Hydrogen Pathways Analysis for Polymer Electrolyte Membrane (PEM) Electrolysis

Project ID: PD102

2014 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Strategic Analysis Inc.

Whitney G. Colella (Presenter)

Brian D. James (PI)

Jennie M. Moton

June 16-20, 2014

Overview

Timeline

- Project start date: 3/15/2013
- Project end date: 3/14/2016
- Percent complete: 27%

Budget

- Total Funding Spent*
  - $271 thousand dollars (K) (total)
    - $197 K Strategic Analysis (SA)
    - $56 K National Renewable Energy Laboratory (NREL)
    - $18 K Argonne National Laboratory (ANL)
- Total DOE Project Value
  - $1 million (M) for all 3 years
- Cost Share Percentage: 0%

(not required for analysis projects)

Barriers

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)**

Collaborators

- Four electrolyzer companies

(names not included in public documents)

* as of 3/31/14

** denotes subcontracted through DOE internal funding mechanism

Relevance and Impact

The objectives of this project include

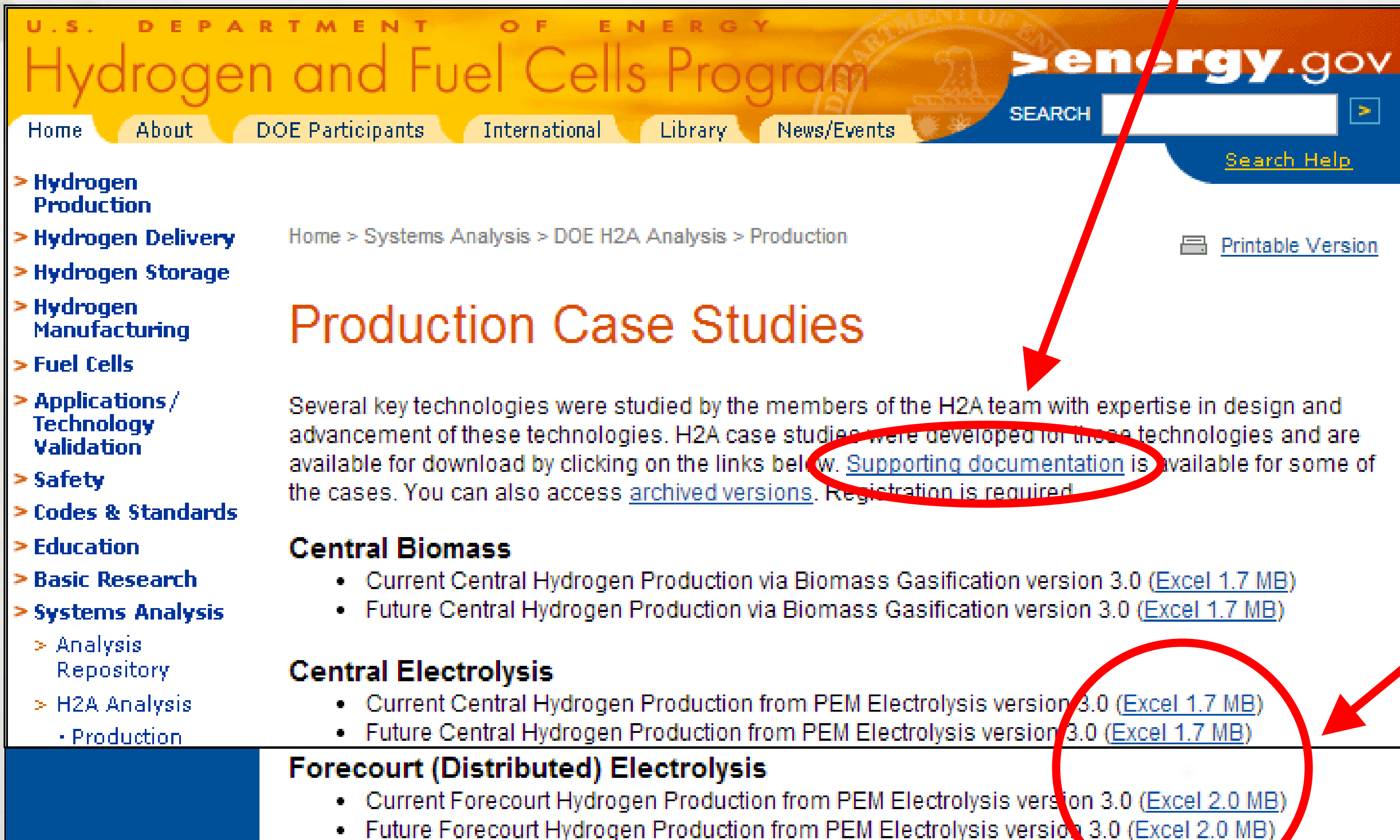
1) Analyze H_2 Production & Delivery (P&D) pathways to determine the most economical, environmentally-benign, and societally-feasible paths for the P&D of H_2 fuel for fuel cell vehicles (FCVs).
2) Identify key "bottlenecks" to the success of these pathways, primary cost drivers, and remaining R&D challenges.
3) Assess technical progress, benefits and limitations, levelized H_2 costs, and potential to meet U.S. DOE P&D cost goals of \$2 to 4 per gasoline gallon equivalent (gge) (dispensed, untaxed) by 2020.
4) Provide analyses that assist DOE in setting research priorities.
5) Apply the H2A Production Model as the primary analysis tool for projection of levelized H_2 costs (\$/kgH_2) and cost sensitivities.

In 2013-2014, these project objectives were applied to develop a validation case based on H_2 generation with standalone, grid-powered Polymer Electrolyte Membrane (PEM) electrolyzers.

- Impact: In 2013-2014, the PEM electrolysis validation case study investigated Barriers F, G, and K and is posted online here: http://www.hydrogen.energy.gov/h2a_prod_studies.html

The PEM Electrolysis Validation Case Study is available for download: http://www.hydrogen.energy.gov/h2a_prod_studies.html

Download final report and summary presentation slides here.


U.S. DEPARTMENT OF ENERGY
Hydrogen and Fuel Cells Program
energy.gov
Home | About | DOE Participants | International | Library | News/Events
SEARCH
Search Help

- Hydrogen Production
- Hydrogen Delivery
- Hydrogen Storage
- Hydrogen Manufacturing
- Fuel Cells
- Applications/ Technology Validation
- Safety
- Codes & Standards
- Education
- Basic Research
- Systems Analysis
  - Analysis Repository
  - H2A Analysis
    - Production

Home > Systems Analysis > DOE H2A Analysis > Production

Printable Version

Production Case Studies

Several key technologies were studied by the members of the H2A team with expertise in design and advancement of these technologies. H2A case studies were developed for these technologies and are available for download by clicking on the links below. Supporting documentation is available for some of the cases. You can also access archived versions. Registration is required.

Central Biomass

- Current Central Hydrogen Production via Biomass Gasification version 3.0 (Excel 1.7 MB)
- Future Central Hydrogen Production via Biomass Gasification version 3.0 (Excel 1.7 MB)

Central Electrolysis

- Current Central Hydrogen Production from PEM Electrolysis version 3.0 (Excel 1.7 MB)
- Future Central Hydrogen Production from PEM Electrolysis version 3.0 (Excel 1.7 MB)

Forecourt (Distributed) Electrolysis

- Current Forecourt Hydrogen Production from PEM Electrolysis version 3.0 (Excel 2.0 MB)
- Future Forecourt Hydrogen Production from PEM Electrolysis version 3.0 (Excel 2.0 MB)

Download Excel models to review assumptions and calculations in detail here.

Project milestones are up to date.

Milestone Number	Project Milestone	Progress Notes	Percent Complete
Year 1 Milestone 1	Delivery of Project Management Plan	Final version submitted to DOE	100%
Year 1 Milestone 2	Delivery of Validation Case Study (on PEM Electrolysis)	Final versions of Excel models, final report, and slide presentation submitted to DOE	100%
Year 2 Milestone	Completed Year 2 Case Studies	Work begun on biofermentation and solid oxide electrolysis cell (SOEC) studies.	5%
Year 3 Milestone	Completed Year 3 Case Studies		0%

Go/No-Go Decision	Evaluation Criteria	Progress Notes
Year 2 Go/No-Go Decision 1	Satisfactory results from the validation case study.	Complete
	Timely completion of assigned case studies.	On track
	Technical soundness of all analysis.	Demonstrated To-Date
	Appropriateness & justification of assumptions.	Demonstrated To-Date
	Ability to work cooperatively with researchers.	Demonstrated To-Date
	Responsiveness to the DOE/DOE Tech Team direction.	Demonstrated To-Date

The team is on-track to succeed in future milestones and go/no-go decisions.

