The #H2IQ Hour

Today's Topic:

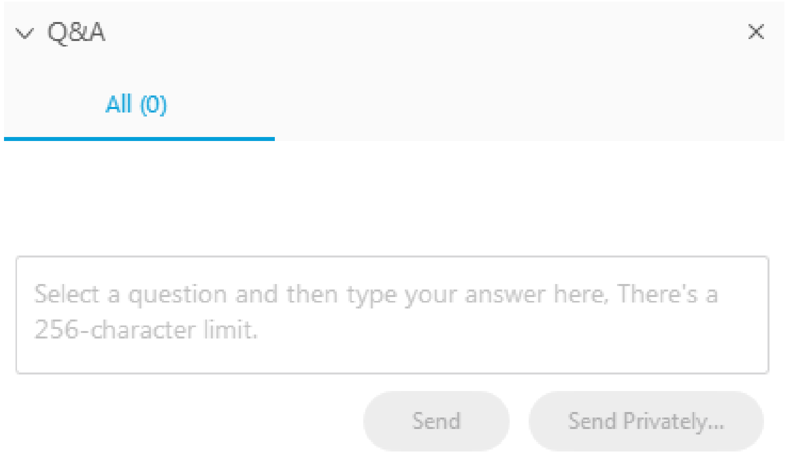
Analysis of Advanced H2 Production & Delivery Pathways

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency and Renewable Energy (EERE)

The #H2IQ Hour

During Q&A session:

Please type your questions into the **Q&A Box**



STRATEGIC ANALYSIS INC

Analysis of Advanced H_2 Production & Delivery Pathways

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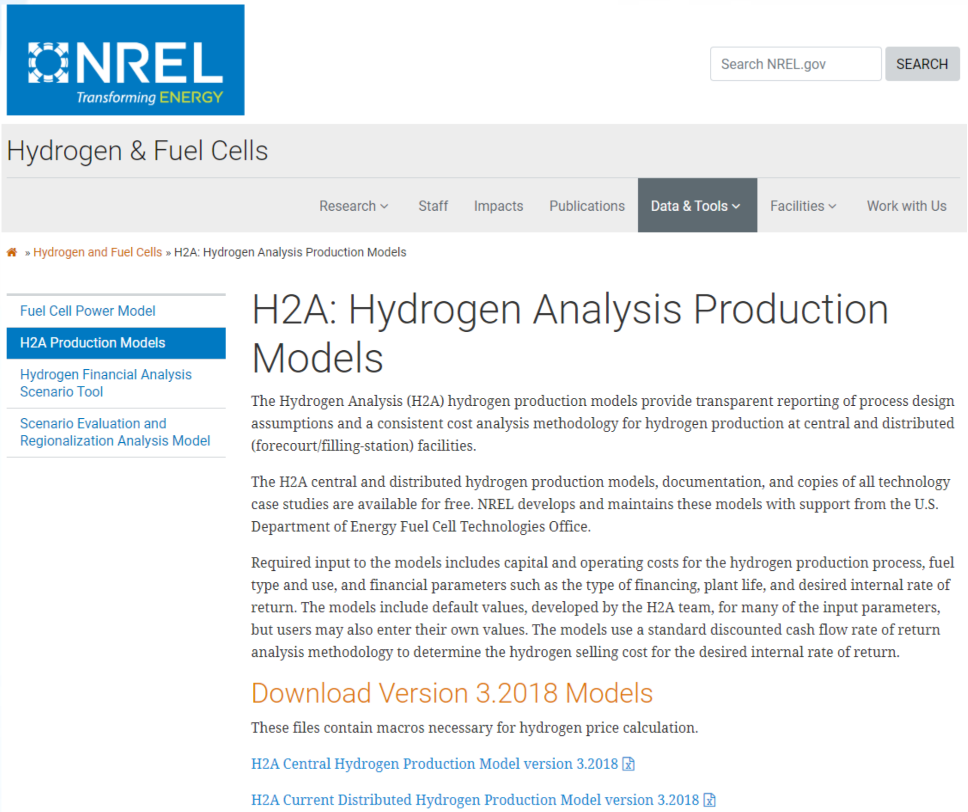
25 March 2020

H2A v3.2018 Resource



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» Hydrogen and Fuel Cells » H2A: Hydrogen Analysis Production Models

- Fuel Cell Power Model
- H2A Production Models
- Hydrogen Financial Analysis Scenario Tool
- Scenario Evaluation and Regionalization Analysis Model

H2A: Hydrogen Analysis Production Models

The Hydrogen Analysis (H2A) hydrogen production models provide transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and distributed (forecourt/filling-station) facilities.

The H2A central and distributed hydrogen production models, documentation, and copies of all technology case studies are available for free. NREL develops and maintains these models with support from the U.S. Department of Energy Fuel Cell Technologies Office.

Required input to the models includes capital and operating costs for the hydrogen production process, fuel type and use, and financial parameters such as the type of financing, plant life, and desired internal rate of return. The models include default values, developed by the H2A team, for many of the input parameters, but users may also enter their own values. The models use a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost for the desired internal rate of return.

Download Version 3.2018 Models

These files contain macros necessary for hydrogen price calculation.

H2A Central Hydrogen Production Model version 3.2018

H2A Current Distributed Hydrogen Production Model version 3.2018

- H2A v3.2018 is available at NREL website
  - https://www.nrel.gov/hydrogen/h2a-production-models.html
- Previously completed project records are also available from the same website
  - https://www.nrel.gov/hydrogen/h2a-production-case-studies.html
- User guide is also available
  - https://www.nrel.gov/hydrogen/assets/pdfs/h2a-production-model-version-3-2018-user-guide-draft.pdf

H2A Model Overview

- H2A is:
  - Excel-based discounted cash flow (DCF) model to project H_2 profited-cost ($/kg$H_2$)
  - Code written and maintained by NREL
  - Two technology/deployment timeframes: Current & Future
  - Two default production sizes: Distributed (1.5 tons per day) and Central (50 tons per day)

- Inputs:
  - Feedstock requirements
  - Energy Usage requirements
  - Site Capital Cost
  - Equipment Replacement schedule
  - Other cost inputs
    - Default relationships for easy use and comparison between cases

- Outputs:
  - Levelized cost of H_2
  - Cost contributions of capital cost, feedstocks, utilities, etc.
  - Sensitivity analysis

Water Splitting by Electrolysis

Project Objective

Conduct technoeconomic analyses of various methods of water splitting:

- 1,500 kg H_2/day distributed production sites
- 50,000 kg H_2/day central production sites
- Two technology levels analyzed
  - Current: current technology (2019) at high-manufacturing rate (700MW/yr)
  - Future: future technology (2035) at high-manufacturing rate (700MW/yr)

Electrolyzer Technology	Production Sizes Reported	Technology Years Reported
Proton Exchange Membrane (PEM)	Distributed & Central	Current & Future
Solid Oxide Electrolysis (SOE)	Central	Current & Future
Alkaline Exchange Membrane (AEM)	Distributed	Future

In Progress

Approach

- Collect data via Industry Questionnaire
- Assess data for consensus and trends
- Validate with system modeling and other tools
- Run H2A model with system data to obtain projected H_2 cost ($/kg)

Approach to data collection

- **Surveyed companies and research groups for key technical and cost parameters**
  - Data response was limited for some parameters which often left insufficient data for statistical analysis
  - When possible, compared to previously conducted TEA/H2A work
  - Various responses received for each

Covered in today's presentation

Electrolyzer Technology	Number of Respondents
PEM	5
SOE	4
AEM	1

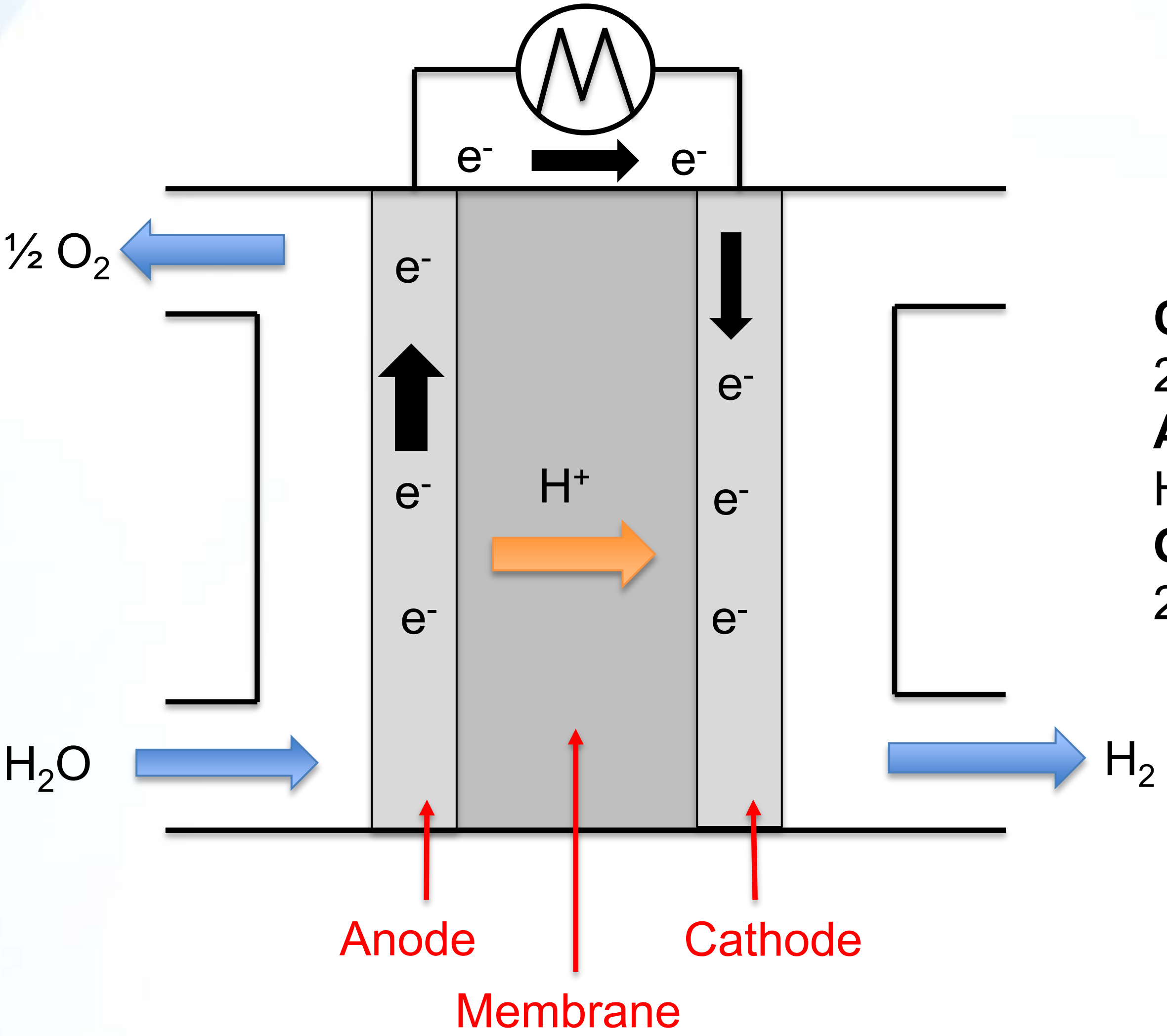
- **Developed technical and cost parameters from multiple sources**
  - Questionnaire responses
  - Literature review
  - Price quotes
  - Techno-economic system analysis based on PFD (incl. DFMA)
  - Learning Curves (for comparison to reported parameter values)

