Hydrogen Production and Delivery Analysis

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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 or photoelectrochemical water splitting) by using Design for Manufacture and Assembly (DFMA), heat & mass balance, and **H2 Analysis (H2A) 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: 10/1/2016
- Project end date: 9/30/2021
- Percent complete: ~90% 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
  - ~$780K SA (though Mar 2021)
- Total DOE Project Value:
  - ~$900k SA
- Cost Share Percentage: 0%
  (not required for analysis projects)

Partners

- National Renewable Energy Laboratory (NREL)
- Argonne National Laboratory (ANL)

Collaborators (unpaid)

- 7 Electrolyzer companies and research groups
  (names not included in public documents)

Relevance and Impact

- Investigates production and delivery pathways selected/suggested by DOE that are relevant, timely, and of value to FCTO.
- 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

Selection of H_2 Production & Delivery Cases

- DOE selects cases that support the FCTO 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 FCTO 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

Cases Completed in Previous Years	**Cases Completed This Year**	**Cases Under Development**

• Wiretough H_2 Storage at Dispensing Station
• Cost of Transmitting Energy
• Proton Exchange Membrane (PEM) electrolysis
  • Update to previous case study
• Solid Oxide Electrolysis (SOE)
  • Update to previous case study
	• Solar Thermochemical (STCH)
	  • Conducted by NREL
	• Anion Exchange Membrane (AEM) electrolysis (Draft submitted)
		• Anion Exchange Membrane (AEM) electrolysis
		  • Update to previous year’s case study
		• Photoelectrochemical (PEC) H_2O splitting
		  • Update to previous case study

Electrolyzer Water Splitting Technology

Project Objective

Conduct technoeconomic analyses of various methods of water splitting:

- 1,500 kg H_2/day distributed sites
- 50,000 kg H_2/day production sites (sometime larger systems)
- Two technology levels analyzed
  - Current: current technology at high-manufacturing rate
  - Future: future technology (2035) at high-manufacturing rate

Approach

- Collect data from Industry/Researchers
- Assess data for consensus and trends
- Validate with system modeling and other tools
- Update H2A model with new values to obtain updated $/kg H_2 projections

H2 Production Technology	Production Sizes Reported	Technology Years Reported
PEM Electrolysis	Distributed & Central	Current & Future
Solid Oxide Electrolysis	Central	Current & Future
Anion Exchange Membrane Electrolysis	Distributed & Central	Future & Far Future
Solar Thermochemical Hydrogen (STCH) Water Splitting	Central	Future
PEC Water Splitting (Type II)	Central	Future & Far Future
PEC Water Splitting (Type IV)	Central	Future & Far Future

Approach to data collection

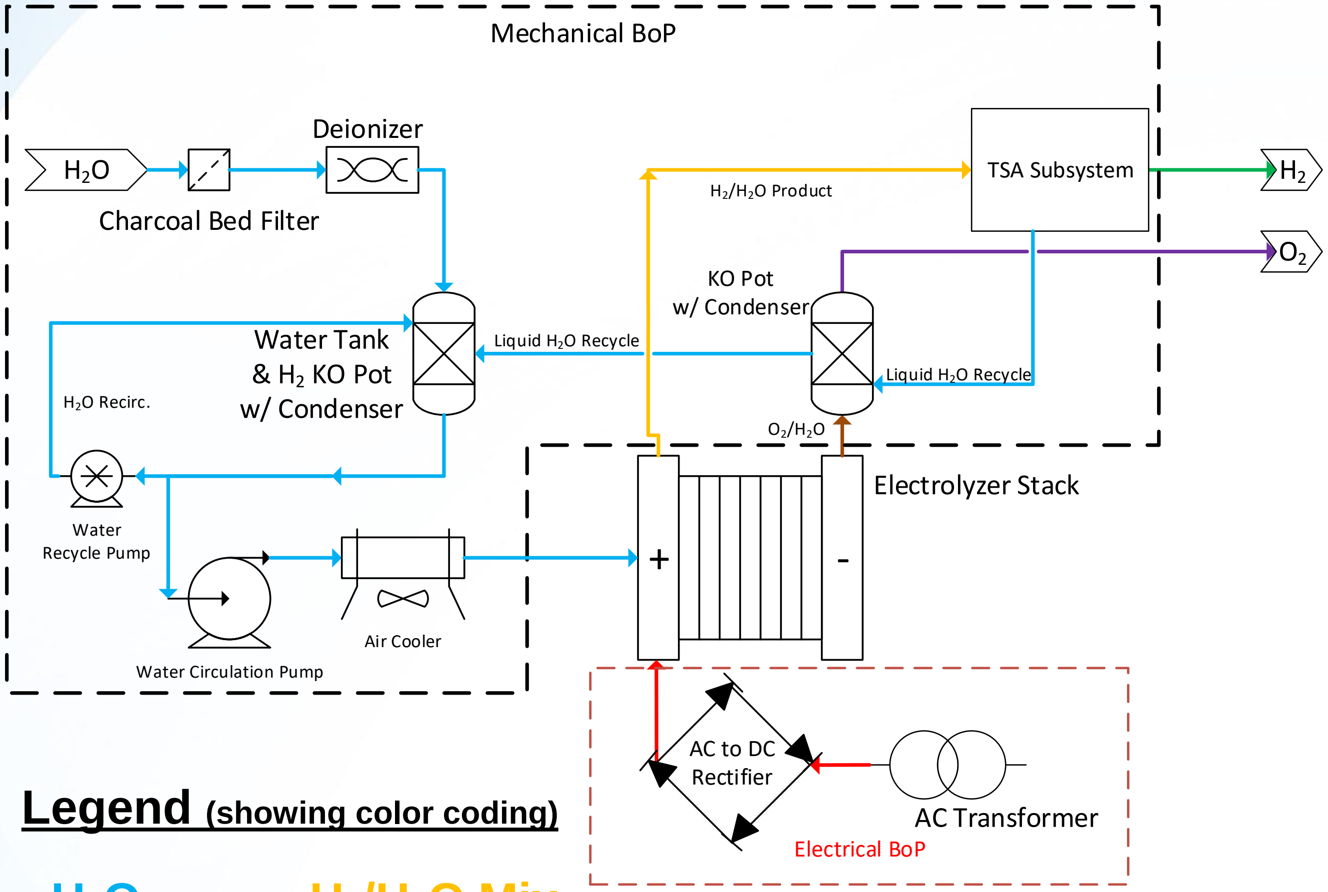
- **Surveyed industry & research groups for key technical & cost parameters**
  - Data response was limited for some parameters which often left insufficient data for statistical analysis
  - Compared with previously modeled system H2A values and previous survey data
  - Various Responses received for each technology

H2 Production Technology	Number of Respondents
PEM (2019 study)	5
SOE (2019 study)	4
AEM	1
STCH	3
PEC (Type II and IV)	2+

- **Developed technical and cost parameters from multiple sources**
  - Interview/Questionnaire responses
  - Literature review
  - Price quotes
  - Techno-economic system analysis based on PFD (incl. DFMA)
  - Learning Curves (for comparison to reported parameter values)

Preliminary AEM Electrolysis System Definition

AEM Electrolysis Process Flow Diagram



Legend **(showing color coding)**

- H_2O - H_2/H_2O Mix
- Electrical - H_2
- O_2 - O_2/H_2O Mix

Recent AEM Advances

- Commercialized Enapter Systems
  - Commercial production of 1 kgH_2/day stacks:
    - approx. 23 cells, 125cm^2 active area
    - 500 NL/h, 2.2 kW, implies 1.82V/cell
  - Operation with 1M KOH
  - Non-PGM catalyst
  - Claimed 30kh lifetime and 0.25%/kh degradation rate (implies 5mV/kh @ constant current))
- Most research is focused on pure-water AEM systems
  - Focus on advanced performance, durable membranes (>1A/cm^2 current density at 1.8V/cell and 15mV/kh degradation)
  - Near-term advances to be expected
  - Maintenance advantage of pure water (no alkaline solution)

Preliminary AEM Electrolysis System Definition

AEM Key Technical and Cost Parameters (Distributed)

	Units	PEM Current	AEM Current/ Near-Future	AEM Future	AEM Far-Future
Current TRL		9	7	5	5
Plant Start Year	-	2019	2021	2040	2060
Plant Size	kg H_2/day	1,500	1,500	1,500	1,500
Capacity Factor	%	97%	97%	97%	97%
H_2 Outlet Pressure	Bar	20.7	20.7	20.7	20.7
Stack Op. Pressure	Bar	20.7	20.7	20.7	20.7
Current Density	A /cm^2	2.0	0.45	0.82	0.87
Voltage	V	1.9	1.8	1.73	1.64
Degradation Rate	mV/1000hrs	1.5	5	1.5	1
Oversize Factor	%	20%	20%	20%	10%
Stack Lifetime	yrs	7	3.5	7	10
Supporting Electrolyte	1M KOH	Water	Water	Water	Water