An iterative approach was applied to develop the PEM Electrolysis Validation Case Study.

1. Select technology pathway
2. Collect information from Researchers/Developers
    - System configuration details
    - System performance
    - Emissions
    - Technical status
    - All other relevant issues, concerns, shortfalls
3. Conduct Techno-economic analysis
    - System definition
        - Develop mass and energy balance models, where appropriate
    - Define system Bill of Materials (BOM)
    - Estimate capital costs
    - Define system performance parameters
        - feedstock/energy consumption rates
        - labor, equipment lifetime, replacement schedule, etc.
    - System performance analysis
4. Model system in DOE's H2A H_2 Production Cost model (Version 3)
5. Initial results vetted with researchers/developers/DOE
6. Conduct sensitivity analysis based on feedback
7. Repeat steps 2 through 6 until team is confident in results

The team gathered data for five PEM electrolysis cases.

Four developed into public cases. One (Existing Case) not public due to corporate sensitivities.

Existing Case ("if you were fabricating today at current volume at the highest capacities")

- Data gathered and case modelled for forecourt-sized H_2 production capacity, but case not publically available due to corporate sensitivities. Based on low volume production.
- Results provide a point of comparison for public cases.

Current Case ("if you were fabricating today at production volume")

- Case assumes high volume production that incorporates economies of scale.
- Demonstrated advances in technology are implemented.
- Potential reduction in capital cost from existing values.
- Plant lifetimes consistent with measured or reported data.

Future Case ("if you were fabricating in the future at production volume")

- Case assumes high volume production that incorporates economies of scale.
- Case assumes new materials and systems with higher H_2 production efficiency, longer plant lifetime, and improved replacement cost schedule.
- Case assumes greater reductions in capital cost

Public Cases	Plant Start Date	Production of H_2 (kilograms (kg)/day)	Plant Life (years)
Current Forecourt	2010	1,500	20
Future Forecourt	2025	1,500	20
Current Central	2010	50,000	40
Future Central	2025	50,000	40

The team gathered technical & economic data from electrolyzer companies and synthesized data into five generalized H2A cases.

The team

- Developed a detailed, quantitative questionnaire soliciting engineering and economic performance data.
- Asked four electrolyzer companies to independently respond to the questionnaire.
- Requested relevant detailed information on:
  - Existing case for Forecourt. (non-public case used for benchmarking purposes)
  - Current and Future cases for Forecourt and Central production. (four public cases)
  - Followed H2A Production model sheet input format:
    - System definition
    - Operating conditions
    - Variable and fixed expenses
    - Capital costs
    - Replacement costs
- Analyzed questionnaire data, and synthesized and amalgamated data into five generalized cases.
- Ensured that four electrolyzer companies vetted the public cases and their sensitivity limits.
- Populated five H2A Production Models and ran models to predict levelized H_2 cost, key cost drivers, and sensitivities.

The four public H2A cases use this input data, which is based on an amalgamation of performance data from four electrolyzer companies.

	Forecourt		Central	
	Current	Future	Current	Future
Technical Parameters				
Production Equipment Availability Factor (%)	97%	97%	97%	97%
Plant Design Capacity (kg of H2/day)	1,500	1,500	50,000	50,000
Single Unit Size (kg/day)	500	750	500	750
System Energy (kW)	3413	3144	113,125	104,583
System H2 Output pressure (psi)	450	1000	450	1000
System O2 Output pressure (psi)	14	14	14	14
Direct Capital Costs				
Basis Year for production system costs	2012	2012	2012	2012
Uninstalled Cost - ($/kW) (with suggested subsystem breakdown, further breakdown desirable if available)	940	450	900	400
Stacks	**41%**	**38%**	**47%**	**37%**
BoP Total	**59%**	**62%**	**53%**	**63%**
Hydrogen Gas Management System-Cathode system side	10%	6%	9%	1%
Oxygen Gas Management System-Anode system side	5%	2%	3%	1%
Water Reacant Delivery Management System	6%	5%	5%	1%
Thermal Management System	5%	5%	5%	7%
Power Electronics	20%	26%	21%	44%
Controls & Sensors	3%	6%	2%	1%
Mechanical Balance of Plant-ss plumbing/copper cabling/Dryer valves...	5%	5%	5%	2%
Item Breakdown- Other	1%	2%	1%	3%
Item Breakdown-Assembly Labor	4%	5%	2%	3%
Installation factor (a multiplier on uninstalled cap cost)	1.12	1.1	1.12	1.1
Indirect Capital Costs				
Site Preparation ($) (may change to construction costs)	18.85%	18.85%	2%	2%
Engineering & design ($ or %)	50,000	50,000	8%	8%
Project contingency ($)	15%	15%	15%	15%
Up-Front Permitting Costs ($ or %) (legal and contractors fees included here)	30,000	30,000	15%	15%
Replacement Schedule				
Replacement Interval of major components (yrs)	7	10	7	10
Replacement cost of major components (% of installed capital)	15%	12%	15%	12%
O&M Costs-Fixed				
Licensing, Permits and Fees ($/year)	1,000	1,000		
Yearly maintenance costs ($/yr) (Please specify in notes types of activities)	3.2%	2.8%	3%	3%
O&M Costs - Variable				
Total plant staff (total FTE's)	0	0	10	10
Feedstocks and Other Materials				
System Electricity Usage (kWh/kg H2)	**54.6**	**50.3**	54.3	50.2
Minimum Process water usage (gal/kg H2)	4.76	3.98	4.76	3.98
Cooling water usage (gal/kg H2)	0	0	0	0
Compressed Inert Gas (Nm3/kg H2)	0	0	0	0

- This H2A Production model input data is a synthesis of the views of several companies. These numbers can be referenced against specific company viewpoints.
- Companies verified the validity of this input data.
- No sensitive information from companies was publicly disclosed.
- Similar data was developed for an Existing Forecourt Case (not shown due to corporate sensitivities).
- Large capital cost reductions predicted between Existing and Current systems, and between Current and Future systems.

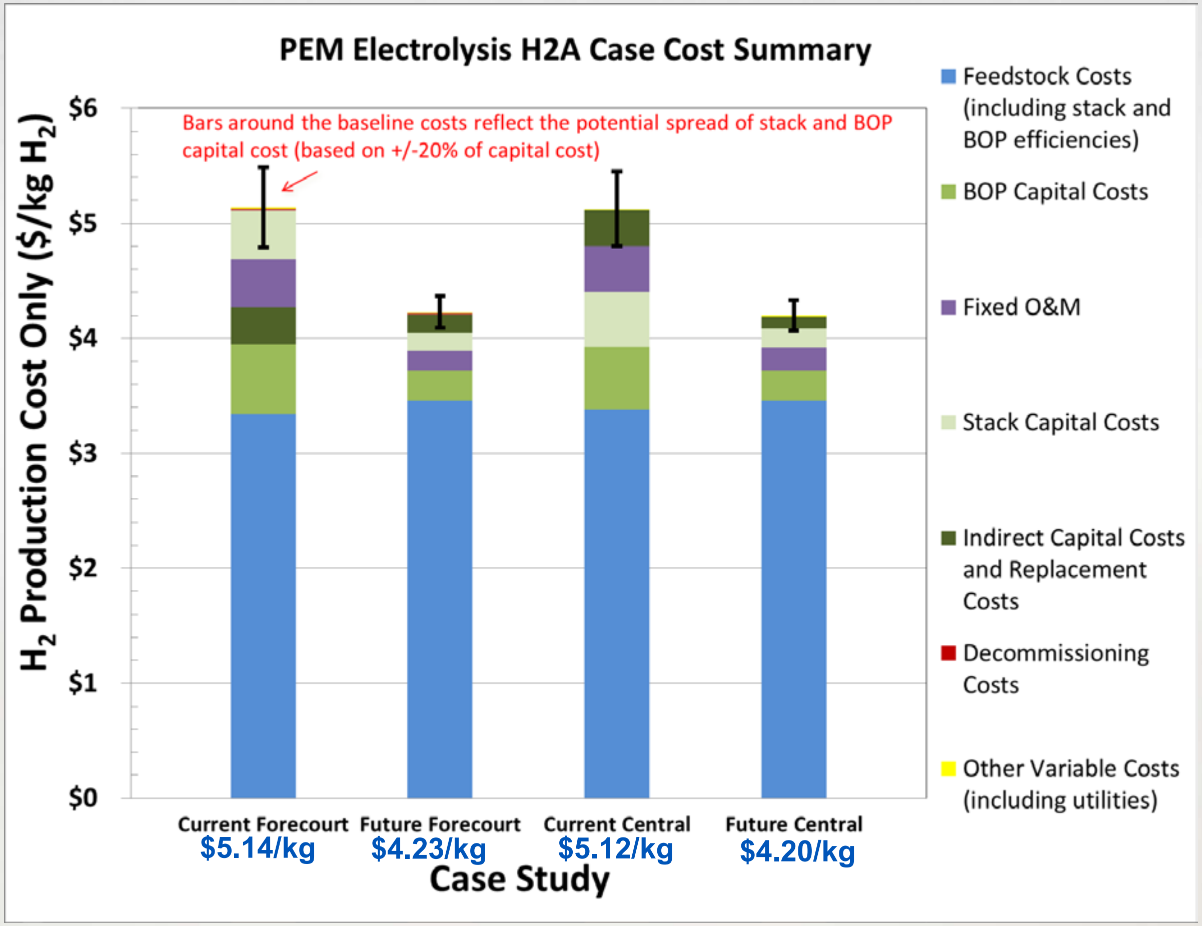
H2A calculates the levelized cost of H_2 as \$4-5/kg, based on these inputs. Capital cost and electrical usage vary, and are key cost drivers.