6 Key Cost Parameters For Electrolysis

- **Current Density** (A/cm^2)
- **Cell Voltage** (V/cell)
- **Electrical Usage** (kWh/kg H_2)
  - Electrical requirement of the stack and plant to produce H_2
- **Stack Cost** ($\$/cm^2$)
  - Normally reported in $\$/ kW_{system\ input}$
  - To decouple cost from performance, stack cost is based on active area in this analysis
- **Mechanical BoP Cost** ($\$/(kg\ H_2/day)$)
  - Capital cost of pumps, dryers, heat exchangers, etc.
  - Scaled with design flow rate of hydrogen
- **Electrical BoP Cost** ($\$/kW_{system\ input}$)
  - Capital cost of Rectifier, Transformers

BoP = Balance of Plant

Proton Exchange Membrane Electrolyzer



Cathode Reaction:

$2H^+ + 2e^- \rightarrow H_2$

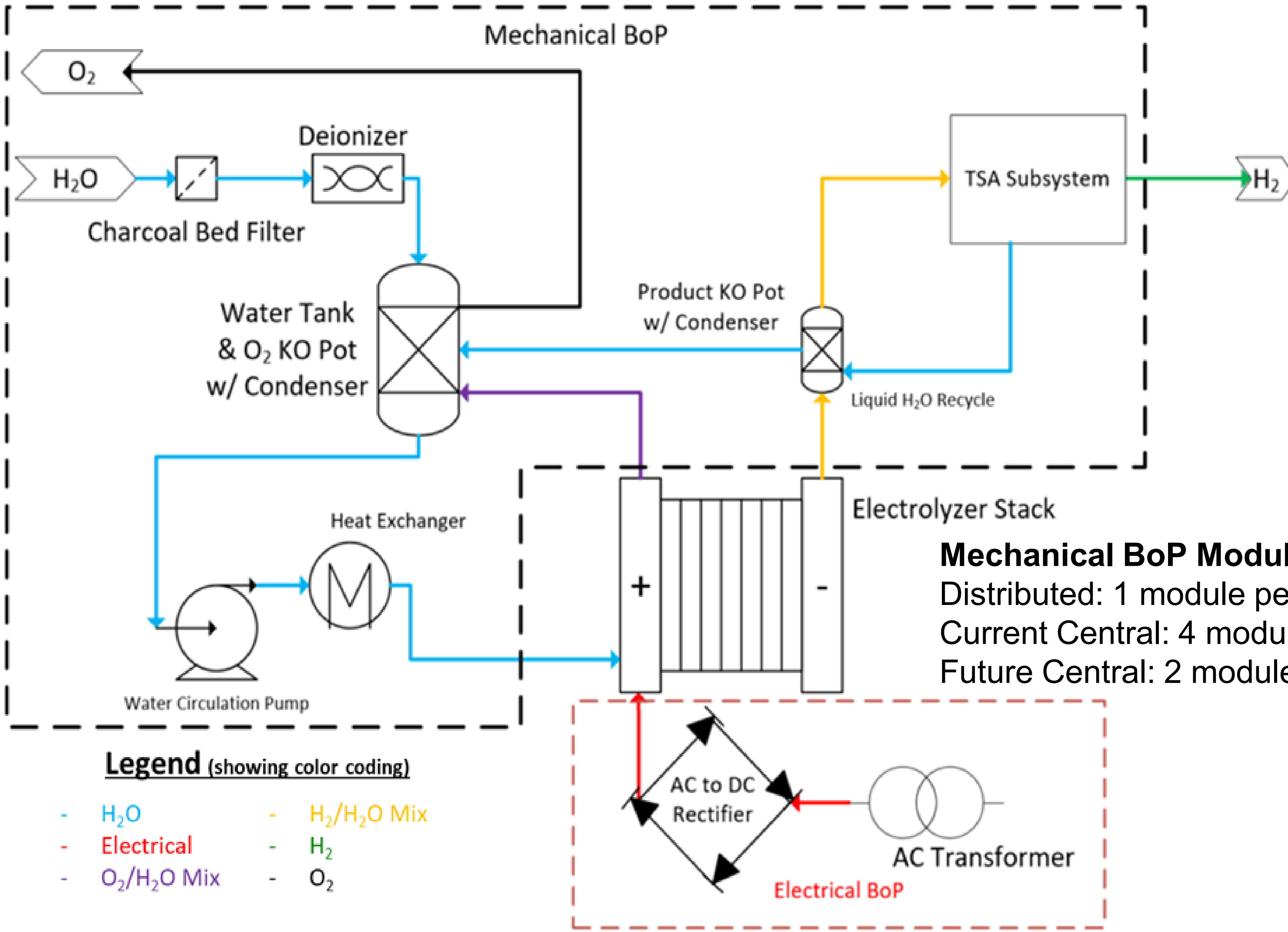
Anode Reaction:

$H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$

Overall Reaction:

$2H_2O \rightarrow H_2 + \frac{1}{2} O_2$

PEM Process Flow Diagram

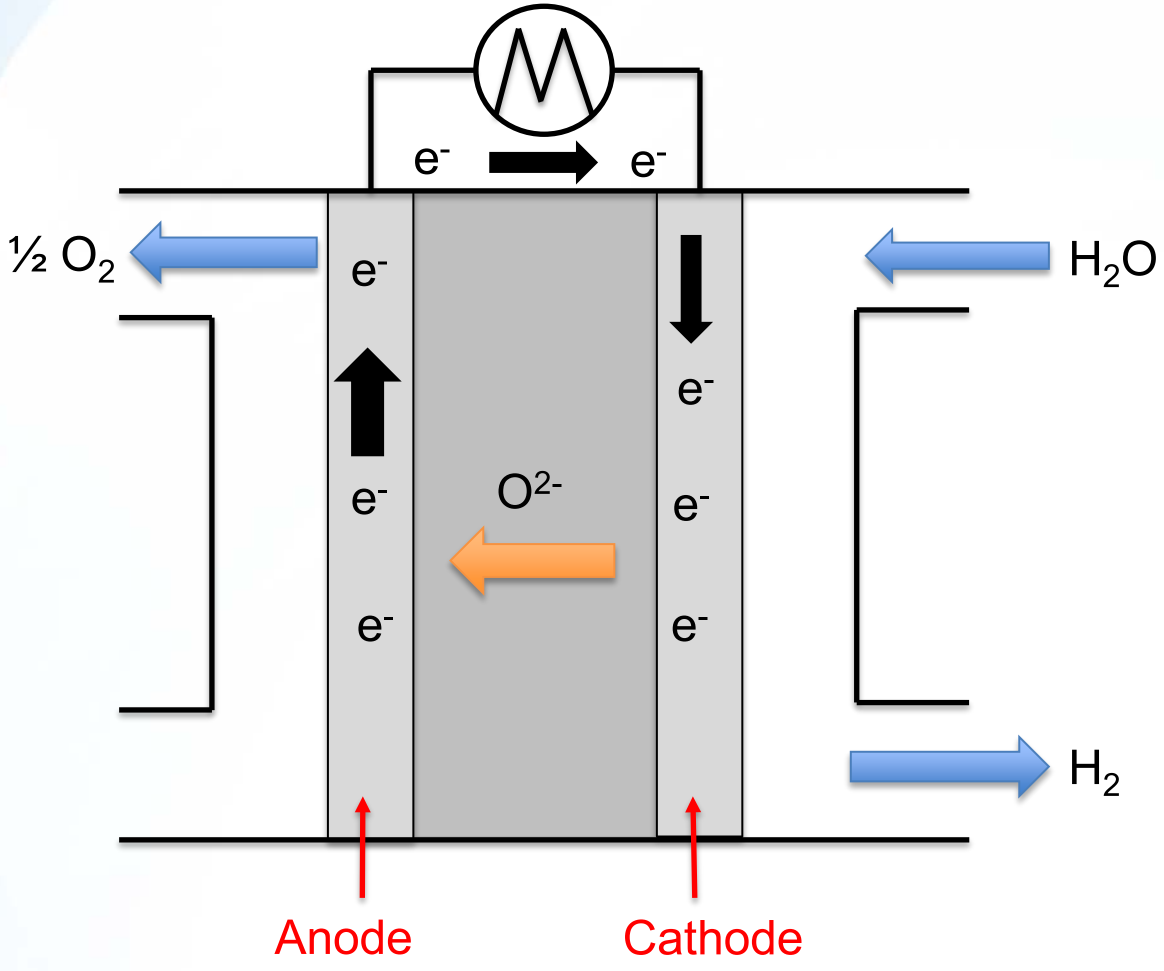


Mechanical BoP Module
Distributed: 1 module per site
Current Central: 4 modules per site
Future Central: 2 modules per site

- Low Temperature 70 – 80°C
- Recycles most water
- TSA Subsystem used to dry H_2

TSA: Temperature Swing Adsorption

Solid Oxide Electrolysis



Cathode Reaction:

$H_2O + 2e^- \rightarrow H_2 + O^{2-}$

Anode Reaction:

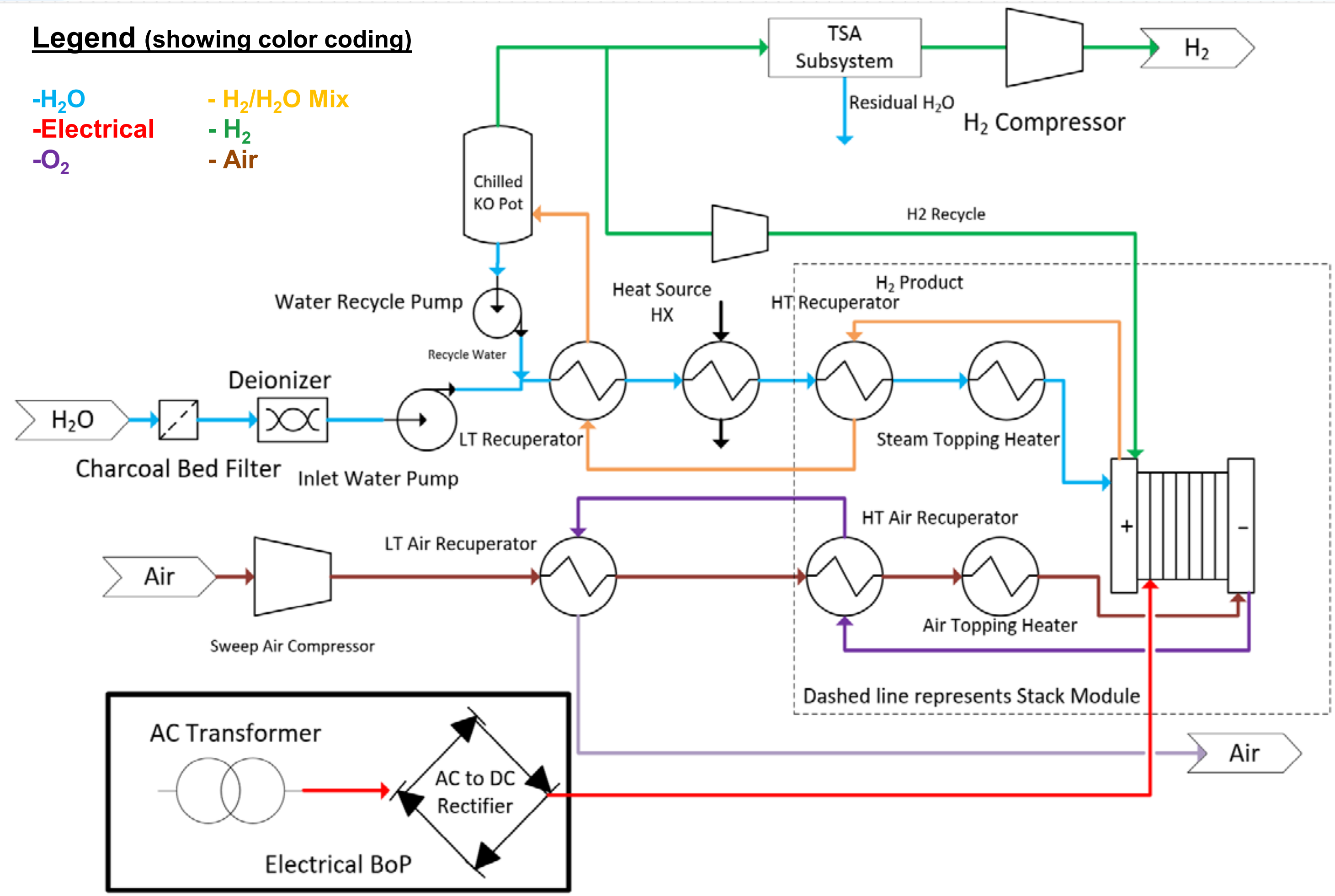
$O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$

Overall Reaction:

$H_2O \rightarrow H_2 + \frac{1}{2} O_2$

Process Flow Diagram

Solid Oxide Electrolysis, Current Case

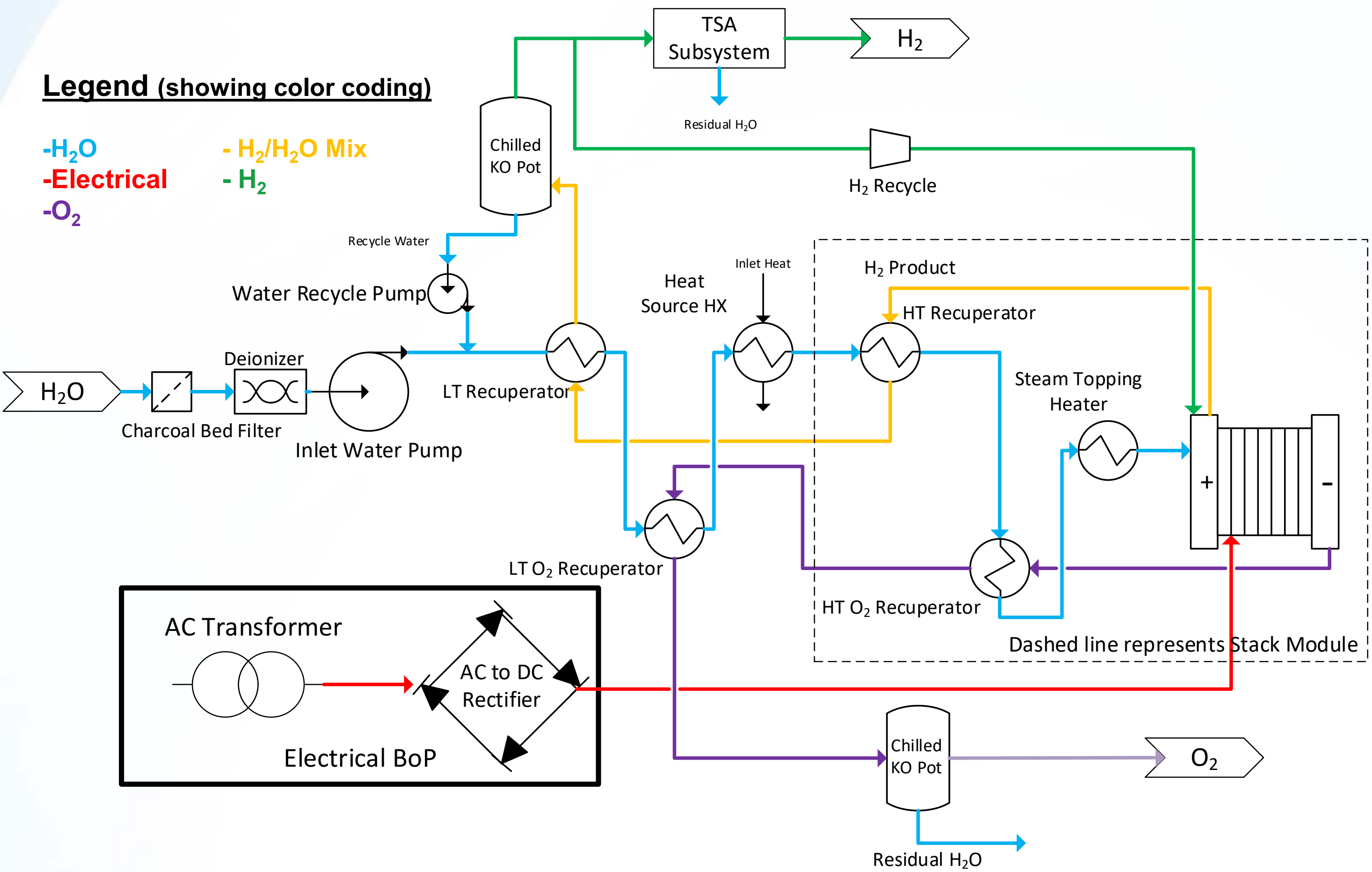


- High Temperature 700 – 800°C
- Utilizes multiple heat recovery systems
- TSA Subsystem used to dry H_2
- All high temperature components in a pressure vessel
- Sweep air on O_2 side
- No O_2 recovery

TSA: Temperature Swing Adsorption

Process Flow Diagram

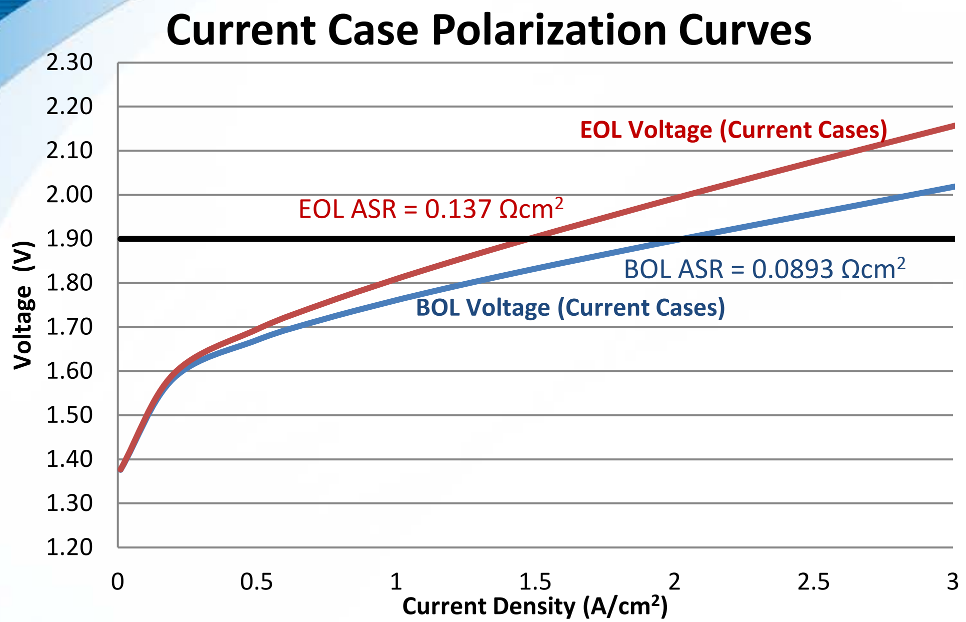
Solid Oxide Electrolysis, Future Case

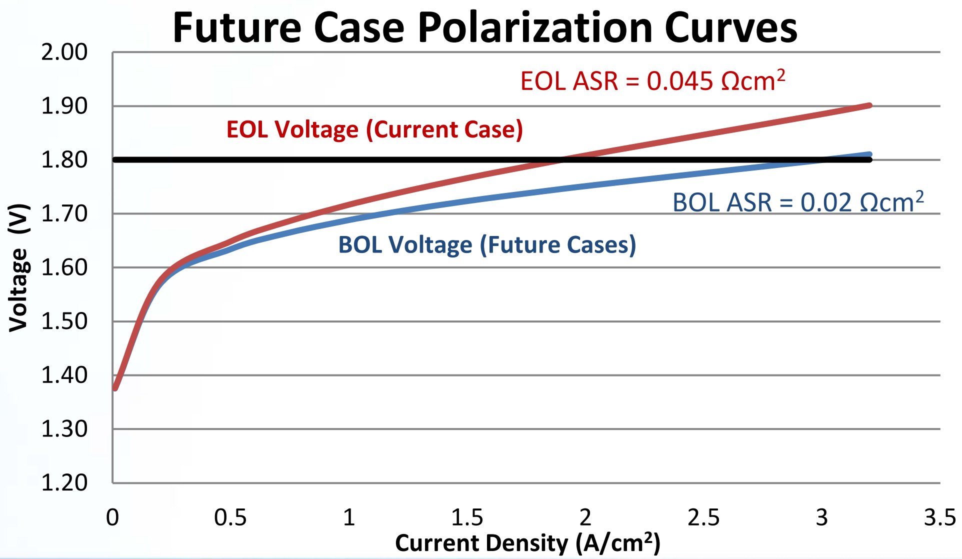


- High Temperature 700 - 800°C
- Utilizes multiple heat recovery systems
- TSA Subsystem used to dry H_2
- All high temperature components in a pressure vessel
- **No air sweep**
- **O_2 recovery for byproduct sales**
- **Water pressurized to ~375 psia (No compressor needed)**