	Units	PEM Current	Current/ Near-Future	Future	Far-Future
Stack Electrical Usage	kWh/kgH2	50.4	TBD	44.98	42.54
System Electrical Usage	kWh/kgH2	55.8	~49	50.28	47.94
Stack Cost	$\$/cm^2$	$1.30	TBD	$0.58	$0.56
Mechanical BoP Cost	$/(kg/day)	$286	TBD	$680	$641
Electrical BoP Cost	$/kW	$121	TBD	$97	$97
Stack Cost	$/kW	$342	TBD	$418	$391
Mechanical BoP Cost	$/kW	$136	TBD	$325	$320
Electrical BoP Cost	$/kW	$121	TBD	$97	$97
Total System Cost (uninstalled, kWDCinlet)	$/kW	$599	TBD	$840	$808

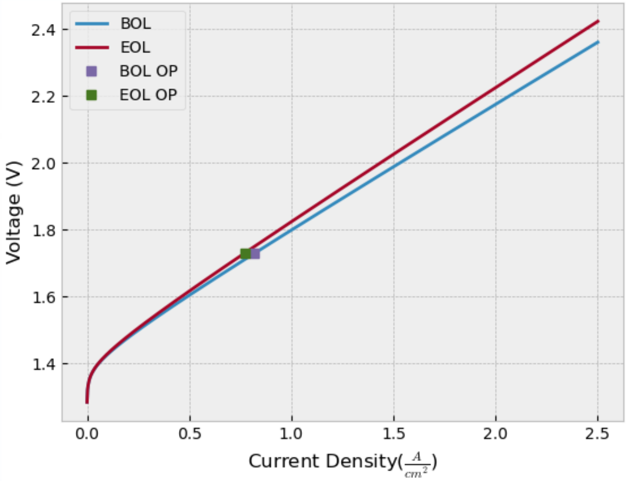
“Costs” are actually prices to H2 production facility. All dollar values are 2016$. All kW are DC input to the stack.

AEM Current Case is being revised to reflect recent advances.

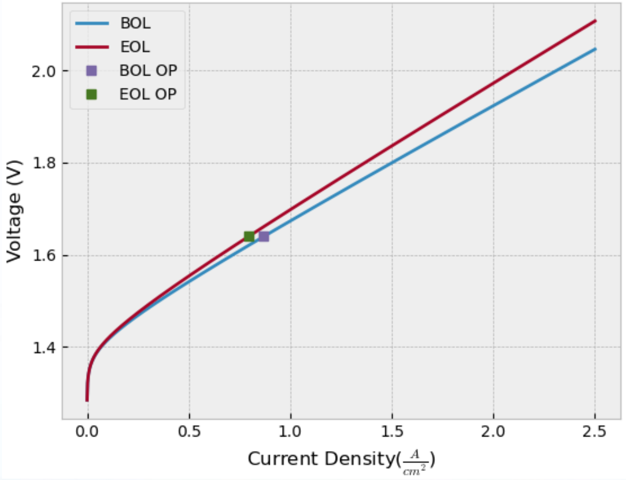
Preliminary AEM Performance Estimates

- Current System is being re-evaluated in light of recent advances.
- Future and Far-Future Cases based on pure-water AEM operation at pressure

AEM Future Distributed

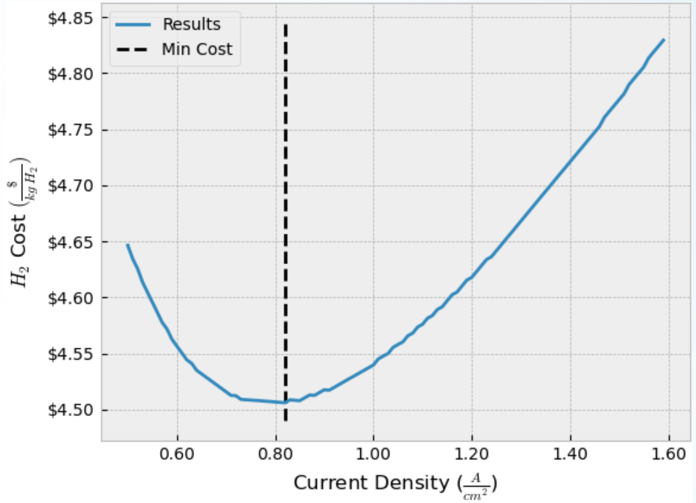


AEM Far-Future Distributed

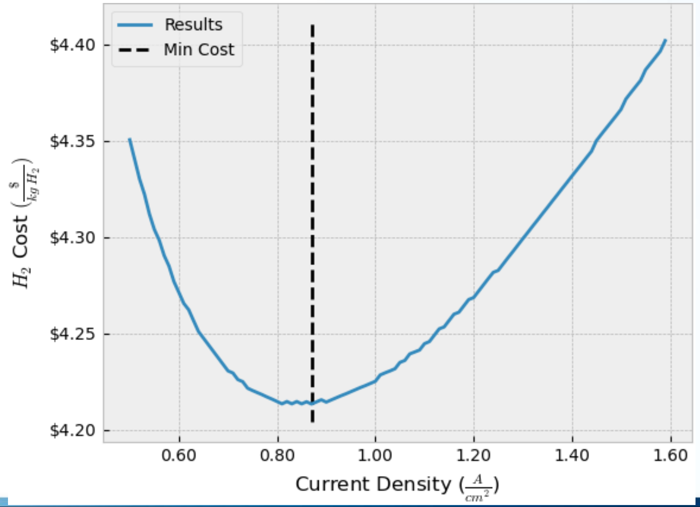


- Basic polarization curves postulated for each system for BOL and EOL
- Current density/voltage parametrically varied within H2A model to determine operating point yielding lowest cost H_2
  - This is a tradeoff between stack size (cost) and electricity usage (cost)
- For projected sets of assumptions, cost-optimized operating point are:
  - Future:
    - 0.82A/cm^2 at 1.73V/cell
  - Far-Future:
    - 0.87A/cm^2 at 1.64V/cell