Parameter	Current Forecourt	Future Forecourt	Current Central	Future Central
Levelized Cost of H_2 (2007\$/kg H_2)	\$5.14	\$4.23	\$5.12	\$4.20
Plant Capacity (kg day)	1,500	1,500	50,000	50,000
Total Uninstalled Capital (2012\$/kW)	\$940	\$450	\$900	\$400
Stack Capital Cost (2012\$/kW)	\$385	\$171	\$423	\$148
Balance of Plant (BOP) Capital Cost (2012\$/kW)	\$555	\$279	\$477	\$252
Total Electrical Usage (kWh/kg) (% LHV H_2)	54.6 (61%)	50.3 (66%)	54.3 (61%)	50.2 (66%)
Stack Electrical Usage (kWh/kg)	49.2 (68%)	46.7 (71%)	49.2 (68%)	46.7 (71%)
BOP Electrical Usage (kWh/kg)	5.4	3.6	5.1	3.5
Electrolyzer Power Consumption (MW)	3.4	3.1	113.1	104.6
Average Electricity Price[1] (2007¢/kWh)	6.12	6.88	6.22	6.89
Electricity Price in Startup Year[2] (H2A Default Values) (2007¢/kWh)	5.74	6.59	5.74	6.59
Hydrogen Outlet Pressure (psi)	450	1,000	450	1,000
Installation Cost (% of Total Capital)	12%	10%	12%	10%
Replacement Interval (years)	7	10	7	10
Replacement Cost of Major Components (% of installed capital cost)	15%	12%	15%	12%

[1] Average electricity price over life of plant (20 years for Forecourt cases and 40 years for Central cases)

[2] H2A Default Values from Energy Information Administration (EIA) Annual Energy Outlook (AEO) data.

All cases reflect a \$4-5/kg cost for H_2 production.* Electricity costs are the key cost driver.



** On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3 tool (reflecting production costs only)*

- The current cases (\$5.14 vs. \$5.12) are similar to each other in cost.
- The future cases (\$4.23 vs. \$4.20) are similar to each other in cost.
- The H_2 cost reduction is greater in moving from a Current to a Future case, compared with moving from a Forecourt to a Central case.
- Feedstock costs (electricity expenditures) are 65-80% of total costs.
- To reduce cost: increase efficiency and/or decrease electricity price.

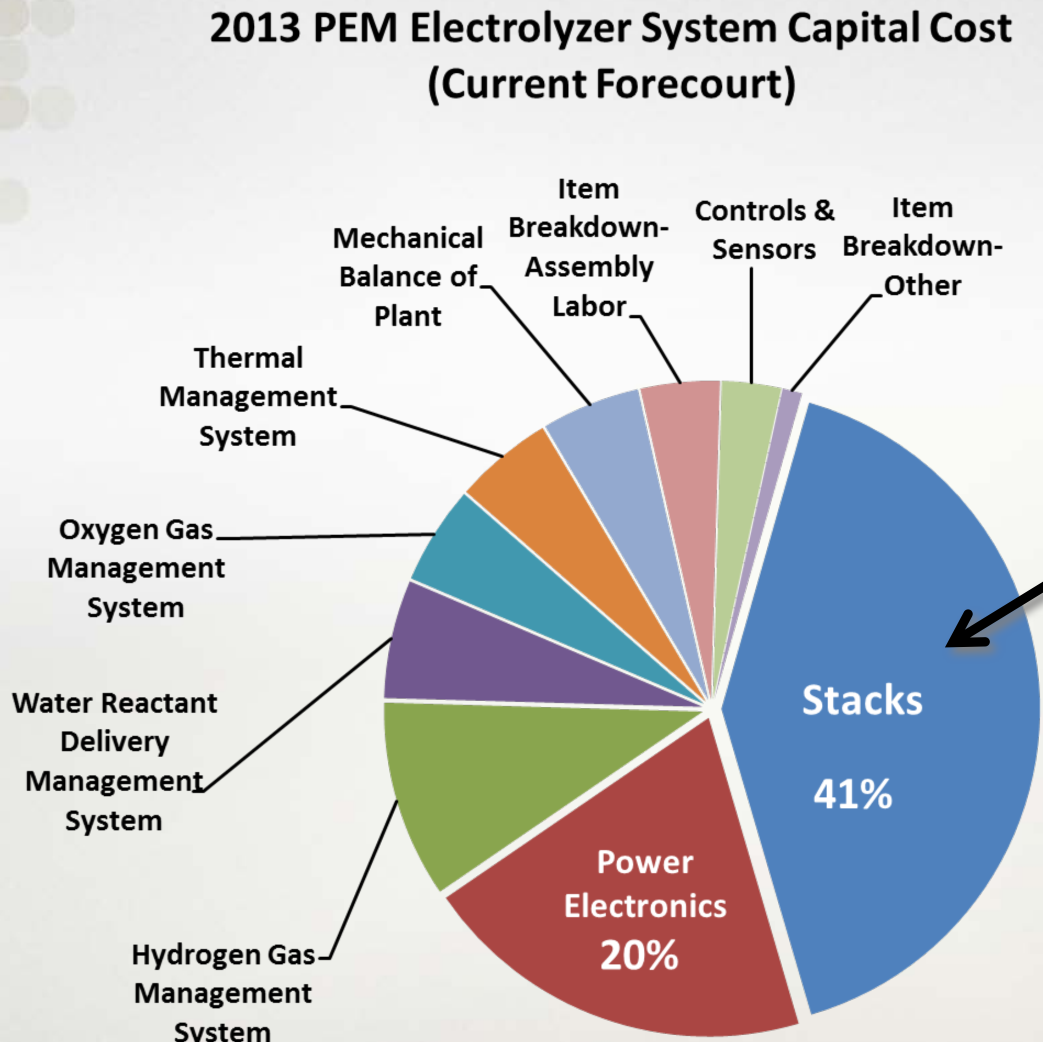
The primary cost drivers for the levelized H_2 cost are (1) electricity cost, (2) electrolyzer electrical efficiency, and (3) electrolyzer capital cost.

1) **Electricity Cost (¢/kWh)**
   a. Based on Annual Energy Outlook (AEO) Reference Tables or DOE Target values
   b. Not governed by PEM electrolysis technology (but relates to electrical efficiency)

2) **Electrolyzer Electrical Efficiency (kWh/kg H_2)**
   a. Stack efficiency based on operating voltage and influenced by H_2 permeation losses.
   b. BOP efficiency based on power inverter module, rectifier, and dryer efficiencies
   c. SA selected stack operating points based on industry feedback for PEM electrolyzer: 1.75 Volts (V) at 1,500 milliamps per centimeter squared (mA/cm^2) (Current Case) and 1.65 V at 1,600 mA/cm^2 (Future Case)

3) **Electrolyzer Capital Cost ($)**
   a. Methodology: Compared and contrasted industry data. Then used a weighted average of individual components based on company stack, balance of plant, and system production experience.
   b. The quality of the PEM electrolysis industry feedback facilitated providing greater detail in the cost breakdown for systems and reflects a more accurate, albeit higher, capital cost for PEM electrolyzers than in previous published H2A Production Model electrolyzer analyses.