TSA: Temperature Swing Adsorption

PEM Polarization Curves





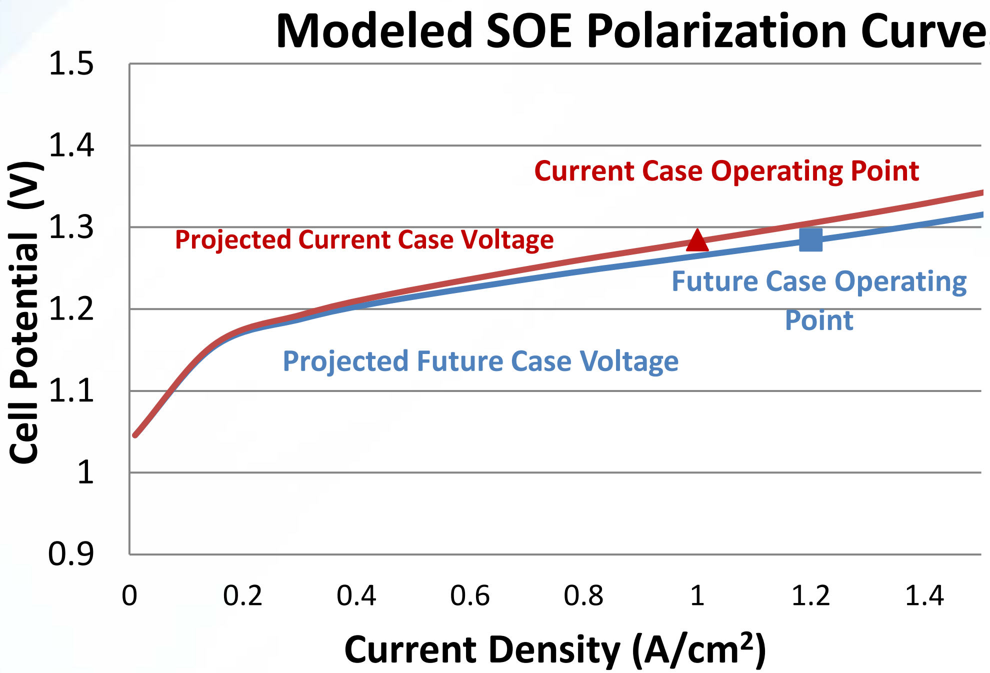
- **A mathematical model developed by Hao et al and an Area Specific Resistance (ASR) from literature, were used to create polarization curves for each case**
  - The polarization curves were adjusted to go through the operating points
  - $E\ (V) = E_o + b \ln\left(\frac{i + i_{loss}}{i_{loss}}\right) + R * i$
  - Mass transfer losses not considered
- **Incorporated degradation rates into cost analysis**
  - End of Life (EOL) polarization curves shown on graphs
  - Constant voltage operation assumed in analysis
  - Stacks were oversized to get an averaged targeted production rate of 1.5 tpd (Distributed) or 50 tpd (Central)

	Current	Future
Degradation Rate (mV/khrs)	1.5	1
Stack Lifetime (years)	7	10

OP = Operation Point

tpd= metric tonnes per day

Solid Oxide Electrolysis Polarization Curve



	Current	Future
Degradation Rate (mV/khrs)	11	4
Stack Lifetime (years)	4	7

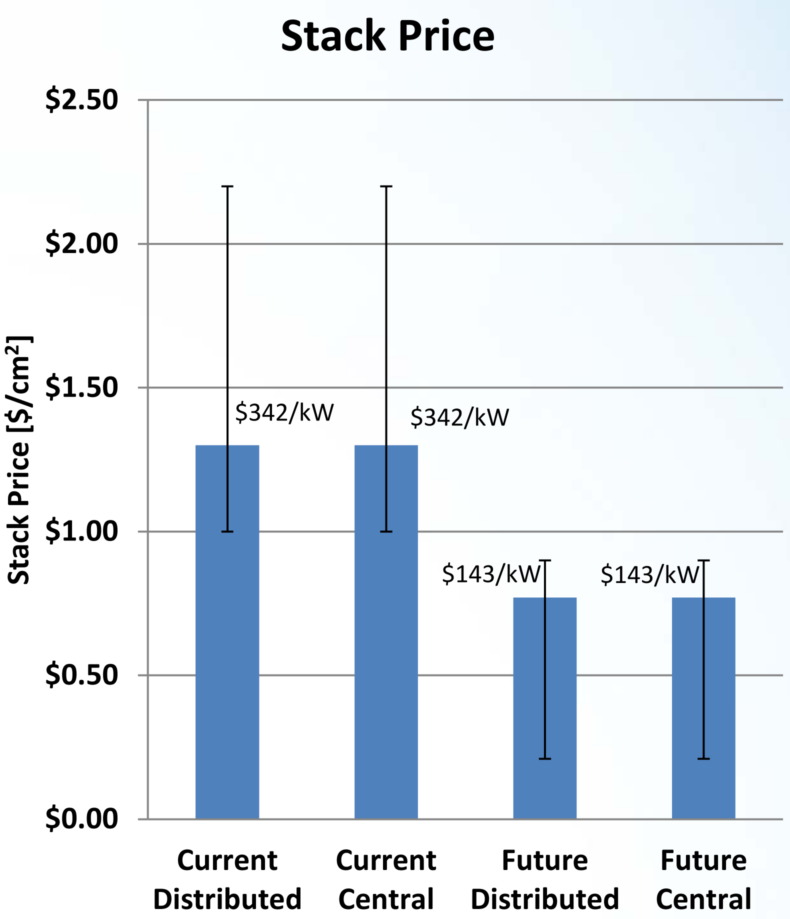
- **Using the same mathematical model developed by Hao et al and an Area Specific Resistance (ASR) from literature, polarization curves were created for each case**
  - The polarization curves were adjusted to go through the operating points

$$E\ (V) = E_o + b \ln\left(\frac{i + i_{loss}}{i_{loss}}\right) + R * i$$

  - Mass transfer losses not considered
- **A loss in production due to degradation was not modeled**
  - Assumed that the operating temperature is increased as degradation increases, thus maintaining H_2 production

Basis for PEM Stack Price Projection

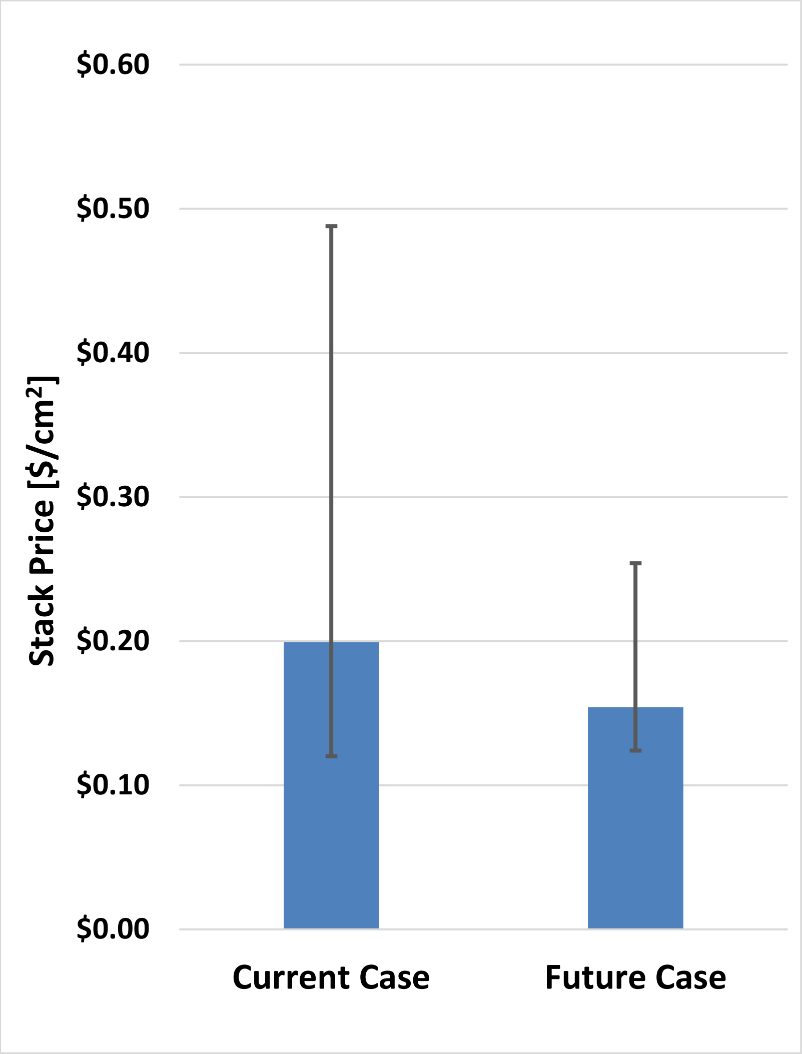
- **Limited data on stack cost provided in questionnaire**
  - Data available largely for respondents existing low-manufacturing rate systems and projected future systems, at high manufacturing rates
- **Current case stack price ($1.30/cm^2) is based on adjustment of the 2013 H2A stack price**
  - The increase in price is proportional to the price increases reported by the respondents between old and new questionnaire values
  - The stack price is generally consistent with values reported by respondents in the previous questionnaire
  - The stack upper price bound is representative of the data for existing units produced at low manufacturing rates
  - The lower stack cost bound is found by learning-curve scaling (0.9 factor for every doubling) between low (existing) and high (current) manufacturing rates
- **Future case stack price ($0.77/cm^2) is based on the new questionnaire data**
  - Fairly good agreement of future price in questionnaire data
  - Adjusting an existing DFMA model for auto PEM stack price suggests that the price of the stack may be substantially lower (~$0.21/cm^2) . This is taken as the stack price lower bound.
  - Upper bound ($0.90/cm^2) is informed by questionnaire data.
- **Price includes manufacturer's markup**



DFMA® = Design for Manufacture and Assembly

Basis for SOE Stack Price Projection

- **Limited data on stack price provided by questionnaires**
  - Data available largely for respondents existing low-manufacturing rate systems and projected future systems, at high manufacturing rates
- **Current case stack price ($0.20/cm²) is based on DFMA analysis and questionnaire results**
  - The lower stack price bound is based on the lowest value reported
  - The stack upper price bound is a midpoint of the data for units produced at low manufacturing rates
- **Future case stack price ($0.15/cm²) is based on the new questionnaire data**
  - The lower bound for SOE cells is taken from the lowest stack price obtained from the questionnaire date ($0.12/cm²) .
  - Upper bound ($0.25/cm²) is informed by questionnaire data.
- **Price includes manufacturer's markup**



DFMA® = Design for Manufacture and Assembly

Basis for PEM Mechanical BoP Cost

- **The Current Distributed mechanical BoP is modeled as a single Mech. BoP module**
  - Mech. BoP provides all the supplemental equipment to run the electrolyzer
  - BoP components sized for 1 module (i.e. 1 module of 1.5tpd)
  - Costs based on quotes for each subsystem (see table)
- **Future Distributed sites would also use 1 module**
- **Central models allow a larger BoP to handle the production rate**
  - Current cases to have 4 BoP modules and are scaled by H_2 production rate (i.e. 4 modules of 12.5tpd)
  - Future cases are assumed to have 2 BoP modules and are scaled by both H_2 production (i.e. 2 modules of 25tpd)
- **Costs are scaled for n^{th} plant**
  - Any piece of equipment with n>5 received a 10% discount (starting with n=5) for every 10x units.
  - $P_n = P_5\left[r^{\left(\frac{\ln(n)/\ln(n_O)}{\ln(10)}\right)}\right]$
  - $P_n = P_5\left[0.9^{\left(\frac{\ln(n)/\ln(5)}{\ln(10)}\right)}\right]$

