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

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)

April 30th 2019

Project ID: P102

Overview

Timeline

- Project start date: 10/1/2016
- Project end date: 9/30/2020
- Percent complete: ~60% of project

Budget

- Total Funding Spent
  - ~$711k (through Feb. '19, including Labs)
- Total DOE Project Value:
  - ~$1.2M (over 4 years, including Lab funding)
- Cost Share Percentage: 0% (not required for analysis projects)

`

Barriers

- **Transmission Methods for Energy Carriers**
  - A: Lack of Hydrogen/Carrier and Infrastructure Options Analysis
  - D: High As-Installed Cost of Pipelines
- Hydrogen (H_2) Generation by Water Electrolysis
  - F: Capital Cost
  - G: System Efficiency and Electricity Cost
  - K: Manufacturing

Partners

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

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

Collaborators (unpaid)

- 6 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

- <u>Previously Completed Cases</u>
  - WireTough
    - High-pressure H_2 Storage at forecourt
  - The Cost of Transmitting Energy

- <u>Cases in Progress</u>
  - PEM Electrolysis
    - Update to previous case
  - Solid Oxide Electrolysis
    - Update to previous case

Water Splitting by PEM Electrolysis

Project Objective

Incorporate new PEM water splitting performance and cost data into updated H2A analyses for:

- 1,500 kg H_2/day distributed sites
- 50,000 kg H_2/day production sites
- Internally referenced PEM perf. & cost data at existing technology level
  - Existing: today's technology produced at today's low-manufacturing rates
- Two technology levels analyzed
  - Current: current technology at high-manufacturing rate
  - Future: future technology (2040) at high-manufacturing rate

