350	\$325	\$321

Design Notes:

- 10,000 m^2/year manufacturing rate chosen for current cases (~\$615/m^2)
- 10,000,000 m^2/year manufacturing rate chosen for current cases (~\$160/m^2)
- 50% manufacturing markup included
- Casing and plexiglass cover included as separate capital item

PEC Type 4: Proposed Layout



Next row of concentrator tracker panels

24 m spacing between concentrator rows

1 m

8 m

5 m

Concentrator Tracker Panel

PEC

Piping Network

Hydrogen Outlet

Oxygen Outlet

Water Inlet

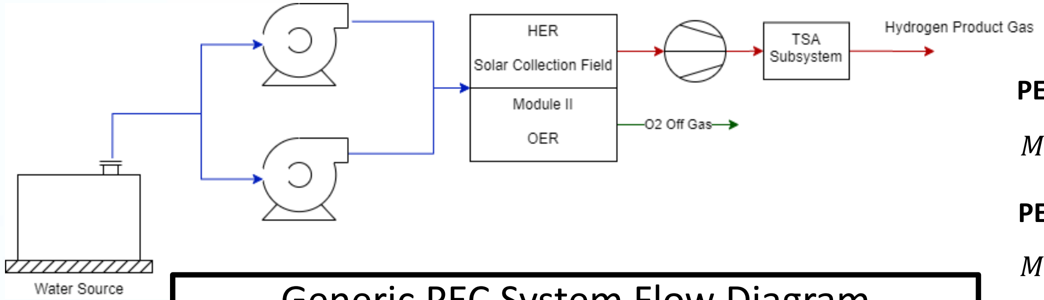
Top View

Design Notes:

- Large spacing required between rows to avoid shadowing effect
- Spacing between panel rows derived in 2009 report and used here (24m spacing per 5m of concentrator height)
- Spacing between concentrator trackers required to allow movement of the panel to track the sun

Preliminary Technical Specifications

- PEC Operation is water splitting with direct solar energy
  - Solar insolation rates are used to calculate the amount of active material needed
  - Separated Hydrogen Evolution Reaction (HER) and Oxygen Evolution Reaction (OER)
    - Separate Hydrogen and Oxygen beds in PEC Type II systems
    - Hydrogen and Oxygen are naturally separated by the shape and angle of the electrode in PEC Type IV System
- PEC typically has solar-to-hydrogen energy conversions below 20%
- A modular PEC design is envisioned in this analysis
  - Each module has a capacity of 1,000 kgH_2/day
  - Multiple modules strung together to reach desired H_2 production
- Preliminary system specs shown in tables to right



Generic PEC System Flow Diagram

PEC Type II System Technical Specifications

	Units	Value
PEC Type	-	Type II
Average Insolation	$kWh\ m^{-2}\ day^{-1}$	5.77
STH Efficiency	%	8%
Average H_2 Mass Flow	$kg\ day^{-1}$	1,000
Area Specific Mass Flow	$Kg\ H_2\ hr^{-1}\ m^{-2}$	5.89E-04
Total Solar Area Required	m^2	70,790
Raceway Length	m	200
Raceway Width	m	20
Raceway Height	m	0.01
Raceway Area	m^2	3800
Floating Cylinder Width	M	0.01
Number of Floating Cylinders per Raceway	#	1425
Number of Raceways	#	19
Assumed Particle Density	$kg\ m^{-2}$	0.00105
Particle Mass	kg	74

PEC Type IV System Technical Specifications

	Units	Value
PEC Type	-	Type IV
Average Insolation	$kWh\ m^{-2}\ day^{-1}$	7.46
STH Efficiency	%	35%
Overall Solar Efficiency	%	33.3%
Collector Efficiency	%	95%
Average H_2 Mass Flow	$kg\ day^{-1}$	1,000
Area Specific Mass Flow	$kg\ H_2\ hr^{-1}\ m^{-2}$	3.33E-03
Total Area Collector Required	m^2	13,200
Collector Length	m	8
Collector Width	m	5
Collector Area	m^2	40
Number of Collectors	#	330
PV Area Required	m^2	440

PEC Type 2 Raceway Estimate:

$$Module\ FTE = \left(\frac{0.0042\ FTE}{Particle\ lifetime\ (yrs)} + 0.018\ FTE\right)\frac{(Solar\ Land\ Required)}{4000m^2} + \frac{13\ FTE}{50\ TPD}(Module\ H2\ Production)$$

PEC Type 4 Estimate:

$$Module\ FTE\ = \frac{0.016\ FTE}{1000\ m^2}(Total\ Land\ Required) + \frac{3\ FTE}{50\ TPD}(Total\ Facility\ H2\ Production)$$

PEC Sensitivity Analysis

PEC Type II

- Case study suggests that the STH efficiency must be >6.5% with a particle lifetime of >1 years to achieve a target hydrogen price of $2/kg

PEC Type IV

- Case study suggests that achieving a cost target of $2/kg H2 will require an STH efficiency >25% with a catalyst lifetime of >1 years, and a concentration ratio of 30
- Concentration ratio of 30 incurs a system temperature of ~185 ℃, requiring a system pressure of 300 psi