Unit	Cost ($)	Cost ($/(kg H_2/day))
Main DI Pump w/motor	$56,099	$33.10
Cleanup Pump w/motor	$4,863	$2.87
Air Cooled Heat Exchanger	$39,850	$23.51
DI Water Tank	$25,219	$14.88
Hydrogen/Water KO Tank	$37,079	$21.88
H2/H2O Jacket Chiller	$10,612	$6.26
Absorbent Bed Dryer	$42,697	$25.19
Dryer H2 Compressor	$81,898	$48.32
Dryer KO Pot	$36,829	$21.73
Dryer KO Pot Jacket Chiller	$10,612	$6.26
Flow Filter	$10,560	$6.23
Deionizing Bed	$10,236	$6.04
Actuated Flow Valve	$5,296	$3.12
Other valves	$3,513	$2.07
Gas Filters	$1,309	$0.77
PRV	$755	$0.45
Indicator/Controllers	$8,609	$5.08
Piping and Tubing (ft)	$11,544	$6.81
Skid Structure	$8,123	$4.79
SubTotal/module	$405,704	$239
Total w/Markup	$377,101	$222
Total w/ Markup & Contingency	**$490,232**	**$289**

Current Distributed Case Mechanical BoP Considered 1 module for a production site

BoP = Balance of Plant

SOE Mechanical BoP

- SA developed a component list from the PFD
  - Costs shown are the scaled uninstalled costs
  - Costs for the component list are based on ASPEN estimates, literature values, or quotes
  - Scaled literature values for nuclear supported SOE BoP costs
- Costs are scaled for n^th plant
  - Any piece of equipment with n>5 received a 10% discount (starting with n=5) for every 10x units.
  - $P_n = P_5\left[r^{\left(\frac{\ln(n)/\ln(n_O)}{\ln(10)}\right)}\right]$
  - $P_n = P_5\left[0.9^{\left(\frac{\ln(n)/\ln(5)}{\ln(10)}\right)}\right]$

Major pieces/systems of equipment	Current	Future
HTSE Vessel Shell	$309,257	$386,571
HTSE Vessel Isolation Valves	$64,199	$64,199
SOE Cells	$12,836,906	$7,958,333
SOEC Module Assembly	$7,445,406	$4,615,833
SOEC Electrical Connector Assemblies	$245,749	$245,749
Sleeved Process Connections	$78,640	$78,640
Steam/H_2 PCHX Recuperator	$1,016,265	$203,253
Steam/H_2 Electrical Topping Heaters	$409,869	$409,869
Sweep Gas PCHX Recuperator	$2,821,370	$0
Sweep Gas Electrical Topping Heaters	$281,836	$0
DC Bus Power Distribution	$393,872	$393,872
Rectifier Power Transformers	$6,708,319	$4,854,583
Steam/H_2, Sweep, and Balancing Gas Piping	$332,264	$332,264
Debris Filter	$424,555	$424,555
Balancing Gas Compressor	$570,260	$570,260
Interstage Cooler	$99,945	$99,945
Purified Water Storage Tank	$1,866,393	$1,866,393
Hydrogen H_2O KO Pot	$4,680	$4,680
Non-HTSE System Steam/H2 Piping	$1,756	$1,756
Feedwater Pumps	$6,267	$39,363
Hydrogen H_2O KO Pot Cooler	$76,771	$13,834
H_2O KO Pot	$48,800	$92,827
Hydrogen H_2O Adsorbing Columns	$2,149,232	$2,149,232
Adsorber Cooling Unit	$102,742	$102,742
Hydrogen H_2O Adsorber Regen Heater	$57,132	$57,132
Hydrogen Compression	$1,135,407	$0
Low Temperature O_2/Steam Recuperator HX	$0	$19,050
Sweep/H_2 Low Temperature HX	$32,866	$43,848
Steam/H_2 Low Temperature HX	$48,625	$167,617
External Heat Source HX	$58,547	$228,852
Total	**$39,627,930**	**$26,457,918**

BoP = Balance of Plant

Basis for Electrical BoP Cost Projection

- **Electrical BoP is based on (modified) rectifier quotes**
  - Quoted rectifier is approximately $0.11/W (SRC rectifier for high efficiency)
  - 20% increase for ancillary equipment is added for all cases
  - The quote is reduced 10% for central plants
  - A corporate mark-up of 43% is applied to all cases
  - Future cases receive a 20% discount for technology improvements
    - E.g. system voltage increase which allows nearly same cost but higher power capacity
- **Costs were compared to reported BoP costs in questionnaire**
  - Generically speaking, the developed cost was near the mid-point or above the midpoint of the questionnaire data
- **+/-25% error range is estimated for the electrical BoP cost**
  - Limited spread among the data required a generic error range be applied

PEM
Key Technical and Cost Parameters

	Units	Current Distributed	Current Central	Future Distributed	Future Central
Plant Size	kg H_2 day^{-1}	1,500	50,000	1,500	50,000
Mechanical BoP Modules	#	1	4	1	2
Stack Pressure	psia	350	350	720	720
System Outlet Pressure	psia	300	300	700	700
Current Density	A cm^{-2}	2	2	3	3
Voltage	V	1.9	1.9	1.8	1.8
Total Electrical Usage	kWh/kg H_2	55.8	55.5	51.4	51.3
Stack Electrical Usage	kWh/kg H_2	50.4	50.4	47.8	47.8
BoP Electrical Usage	kWh/kg H_2	5.4	5.1	3.6	3.5
Stack Cost	$ cm^{-2}	$1.30	$1.30	$0.77	$0.77
Mechanical BoP Cost	$ $kg^{-1}day^{-1}$	$289	$76	$278	$46
Electrical BoP Cost	$ kW^{-1}	$121	$82	$97	$68
System Cost	**$ kW^{-1}**	**$601**	**$460**	**$379**	**$234**
Stack Cost	$ kW^{-1}	$342	$342	$143	$143
Total BoP Cost	$ kW^{-1}	$259	$118	$237	$91
Mechanical BoP Cost	$ kW^{-1}	$138	$36	$140	$23
Electrical BoP Cost	$ kW^{-1}	$121	$82	$97	$68

- **General agreement for current density and voltage among survey respondents**
  - Given current density and voltage, stack electrical usage can be calculated
  - Data provided for BoP Electrical Usage was consistent with values used in previous H2A cases and are unchanged
- **Limited new data provided from questionnaire made analysis difficult**
  - When possible, used information from respondents for cost data
    - Most data provided was for existing case
  - Generated data for different system sizes and case parameters with several techniques:
    - Simple ground-up techno-economic analysis at the subsystem level
    - Learning curves

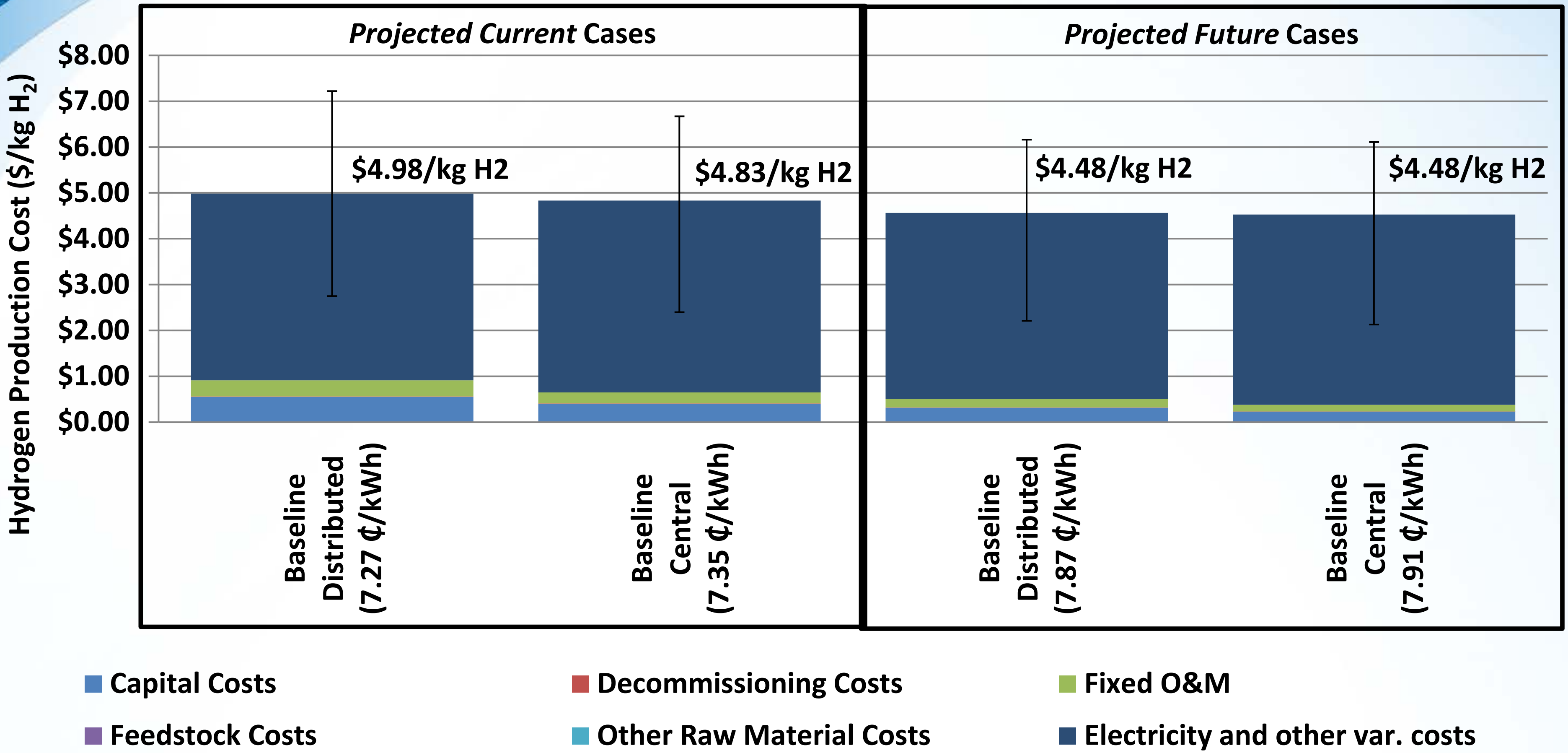
SOE
Key Technical and Cost Parameters

Parameter	Units	Current	Future
Plant Size	kg H_2 day^{-1}	50,000	50,000
Stack Pressure	psia	72.5	300
Outlet Pressure	psia	300	300
Current Density	A cm^{-2}	1.00	1.20
Voltage	V	1.285	1.285
Total Energy Usage	kWh/kg H_2	46.6	44.2
Stack Electrical Usage	kWh/kg H_2	34.0	34.0
Thermal Energy Usage	kWh/kg H_2	6.86	7.10
BoP Electrical Usage	kWh/kg H_2	5.76	3.06
Stack Cost	\$ cm^{-2}	\$0.20	\$0.15
Mechanical BoP Cost	\$ $kg^{-1}day^{-1}$	\$402	\$228
Electrical BoP Cost	\$ kW^{-1}	\$85	\$65
System Cost	\$ kW^{-1}	\$522	\$326
Stack Cost	\$ kW^{-1}	\$155	\$100
Mechanical BoP Cost	\$ kW^{-1}	\$282	\$160
Electrical BoP Cost	\$ kW^{-1}	\$85	\$65