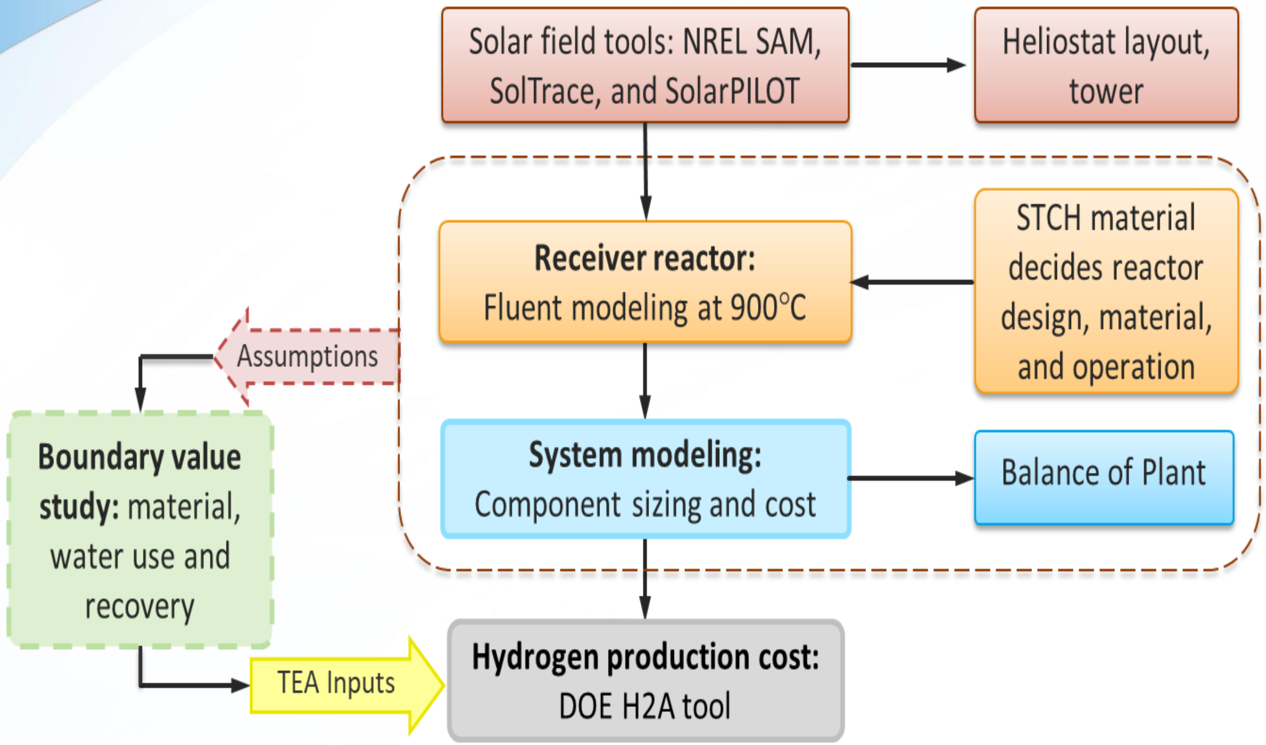
AEM Future Distributed



AEM Far-Future Distributed



Approach: STCH Techno-economic analysis



Solar field tools: NREL SAM, SolTrace, and SolarPILOT

Heliostat layout, tower

Receiver reactor: Fluent modeling at 900°C

STCH material decides reactor design, material, and operation

System modeling: Component sizing and cost

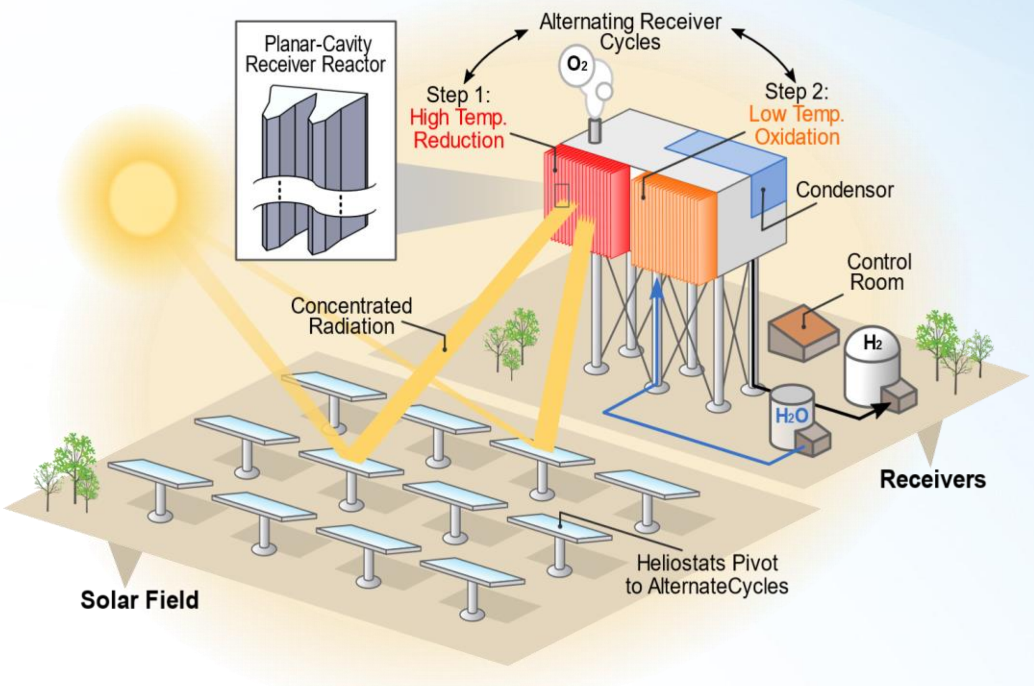
Balance of Plant

Assumptions

Boundary value study: material, water use and recovery

TEA Inputs

Hydrogen production cost: DOE H2A tool



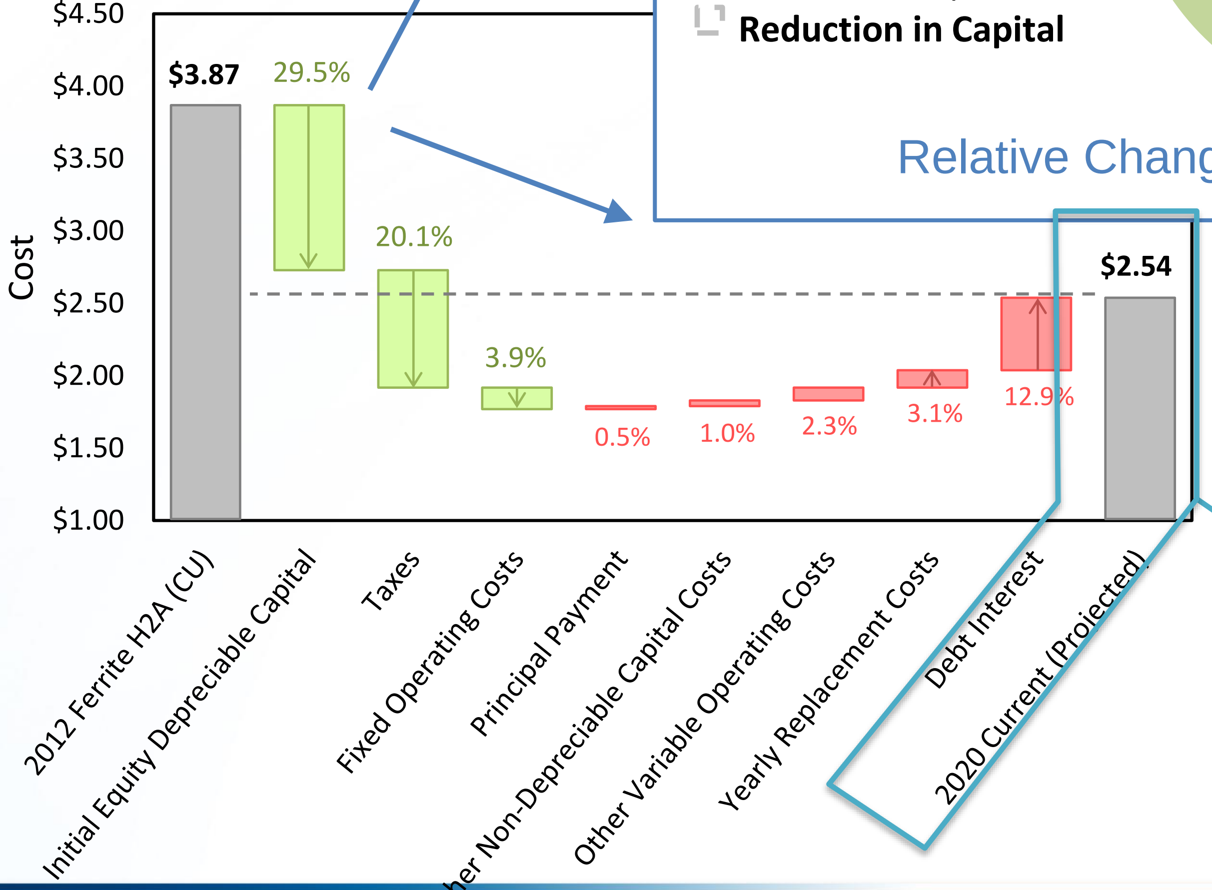
Conceptual STCH platform used as a reference for techno-economic inputs

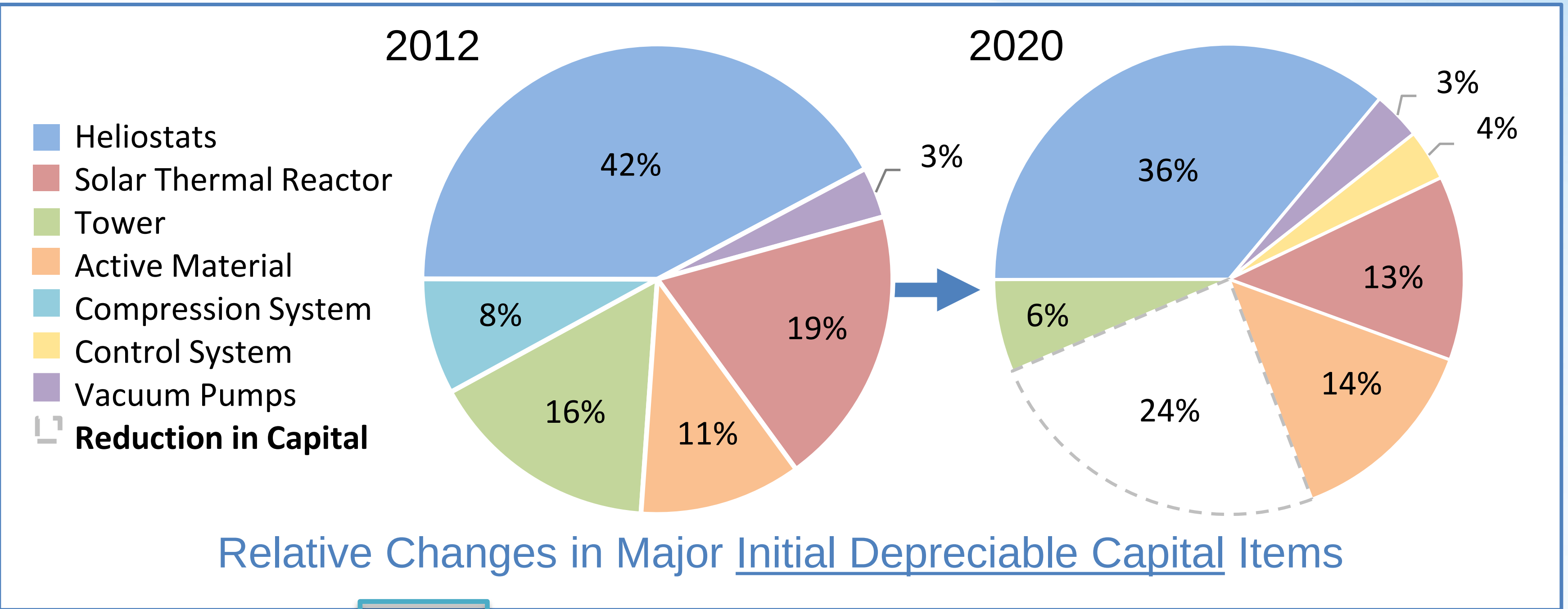
- Boundary case focusses on two aspects of solar-hydrogen production: 1) solar energy collection & 2) thermal-hydrogen conversion
- An analysis gap is that without a working material specified, other system aspects cannot be definitively conceived
- A general analysis approach was developed for the flexibility of assessing material candidates that are under development