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

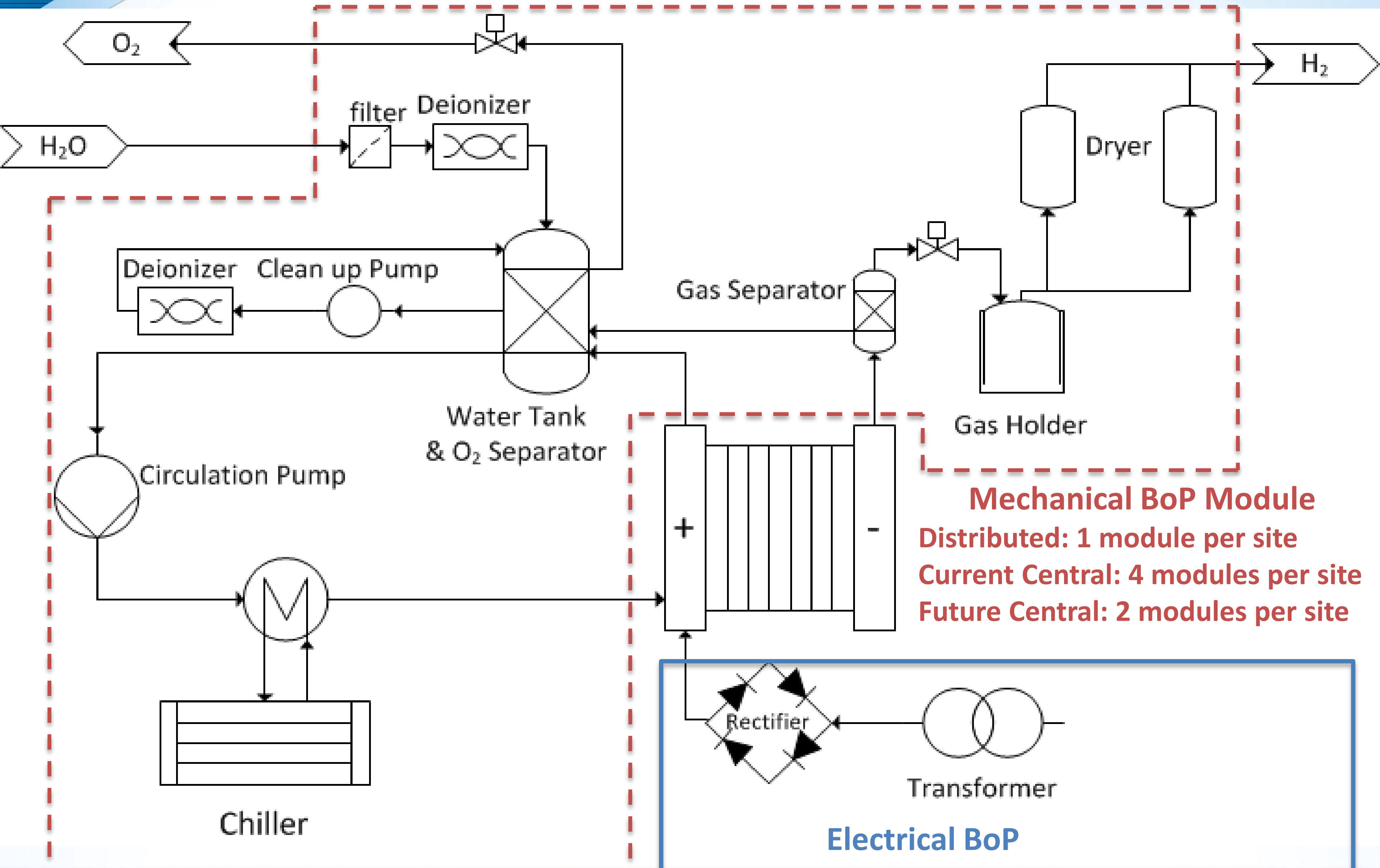
Approach to data collection

- **Surveyed multiple companies and research groups for key technical and cost parameters**
  - Responses received from 4 groups
  - Data response was limited for some parameters which often left insufficient data for statistical analysis
  - Compared with previous PEM H2A values and previous survey
- **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)

6 Key Cost Parameters For PEM Electrol.

- **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 \$/ $kW_{stack\ input}$
  - 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** (\$/$kW_{stack\ input}$)
  - Capital cost of Rectifier, Transformers

Process Flow Diagram



Mechanical BoP Module

Distributed: 1 module per site

Current Central: 4 modules per site

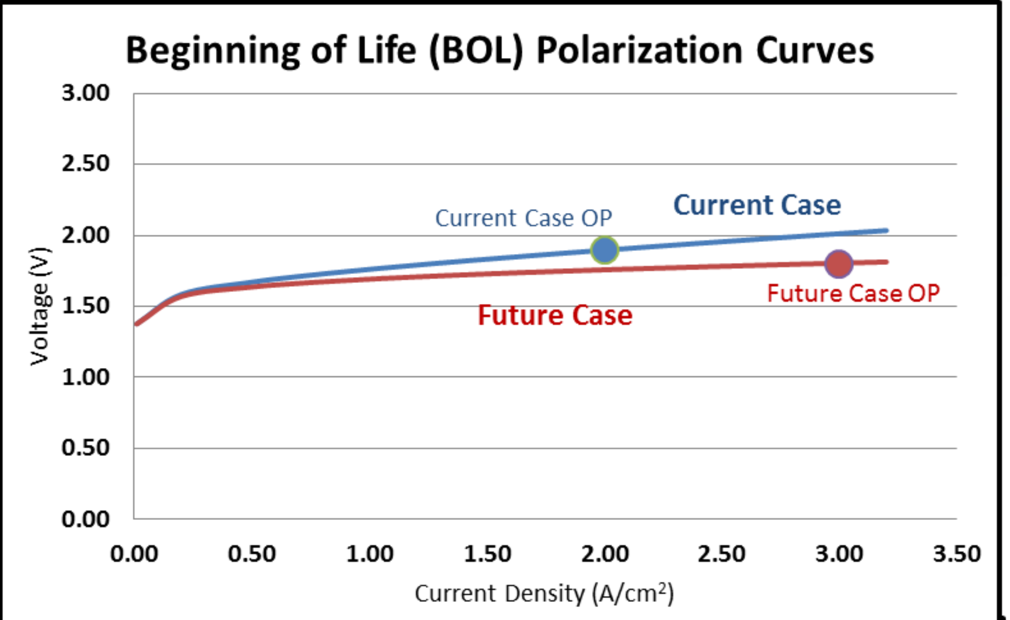
Future Central: 2 modules per site

Key Analysis Parameters for Updated Case Study

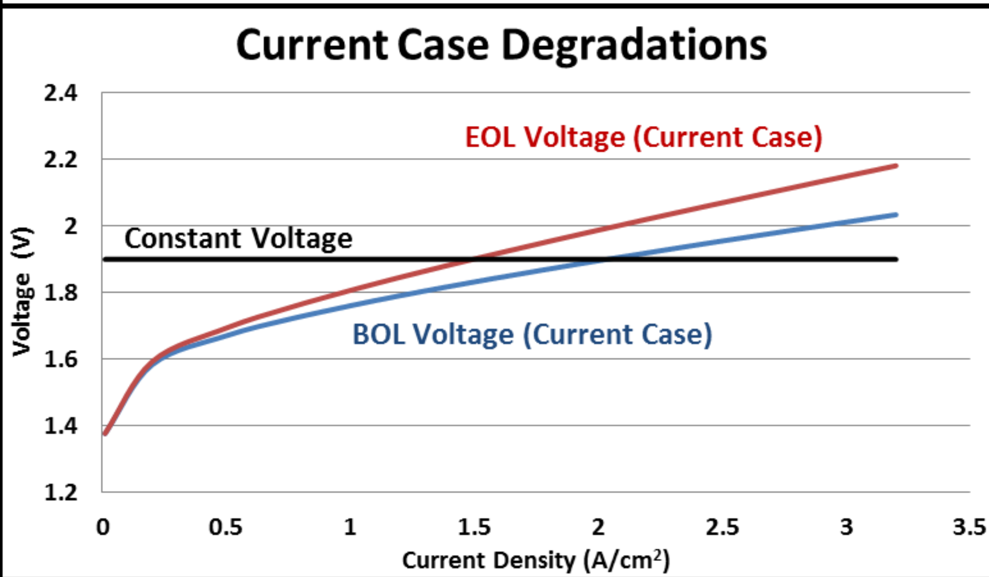
	Units	Current		Future	
		Distributed	Central	Distributed	Central
Plant Size	kg H_2 / day	1,500	50,000	1,500	50,000
Mech. BoP Modules	#	1	4	1	2
Current Density	A /cm^2	2	2	3	3
Voltage	V	1.9	1.9	1.8	1.8
Total Electrical Usage	kWh/kg H_2	55.8	55.5	51.4	51.3
Stack Electrical Usage	kWh/kg H_2	50.4	50.4	47.8	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/day)	$210	$80	$214	$76
Electrical BoP Cost	$ / kW	$189	$170	$151	$136