SOE Stack cost is ~1/5th of PEM stack cost

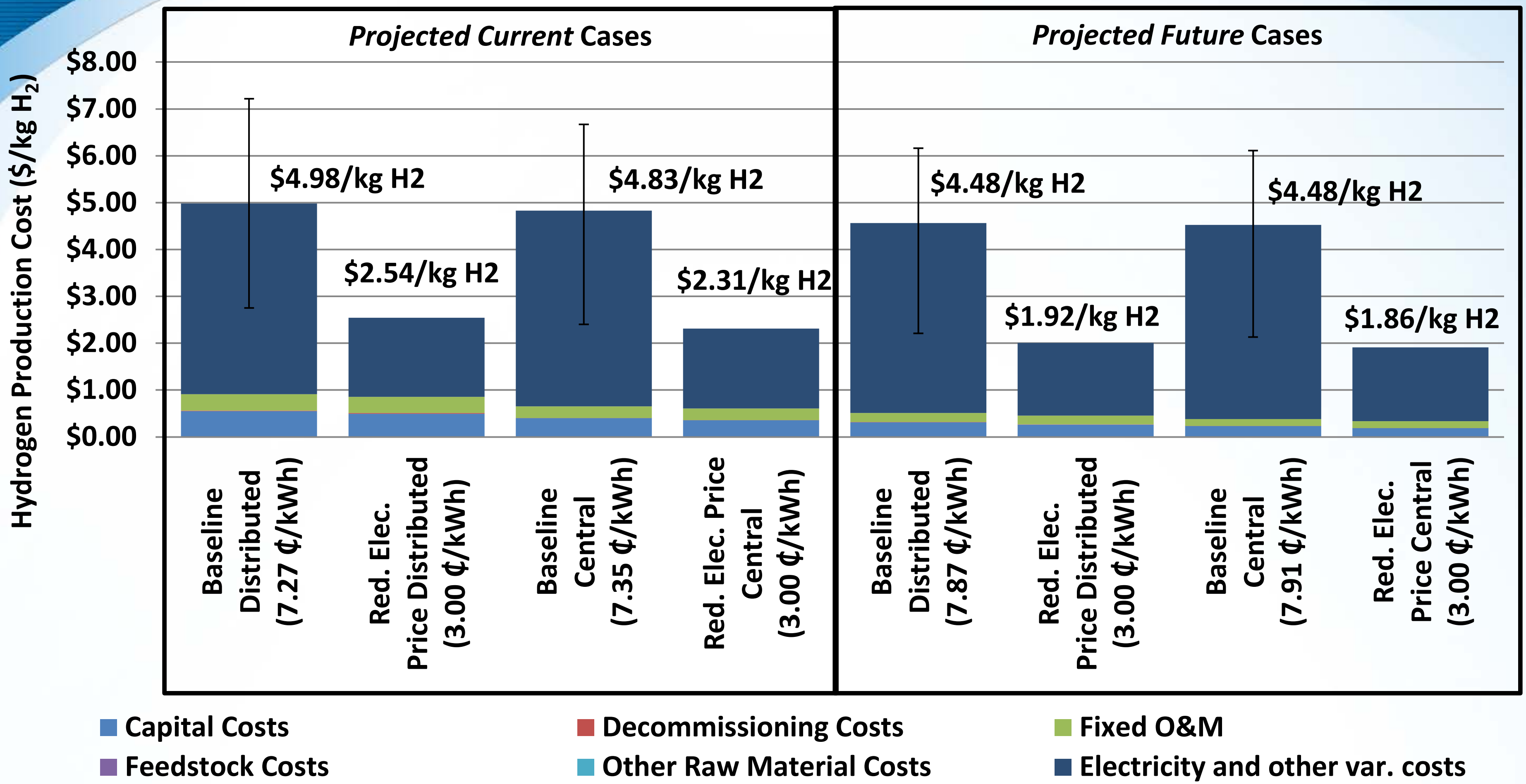
SOE System cost is ~39% higher than PEM

H2A Cost Results – PEM Electrolysis



- Electricity Price continues to be the most significant cost element of PEM electrolysis
  - Effective electricity price over the life of the modeled production site is shown in the labels of each bar above
  - Start-up year changes raised electricity prices between the previous case study and this years update
  - Electricity prices increased according to AEO projections
- Capital cost reduction was largely offset by several factors
  - Incorporation of degradation losses into analysis
  - Electricity price increases between start-up years

H2A Cost Results – PEM Electrolysis



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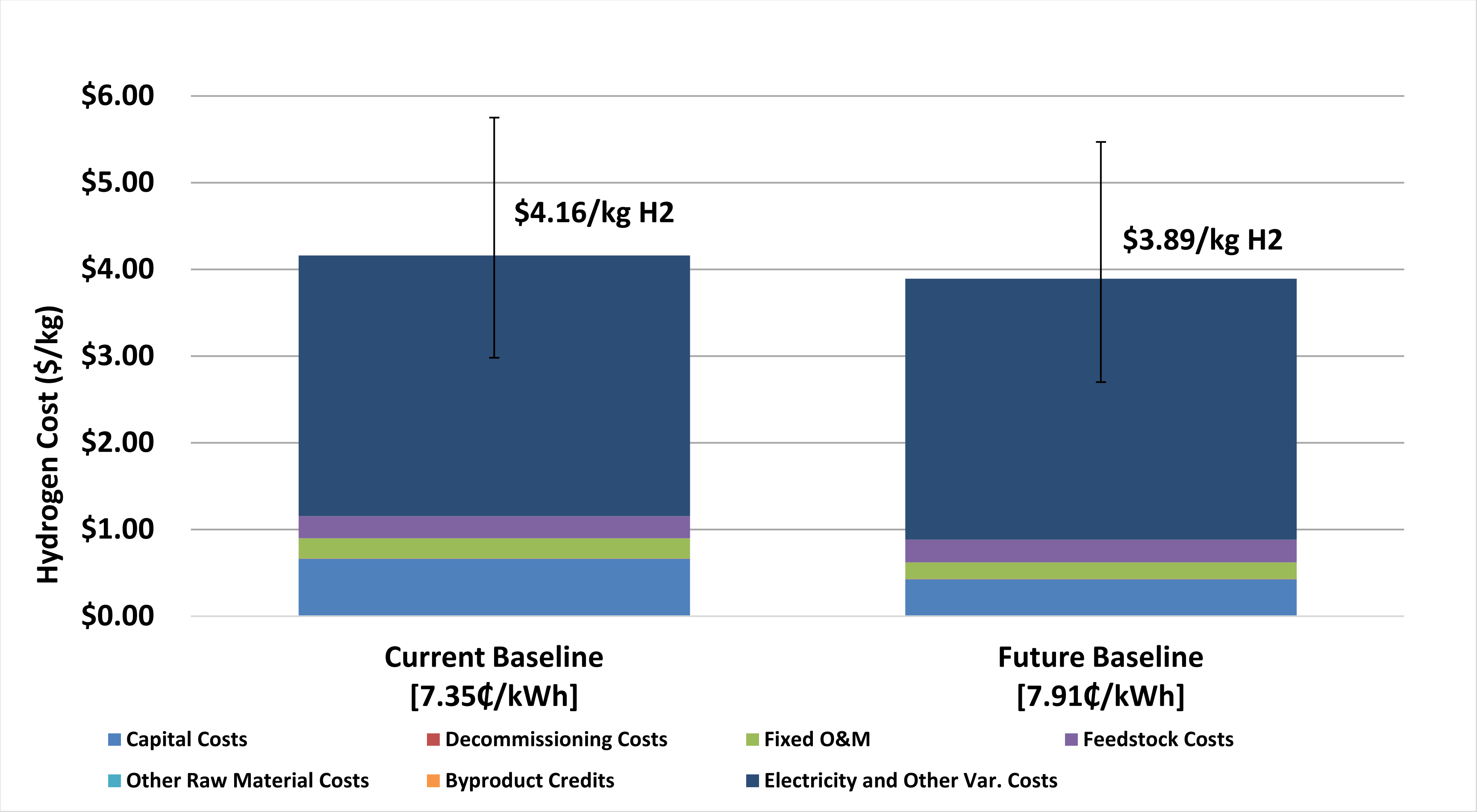
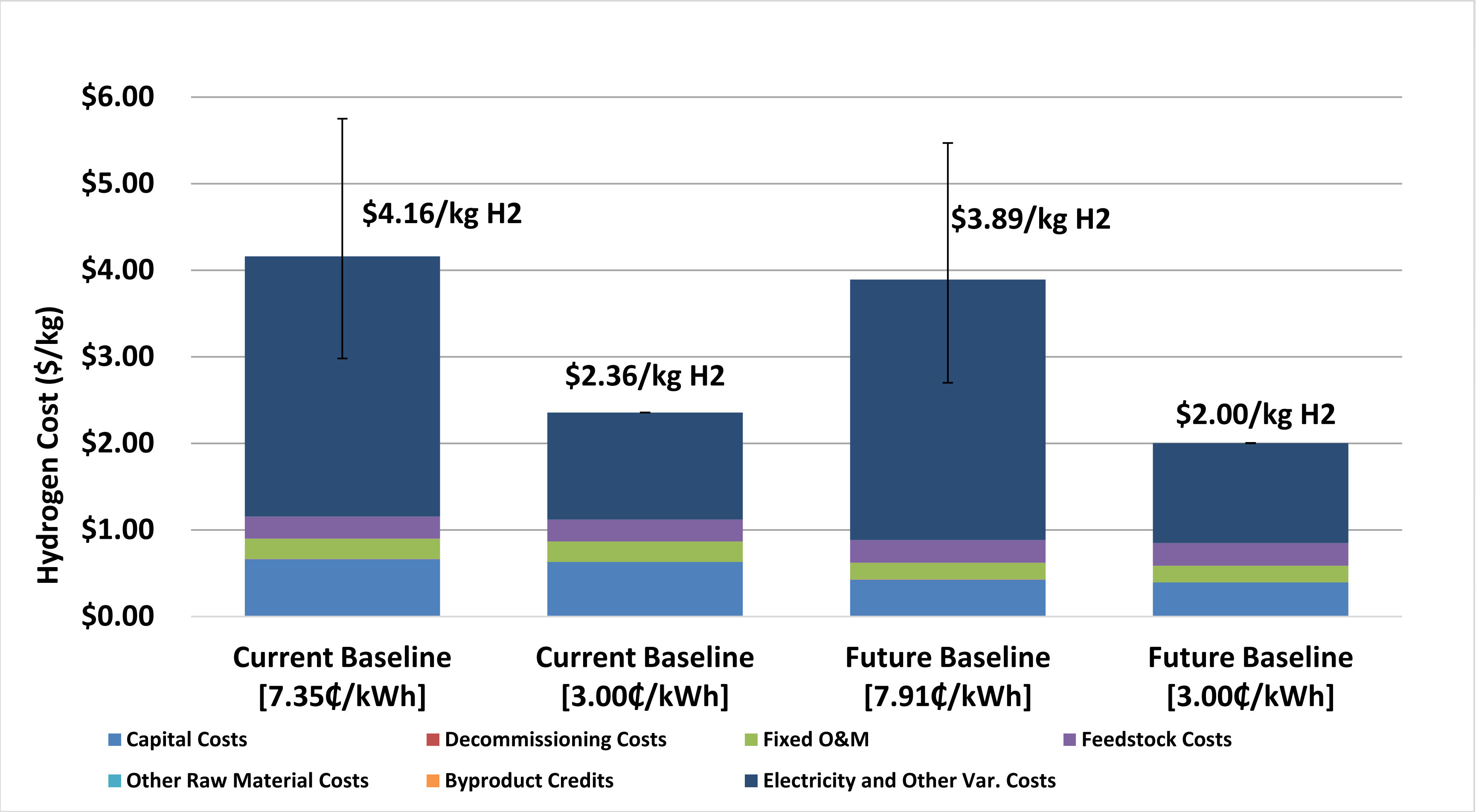
SOE H2A Cost Results