Design Features

- Sandia National Laboratory's CPR2 configuration
- University of Colorado's fluidized bed reactor
- NREL's planar-cavity receiver concept

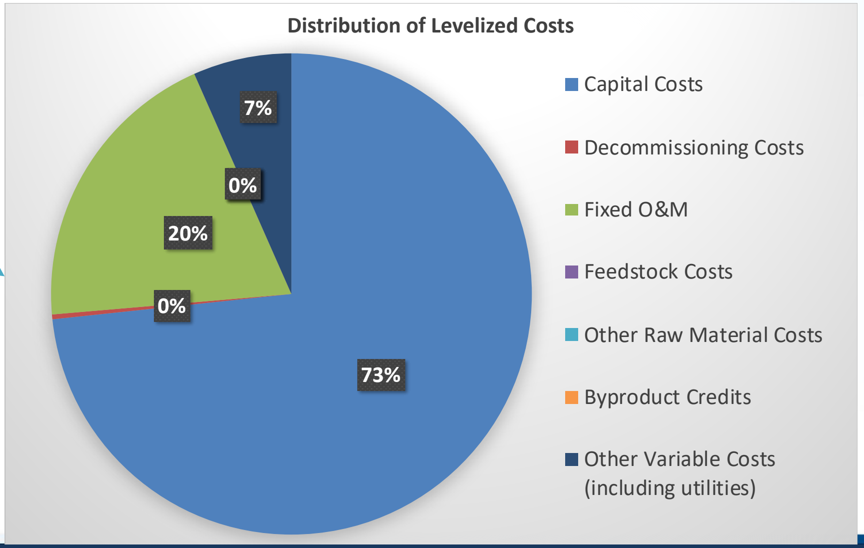
STCH TEA Comparison with previous H2A Case





Relative Changes in Major Initial Depreciable Capital Items

- Capital costs dominate the levelized cost of H2

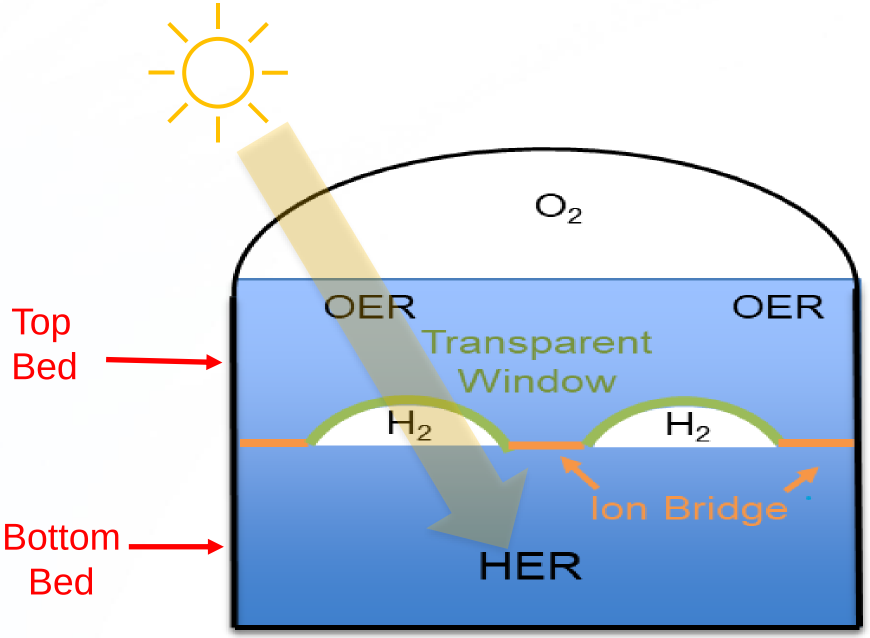


24% projected capital cost reduction lowers $/kg$H_2$ estimate

Photoelectrochemical Water Splitting

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

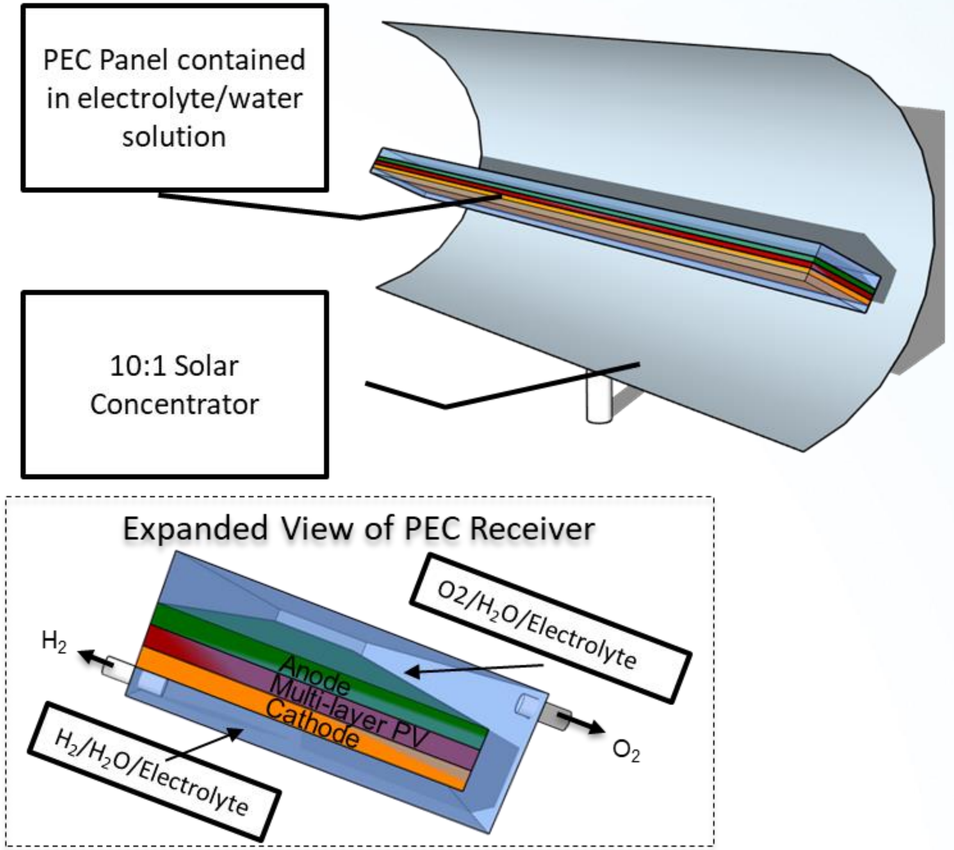
PEC Type II Baggie-on-Baggie System



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 Drawing

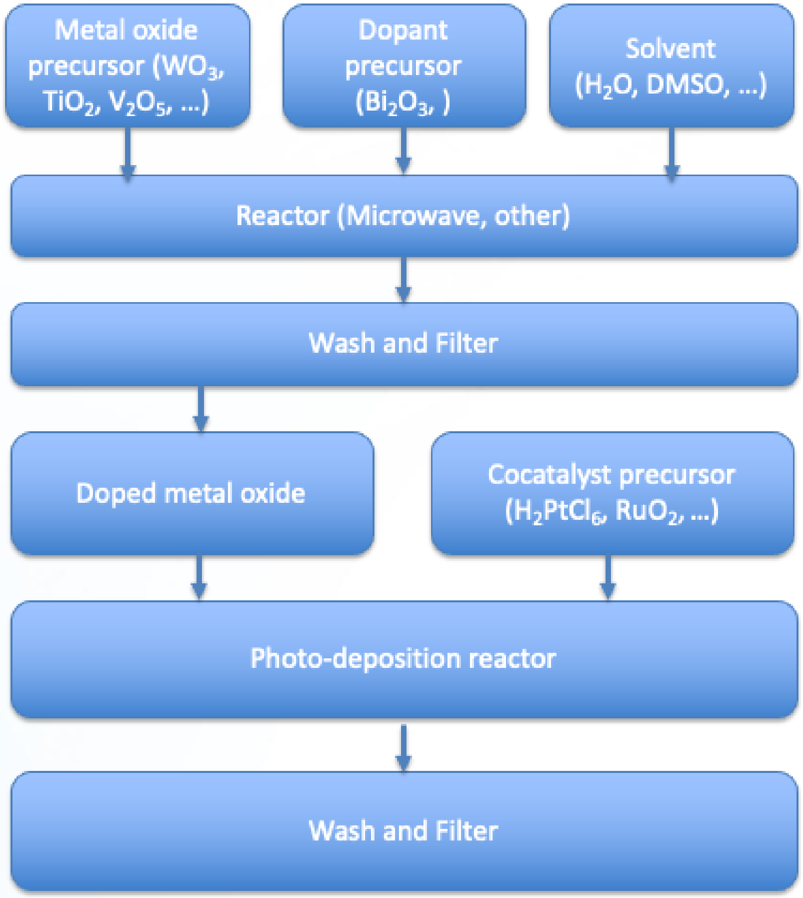


Advanced “baggie-on-baggie” Type II PEC concept is being modeled.