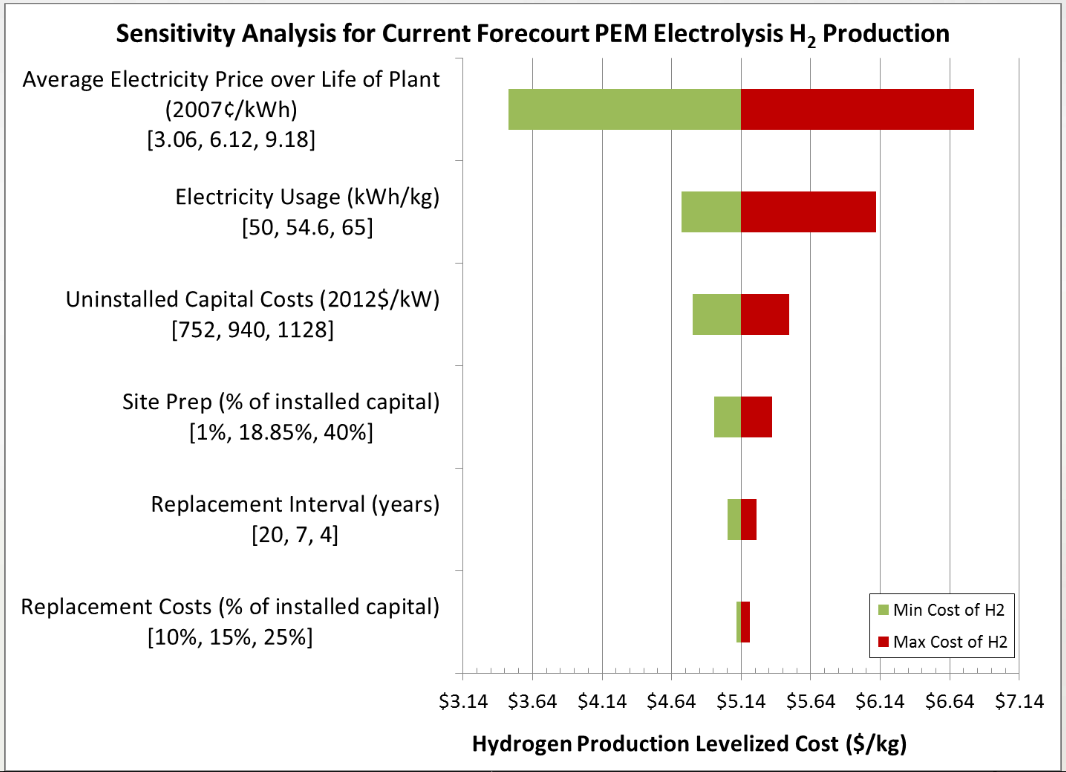
A unique contribution of this work is the detailed capital cost breakdown.



Stack costs are the main cost driver for system capital costs.

Stack, power electronics, and hydrogen gas management sum to a combined 71% of total system capital cost. Within the stack cost (blue pie piece), the combined membrane, catalyst, anode, and cathode costs make up ~60% of the stack capital costs (not plotted due to corporate sensitivities).

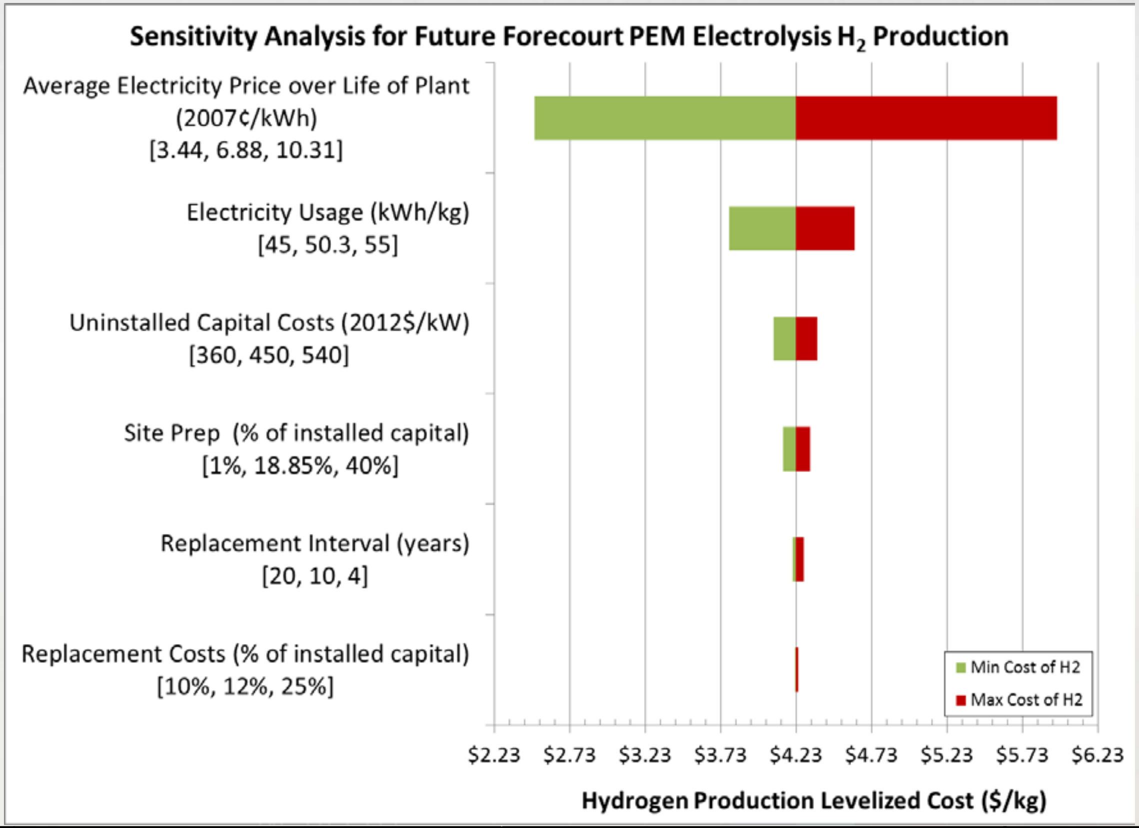
Tornado Chart shows results for single variable sensitivity analysis for Current Forecourt Case. Levelized H_2 cost is most greatly influenced by electricity price, electricity usage, and capital costs.



Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.06¢/kWh	$3.47	6.12¢/kWh	$5.14	9.18¢/kWh	$6.81
Electricity Usage	50kWh/kg	$4.71	54.6kWh/kg	$5.14	65kWh/kg	$6.11
Uninstalled Capital Costs	$752/kW	$4.79	$940/kW	$5.14	$1,128/kW	$5.49
Site Prep	1%	$4.95	18.85%	$5.14	40%	$5.36
Replacement Interval	20yr	$5.04	7yr	$5.14	4yr	$5.25
Replacement Costs	10%	$5.11	15%	$5.14	25%	$5.20

Table shows parameter values used in Tornado Chart. A similar pattern of sensitivities holds for the Current Central case, shown in the back-up slides.