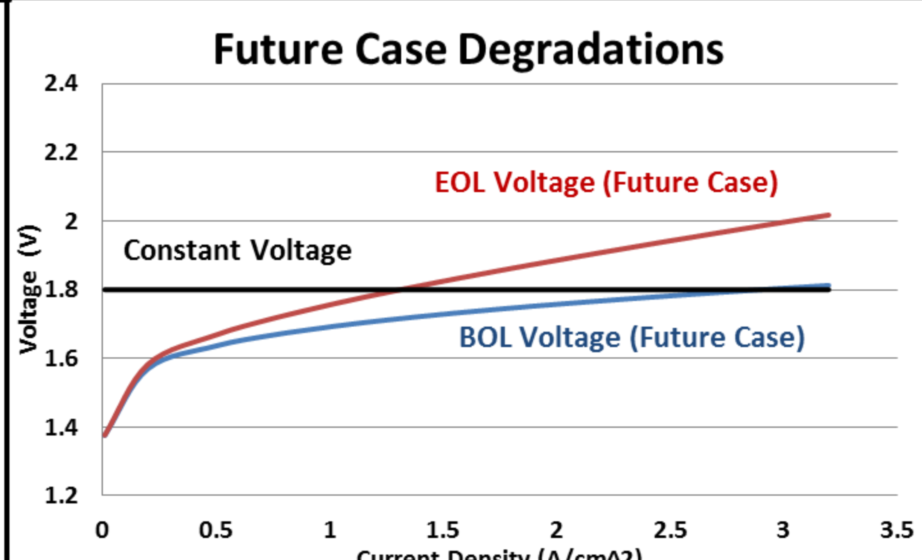
- **General agreement for current density and voltage among survey respondents**
  - Given current density and voltage, stack electrical usage can be calculated
  - Data provided for BoP Electrical Usage was consistent with values used in previous H2A cases and are unchanged
- **Limited new data provided 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
    - Six-Tenths rule of scaling

Modeled Polarization Curves



- **Using a 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
- **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

Basis for 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.

Basis for 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 6/10^{ths} 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