Type II PEC Material Fabrication

- Nano-particle materials development is an active area of investigation, so cost approach is chosen for flexibility
- Solvothermal and hydrothermal are scalable synthesis pathways for bulk production of doped metal oxides
- Other pathways (e.g vapor deposition, pyrolysis, etc.) and coating options should be addressed as needed

General process flow for catalyst-coated doped metal-oxides

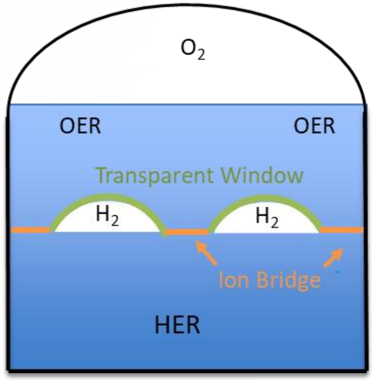

Metal oxide precursor (WO_3, TiO_2, V_2O_5, …)
Dopant precursor (Bi_2O_3,)
Solvent (H_2O, DMSO, …)
Reactor (Microwave, other)
Wash and Filter
Doped metal oxide
Cocatalyst precursor (H_2PtCl_6, RuO_2, …)
Photo-deposition reactor
Wash and Filter

Item	Expected Range of Values	Rationale
Annual production	60-3,000 tonnes/year	Assumed 100 kg per 1 TPD module, 50 TPD systems, 60-300 systems installed, Particle lifetime: 0.5-5 years
Metal oxide salts	\$1-\$100/kg	Range of quotes for bulk (10-1,000 kg) orders of metal oxides
Plant capital cost	\$2M-\$10M	Estimate based on analogous metal organic framework (MOF) analysis scaled for annual material production
Unrecovered solvent costs	\$0-\$25/kg PEC	Based on analogous MOF work. Range depends on yield, solvent choice, and recovery
Co-catalyst cost	\$100-\$1,000/kg PEC	Modeled as 0.2-2 wt% Pt:metal oxide, \$50k/kgPt
Range of material costs	\$105/kg PEC - \$1,200/kg PEC	Materials + Synthesis (approx. first-pass range of particle price)

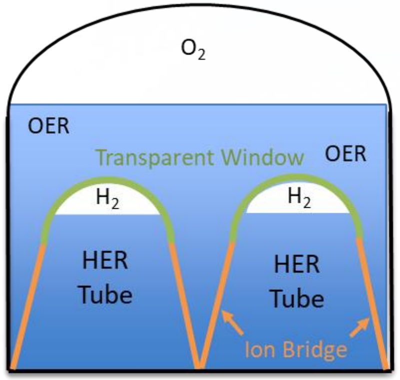
Approach: analysis of potential raw material & syn. costs to assess cost range of nano-particles

Type II PEC Alternative Physical Designs/Structures Under Consideration

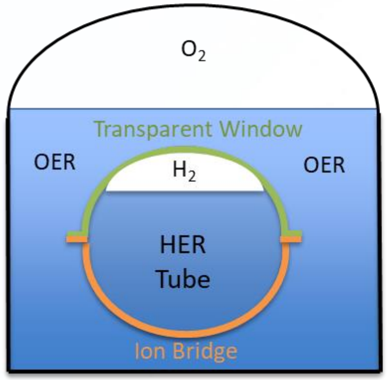
A: Baggie-on-Baggie Design



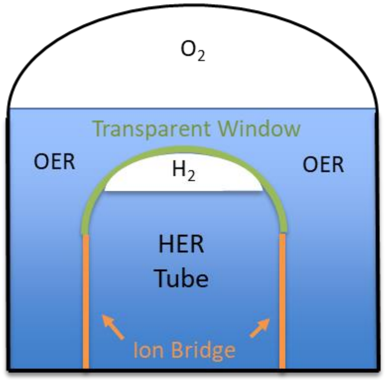
B: Flexible V-Tube Design



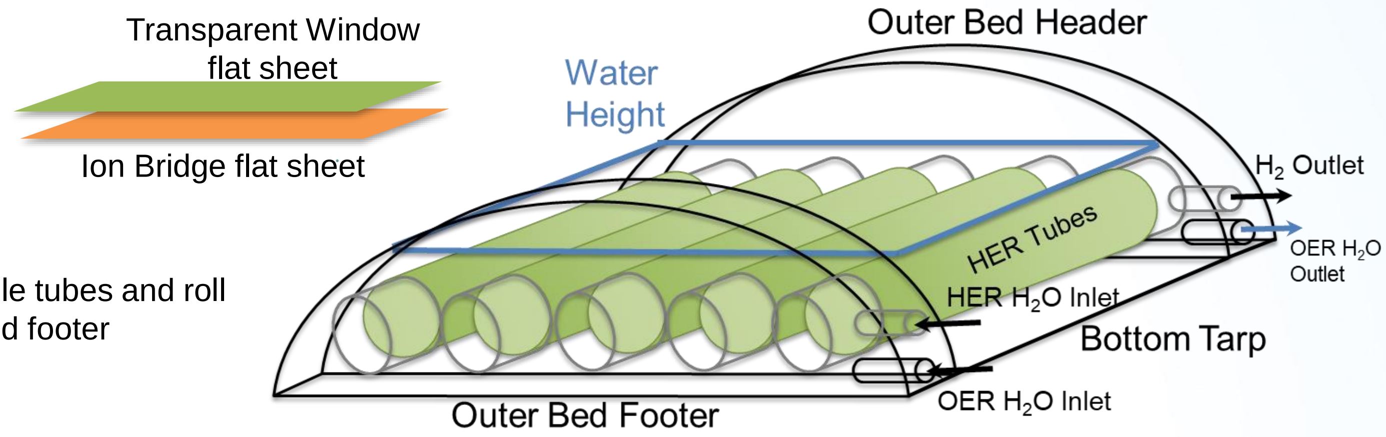
C: Flexible Tube Design



D: Flexible D-Tube Design



- Working with UC Irvine and Univ. of Michigan to evaluate the feasibility of each design:
  - The required ion bridge area and material for sufficient transfer of H^+ ions and redox shuttle intermediaries
  - Passive mixing for greater number of reactions
  - Light scattering and energy losses within the system



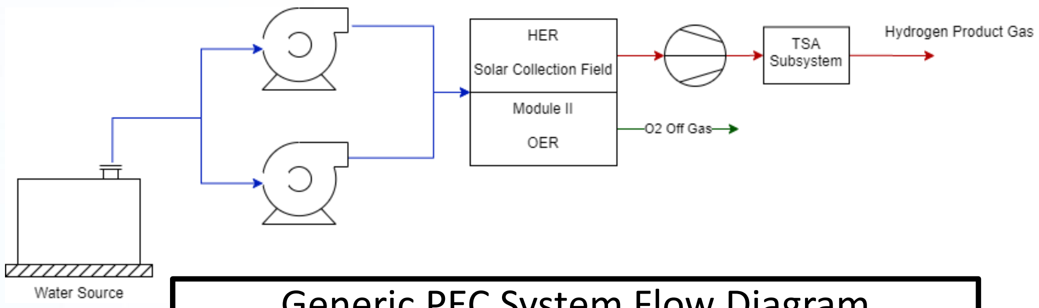
Manufact. & Assembly in Field for Flexible Tube Design (C)

1. Hot press flexible sheets together on long edges to form flexible tubes and roll
2. Unroll tubes on bottom tarp and fasten to outer bed header and footer
3. Attach transparent cover to outer bed
4. Fill tubes and outer bed with electrolyte and water

Further Type II PEC concepts focus of discussions with UC-Irvine/Univ. of Michigan Research Teams