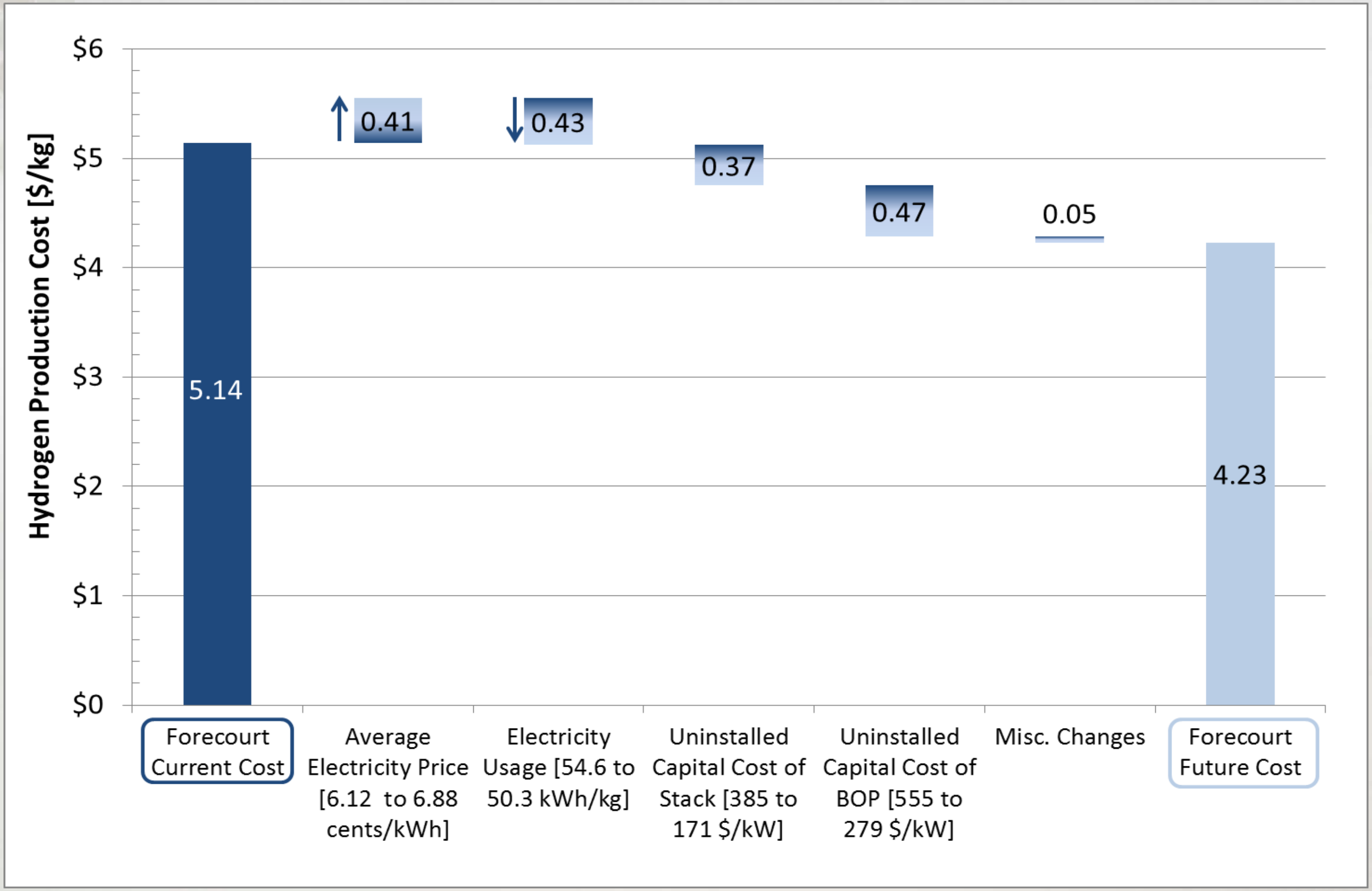
Chart shows similar pattern for the Future Forecourt Case. H_2 cost is most influenced by electricity price, usage, and capital costs.



Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.44¢/kWh	$2.50	6.88¢/kWh	$4.23	10.31¢/kWh	$5.96
Electricity Usage	45kWh/kg	$3.79	50.3kWh/kg	$4.23	55kWh/kg	$4.62
Uninstalled Capital Costs	$360/kW	$4.08	$450/kW	$4.23	$540/kW	$4.37
Site Prep	1%	$4.14	18.85%	$4.23	40%	$4.32
Replacement Interval	20yr	$4.21	10yr	$4.23	4yr	$4.28
Replacement Costs	10%	$4.22	12%	$4.23	25%	$4.24

Table shows parameter values used in Tornado Chart. A similar pattern of sensitivities holds for the Future Central case, shown in the back-up slides.

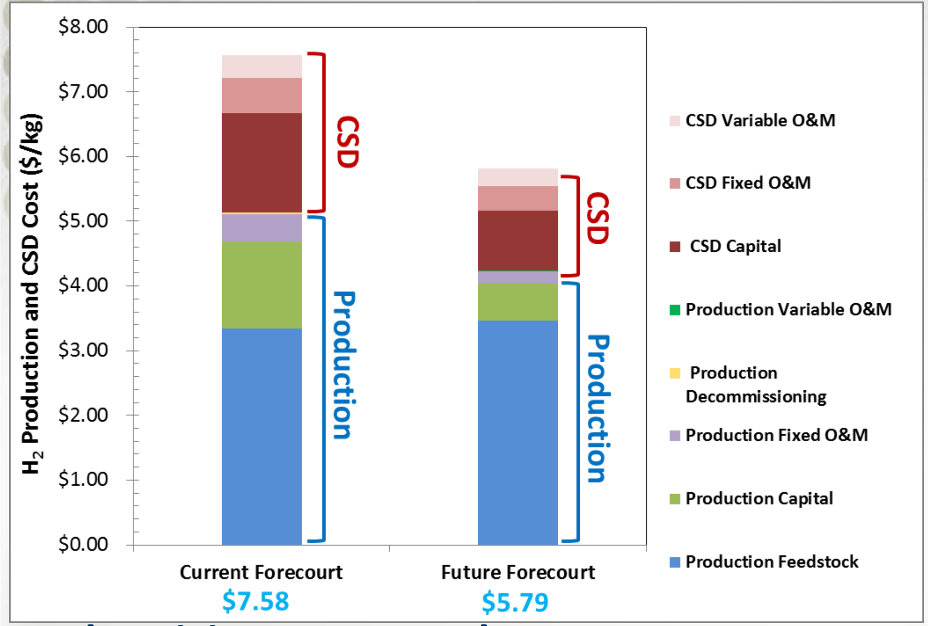
Waterfall Chart shows a progression of changes in cost in moving from the Forecourt Current Case to the Forecourt Future Case.



Although electricity price increases between Current and Future Cases (2nd column from left), electrical efficiency rises (3rd column), and thereby reduces net electricity expenditures, and brings the levelized H_2 cost down.

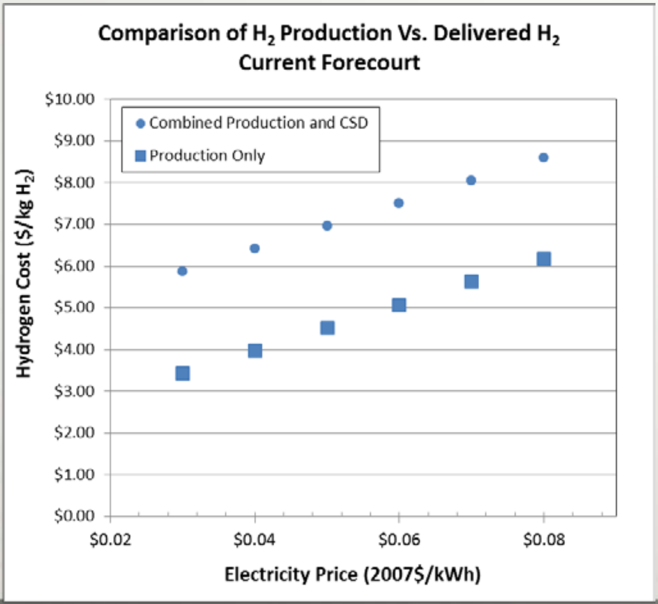
A similar pattern of cost progression is seen with the Central cases, as shown in the back-up slides.

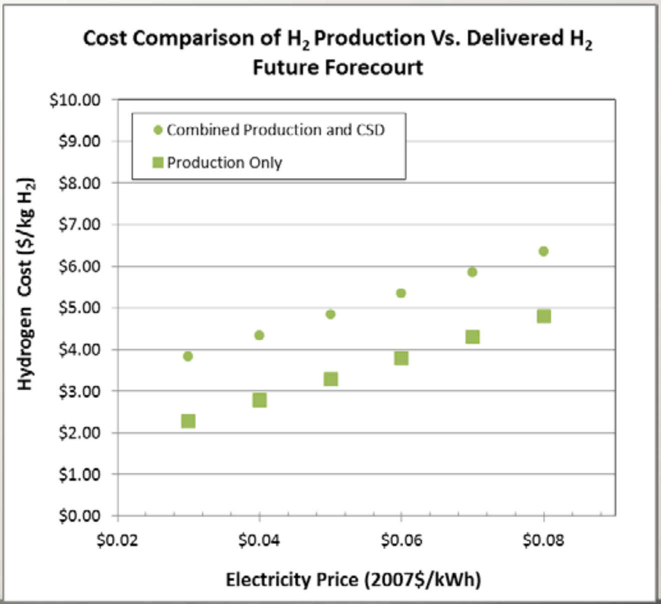
Compression, Storage, & Dispensing (CSD) cost adds 37% to 47% to H_2 cost total, based on H2A Production Model V3 (refueling station tab).



