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

STRATEGIC ANALYSIS INC

Analysis of Advanced H_2 Production & Delivery Pathways

Brian D. James (SA)

Daniel A. DeSantis (SA)

Jennie M. Huya-Kouadio (SA)

Cassidy Houchins (SA)

Genevieve Saur (NREL)

May 19th

Project ID: P102

Overview

Timeline

- Project start date: 10/1/2016
- Project end date: 9/30/2020
- Percent complete: ~85% 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
  - ~$637K SA (though Mar 2020)
- Total DOE Project Value:
  - ~$749k 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
		• Anion Exchange Membrane (AEM) electrolysis
		• Photoelectrochemical (PEC) H_2O splitting
		  • Update to previous case study
		• Solar Thermochemical (STCH)
		  • Conducted by NREL

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
- Two technology levels analyzed
    - Current: current technology at high-manufacturing rate
    - Future: future technology (2035) at high-manufacturing rate

Electrolyzer Technology	Production Sizes Reported	Technology Years Reported
Proton Exchange Membrane	Distributed & Central	Current & Future
Solid Oxide	Central	Current & Future
Anion Exchange Membrane	Distributed	Future & Far Future

Approach

- Collect data via Industry Questionnaire
- 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

Approach to data collection

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

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 PEM PFD (incl. DFMA)
  - Learning Curves (for comparison to reported parameter values)

Semi-Qualitative Comparison of Electrolyzers

	PEM	SOE	AEM (Future)	AEM (Far-Future)
Current Technology Readiness Level (TRL)	9	8	5	5
Catalyst Basis	Pt/C	YSZ	Pt/C	Non-Pt
Ion Transport	H^+	O^{2-}	OH^-	OH^-
Transport Layer	Nafion	Ceramic Solid	PolyArylPiperdinium	PolyArylPiperdinium
Operating Temperature	Low	High	Low	Low
Current Density (A/cm^2) (at typ. oper. point)	High (2.0-3.0)	Low (1.0-1.5)	Low (0.5-1.0)	Low (1-?)
Degradation Rate	Low	Moderate	Current: Very High Future: Similar to PEM	Current: Very High Far-Future: Similar to PEM

Expanded AEM Information

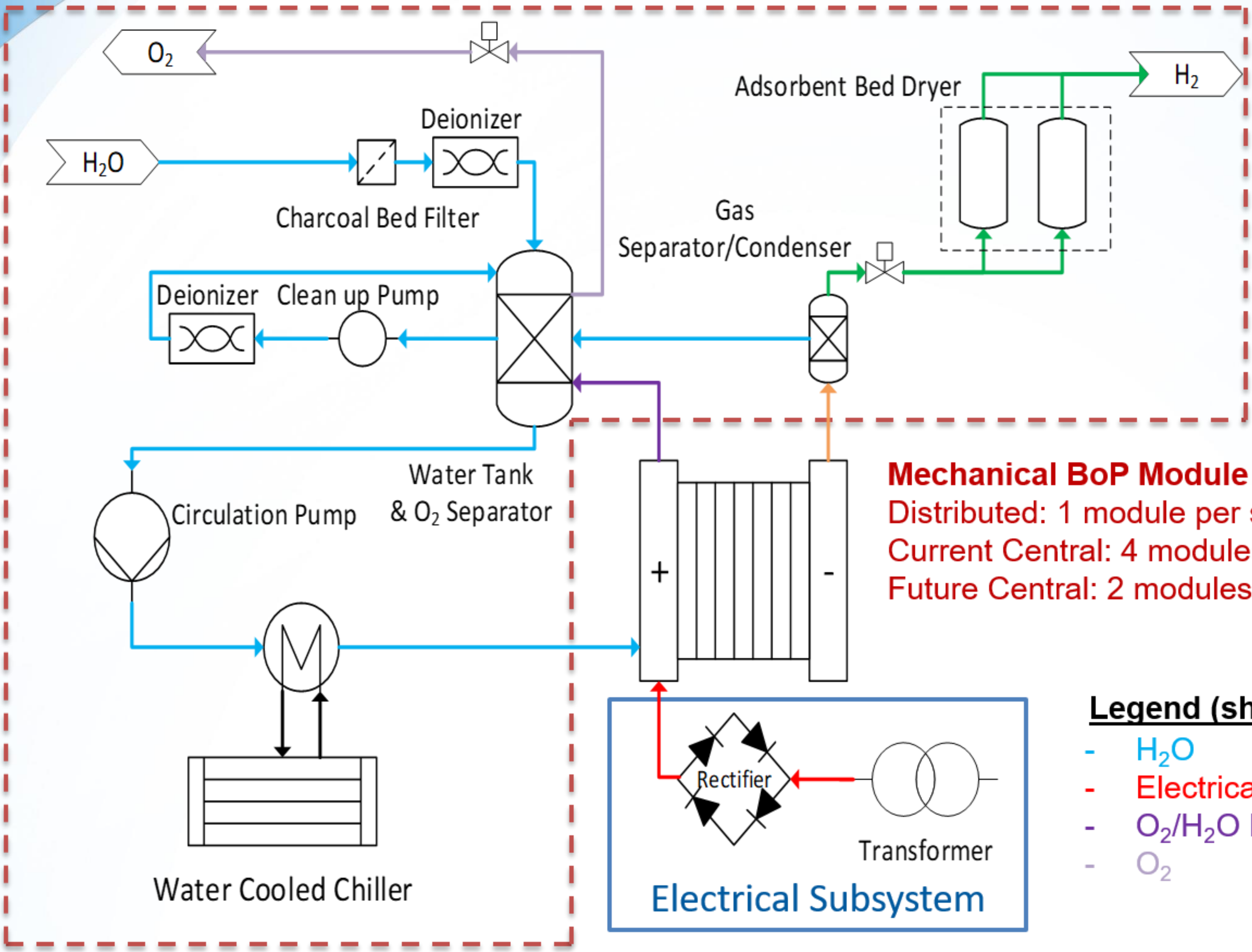
- AEM technology is largely still under development with existing systems being researched.
  - New ion transfer membrane are under development
  - Trying to achieve the same system performance with non-Pt based catalyst that is available with Pt catalysts
- TRL rating basis:
  - Research groups focused on fundamental technology parameters (i.e. membranes and catalysts) suggest low-TRL (3-4)
  - TRL level raised to 5 due to a single company selling small (1kg H_2/day) units

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

PEM Process Flow Diagram



Mechanical BoP Module

Distributed: 1 module per site

Current Central: 4 modules per site

Future Central: 2 modules per site

Legend (showing color coding)

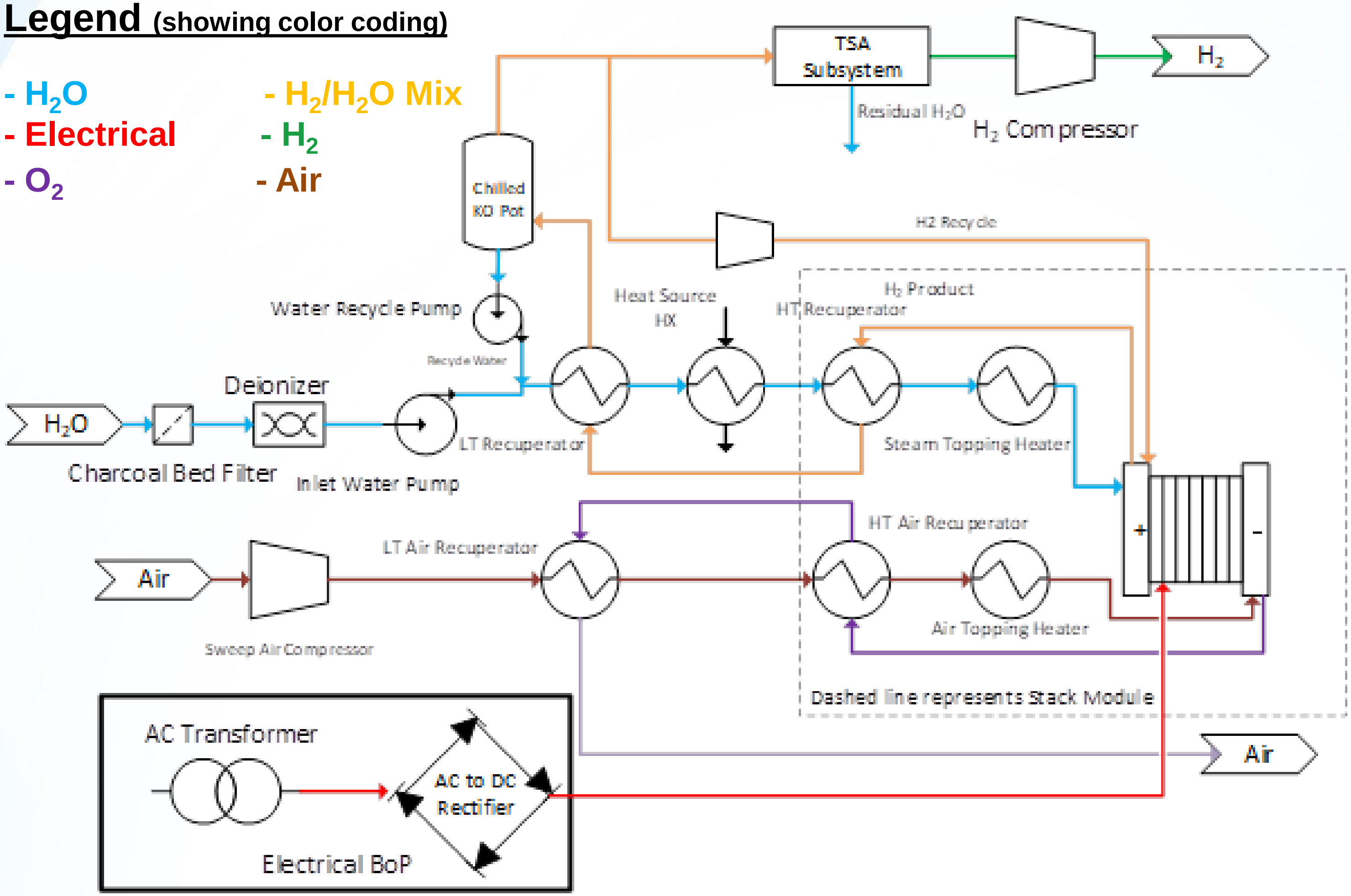
- H_2O
- Electrical
- O_2/H_2O Mix
- O_2
- H_2/H_2O Mix
- H_2