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	%	5%
Average H_2 Mass Flow	kg day^{-1}	1,000
Area Specific Mass Flow	Kg H_2 hr^{-1} m^{-2}	3.67E-04
Total Area Required	m^2	113,266
Bed Length	m	61
Bed Width	m	6.1
Bed Height	m	0.37
Bed Area	m^2	372
Bed Volume	m^3	136
Number of Beds	#	305
Assumed Particle Density	kg m^{-3}	0.199
Particle Mass	kg/bed	199

PEC Type IV System Technical Specifications

	Units	Value
PEC Type	-	Type IV
Average Insolation	kWh m^{-2} day^{-1}	7.46
STH Efficiency	%	15%
Cell Efficiency	%	18%
Collector Efficiency	%	85%
Average H_2 Mass Flow	kg day^{-1}	1,000
Area Specific Mass Flow	kg H_2 hr^{-1} m^{-2}	1.43E-03
Total Area Collector Required	m^2	29,202
Collector Length	m	6
Collector Width	m	3
Collector Area	m^2	18
Number of Collectors	#	1,623
PV Area Required	m^2	2,921

Capital Cost Assumptions	$
Capital Cost per Module (H_2 Compressor, %)	$1,014,513 ($872,400, 86%)
Capital Cost per Bed (Excluding PEC particles)	$2755

Capital Cost Assumptions	$
Capital Cost per Module (H_2 Compressor, %)	$3,286,065 ($872,400, 27%)

Labor:

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

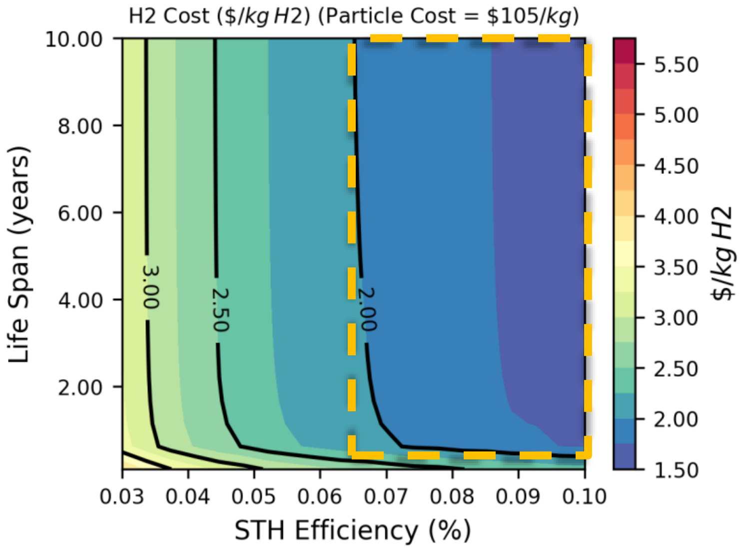
PEC Sensitivity Analysis

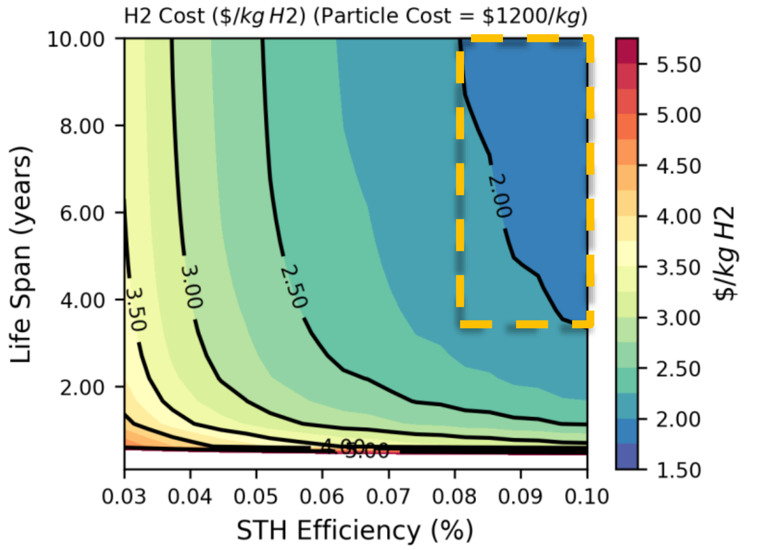
PEC Type II

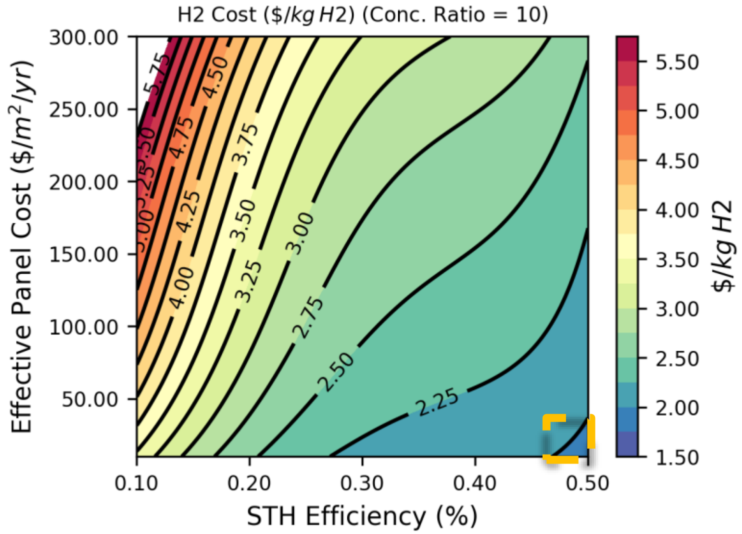
- Case study suggests that the STH efficiency must be >6.5% with a particle lifetime of >1 years to achieve a target hydrogen price of $2/kg

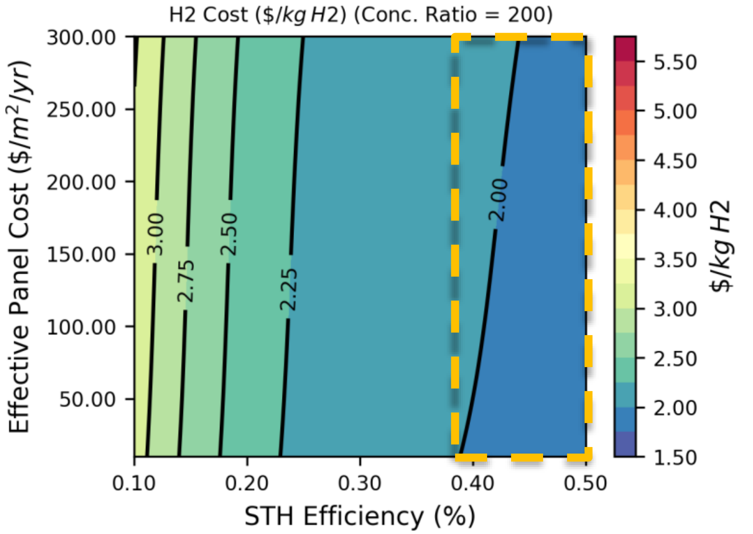
PEC Type IV

- Case study suggests that achieving a cost target of $2/kg H2 will require an STH efficiency >40% and will need the right combination of PEC material cost, lifetime, and concentration ratio


H2 Cost ($/kg H2) (Particle Cost = $105/kg)


H2 Cost ($/kg H2) (Particle Cost = $1200/kg)


H2 Cost ($/kg H2) (Conc. Ratio = 10)


H2 Cost ($/kg H2) (Conc. Ratio = 200)

Conclusions, Remaining Challenges and Barriers

- **AEM Systems**
  - AEM systems are promising for their potential for non-PGM catalysts, low membrane cost, and use of stainless components (i.e. Titanium is not required)
    - They are currently divided into two categories
      - Supporting-electrolyte system (such as KOH) characterized by:
        - improved durability, (currently) poor current density, and higher maintenance-cost/inconvenience due to the presence of an alkaline solution
      - Pure Water systems are characterized by:
        - poor membrane stability but are an active research area with focus on the advanced membranes and non-PGM/low-PGM catalysts to improve performance and durability
  - 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
- **STCH**
  - STCH system projections show reduced capital costs compared to the 2012 STCH analysis. This results in lower total H_2 cost (previously \$3.87/kgH_2, now \$2.54/kgH_2)
  - System design for STCH pathway is difficult to define if working material is not clearly specified.
- **PEC**
  - PEC Type II (nano-particle) material durability remains a key challenge although starting material and material synthesis costs are not likely to be key cost drivers.

Response to 2019 AMR Reviewer Comments

- "The project team should evaluate more scalable systems for water splitting, such as particle-based systems and possibly PEC."
  - Response: PEC Type II system is currently under evaluation
- "The project team should consider ways in which the results from these studies could affect and drive further research and development in the science and engineering communities."
  - Response: The team considers the impacts and seeks feedback on areas of interest from the R&D community such as through the DOE Water splitting workshop (March 2021).