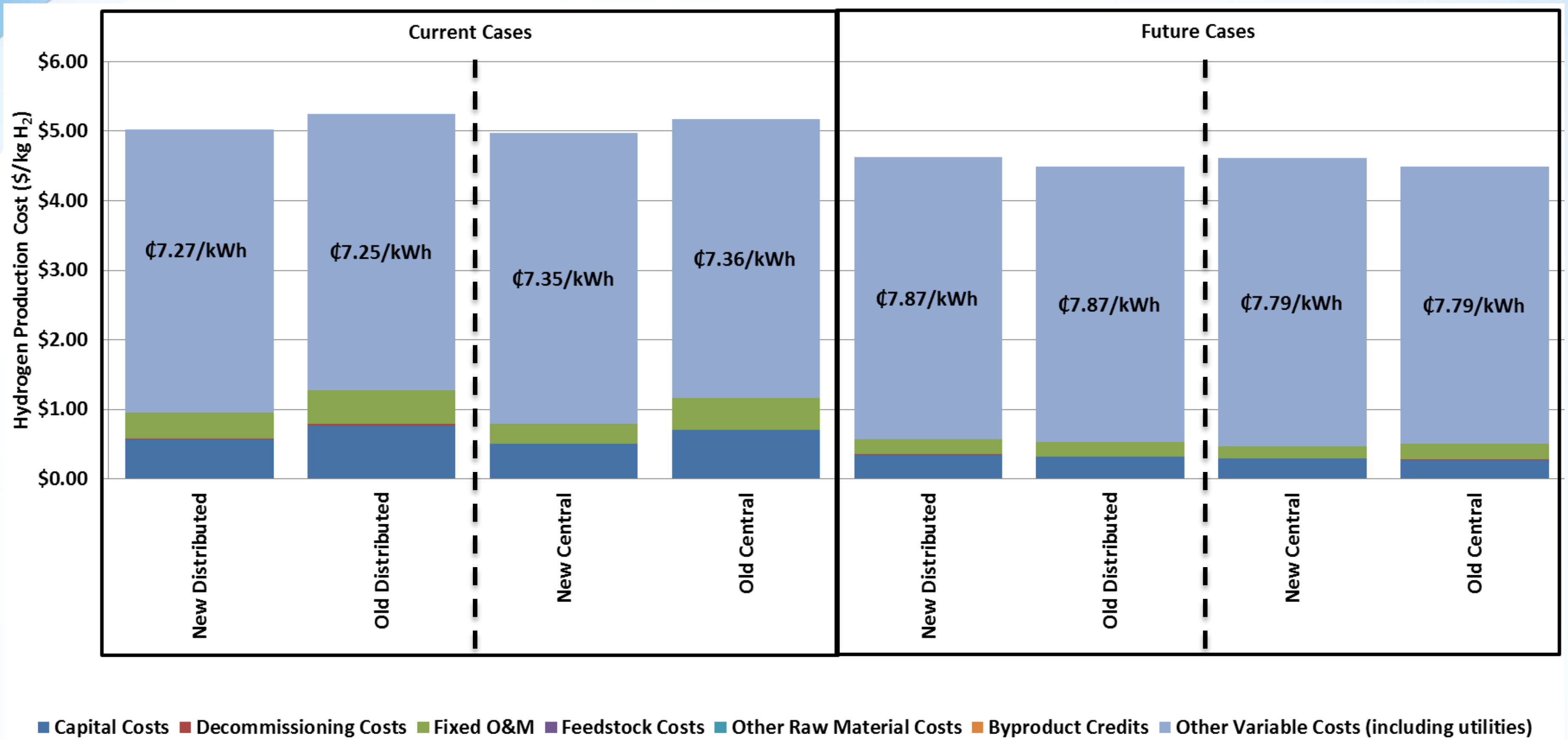
Unit	Cost ($)	Cost ($/ (kg H_2/day)
Flow Filter	$13,000	$9
Deionizing Bed	$12,600	$8
Actuated Flow Valve	$6,520	$4
Main DI Pump w/motor	$3,687	$2
Cleanup Pump w/motor	$3,687	$2
Other valves	$4,325	$3
Gas Filters	$1,611	$1
PRV	$930	$1
Heat Exchanger	$2,400	$2
DI Water Tank	$12,500	$8
Hydrogen/Water Separator 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

Basis for Electrical BoP Cost Projection

- **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

Preliminary 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

Water Splitting by Solid Oxide Electrolysis

Project Objective

Incorporate new SOE water splitting performance and cost data into an updated H2A analysis for:

- 50,000 kg H_2/day production sites
- Two technology levels
  - Current: current technology at high-manufacturing rate
  - Future: future technology (2040) at high-manufacturing rate

Approach (same approach as used in PEM electrolysis analysis)

- 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

Solid Oxide Electrolysis

- High-temperature water splitting
- Previous H2A case developed in 2015
  - Case study parameters were obtained from a questionnaire
- New questionnaires have been sent to industry and researchers
  - Responses are still coming in
  - Key parameters are similar to those of PEM
    - Temperature and thermal recuperation play a more significant role in SOEC design & cost
- A similar analysis to PEM will be conducted
  - Central plants only
- Preliminary Findings
  - Stack operation: ~800°C at 1.28 V/cell (thermo-neutral)
  - Stack operation at elevated pressure feasible
  - At high manufacturing volume, the stack may be a (relatively) low fraction of total system capital cost
    - Plant BoP costs will be very important in cost assessment

Long-Distance Energy Transmission

Project objective:

Compare the cost of long-distance, bulk transport of electrical or chemical energy independent of production method or end-use.