Process Flow Diagram

Solid Oxide Electrolysis, Current Case

Legend (showing color coding)

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

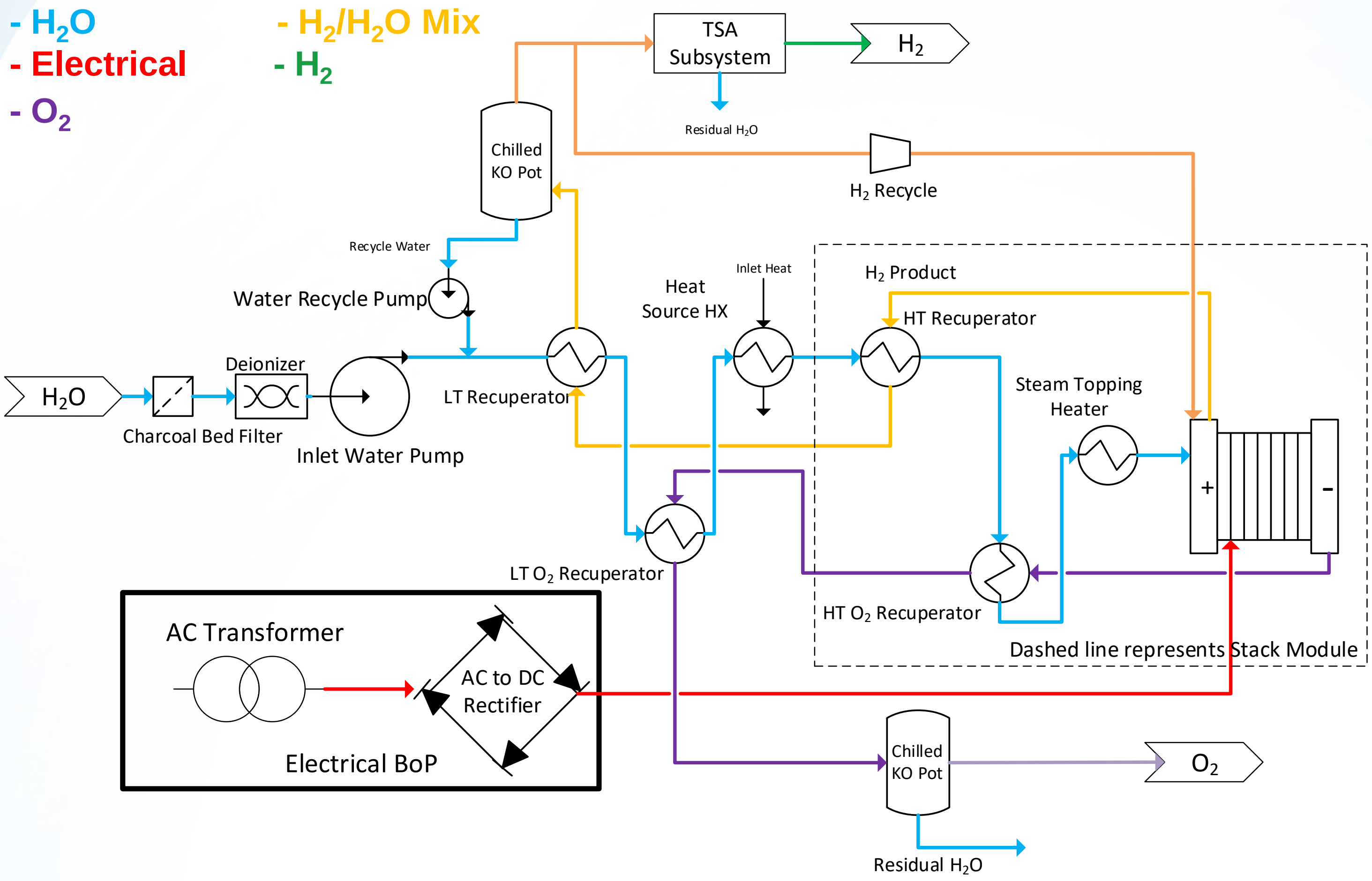


- Utilizes multiple heat recovery systems
- TSA Subsystem used to dry H_2
- All high temperature components in a pressure vessel
- No O_2 recovery

Process Flow Diagram

Solid Oxide Electrolysis, Future Case

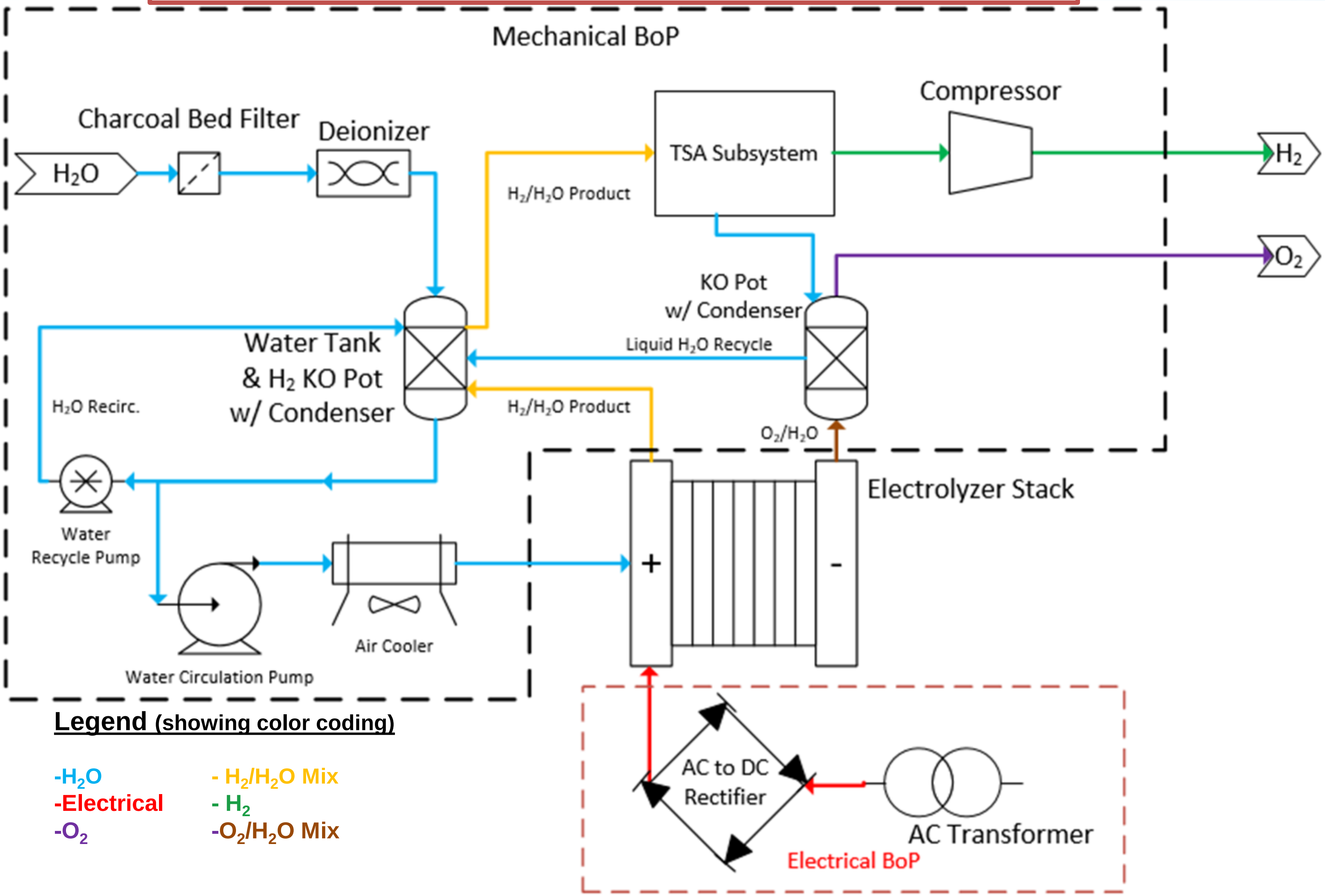
Legend (showing color coding)