Proposed Future Work

- **Complete AEM Analysis**
  - System Cost analysis
    - Explore cost of the supporting-electrolyte in light of recent advances by Enapter
    - Preliminary cost results and sensitivity analysis to be reviewed by University of Delaware, NREL, & LANL
  - Publish H2A Results in Case Study DOE Record
- **Publish STCH H2A Cost Results (based on NREL analysis)**
  - H2A Documentation currently under final review for publication
- **Complete PEC H2A analysis**
  - System Cost analysis
    - Continue dialog with UC Irvine and University of Michigan to refine Type II system design
    - Obtain feedback on final PEC material choice for Type II and IV
  - Refine capital cost with feedback from researchers
  - Conduct sensitivity analysis
  - Publish H2A Results in Case Study DOE Record

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

Collaborators

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur • Zhiwen Ma • Patrick Davenport • Hailey Boyer	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 • Conducted boundary analysis of STCH case and H2A case study
Argonne National Lab (ANL) • Rajesh Ahluwalia • Amgad Elgowainy	Subcontractor	• Participated in select project calls • Vetted process work • Expert review of transmission analysis
Department of Energy (DOE) • Ned Stetson • Dave Peterson • Katie Randolph • Max Lyubovsky • James Vickers	Sponsor	• Participated in some weekly project calls • Assisted with H2A Model and sensitivity parameters • Reviewed reporting materials • Direct contributors to energy transmission work

Summary

- **Overview**
  - Conduct technoeconomic analyses for various 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
- **Accomplishments**
  - H2A Model and Case Study Updates
  - Analyzed three production system (AEM, STCH, PEC)

Technical Backup and Additional Information Slides

Technology Transfer Activities

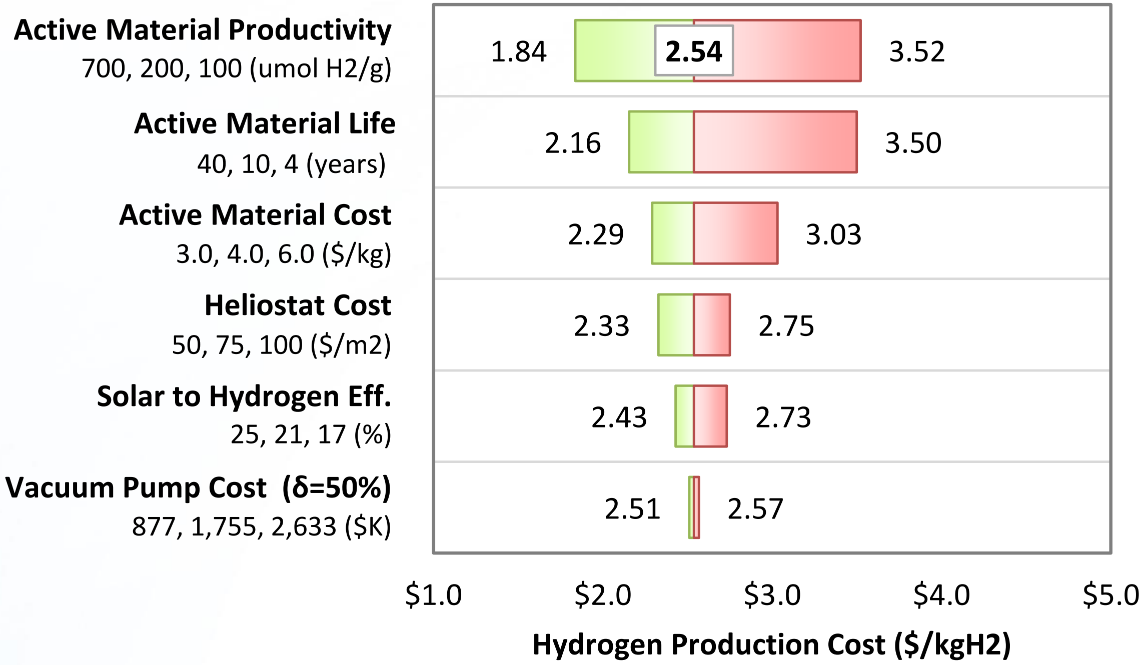
Technology transfer does not apply to this analysis-type project

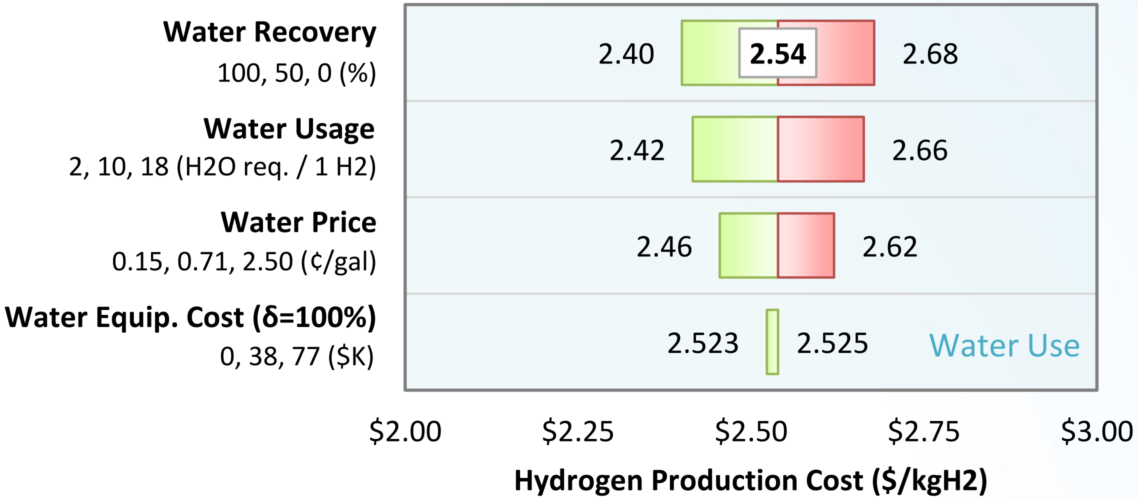
Progress Toward DOE Targets or Milestones

Levelized Cost of H2 Production ($/kg)	SA H2A Current Status	SA H2A Future Status	DOE 2025 Target	DOE Ultimate Target
Distributed Water Electrolysis Cost (1.5 Tons/Day)	4.98 (PEM)	4.48 (PEM) 4.52 (AEM Future) 4.23 (AEM Far Future)	2.30	NA
Central Water Electrolysis Cost (50 Tons/Day)	4.83 (PEM) 4.16 (SOFC)	4.48 (PEM) 3.89 (SOFC)	2.00	NA
Solar Thermochemical (STCH) (100 Tons/day)	NA	2.54	3.70	2.00
Photoelectrolchemical (Type IV)	NA	TBD	5.70	2.10
Photoelectrolchemical (Type II)	NA	TBD	4.60	2.10

Accomplishments:
TEA Comparison for STCH

- Sensitivity analysis of potential STCH material effects shows productivity and lifetime are more important than cost (material and heliostat) and Solar-to-H2 efficiency.
- Water recovery, usage, and cost also important factors

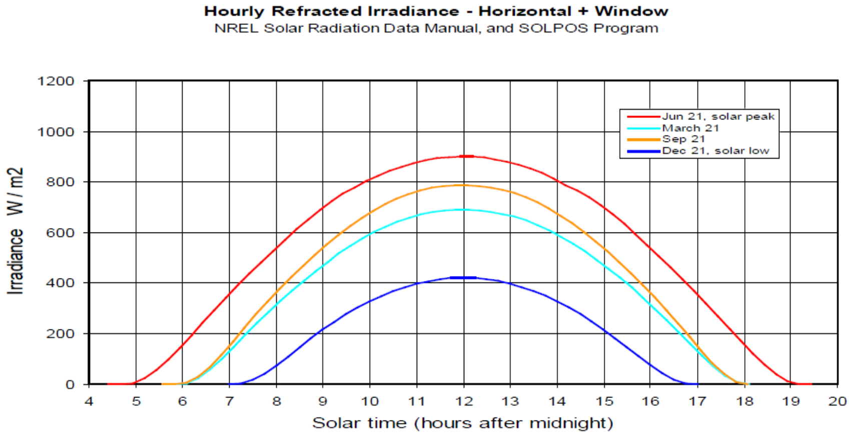


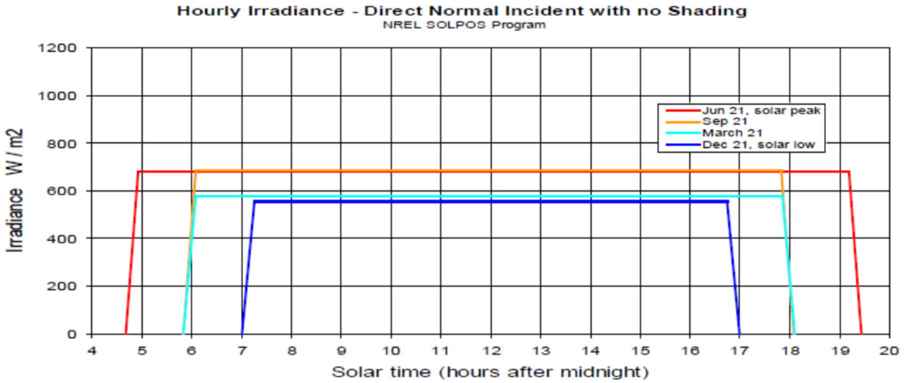


Preliminary System Model

Central system with multiple 1 tpd modules.
Optimal size of Central system to be determined (considering 10-50 tpd)

