HydroGEN
Advanced Water Splitting Materials

Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop

Breakout Session Supplemental Slides
High Temperature Electrolysis (HTE)

March 2 – 3, 2021

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HTE Breakout Sessions

Session ID	Topic	Lead
HTE-2	HTE Roadmap	Jamie Holladay (PNNL)
HTE-3	HTE Techno-Economic Analysis	Brian Murphy (Strategic Analysis)
HTE-4	Standard Cell and Test Methods	Dong Ding (INL)
HTE-6	Stack Testing Protocols	Neal Sullivan (CO School of Mines)
HTE-7	Performance/Durability Test Protocols	Xingbo Liu (WVU)

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Techno-Economic Analysis Breakout Session
High Temperature Electrolysis (HTE)

Session ID: HTE-3
Session Chair: Brian Murphy
Affiliation: Strategic Analysis Inc.
Date: March 2, 2021

Overview of Techno-Economic Analysis Methodology

- The objective of techno-economic analysis (TEA) is to **evaluate** and **compare** competing technologies and **chart progress** in performance and cost
- **TEA Method Steps** *(iterative)*
  - Define system: develop flow schematic and bill of materials
  - Perform system mass & heat balance modeling to identify critical design parameters
  - Enumerate H_2 production plant capital cost
  - Investigate and input technical and financial values into discounted cash flow analysis model H2A to evaluate the levelized cost of hydrogen ($/kg H_2)
- **Results and Post-Analysis**
  - Perform sensitivity analyses to identify components with greatest impact on cost
  - Obtain external review and feedback
  - Use feedback to update models
- **Case Study**: SOEC (2020) – DOE Record 20006
  - Targets: $2/kg H_2 w/ $100/kW stack
  - Using H2A v3.2018 w/ default financial parameters

DOE Record 20006: SOE Central Production Models

Current

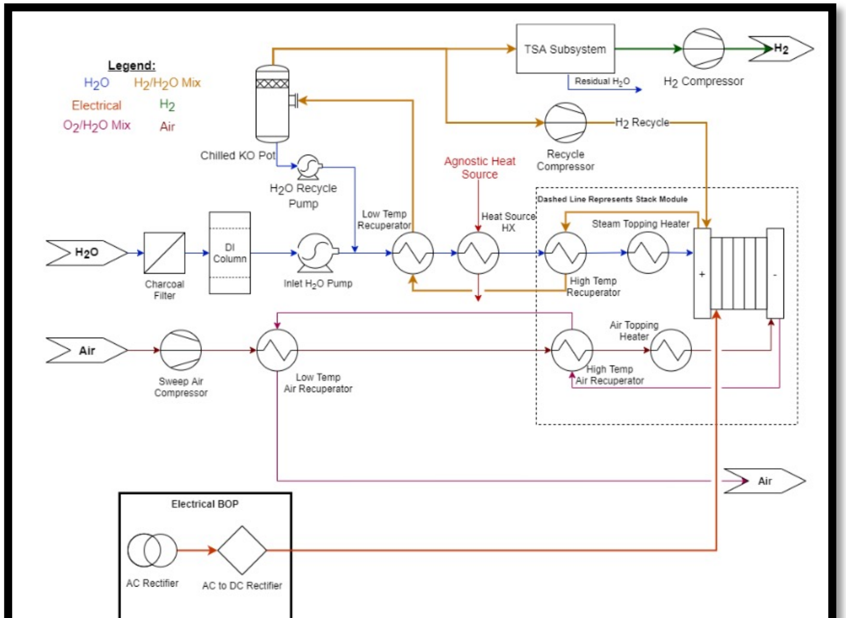


Figure 1 - Projected Current HTE Baseline Design.