- TSA Subsystem used to dry H_2
- All high temperature components in a pressure vessel
- O_2 recovery for byproduct sales
- No Air Sweep

Process Flow Diagram
(AEM Electrolysis)

Similar to PEM Electrolysis system



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
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
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

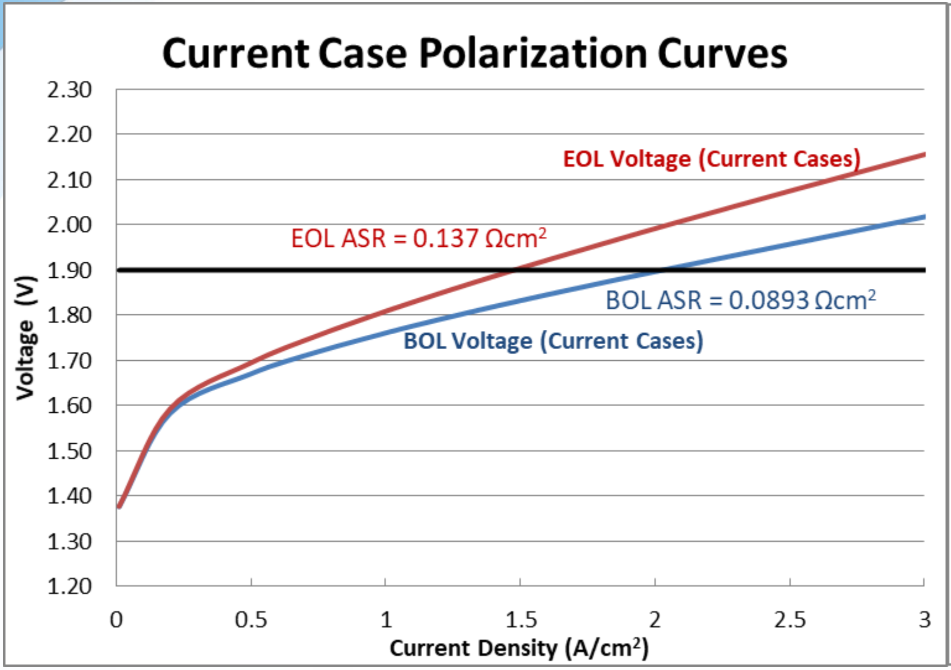
SOE Stack cost is ~1/5th of PEM stack cost on \$/area basis

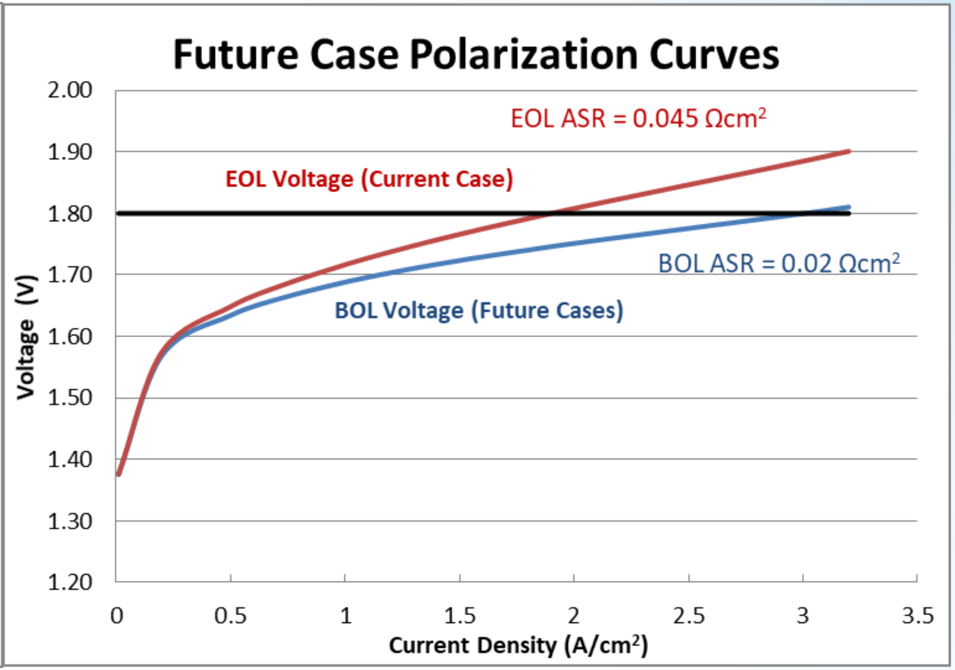
AEM Key Technical and Cost Parameters

	Units	Future	Far-Future
Plant Start Year	-	2040	2060
Plant Size	kg H_2/day	1,500	1,500
Capacity Factor	%	90%	90%
H_2 Outlet Pressure	Bar	20.7	20.7
Stack Op. Pressure	Bar	5	5
Current Density	A /cm^2	1	1.5
Voltage	V	1.8	1.8
Degradation Rate	mV/1000hrs	1.5	1
Oversize Factor	%	20%	24%
Stack Lifetime	yrs	7	10
Total Electrical Usage	kWh/kg H_2	53.3	53.3
Stack Electrical Usage	kWh/kg H_2	47.9	47.9
BoP Electrical Usage	kWh/kg H_2	5.4	5.4
Stack Cost	\$/cm^2	\$0.88	\$0.87
Mechanical BoP Cost	\$/(kg/day)	\$584	\$570
Electrical BoP Cost	\$/kW	\$97	\$97
Stack Cost	\$/kW	\$492	\$324
Mechanical BoP Cost	\$/kW	\$263	\$256
Electrical BoP Cost	\$/kW	\$97	\$97