Component	Current Forecourt	Future Forecourt	Current Central	Future Central
Total Production Cost (2007$/kg)	$5.14	$4.23	$5.12	$4.20
Capital	$1.35	$0.58	$1.33	$0.53
Decommissioning	$0.02	$0.00	$0.00	$0.00
Fixed operations and maintenance (O&M)	$0.42	$0.18	$0.40	$0.20
Feedstock	$3.34	$3.46	$3.38	$3.46
Variable O&M	$0.01	$0.01	$0.01	$0.01
Total CSD (Forecourt only) (2007$/kg)	$2.44	$1.56	Not Applicable	
Capital	$1.53	$0.92		
Fixed O&M	$0.54	$0.38		
Variable O&M	$0.37	$0.26		
Total Cost (2007$/kg)	$7.58 (Prod. & CSD)	$5.79 (Prod. & CSD)	$5.12 (Prod. only)	$4.20 (Prod. only)

Electricity Cost Greatly Impacts H_2 Cost





Response to Previous Year Reviewers' Comments

- This is the first year that the project is being reviewed. There are no reviewer comments available from the previous year.

Summary Conclusions

- A validation case was completed for H_2 generation with grid-powered PEM electrolyzers using the H2A Production Model (V3) (Year 1, Milestone 2).
- Four PEM electrolysis companies were surveyed for input information, and five generalized cases were developed (4 public, 1 non-public).
- Large capital cost reductions are predicted between Existing and Current systems, and between Current and Future systems.
- All cases reflect a \$4 to \$5/kg H_2 production cost, based on an average cost of electricity of 6.1¢ to 6.9¢/kWh. Electricity costs are the primary cost driver.
- The H_2 cost reduction is greater in moving from a Current to a Future case, compared with moving from a Forecourt to a Central case.
- The three main cost drivers for the levelized H_2 cost are 1) electricity price, 2) electrolyzer electrical efficiency, and 3) electrolyzer capital cost.
- A unique contribution of this work is the detailed capital cost breakdown.
  - The stack contributes ~41% to system costs in the Current Forecourt Case, and is the primary cost driver in all cases.
  - Within the stack, the combined membrane, catalyst, anode, and cathode contribute ~60% to stack capital costs in the Current Forecourt Case.
- Compression, Storage, & Dispensing (CSD) cost is expected to add ~37% to ~47% to the levelized H_2 production cost.

Summary

- **Overview**
  - Exploration of selected H_2 production and delivery pathways to find most feasible
  - Transparent, objective, and internally consistent comparison of alternatives
  - In year 2 of 3 year analysis project
- **Relevance**
  - Identify key “bottlenecks” to the success of these pathways, primary cost drivers, and remaining R&D challenges
  - Assess technical progress, levelized H_2 costs, benefits and limitations
  - Analyses assist DOE in setting research direction & priorities
- **Approach**
  - Input based on interviews of technical experts
  - Projected cost results from use of H2A Production Model Version 3
- **Accomplishments**
  - Analysis of PEM electrolysis H_2 Production systems
- **Collaborations**
  - ANL and NREL provide cooperative analysis and vetting of assumptions/results
- **Future Work**
  - Detailed case study of bio-fermentation
  - Updated analysis of high temperature solid oxide electrolysis

Proposed Future Work: DOE requested two more studies -- (1) bio-fermentation and (2) high temperature steam electrolysis

- Analysis will follow the methodology used for the PEM electrolysis case study.
- Researchers and industry experts to be surveyed for input data.
- Case studies will be generalized/non-company-specific.

Bio-Fermentation

- Detailed H2 Pathway Case Study
- Current and Future Central cases envisioned (50 tons/day)
- H_2 production via Dark Fermentation
- Initially Planned Types of Feedstock:
  - **1) Energy Crop Biomass, 2) Waste Stream, and 3) Refined Bio-product**

High Temperature Steam Electrolysis

- Updated analysis of H2 Pathway Case Study
- Current and Future Central cases envisioned
- Cost of heat and electricity to be based on input source (nuclear, solar, etc.) (thus capital cost/maintenance/etc. of electricity generation will not be modeled)

Year 2 Go/No-Go Decision 1 evaluation criteria (slide 5) are being met.

Year 2 Milestone to complete Year 2 Case Studies (slide 5) is on track.

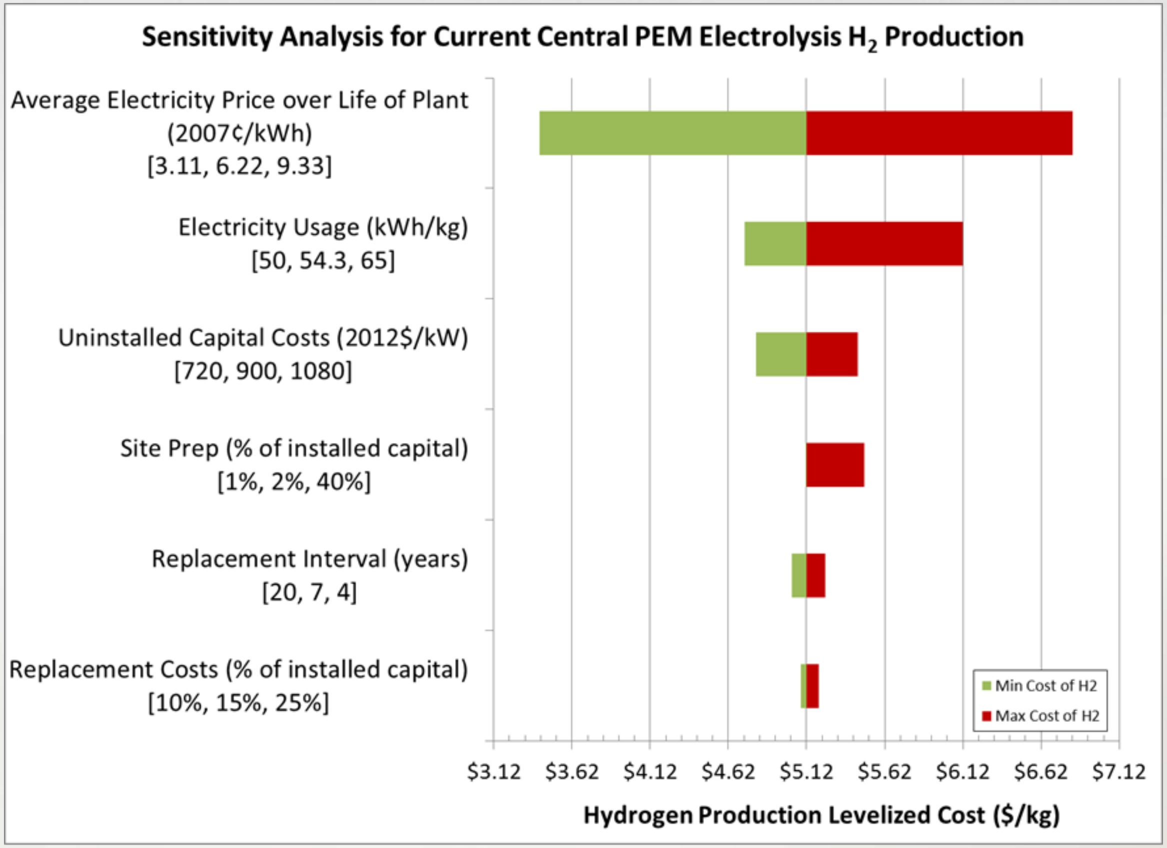
Additional case studies will be pursued as directed by DOE.

Collaborators

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur • Todd Ramsden	Subcontractor	• Participated in weekly project calls. • Worked with the four PEM electrolyzer companies to gather data for H2A Production Model cases. • Assisted with H2A Production Model runs and sensitivity analyses. • Drafted reporting materials • Reviewed reporting materials • Facilitated publishing materials on the web.
Argonne National Lab (ANL) • Rajesh Ahluwalia • Thanh Quoc Hua	Subcontractor	• Participated in select project calls. • Scoping investigation: Evaluated four classes of technologies for producing hydrogen via high-temperature thermochemical water splitting cycles.
Four electrolyzer companies	Collaborators	• Participated in technical questionnaire • Provided extensive company-sensitive information. • Clarified input data • Vetted H2A Production Model input data, sensitivity parameters, and results • Reviewed public documentation.