Future

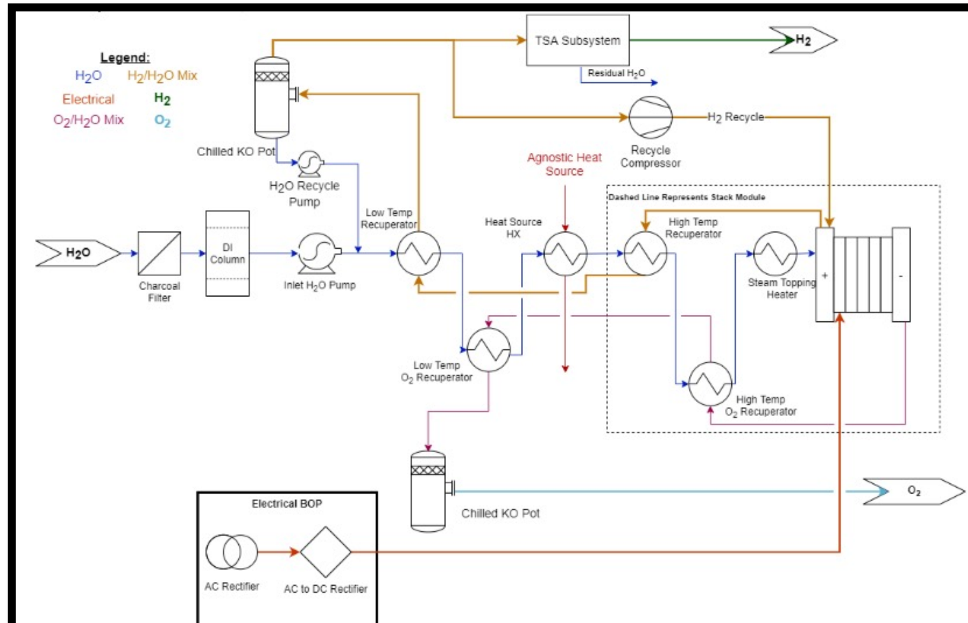


Figure 2 - Projected Future HTE Baseline Design.

Thermo-neutral stack operation	
TSA system for product purification	
Electrical topping heaters to maintain stack temperature	
Agnostic external heat source, used only to heat water feed	
73 psi (5 bar) stack pressure, outlet compressor to **300 psi**	**320 psi (21 bar)** stack pressure, no outlet compressor
Air sweep gas on oxygen electrode	No sweep gas

SO Electrolyzer TEA Model Assumptions – Technical

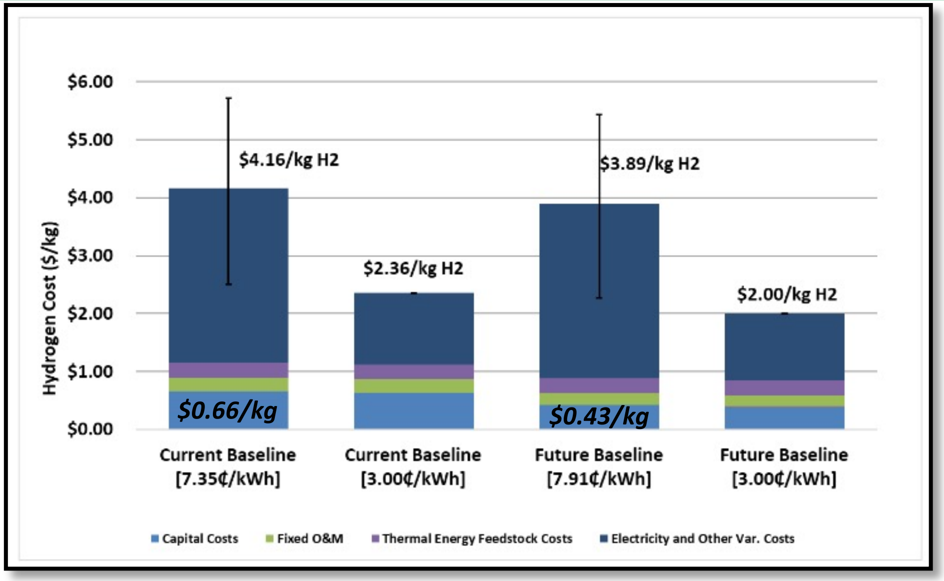
Parameter	***Proj.* Current Central 50,000 kg/day *(83 MW)***	***Proj.* Future Central 50,000 kg/day *(80 MW)***
Technology Year	2019	2035
Start-up Year	2015	2040
Stack Current Density (A/cm²)	**1.0**	**1.2**
Cell Voltage (V)	1.285	1.285
Stack Electrical Usage (kWh/kg) [% LHV] (% HHV)	**34.0** [98%] (116%)	**34.0** [98%] (116%)
BoP Electrical Usage (kWh/kg)	5.8	3.1
Total Electrical Usage (kWh/kg) [% LHV] (% HHV)	**39.8** [83.7%] (98.6%)	**37.1** [89.8%] (105%)
Outlet Pressure from Electrolyzer (psi)	74	320
Stack Replacement Interval (years)	**4** ***11 mV/kh***	**7** ***4 mV/kh***
Stack Replacement Cost Percentage (% of stack capital cost/year)	22%	11%
Plant Life (years)	20	20
Capacity Factor (%)	90%	90%