AEM has Reduced Power Density compared to PEM

Modeled PEM Polarization Curves



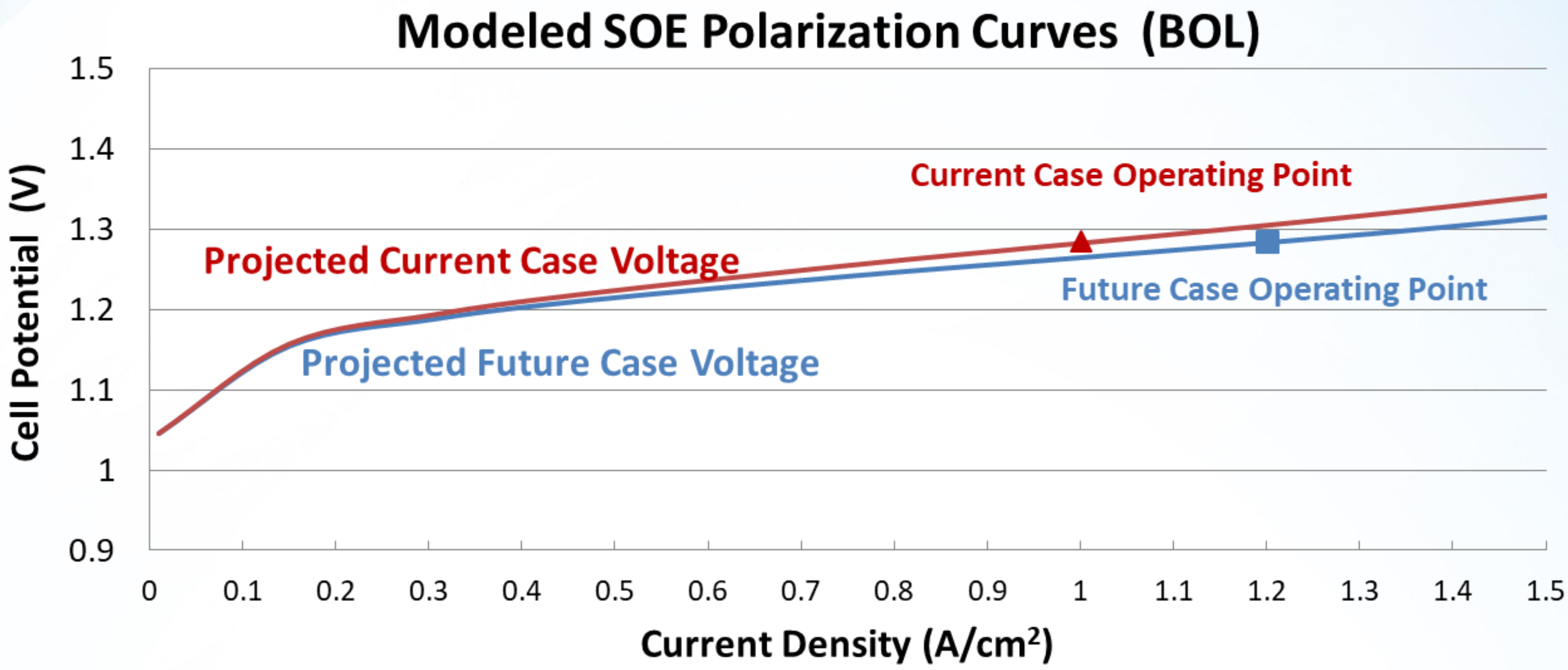


- **Created a set of polarization curves for each case from a model developed by Hao et al**
  - Compared polarization curves and Area Specific Resistances (ASRs) to literature values
  - The polarization curves were adjusted to go through the operating points
  - $E\ (V) = \ E_o + b \ln\left(\frac{i - i_{loss}}{i_{loss}}\right) + R * i + m * e^{n*i}$
  - Mass transfer losses not considered
- **Incorporated degradation rates into cost analysis**
  - End of Life (EOL) polarization curves shown below
  - Allows for constant voltage in the analysis
  - Stacks were oversized to get an averaged targeted production rate of 1.5 tpd (Distributed) or 50 tpd (Central)

OP = Operation Point

tpd= metric tonnes per day

SOE Polarization Curve

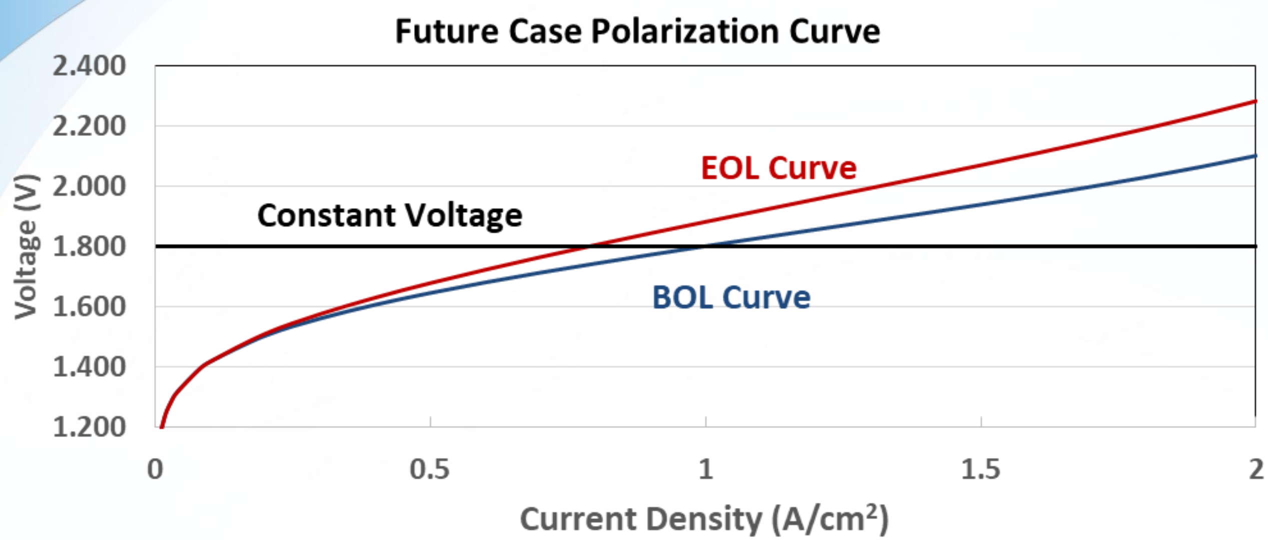


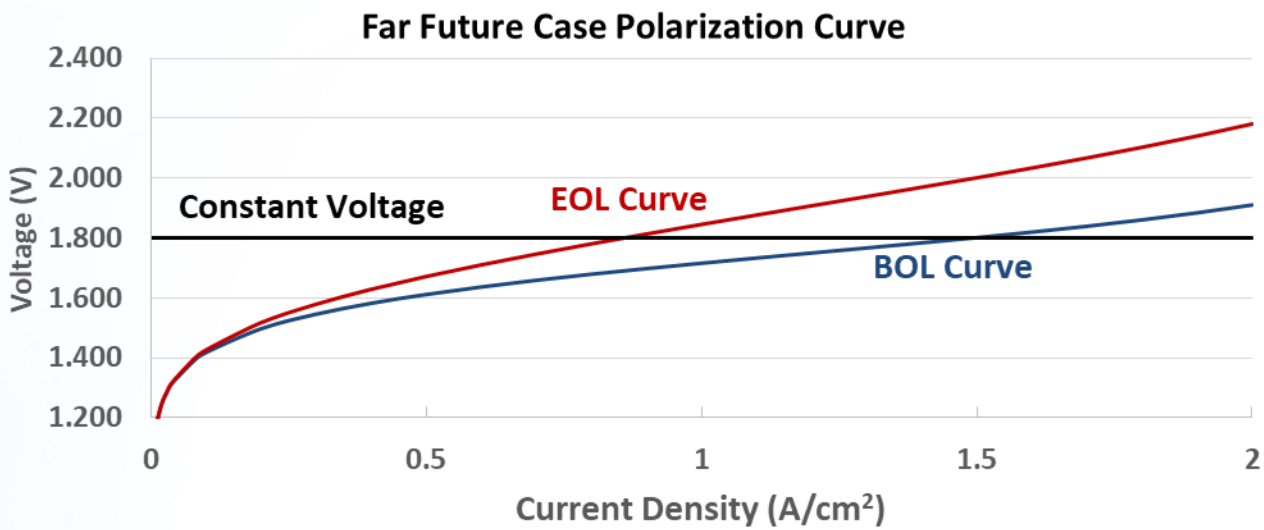
- **Using the same mathematical model developed by Hao et al and starting with an Area Specific Resistance (ASR) from literature, polarization curves were created for each case**
  - The polarization curves were adjusted to go through the operating points