Technical Backup Slides

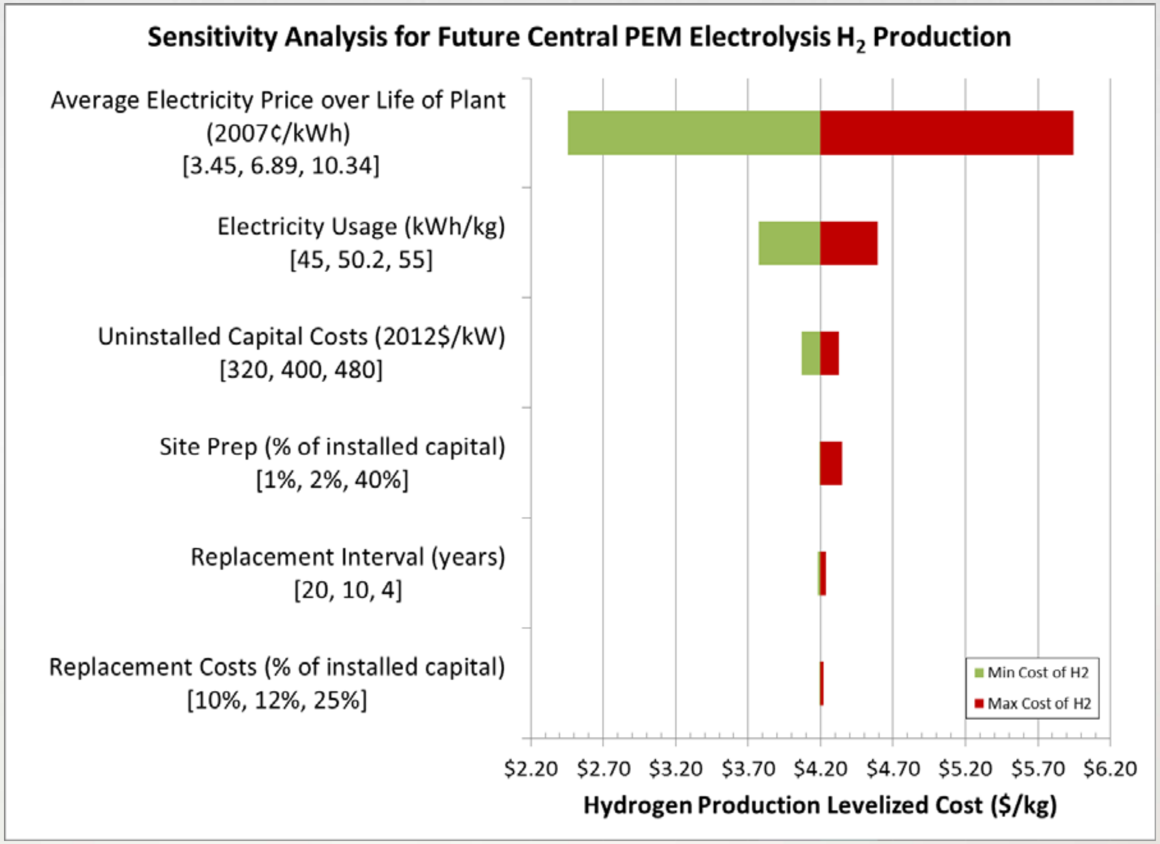
Sensitivity Analysis: Current 2010 Central Technology Projection



Parameter values used within the Tornado Chart

Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.11¢/kWh	$3.41	6.22¢/kWh	$5.12	9.33¢/kWh	$6.82
Electricity Usage	50kWh/kg	$4.72	54.3kWh/kg	$5.12	65kWh/kg	$6.12
Uninstalled Capital Costs	$720/kW	$4.80	$900/kW	$5.12	$1080/kW	$5.45
Site Prep	1%	$5.11	2%	$5.12	40%	$5.49
Replacement Interval	20yr	$5.03	7yr	$5.12	4yr	$5.24
Replacement Costs	10%	$5.09	15%	$5.12	25%	$5.20

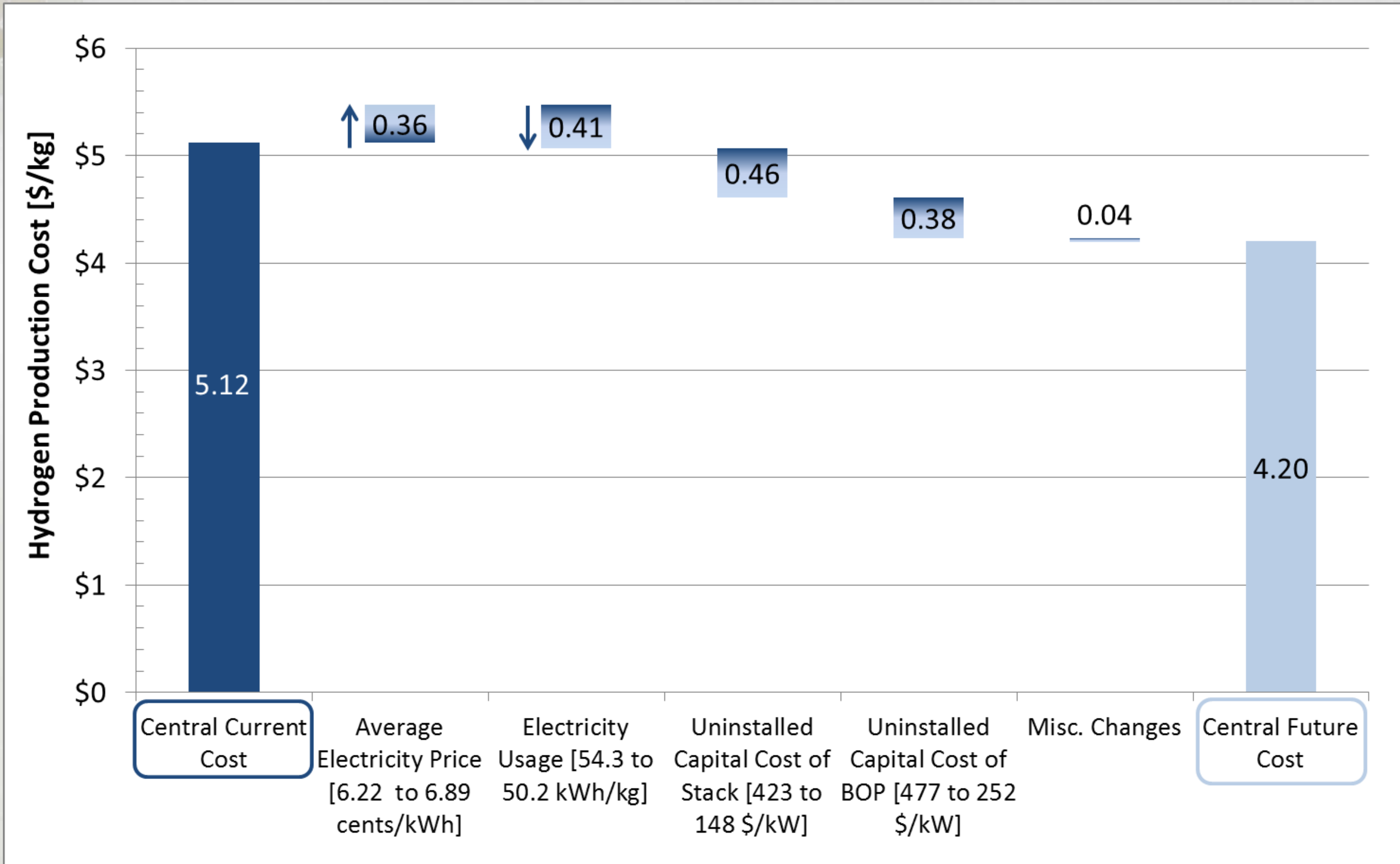
Sensitivity Analysis: Future 2025 Central Technology Projection