Approach:

- Collected cost models for each transmission method
- Incorporated additional costs into the collected models
- Compared model results for long distance transmission applications

Analysis Outline

- **Energy Transmission Methods Analyzed:**
  - Electrical Transmission Lines, Liquid Pipelines, Gas Pipelines
- **Estimate capital cost based on existing cost models but normalized to our specs**
  - Compare costs for 1,000 miles of transmission
  - Compare all costs on an even basis
    - Present data as $/mile (traditional) as well as $/mile-MW and $/MWh
  - Models include CapEx for materials, labor, Right of Way (ROW), pumping/compression stations, and miscellaneous expenses
- **Develop total costs for transmitting energy**
  - Some sources report capital cost as the total cost of transmission
    - A few studies suggest that a set percentage of the total transmission cost is the capital cost
    - Transmission cost should include capital cost and operating cost
  - Include costs of pumping and compressor stations for pipelines
  - Include transmission line losses for electrical lines
- **Costs for electricity production, fuel production, and fuel conversion are not included**

Cost Metrics

- Most studies compare electrical & pipeline cost on $/mile basis
  - Does not account for capacity
  - Only represents capital cost
  - Usually shows electrical and pipeline capital cost on a similar order of magnitude
- By comparing the transmission cost on a $/mile-MW basis, the capacity of the transmission method is included
- Amortizing the capital cost to derive an annual capital repayment amount allows for a comparison of total transmission cost in operating $/MWh

Thus we compare transmission methods on three bases:

- **$Capital Cost/mile, $Capital Cost/mile-MW, and $Operating/MWh**

Electrical Transmission Lines

- Modeled parameters:
  - Aluminum Core Steel Reinforced (ACSR) lines on a new lattice structure
  - 500 kV HVDC lines modeled with 2 substation locations
  - Terrain estimates are broken up evenly between 8 types, ranging from flat ground to wetland & mountain terrain
  - Similarly, Right-Of-Way (ROW) costs are broken up into 12 zones, evenly distributed among each zone for a representative model
- Capital costs and resistive losses are based on *Capital Costs for Transmission and Substations*. (2014)
  - Electrical line losses based on line resistance ($P=I^2*R$) at maximum current per circuit

Representative transmission tower. Courtesy of wikicommons.com

Assumptions consistent with large-scale transmission.

Gas & Liquid Pipelines

- Pipeline cost models taken from literature (Rui et al)
  - Pipeline models are derived from *Oil and Gas Journal* data.
  - Data is for on-shore, natural gas pipelines from 1992-2008.
  - No reliable cost data was found for liquid pipelines. Following common practice, the same cost models used for gas pipelines were also used for liquid pipelines.
- Pipeline cost models predict materials, labor, ROW, and miscellaneous expenses.
- Pumping/Compression models were further incorporated for a complete model
  - Models were optimized for lowest cost (by selecting optimal pumping station spacing)
  - Capital costs and operating power requirements were assessed
  - Power (purchase) requirements were costed at 5 cents/kWh

Transmission Method	Liquid Pipeline			Gas Pipeline	
Energy Carrier	Crude Oil	Methanol	Ethanol	Nat Gas	Hydrogen
Pipe diameter (in)	36	36	36	36	36
Flow velocity (m/s)	3.7	3.9	3.9	18	18
Pressure Drop (bar/mile)	2.5	2.5	2.5	0.67	0.19
Pump / compressor load (MW/station)	29	30	30	39	18
Pipeline Operating Power (MW/1000mi)	715	757	758	464	162

Assumptions consistent with large-scale transmission.