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

  - 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

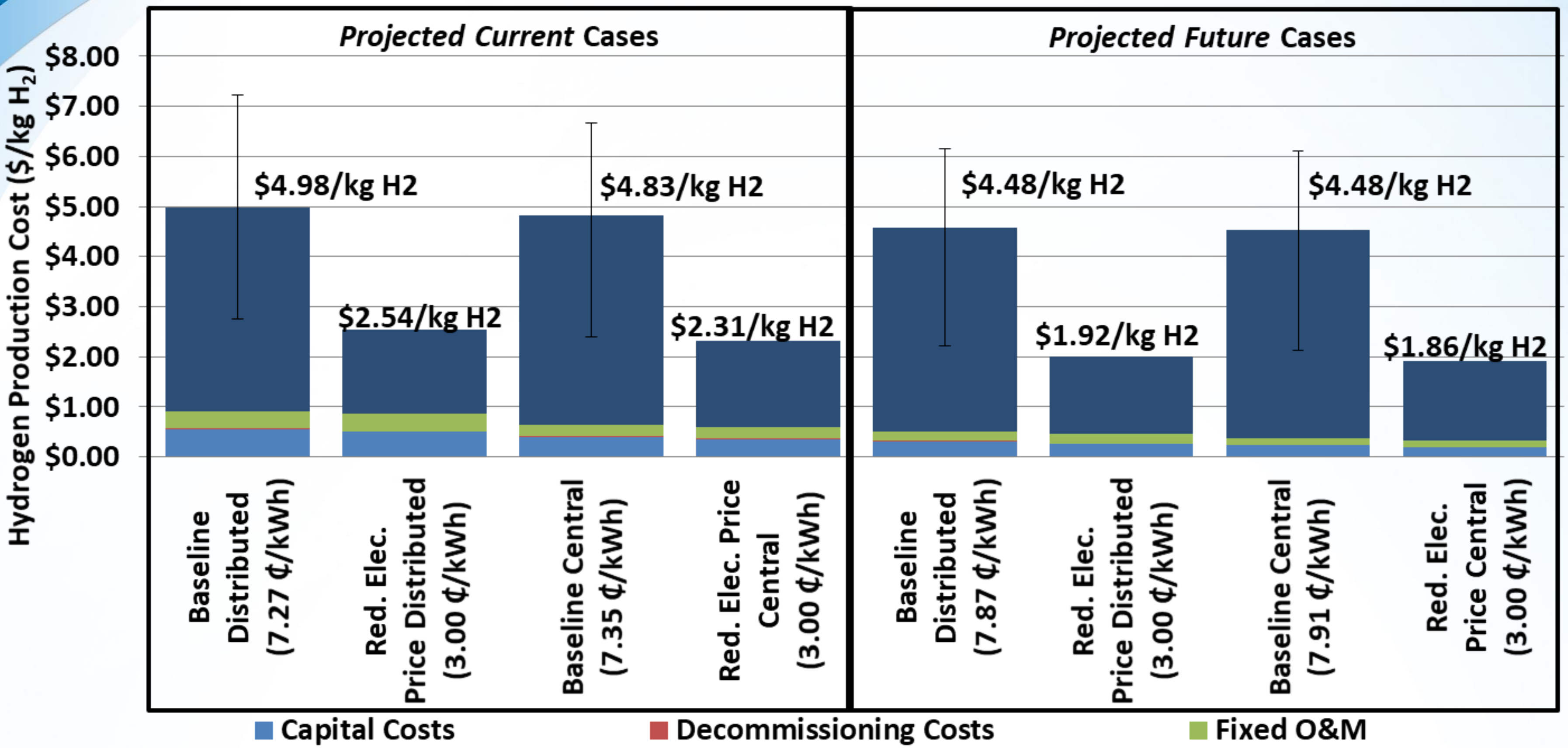
Modeled AEM Polarization Curve





- Modeled polarization curve in the same manor as other electrolyzers
- Significantly lower current density than PEM
- 2 polarization curves shown for each case
  - Beginning of Life, End of Life
- Operation is assumed to be at constant voltage between BOL and EOL
- Polarization Curve Model from Hao et al
  - $E\ (V) = E_o + b \ln\left(\frac{i + i_{loss}}{i_{loss}}\right) + R * i + m * e^{n*i}$

H2A Cost Results – PEM Electrolysis

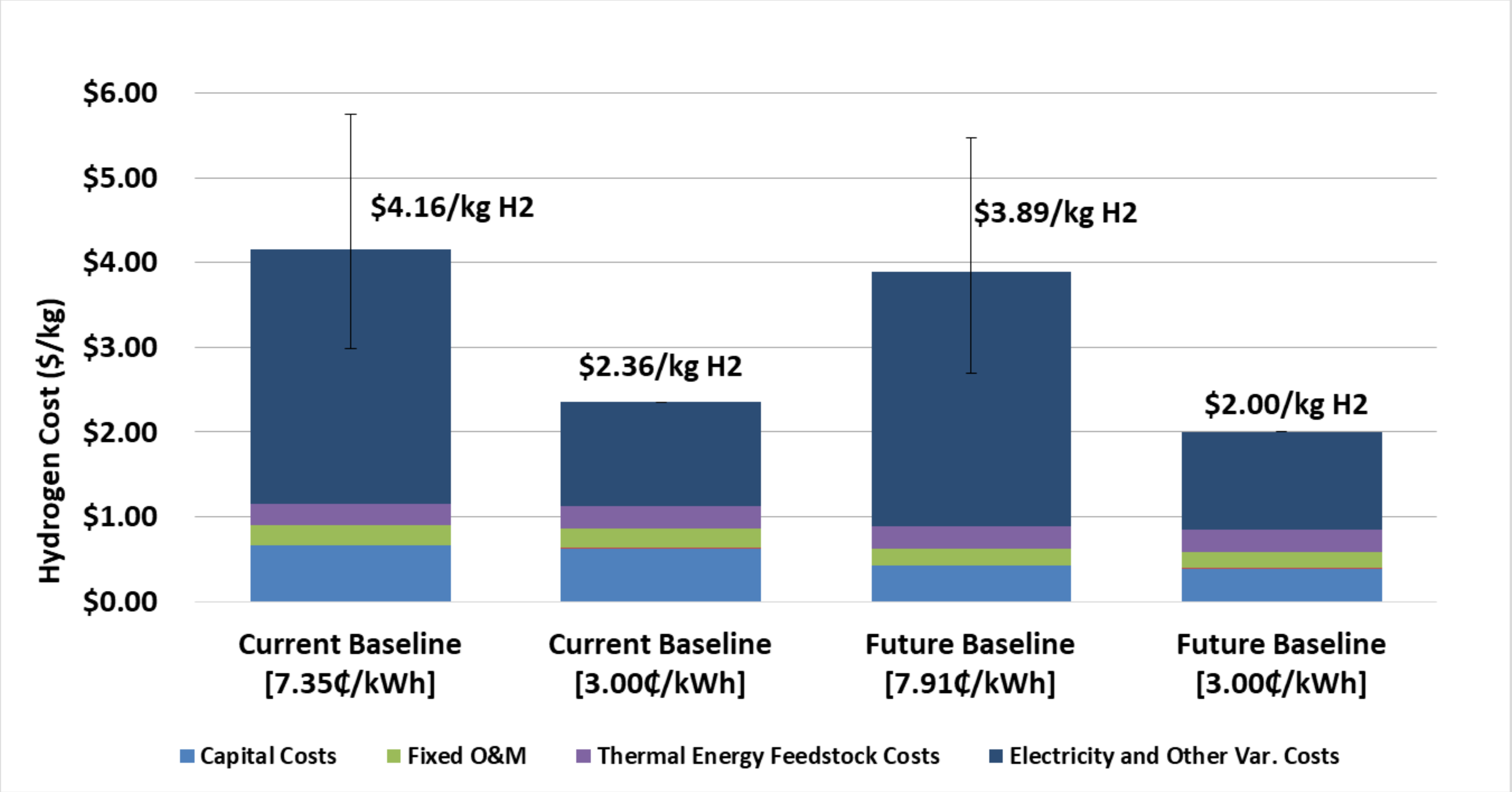


- **Electricity Price continues to be the most significant cost element of PEM electrolysis**
  - Effective electricity price over the life of the modeled production site is shown in the labels of each bar above
  - Start-up year changes raised electricity prices between the previous case study and this years update
  - Electricity prices increased according to AEO projections
- **Capital cost reduction compared to 2014 H2A case was largely offset by several factors**
  - Incorporation of degradation losses into analysis
  - Electricity price increases between start-up years

Error bars are the result of Monte Carlo Analysis: No error analysis conducted for 3₵/kWh Case.
More information available at: https://www.nrel.gov/hydrogen/h2a-production-case-studies.html

SOE H2A Cost Results

(All Central Cases)