- Electricity remains a the primary cost driver in Solid Oxide Electrolysis
- Thermal energy costs (feedstock) are secondary to electrical costs
  - Cost is assumed to be agnostic of the source of heat

SOE H2A Cost Results



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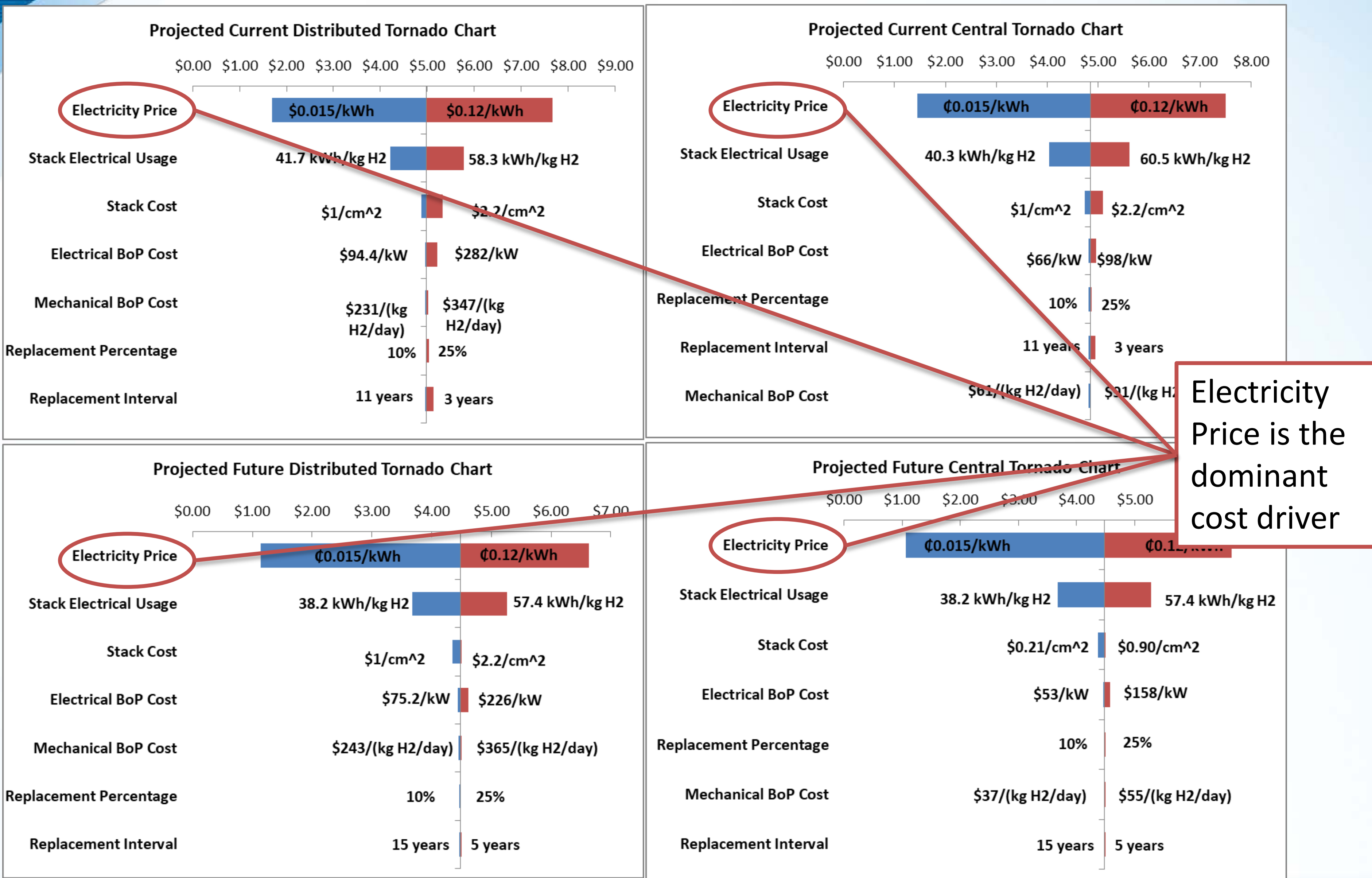
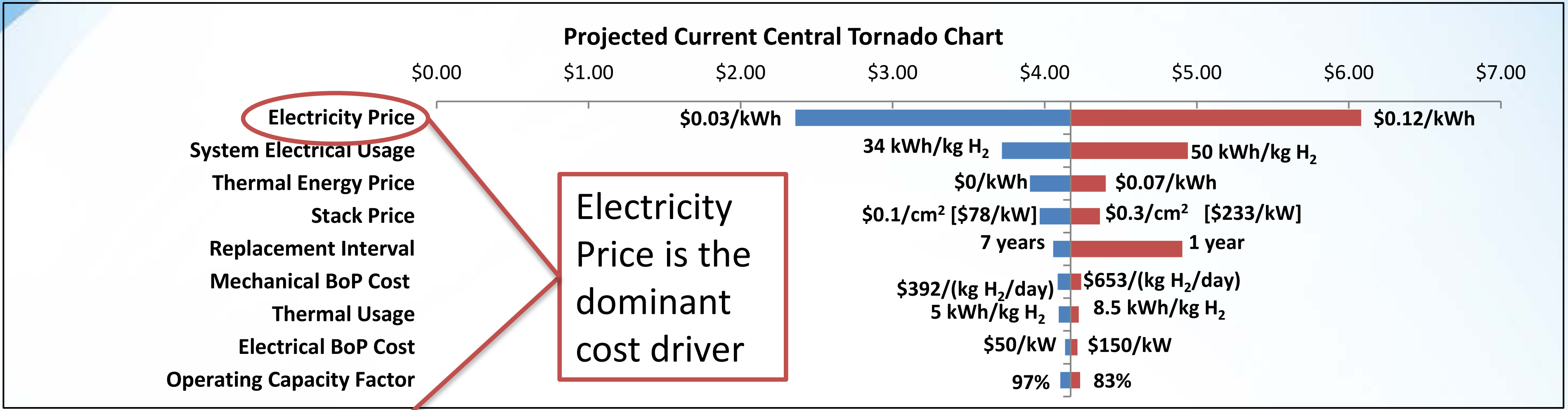
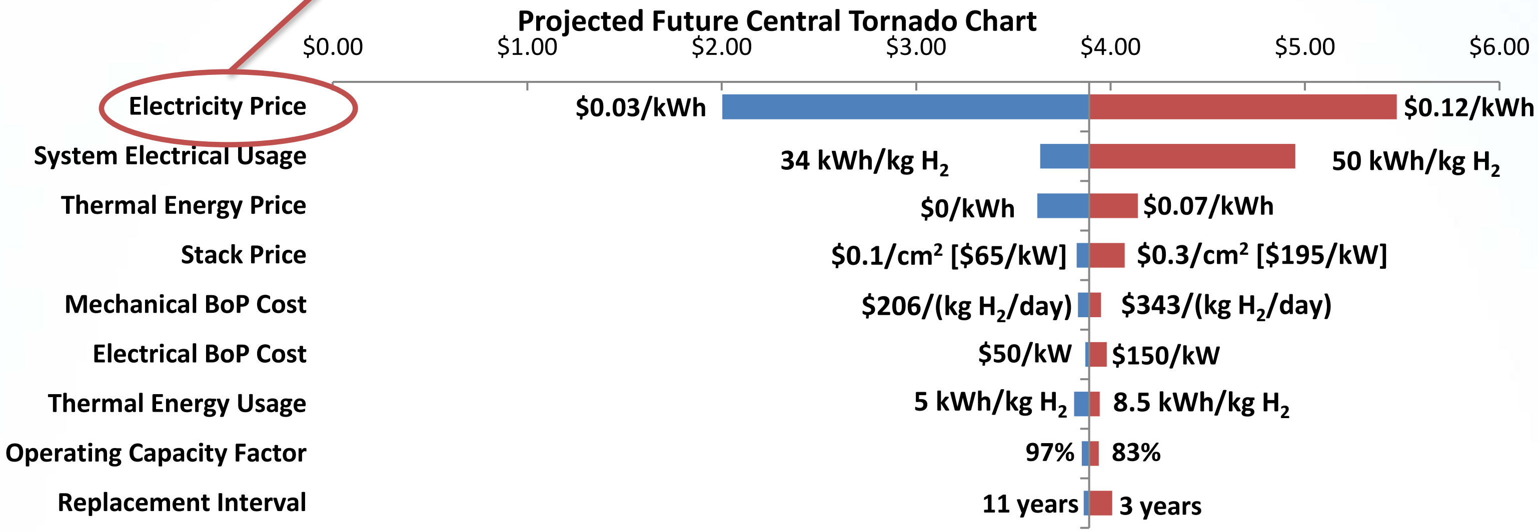
PEM Sensitivity Studies