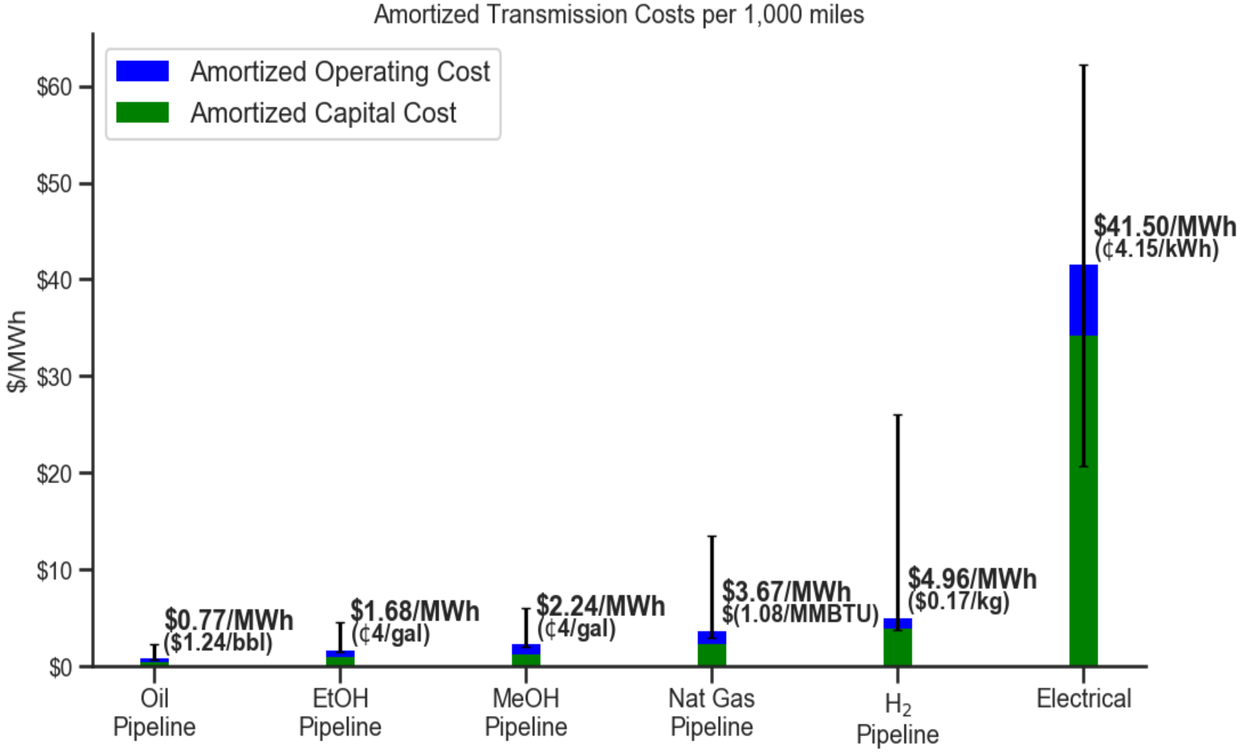
Pipelines – Special Cases

Whereas, natural gas and oil pipelines are common, other gases/liquids require special consideration:

- **Ethanol and Methanol**
  - Proof of existence case: Kinder-Morgan modified a 106-mile pipeline to carry ethanol.
    - Cost of these modifications were linearly scaled with length and surface area and added to pipeline capital cost models for ethanol and methanol.
  - No methanol analogue has been reported. Ethanol cost modifications were assumed to be suitable for methanol.
- **Hydrogen**
  - Recent paper by Fekete *et al* describes material and labor cost adders to account for steel thickness and welding differences between natural gas and hydrogen pipelines.
  - Proposes that, under upcoming ASME changes, the material and labor costs of hydrogen pipelines will be approximately 8% higher than natural gas lines.

Amortized Transmission Cost

Interest (Discount) Rate	Operating Expenses	Misc. Costs per year	Maintenance Costs per Year	Corporate Tax Rate	Capital Recovery Factor	Equipment Lifetime (Amort. Period)
8%	Pump/Comp. costs + 0.5% of Pipeline Cost	5% of CapEx	5% of CapEx	26.6%	~12%	Pipelines: 33 yrs Elect. Line: 60 yrs



1. **Capital cost is amortized over equipment life time.**
2. **Annual Operational expenses included in amortization.**
3. **Operating cost consist of Pumping/Compression costs and Other Oper. Costs. Pump/Compr. Cost based on calculation of station capital cost and power required. Other Oper. Cost estimated at 0.5% of the capital cost of the pipeline only per year.**

All data is for transmission in the base energy state and does not include costs for converting any fuels to electricity for use in electrical applications.

Results

(Relatively) Low-Capacity drives electrical transmission costs up.