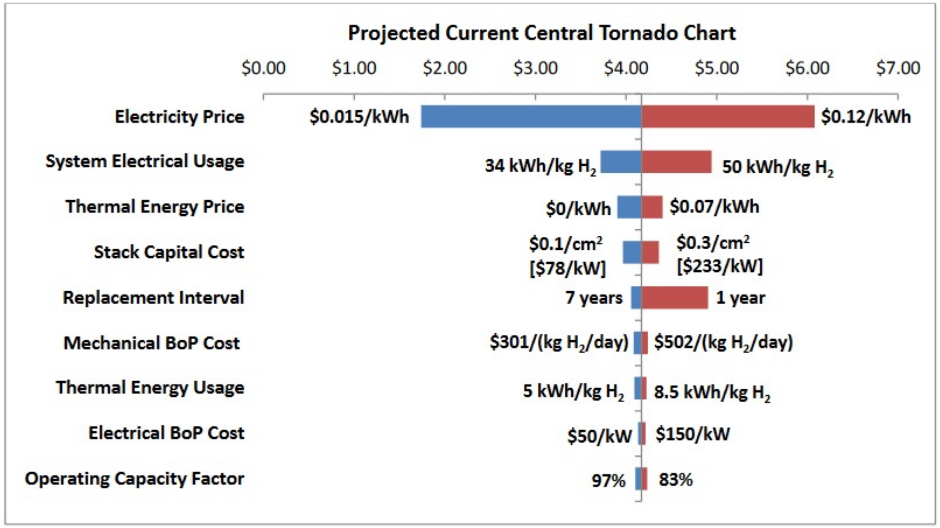
- Proj. Current/Future = hypothetical @ 700 MW/year volume
- Assumed T is ≥800 °C
- Should future current density be 1.5 A/cm^2?

SO Electrolyzer TEA Model Assumptions – Costs

Parameter	Current Central 50,000 kg/day *(83 MW)*	Future Central 50,000 kg/day *(80 MW)*
Technology Year	2019	2035
Start-up Year	2015	2040
Total Uninstalled Capital (2016$/kW)	$522	$357
Stack Capital Cost (2016$/kW)	$155	$100
BoP CapEx (2016$/kW)	$368	$257
Mechanical BoP Cost (2016$/kW)	$283	$192
Electrical BoP Cost (2016$/kW)	$85	$65
Effective Electricity Price over Life of Plant (2016¢/kWh)	**7.35**	7.91
Effective Thermal Energy Price over Life of Plant (2016¢/kWh)	3.63	3.63
Installation Cost (% of uninstalled capital cost)	52%	63%
Indirect Costs (% of installed capital cost)	42%	42%
Total Uninstalled Capital (2016$/kW)	**$522**	**$357**
Total Installed Capital Cost (2016$/kW) [2016$ total]	**$783** [$65.0M]	**$582** [$46.6M]
Total Capital Investment (2016$/kW) [2016$ total, millions]	**$1,112** [$93.3 M]	**$826** [$66M]