SOE Sensitivity Study





Summary

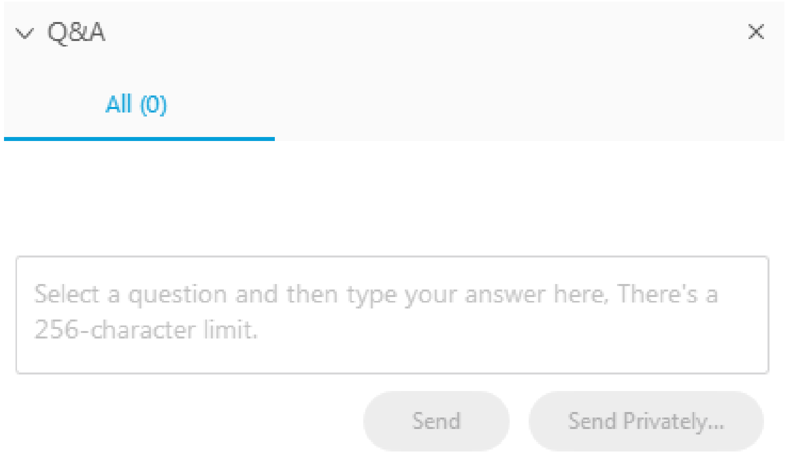
- **Overview**
  - Examine H_2 Production Technologies by techno economic analysis
    - Specific focus on electrolyzers
- **Relevance**
  - Cost analysis is a useful tool because it:
    - Defines a complete production and delivery pathway
    - Identifies key cost-drivers and helps focus research on 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 electrolyzer system: PEM, SOE, AEM (Ongoing)
- **Future Work**
  - Complete AEM Electrolyzer case study

Q&A Session

INCREASE YOUR H2IQ

The #H2IQ Hour

Please type your questions into the **Q&A Box**



Thank You

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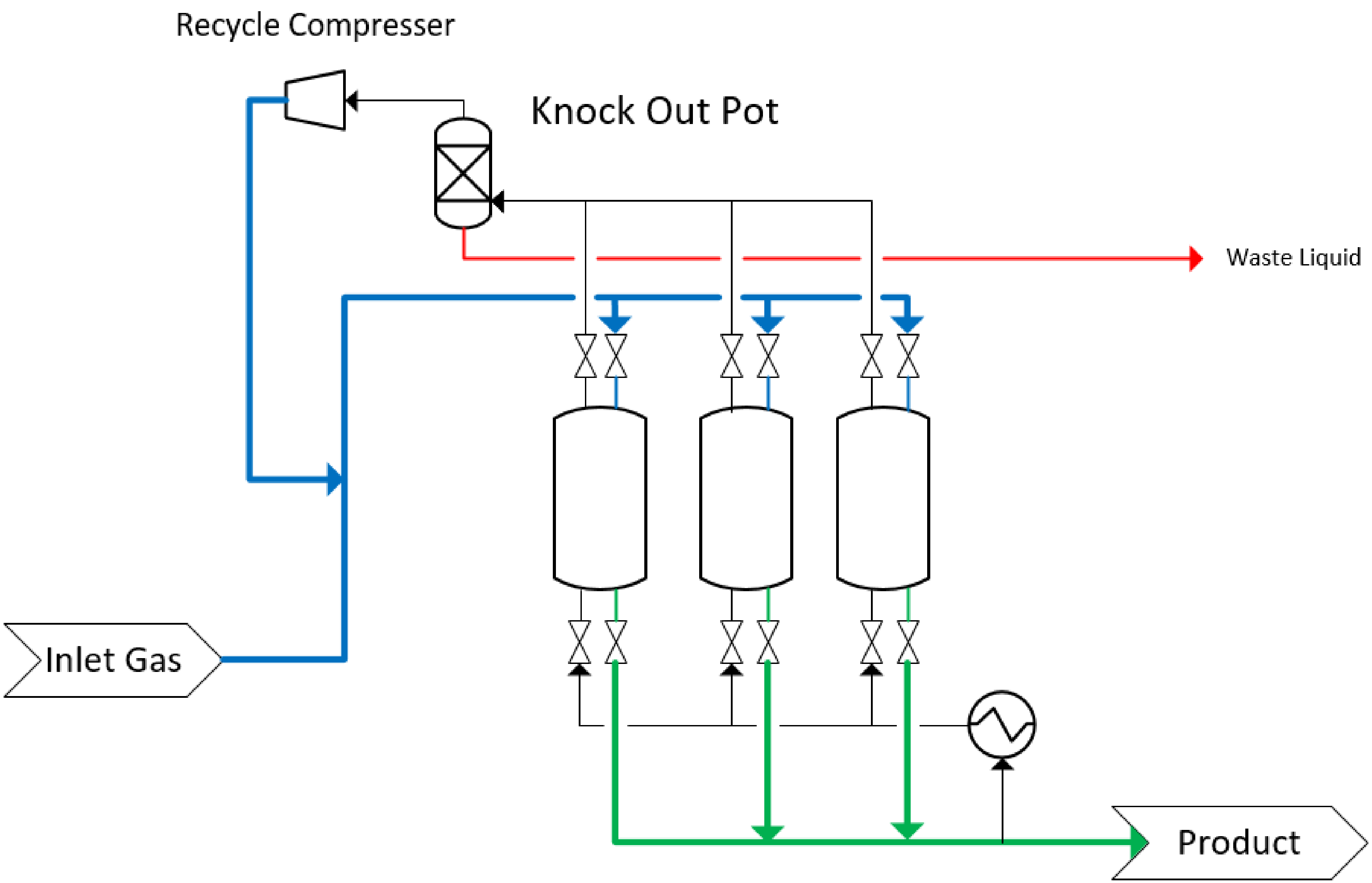
Looking for more info?

#H2IQ

www.energy.gov/fuelcells
www.hydrogen.energy.gov

Backup Slides

TSA Subsystem



Pressure Credit

- H2A baseline has an outlet pressure of H_2 at 300 psi
- Future case PEM systems were run at 700 psi
  - A "credit" is applied to the final cost to account for their excess pressure
- The credit pressure is based off of a nominal cost of compression
  - Compression costs determined by HDSAM
- Future Distributed received a \$0.09/kg H_2 credit
- Future Central received a \$0.05/kg H_2 credit
  - Cost variation is largely due to the cost of the compressor which is larger and more expensive in the central case

Cost Analysis Process

(Uses H2A but additional modeling is also required)

Technology Transfer to Strategic Analysis
- Description of system as currently envisioned
- Target and Goals
- Process Conditions
- Function & Concept

H2A Cost Analysis
- Addition of further business related expenses
- Projection of system sales price
- Discounted Cash Flow Analysis

DFMA® Cost Summary
- Combine costs to get cost of product
- Allows for easy identification of key process steps

Internal Modeling

Engineering Design
- Investigate system
- Performance modeling
- Design/configuration optimization
- Develop full-scale system parameters

Conceptual Design
- Bill of Materials, dimensions, functional concept, sufficient info to make drawings, fabrication and assembly concept

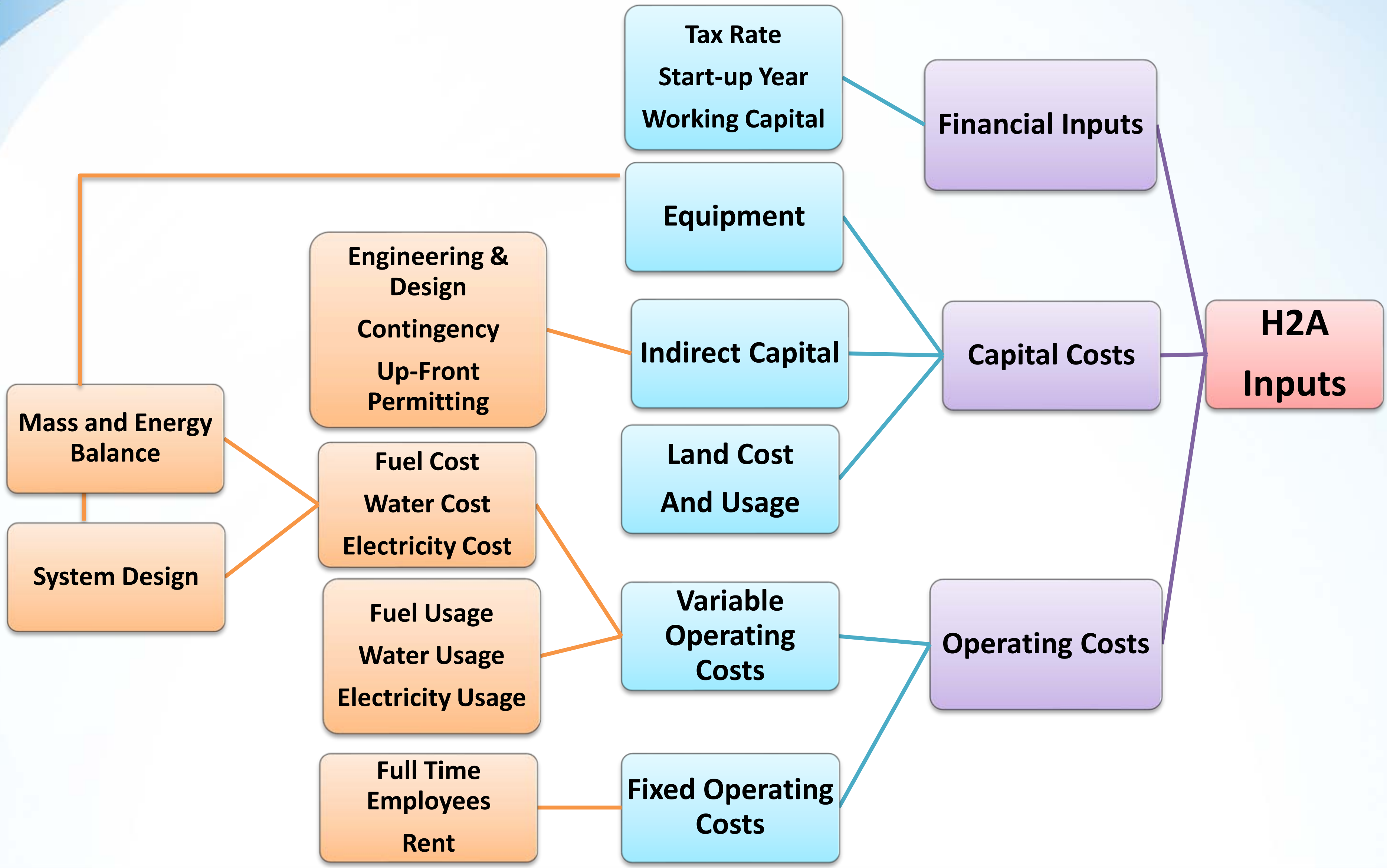
Process Flow Diagram

Process Train Analysis
- Identify Machinery
- Identify Process Feeds

Cost Estimates of Fabrication Machinery
- Estimate/quote machinery costs
- Estimate/quote raw materials costs
- Utilize SA's database of previous cost estimates and quotes

Develop Process Models
- Broken up by Process Step
- Plan for high automation in process
- Calculates Machine Rate
- Determines cost of each step
- Simultaneously estimate costs for a variety of production rates

H2A Inputs


Tax Rate
Start-up Year
Working Capital
Financial Inputs
Equipment
Engineering & Design
Contingency
Up-Front Permitting
Indirect Capital
Capital Costs
H2A Inputs
Mass and Energy Balance
Fuel Cost
Water Cost
Electricity Cost
Land Cost And Usage
System Design
Fuel Usage
Water Usage
Electricity Usage
Variable Operating Costs
Operating Costs
Full Time Employees
Rent
Fixed Operating Costs