Liquids have high energy densities and low pumping costs

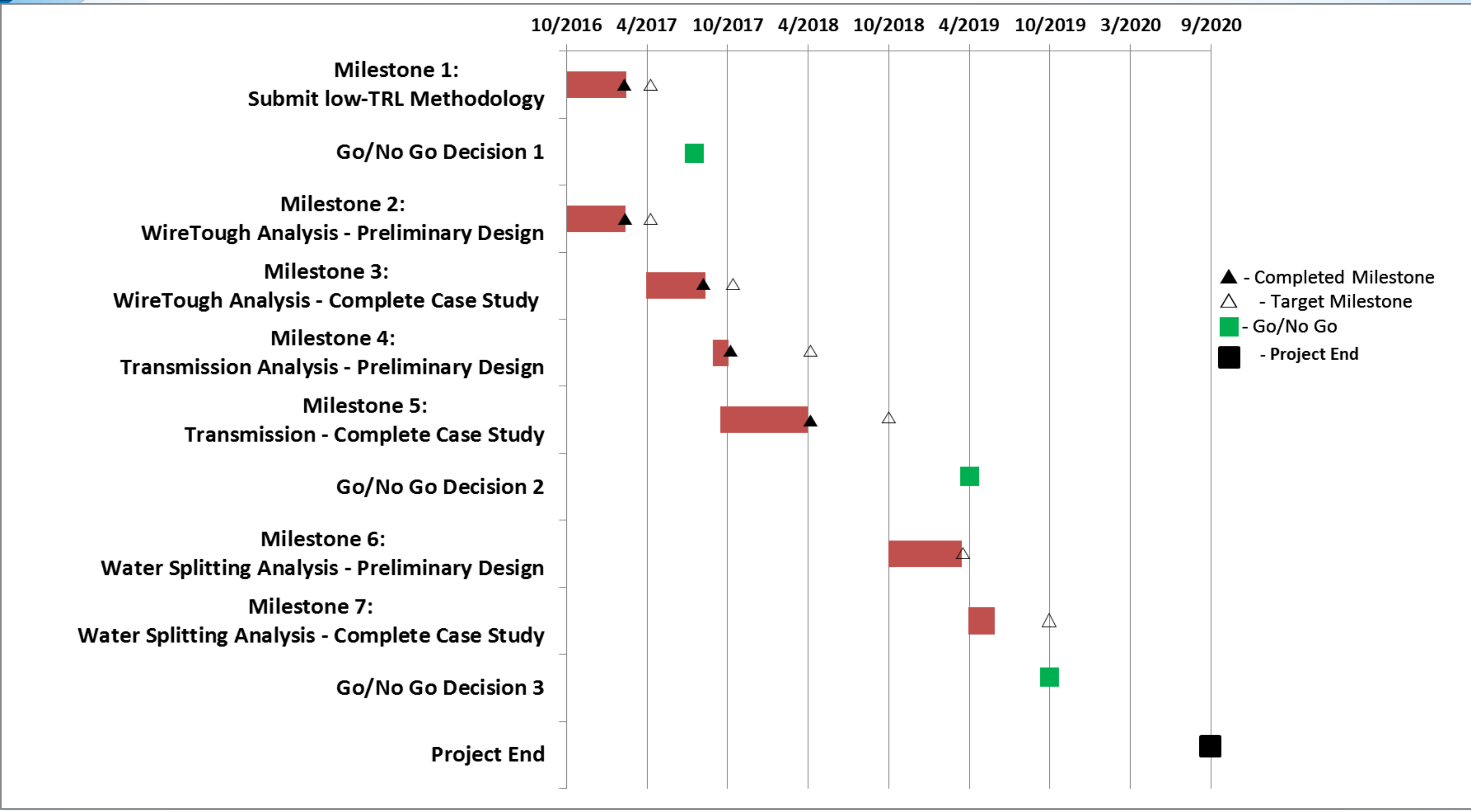
	Electrical	Liquid Pipeline			Gas Pipeline	
Energy Carrier	HVDC	Crude Oil	MeOH	EtOH	NG	H_2
Total flow (Amp, kg/s)	6,000	1,969	1,863	1,859	368.9	69.54
Delivered power (MWe, MW_{LHV})	2,656	91,941	37,435	50,116	17,391	8,360
Capital Cost ($M/mile)	$3.90	$1.47	$1.92	$1.92	$1.69	$1.38
Transmission Power Loss	12.9%	0.78%	2.02%	1.51%	2.67%	1.94%
Capital Cost ($/mile MW)	$1,467	$16	$51	$38	$97	$166
Amortized Cost ($/MWh/1000 mi)	$41.5	$0.77	$2.2	$1.7	$3.7	$5.0
Assumed fuel utilization eff	100%	25%	25%	25%	33%	60%
Normalized cost of transmission ($/MWh)	$41.5	$3.1	$8.8	$6.8	$11.2	$8.3

Electrical transmission faces high cost for sending electricity

Status of Energy Transmission Analysis

- Preliminary results reported in 2017 AMR
- Since then, analysis extensively reviewed by DOE, researchers, and industry
  - Updates made at the request of various reviewers
  - Incorporated a presumed fuel efficiency to better account for the conversion of fuel to electricity for use in automobiles or other electrical applications
- Thorough documentation of work in 2018
  - Detailed report has been provided to DOE

Project Status



Project On-Schedule

Some deliverable tasks completed ahead of schedule

Proposed Future Work

- **Complete PEM Electrolysis H2A analysis**
  - Sensitivity analysis
  - Error analysis
  - Industry review
  - Documentation
- **Solid Oxide Electolyzer H2A Analysis**
  - Performance and Cost assessment
  - Sensitivity/Error analysis, Industry Review, Documentation
- **Other P&D cost analysis as directed by DOE**
  - Photoelectrochemical (PEC) hydrogen production
  - Solar Thermochemical Hydrogen (STCH) production
- **Continuing coordination between FCTO sub-areas**
  - Production and 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**
  - Completed an Energy Transmission Cost analysis
    - Incorporates metrics beyond a simple cost per mile analysis
  - H2A Model and Case Study Updates
  - Preliminary update of PEM technoeconomic analysis
  - Initiation of SOEC technoeconomic analysis