SO Electrolyzer Results and Sensitivity Study





- "Future" case can hit $2.00/kg H_2 target provided cheap ($30/MWh) electricity and volume electrolyzer production
- Electricity price largest contributor to H_2 price, but least R&D control
- Stack cost and durability inputs are *projected current*, not actual
- DOE Record Case doesn't consider *modular* construction; likely path forward

Major Cost Contributors at Present

Stack	BOP
High-temperature thermal treatments	Compressors
Precision cutting *(green or fired)*	Hydrogen product treatment *(compression / TSA or PSA)*
Interconnect fabrication	High-temperature equipment *(heat exchangers)*
Number of parts/processing steps	Electrical BOP

Contour Plots from DOE Record

System Electricity Usage

Uninstalled Capital Cost

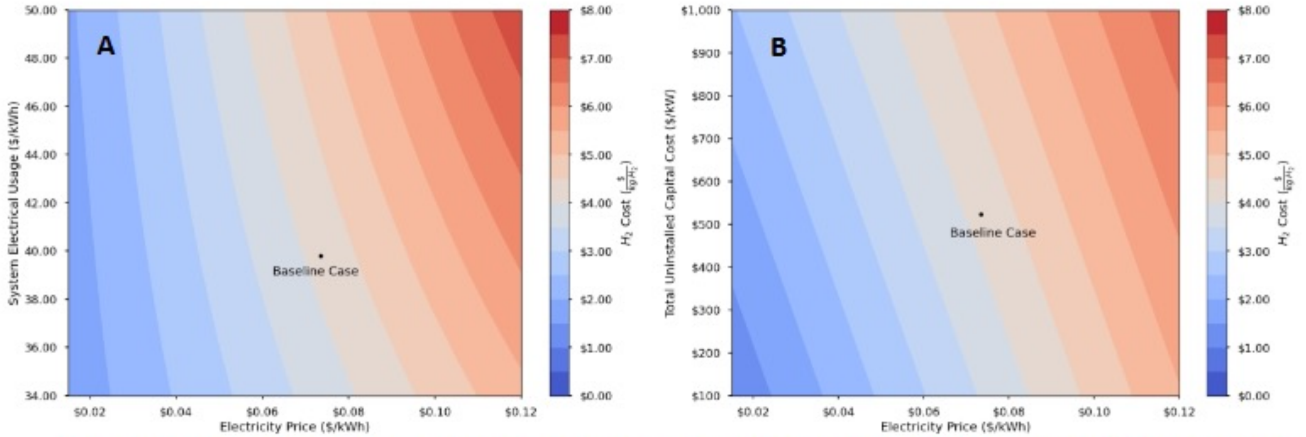


Figure 6 – Contour plots depicting results of the two-parameter sensitivity studies for the Projected Current case. The dependency of H_2 cost based on electricity price and System Electrical Usage is shown in (A). The dependency of H_2 cost based on electricity price and uninstalled capital cost ($/kW) is shown in (B).