Parameter values used within the Tornado Chart

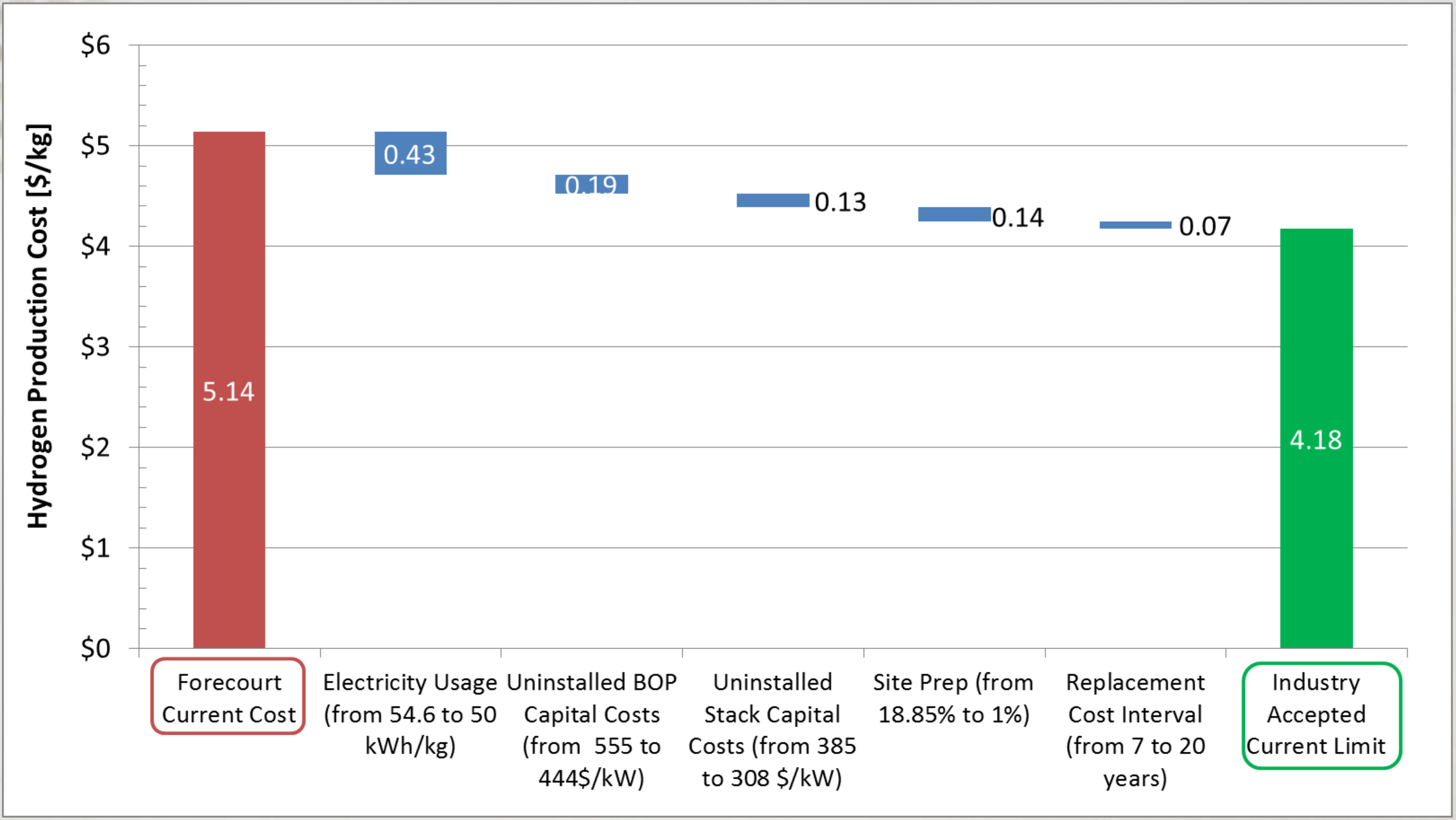
Variable Name	Low Value	Minimum H_2 Selling Price ($/kg)	Likeliest Value	Minimum H_2 Selling Price ($/kg)	High Value	Minimum H_2 Selling Price ($/kg)
Average Electricity Price	3.45¢/kWh	$2.46	6.89¢/kWh	$4.20	10.34¢/kWh	$5.95
Electricity Usage	45kWh/kg	$3.77	50.2kWh/kg	$4.20	55kWh/kg	$4.59
Uninstalled Capital Costs	$320/kW	$4.07	$400/kW	$4.20	$480/kW	$4.33
Site Prep	1%	$4.19	2%	$4.20	40%	$4.35
Replacement Interval	20yr	$4.18	10yr	$4.20	4yr	$4.24
Replacement Costs	10%	$4.19	12%	$4.20	25%	$4.22

Waterfall Chart: Central Current to Future



Waterfall Chart

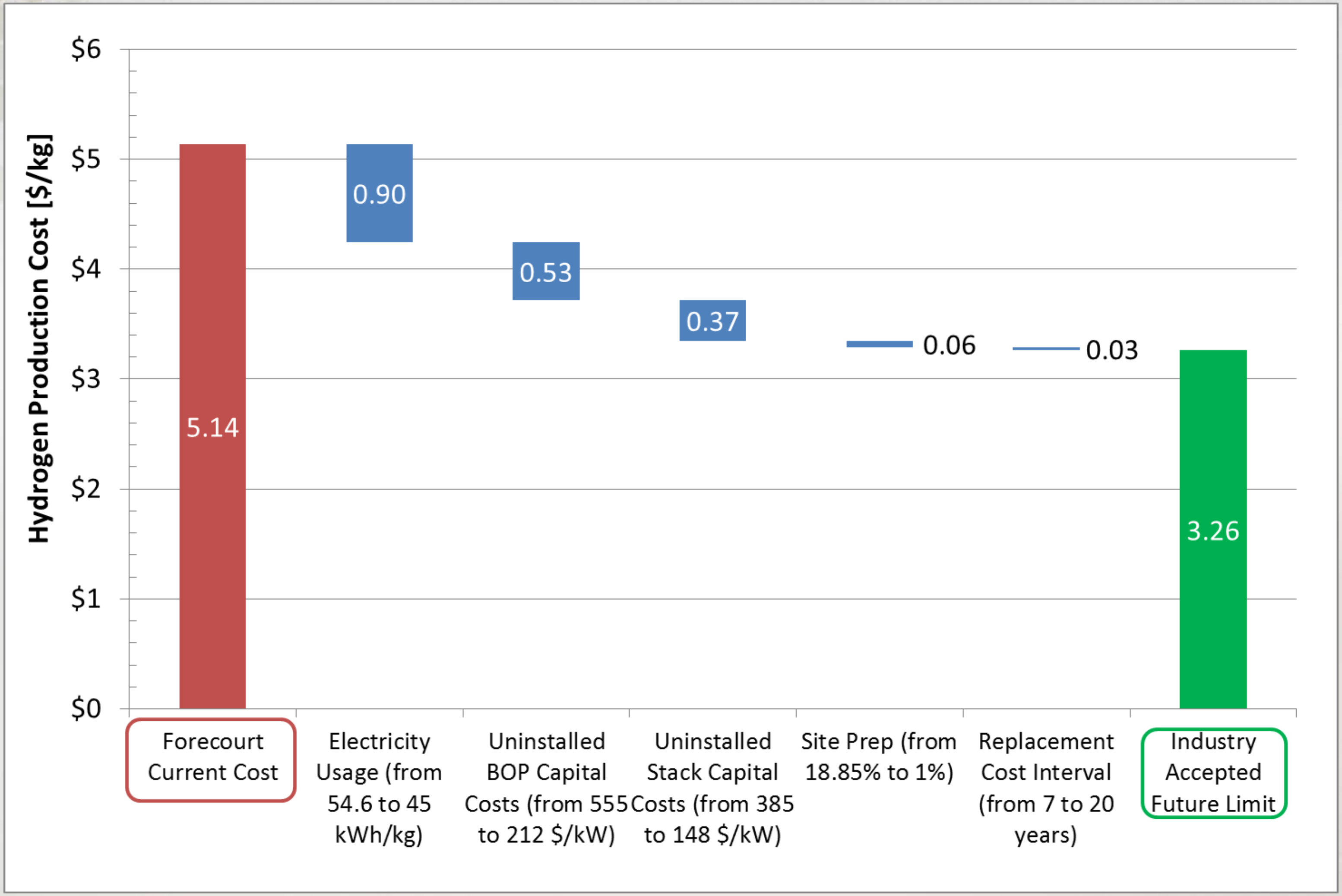
PEM Electrolysis Case (starting at Current Forecourt Cost)



Model input values are changed from 'base case' values for the current forecourt case to the most optimistic limits from the industry accepted sensitivity limits for the current forecourt case. The final low cost is not a 'target,' but a result of applying these changes to model input values.

Waterfall Chart

PEM Electrolysis Case (starting at Current Forecourt Cost)



Model input values are changed from ‘base case’ values for the current forecourt case to the most optimistic limits from the industry accepted sensitivity limits for the <u>future</u> forecourt case. The final low cost is not a ‘target,’ but a result of applying these changes to model input values.