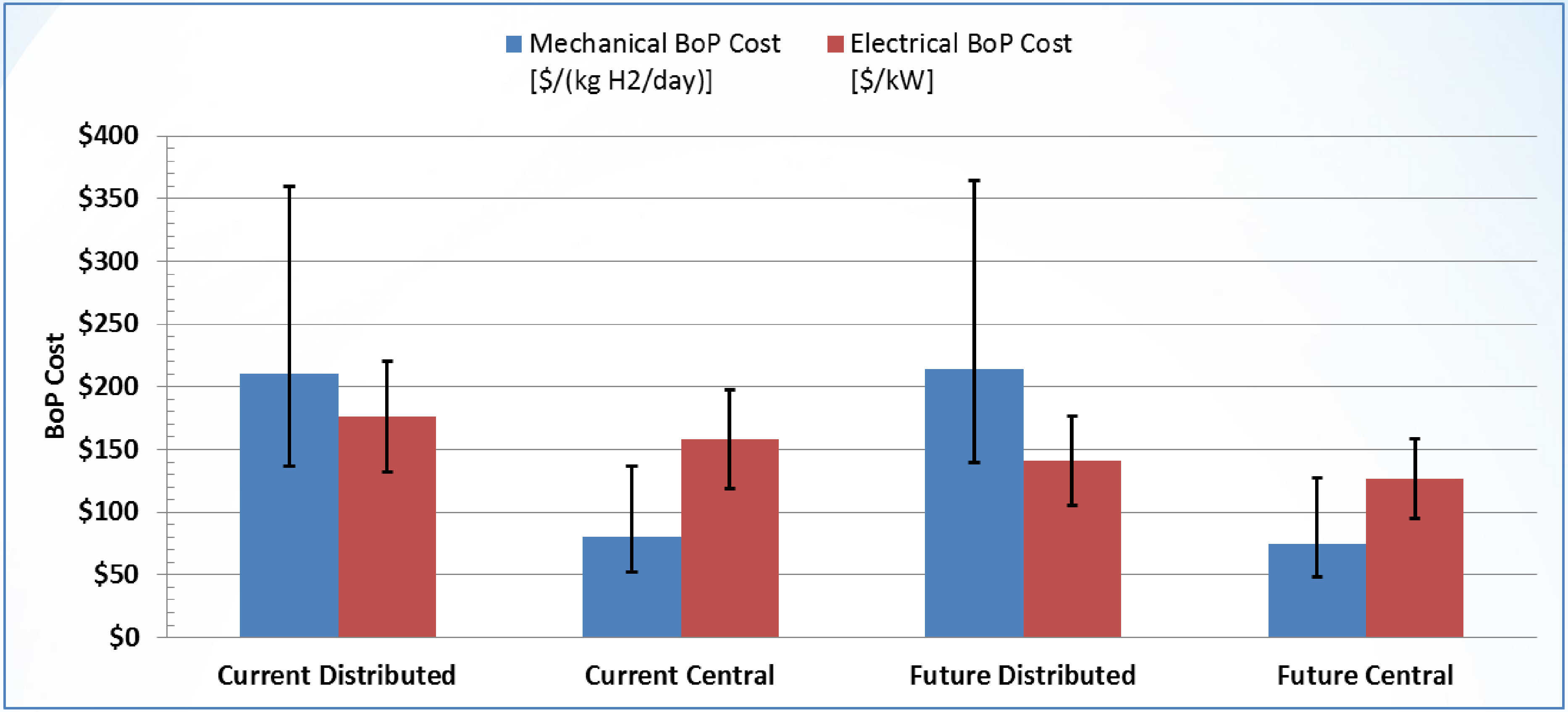
Backup Slides

Preliminary H2A Cost Results

	Current				Future			
	Distributed		Central		Distributed		Central	
	2019 Study Results	2013 Study Results	2019 Study Results	2013 Study Results	2019 Study Results	2013 Study Results	2019 Study Results	2013 Study Results
Capital Costs	\$0.57	\$0.77	\$0.51	\$0.70	\$0.35	\$0.31	\$0.29	\$0.27
Decommissioning Costs	\$0.01	\$0.02	\$0.00	\$0.00	\$0.01	\$0.01	\$0.00	\$0.00
Fixed O&M	\$0.37	\$0.48	\$0.28	\$0.46	\$0.22	\$0.20	\$0.17	\$0.23
Feedstock Costs	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	
Other Raw Material Costs	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Byproduct Credits	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Other Var. Costs (including utilities)	\$4.07	\$3.98	\$4.18	\$4.01	\$4.06	\$3.97	\$4.15	\$3.98
Total Production Cost	**\$5.02**	**\$5.25**	**\$4.97**	**\$5.18**	**\$4.63**	**\$4.50**	**\$4.61**	**\$4.49**
CSD Cost	\$2.07	\$1.75	N/A	N/A	\$2.00	\$1.74	N/A	N/A
Total P&D Cost	**\$7.09**	**\$7.00**	**\$4.97**	**\$5.18**	**\$6.63**	**\$6.24**	**\$4.61**	**\$4.49**

All costs listed are in \$/kg H_2

BoP Error ranges



- Mechanical BoP Cost based on quotes and scaling. Estimated error range is +/- 68%.
- Electrical BoP Cost based on quotes for transformer-rectifier. Estimated error range is +/- 25%.