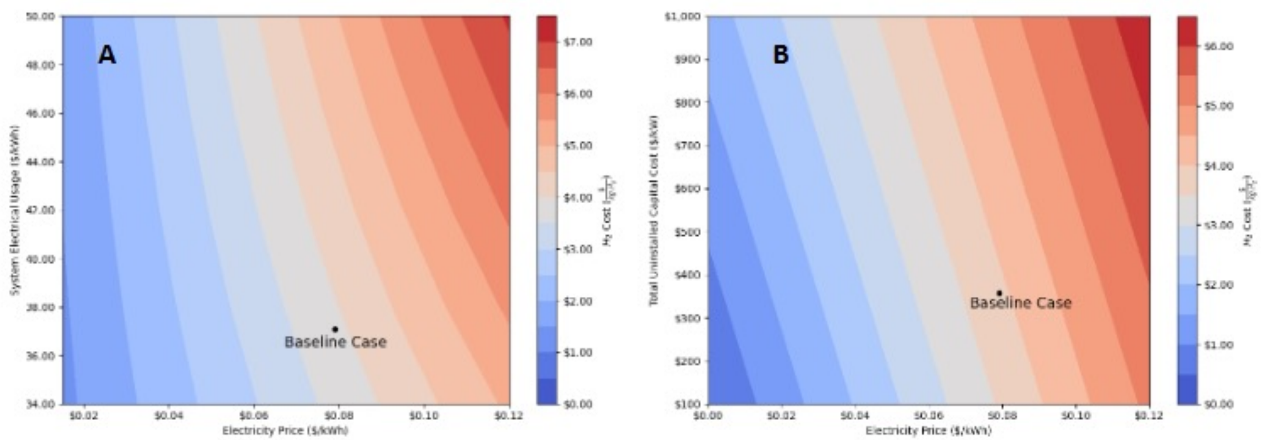


Figure 7 – Contour plots depicting results of the two-parameter sensitivity studies for the Projected Future case. The dependency of H_2 cost based on electricity price and System Electrical Usage is shown in (A). The dependency of H_2 cost based on electricity price and uninstalled capital cost ($/kW) is shown in (B).

Discussion Topics

1. Feedback on TEA & discussion of future TEA's
   - Parameter validity:
     - Technical: current densities, stack pressure, electricity usage, sweep gas
     - Direct and Indirect costs *(different from H2A default?)*
     - "Heat source agnostic" design
   - Appropriate "Future Case" TEA parameters given state-of-the-art and projected RD&D directions
   - What do you want to get out of TEA studies
     - Other sensitivity studies? Alternative case studies?
     - What factors or parameters have the most uncertainty?

2. Intersection of stack design and manufacturing
   - Barriers to cost targets; Methods for reducing major stack cost contributors
     - Combination of heat treatment steps
     - Elimination of parts *(barrier layer? Contact layers?)*
   - Stack design to reduce BOP costs: lower T, integrative designs, etc.
   - Other potential design / manufacturing topics:
     - Effect of cell construction (cathode/electrolyte/metal-supported, PCEC) on manufacturing costs? Can we make any general statements?
     - Technical pros and cons of comparable manufacturing methods
       - Tape casting / screen printing / dip-coating
       - Stamping vs. cutting
     - Potential supply chain issues with *any* common stack materials as production scales up? *(Yttrium, scandium, nickel, lanthanides)*

Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop

Stack Testing Protocols
High-Temperature Electrolysis

Session ID: HTE-5
Session Chair: Neal Sullivan
Affiliation: Colorado School of Mines
Date: March 3, 2021

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Session Goals: Develop stack-characterization protocols within IP concerns of developers

- Define metrics for which HTE stack developers will hold few IP concerns
  - Bad examples would be metrics normalized to active area
    - Area-specific resistance (Ω cm^2), current density (A cm^{-2})
    - H_2 production per unit cell active (moles H_2 / cm^2 s)
    - Frequently the metrics of most interest to the community
      - Suffer less information to ease developers' concerns
  - Consider broader stack-performance characteristics
    - Rated by total H_2 production rate (moles H_2 / sec)
    - Voltage and current at start of life
    - Cold-state leakage rate
    - Efficiency
    - Degradation rate
    - Specific H_2 production rate (moles H_2 / s / kg of stack)
    - Volumetric H_2 production rate (moles H_2 / s / L of stack)

HydroGEN
Advanced Water Splitting Materials

Advanced Water-Splitting Technology Pathways Benchmarking & Protocols Workshop

Performance/Durability Test Protocols
Technology: HTE

Session ID: HTE-7
Session Chair: Xingbo Liu
Affiliation: West Virginia University
Date: March 3, 2021

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Session Goals

- Performance
  - O-SOEC vs. H-SOEC
  - Temperature, pressure, steam concentration, I-V, electrochemical (EIS, what else?)
  - H_2 production rate (under what condition), steam utilization
  - Efficiencies
  - Protocols on other components (coatings, seals, contact layers etc.)

- Durability
  - Accelerated tests
  - Temperature, steam, voltage, current,
  - Cycling (thermal, V-I, etc.)
  - …