	Units	Type II	Type IV
Design		Horizontal Bed	Concentrated Panel
Target H_2 Production Rate	kg/day	1,000 (module)	1,000 (module)
Irradiance	W/m^2	240	311
Total Active Area Required	m^2	113,460	29,214
Active Area (1 bed or panel)	m^2	372	18
Number of beds or panels	m^2	305	1,623


Hourly Refracted Irradiance - Horizontal + Window
NREL Solar Radiation Data Manual, and SOLPOS Program


Hourly Irradiance - Direct Normal Incident with no Shading
NREL SOLPOS Program

Aspen Simulation Model for sizing/costing BOP components for PEC Type IV

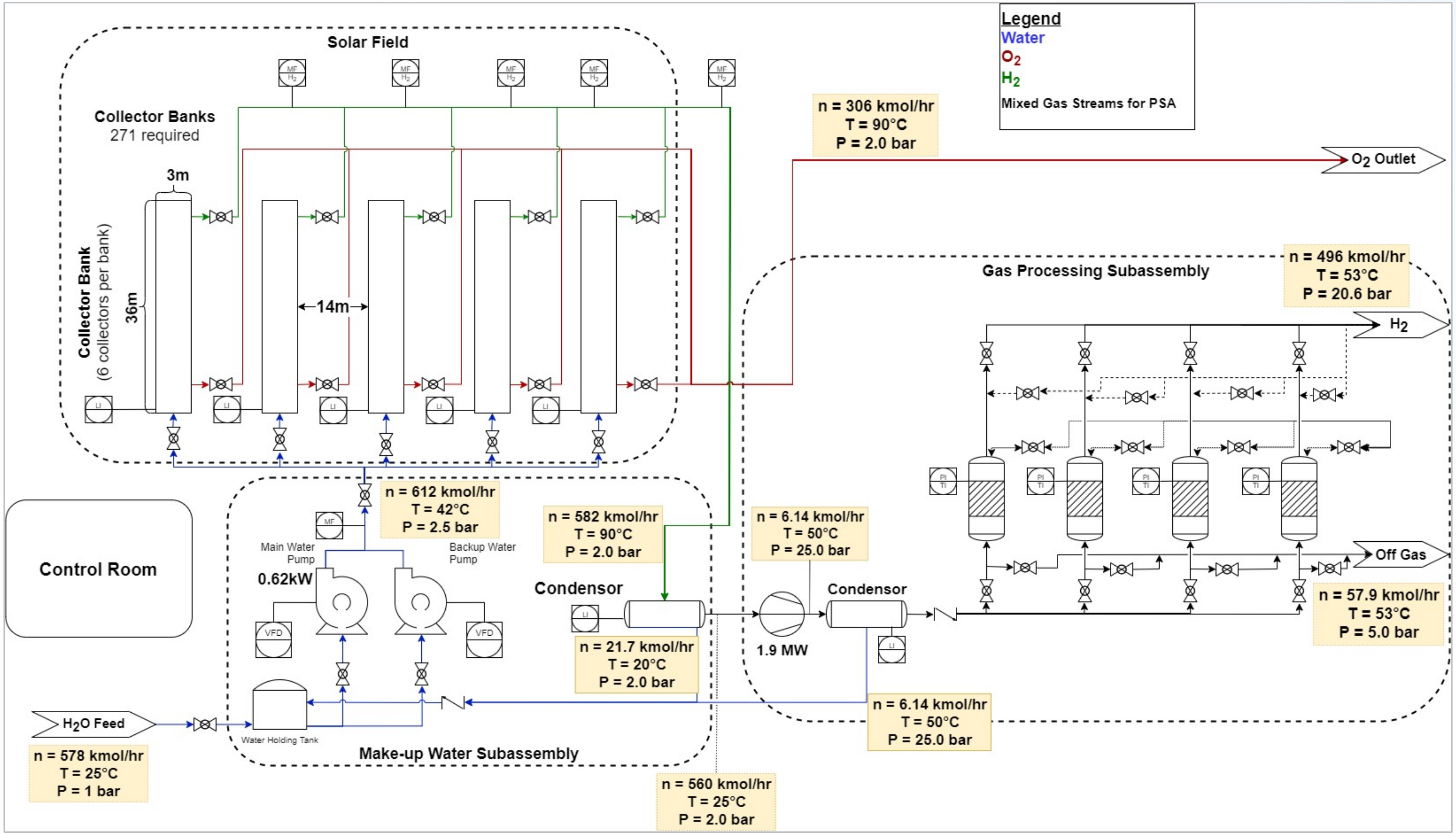


Table of PEC II System Materials

Physical Components	Material	Dimensions/ Amount	Other Guiding Parameters/Conditions for Cost Model
Top Bed	Transparent HDPE with anti-fog hydrophilic coatings	Film Thickness: 0.15mm Area for 1TPD:	- 90% of incident light passes through (at BOL) - Interference from internal reflection - Low cost/Durable
Top of Bottom Bed	Transparent HDPE with anti-fog hydrophilic coatings	Film Thickness: 0.15mm HDPE < 56' x 1000'	- Channel spacing - Low cost
Bottom of Bottom Bed	Multi-layer Opaque/Reflective HDPE	Film Thickness: 0.3mm Area for 1TPD:	- Tear resistant/durable - Low Cost
Ion Bridge	Possible materials under review: - PPE woven mat (flexible) - S-PEEK - Regenerated Cellulose (Spectra/Por® 3)	Thickness: 1mm Length: TPD Width: TPD	- Ionic conductivity - Minimal/No Porosity - Area Coverage - Flexibility/Rollability - Durability - Physical attachment to HDPE
HER Catalyst	- Ir-doped $SrTiO_3$ - Other material	Particle size: Between 40nm and 1µm	- Loading (g/L) - Lifetime (hrs or days) - Fabrication - Fabrication processes can create large PSD and could impact Mie scattering
OER Catalyst	- $BiOV_4$ - Other material	Particle size: Between 40nm and 1µm	- Loading (g/L) - Lifetime (hrs or days) - Fabrication
Electrolyte	- KOH (Included in both beds)	0.1 molar concentration in water	
Intermediary Reactant	- Iodine, bromine, iron or other element		

Table of PEC II System Concepts

Topic Area	Options/Ideas	Guiding Parameters for Cost Model
Energy Loss Mechanisms	- Absorption (IR and UV) losses in baggy - Scattering and strong absorption in NIR from broad OH stretch in water condensate - Scattering and absorption in OER catalyst	-HDPE transmits an average of 90% incident light
Bed Depth	- Too large => lowers light intensity - Too small => flat foundation a challenge - Active Vs Passive mixing	- 2009 light extinction analysis: 10cm bed depth is sufficient for 40nm particles at a concentration of 200nm equivalent thickness (depth of particle layer if settled at bottom)
Cell Construction	-Baggie -Upholstered/quilted -Tube Style (flexible/rigid)	- Materials - Sizing/Scale - Fabrication - Assembly
H_2 Loss Mechanisms	HDPE allows H_2 to crossover (For 0.15mm thick, 156cm^3●mm/m^2●atm●day) -PSA separation process	- Thickness of HDPE for minimum allowable H_2 crossover - PSA H_2 recovery efficiency: 60% to 90% (Air Liquide PSA H2 purification)

Publications and Presentations

1. Peterson, D., Vickers, J., DeSantis, D., “Hydrogen Production Cost From High Temperature Electrolysis – 2020”, DOE Hydrogen and Fuel Cells Program Record # 20006, September 2020. https://www.hydrogen.energy.gov/pdfs/20006-production-cost-high-temperature-electrolysis.pdf
2. Peterson, D., Vickers, J., DeSantis, D., “Hydrogen Production Cost From PEM Electrolysis - 2019 ”, DOE Hydrogen and Fuel Cells Program Record # 19009, February 2020. https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf
3. James, B., “Techno-Economic Analysis Breakout Session for Photoelectrochemical (PEC),” Presentation and Session Lead at the 2021 Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop, March 2021.
4. James, B., “Techno-Economic Analysis Breakout Session for Low Temperature Electrolysis (LTE),” Presentation and Session Lead at the 2021 Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop, March 2021.
5. Murphy, B., “Techno-Economic Analysis Breakout Session for High Temperature Electrolysis (HTE),” Presentation and Session Lead at the 2021 Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop, March 2021.