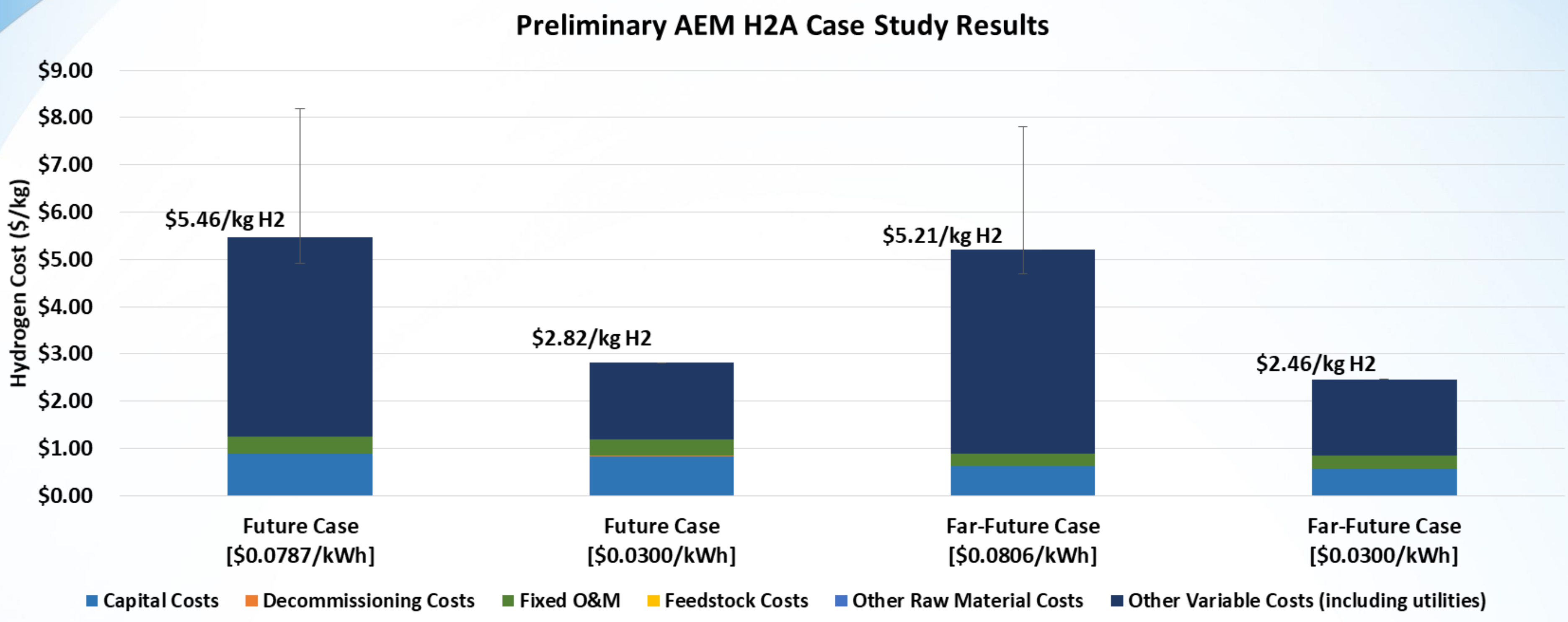


- Electricity remains a the primary cost driver in Solid Oxide Electrolysis
- Thermal energy costs (feedstock) are secondary to electrical costs
- Cost is assumed to be agnostic of the source of heat

Error bars are the result of Monte Carlo Analysis. No error analysis was conducted for 3₵/kWh Case. More information available at: https://www.nrel.gov/hydrogen/h2a-production-case-studies.html

STRATEGIC ANALYSIS INC

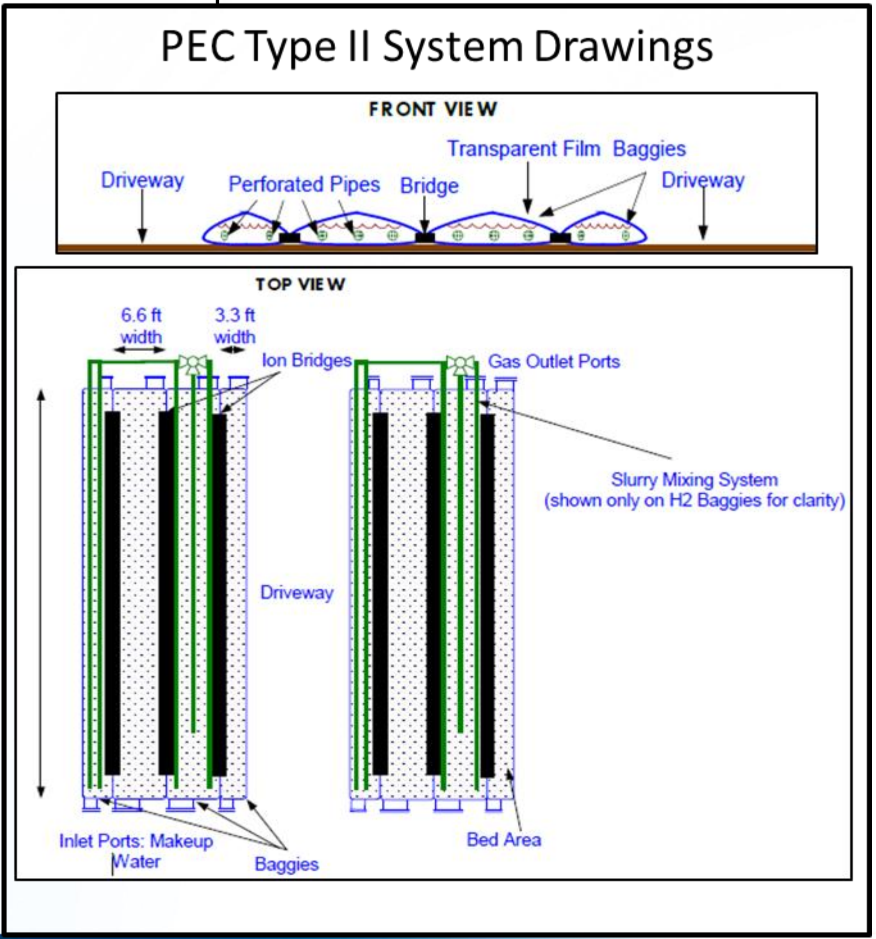
H2A Preliminary Cost Results – AEM Electrolysis

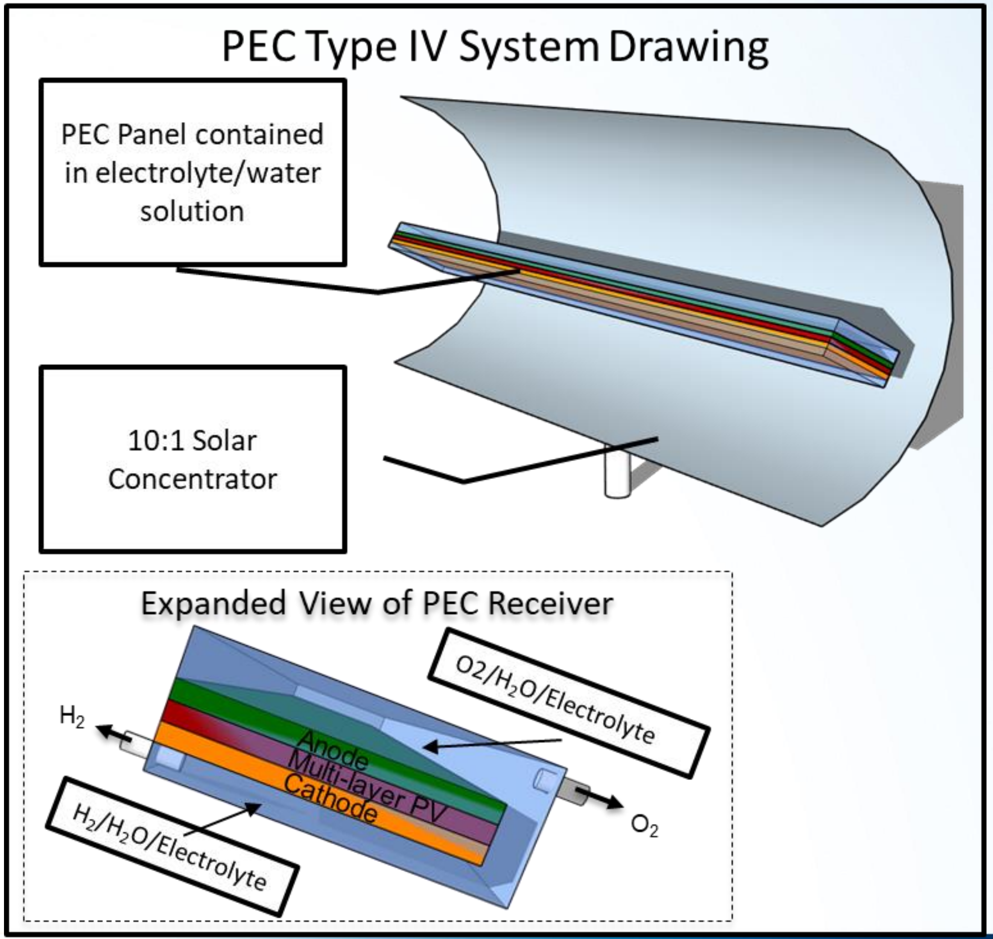


- Electricity Price is the primary cost driver of AEM electrolysis in the Future & Far-Future Cases
- Current case is driven by capital cost, due to annual stack replacement of expensive stacks
- All electricity prices increased according to AEO projections
- Sensitivity and Monte Carlo analysis not conducted yet
  - Displayed error bars represent +50% of Total Cost and -10% of Total Cost

Photoelectrochemical Water Splitting

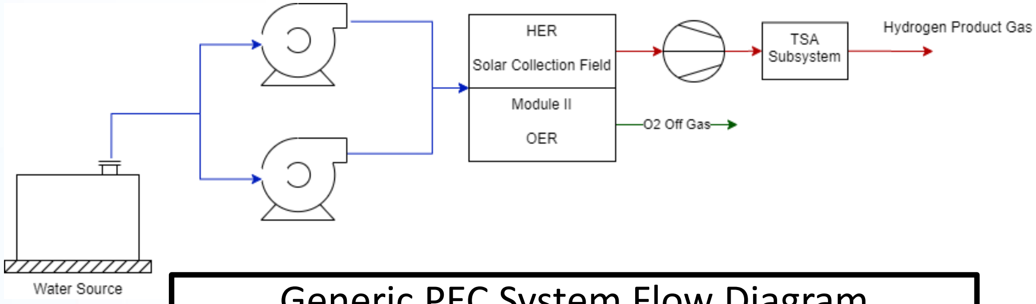
- Four Types of PEC Considered: Two selected for investigation by DOE
  - Type II: Particulate Bag System - nanoparticle catalysts contained in a HDPE bag
    - HER and OER reactions occur in separate HDPE bags connected via ion bridges
  - Type IV: Concentrated PV Panel – A PEC receiver contained in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





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 1,500 kgH_2/day
  - Multiple modules strung together to reach desired H_2outlet flow rate
- Preliminary system specs shown in tables to right



Generic PEC System Flow Diagram

PEC Type II System Technical Specifications

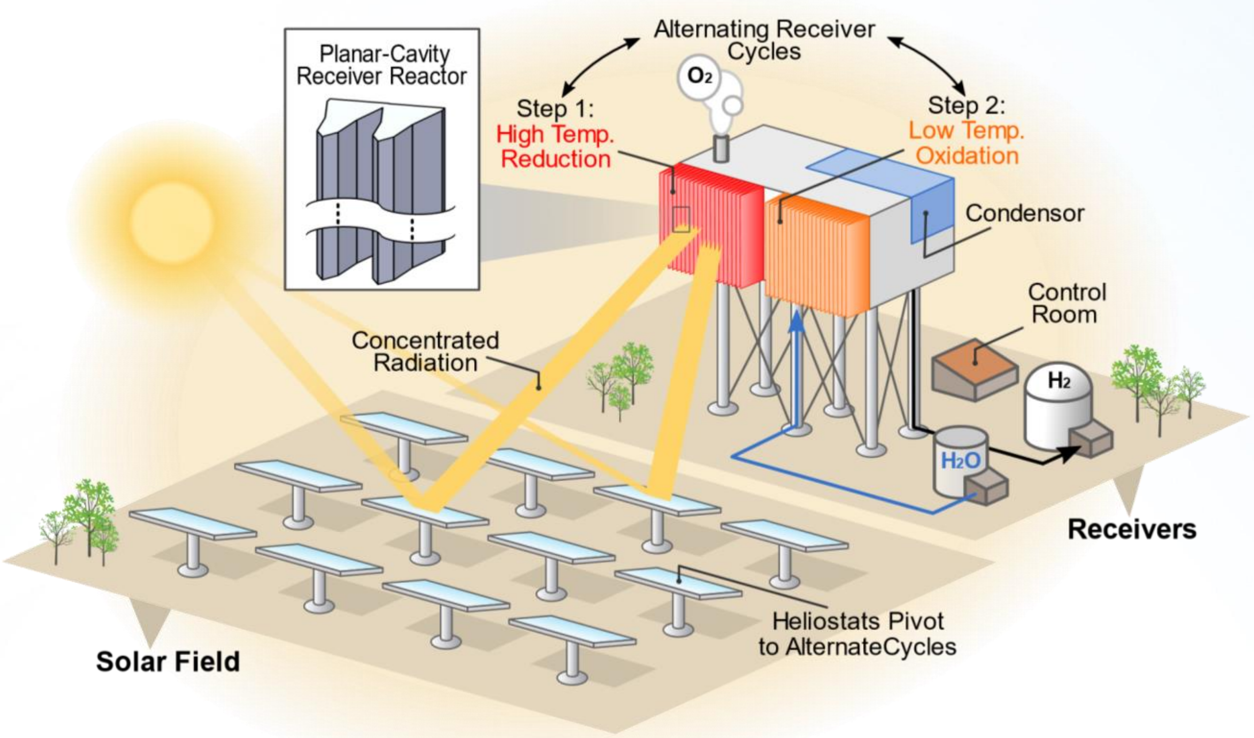
	Units	Value
PEC Type	-	Type II
Average Incident Rad.	kWh m^{-2} day^{-1}	5.77
STH Efficiency	%	5%
Average H_2 mass flow	kg day^{-1}	1,500
Area Specific Mass Flow	Kg H_2 hr^{-1} m^{-2}	3.67E-04
Total Area Required	m^2	170,195
Bed Length	m	61
Bed Width	m	3
Bed Height	m	0.1
Bed Area	m^2	183
Bed Volume	m^3	18
Number of Beds	#	183
Assumed particle density	kg m^{-3}	0.30
Particle Mass	kg/bed	5.49

PEC Type IV System Technical Specifications

	Units	Value
PEC Type	-	Type IV
Average Incident Rad.	kWh m^{-2} day^{-1}	7.46
STH Efficiency	%	15%
Cell Efficiency	%	18%
Collector Efficiency	%	85%
Average H_2 mass flow	kg day^{-1}	1,500
Area Specific Mass Flow	kg H_2 hr^{-1} m^{-2}	1.43E-03
Total Area Collector Required	m^2	43,780
Collector Length	m	6
Collector Width	m	3
Collector Area	m^2	18
Number of Collectors	#	2,433
PV Area required	m^2	37.78

Solar ThermoChemical (STCH) H_2 Production

Conceptual Design for Techno-Economic Analysis



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

Design Features

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

Baseline Inputs for STCH H2A case

Parameter	Value	Notes
Daily Field Production Target	100 TonH_2/day	DOE Target
Thermal Power to a Modular Plant	200 MWt	At the receiver aperture
Module Daily H_2 Production	14.9 Ton H_2/day	Assumed 25% STH efficiency, 90% capacity factor
Number of Modules in Plant	6	Each 200MWt plant produce 14.9 TonH2/day
Modular Field Size	~585 m radius	Determined by SolarPILOT model
Number of Heliostats per Field	17,128	Heliostat size 4.25 m x 4.25 m
Tower Height	130 m	Result from parametric SolarPILOT optimization
Tower Cost	$3,375,880	(2005$) Determined from literature
Field Optical Efficiency (annual)	63.9% (52.8%)	Design point, determined by SolarPILOT model
Solar Receiver Thermal Efficiency	80%	Referred to design at 900°C, but further optimization is needed for STCH condition.
Thermochemical Efficiency	50%	Engineering Judgement
STH Efficiency	21%	LHV basis, 21% baseline
Annual Water Utility Usage	430.7 million gal	Assumed 11.8 gals/kgH_2
Water recovery	50%	Used as part of water usage estimates

Conclusions

- All of the electrolyzer technologies have a significant dependence on the price of electricity
  - Capital cost is of secondary importance in almost every case examined
- PEM and SOE technologies both have the potential to meet DOE targets for H_2 cost if the cost of electricity can be reduced to about 3 cents/kWhr.
- The potential for AEM technologies is promising given several potential future improvements:
  - A non-Pt based catalyst can be used while achieving the similar performance
  - The stack cost is lowered to <$1.00/cm^2 while maintaining an appropriate power density for production

Proposed Future Work

- **Complete AEM Analysis**
  - Error and Sensitivity analysis
    - Error bars for case study results
  - Industry Review
- **Conduct optimization studies of electrolysis work**
  - Vary capital cost & current density operating point to assess impact on H_2 production cost
- **Complete PEC Electrolysis H2A analysis**
  - System Cost analysis
  - Sensitivity analysis
  - Documentation
- **Publish STCH H2A Cost Results**
- **Continuing coordination between FCTO sub-areas**
  - Production & Delivery, Analysis, and Target Setting are all areas that require coordination

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	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
Argonne National Lab (ANL) • Rajesh Ahluwalia • Amgad Elgowainy	Subcontractor	• Participated in select project calls • Vetted process work • Expert review of transmission analysis • Developing Electrolyzer Performance Model
Department of Energy (DOE) • Eric Miller • 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

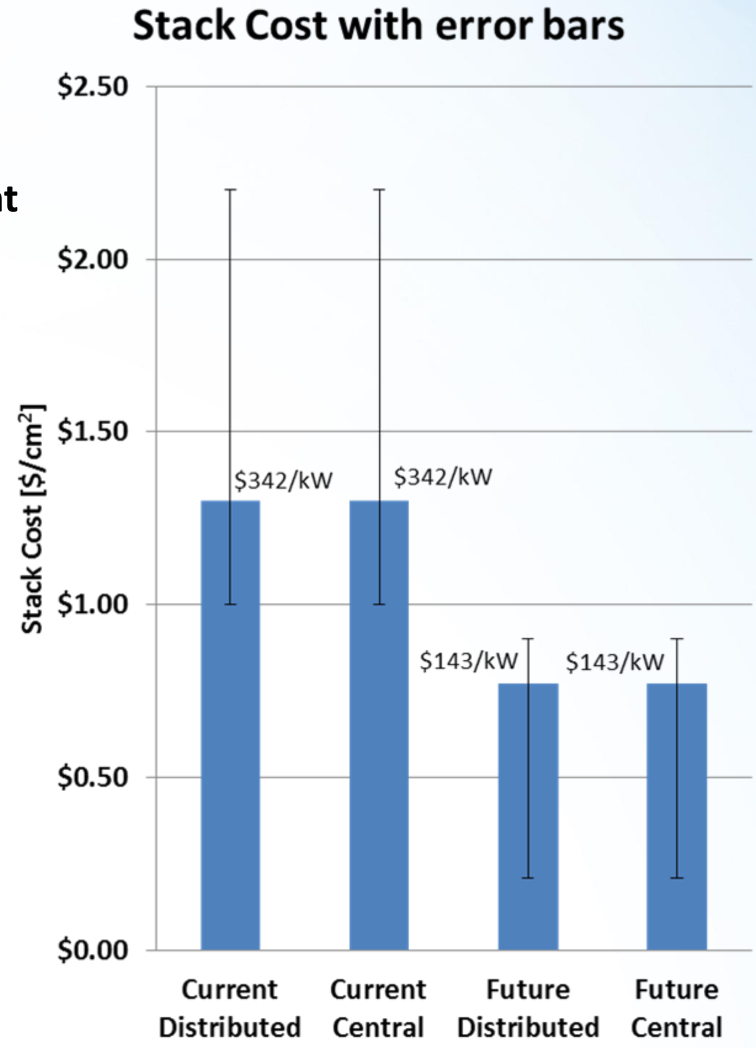
Summary

- **Overview**
  - Conducted a cost analysis of transmitting energy over long distances
  - Began renewed analysis of Water Splitting technologies in H2A
- **Relevance**
  - Increase analysis and understanding of areas demonstrating information deficiencies
  - 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)

Backup Slides

Basis for PEM Stack Cost 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 cost ($1.30/cm²) is based on adjustment of the 2013 H2A stack cost**
  - The increase in cost is proportional to the cost increases reported by the respondents between old and new questionnaire values
  - The stack cost is generally consistent with values reported by respondents in the previous questionnaire
  - The stack upper cost 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 cost ($0.77/cm²) is based on the new questionnaire data**
  - Fairly good agreement of future cost in questionnaire data
  - Adjusting an existing DFMA model for auto PEM stack cost suggests that the cost of the stack may be substantially lower (~$0.21/cm²) . This is taken as the stack cost lower bound.
  - Upper bound ($0.90/cm²) is informed by questionnaire data.



A DFMA® analysis is underway to better understand stack cost at high manufacturing rates.

DFMA® = Design for Manufacture and Assembly

Basis for PEM Mechanical BoP Cost Projection

- 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
  - Cost scaled between Current and Future to reflect stack pressure difference
- 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 and electrical power (i.e. 2 modules of 25tpd)
- All costs scaled on the 6/10ths rule
  - $C_{new} = C_{old}\left(\frac{Scaling\ Factor\ New}{Scaling\ Factor\ Old}\right)^{0.6}$
  - Where Scaling Factor is manufacturing rate or motor power depending on component
- Error bars are based on summation of low-end and high-end quotes for each subsystem or component

Unit	Cost ($)	Cost ($/ (kg H_2/day)
Flow Filter	$13,000	$9
Deionizing Bed	$12,600	$8
Actuated Flow Valve	$6,520	$4
Main DI Pump w/motor	$3,687	$2
Cleanup Pump w/motor	$3,687	$2
Other valves	$4,325	$3
Gas Filters	$1,611	$1
PRV	$930	$1
Heat Exchanger	$2,400	$2
DI Water Tank	$12,500	$8
Hydrogen/Water Separator Tank	$12,500	$8
Chiller	$21,500	$14
Indicator/Controllers	$10,598	$7
Piping and Tubing (ft)	$13,635	$9
Skid Structure	$10,000	$7
Dryer	$40,000	$27
Sub Total	$169,493	$113
Sub Total w/Markup (43%)	$242,375	$162
Total (Includes Markup & 30% Contingency)	**$315,088**	**$210**

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

PEM Data for H2A Analysis

Parameter	Units	Current Distributed	Current Central	Future Distributed	Future Central
Technical Parameters					
Plant Capacity	kg/day	1,500	50,000	1,500	50,000
Plant Life	year	20	40	20	40
Current Density	A/cm^2	2	2	3	3
Voltage	V/cell	1.9	1.9	1.8	1.8
$T_{Operating}$	°C	80	80	80	80
Outlet Pressure	psa	450	450	700	700
Capacity Factory (Net	%	97%	97%	97%	97%
Degradation Rate	mV/khrs	1.5	1.5	1	1
Degradation Rate	%/khrs	0.079%	0.079%	0.056%	0.056%
Cell Active Area	cm^2/cell	450	450	1,500	1,500
Cell/stack	#	150	150	150	150
Total Active Area (full system)	m^2	83	2,764	55	1,843
Number of cells per system	#	1,843	61,426	369	12,286
Number of stacks per system	#	12	410	2	82
Electrical Usage Parameters					
Total System 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
Water Usage					
Water Type	-	Process Water	Process Water	Process Water	Process Water
Water Feed Ratio	Gal/kg H_2	3.78	3.78	3.78	3.78

PEM H2A Case Values

	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
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

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

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	$7,446,340	$4,615,833
SOEC Electrical Connector Assemblies	$245,749	$245,749
Sleeved Process Connections	$78,640	$78,640
Steam/H2 PCHX Recuperator	$1,016,265	$203,253
Steam/H2 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	$7,039,594	$5,172,917
Steam/H2, 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 H2O KO Pot	$4,680	$4,680
Non-HTSE System Steam/H2 Piping	$1,756	$1,756
Feedwater Pumps	$6,267	$39,363
Hydrogen H2O KO Pot Cooler	$76,771	$13,834
H2O KO Pot	$48,800	$92,827
Hydrogen H2O Adsorbing Columns	$2,149,232	$2,149,232
Adsorber Cooling Unit	$102,742	$57,132
Hydrogen H2O Adsorber Regen Heater	$57,132	$1,135,407
Hydrogen Compression	$1,135,407	$39,363
Low Temperature O_2/Steam Recuperator HX	$0	$19,050
Sweep/H2 Low Temperature HX	$32,866	$43,848
Steam/H2 Low Temperature HX	$48,625	$167,617
External Heat Source HX	$58,547	$228,852
Total	**39,961,751**	**$26,776,251**

Basis for Electrical BoP Cost Projection
(applied to PEM, SOE, AEM)

- **Electrical BoP is based on rectifier quotes**
  - Quoted rectifier is approximately $0.11/W (IGBT 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
    - Eg. 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

SOE System Parameters

Operating Conditions		Current	Future
Plant Capacity	kg/day	50,000	50,000
Plant Life	year	40	40
Current Density	A/cm^2	1.00	1.20
Voltage	V/cell	1.285	1.285
Operating Temperature	°C	800	750
Outlet Pressure	psia	300	700
Capacity Factory (Net)	%	90%	90%
Degradation Rate	mV/khrs	11	4
Cell Active Area	cm^2/cell	100	100

Preliminary
AEM Electrolysis H2A Results

	Future Case Start Year: 2040	Far-Future Case Start Year: 2060
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Hydrogen Production Cost Contribution ($/kg)**
Capital Costs	$0.89	$0.62
Decommissioning Costs	$0.01	$0.01
Fixed O&M	$0.35	$0.27
Feedstock Costs	$0.00	$0.00
Other Raw Material Costs	$0.00	$0.00
Byproduct Credits	$0.00	$0.00
Other Variable Costs (including utilities)	$4.21	$4.31
Total	**$5.46**	**$5.21**

- Electricity Price is the primary cost driver of AEM electrolysis in the Future and Far-Future Cases
- Current case is driven by capital cost, due to annual stack replacement of expensive stacks
- All electricity prices increased according to AEO projections

References

References:

1. Hao, D., Shen, J., Hou, Y., Zhou, Y. & Wang, H. An Improved Empirical Fuel Cell Polarization Curve Model Based on Review Analysis. *International Journal of Chemical Engineering* **2016**, 1–10 (2016).
2. Villagra, A. An analysis of PEM water electrolysis cells operating at elevated current densities. *International Journal of Hydrogen Energy* 10 (2018).