STRATEGIC ANALYSIS INC

Techno-economic Analysis of PEM Electrolysis for Hydrogen Production

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Introduction and Purpose

- Analyze H_2 Production & Delivery (P&D) pathways to determine the most economical, environmentally-benign, and societally-feasible paths forward for the production and delivery of H_2 fuel for fuel cell vehicles (FCVs).
- Identify key "bottlenecks" to the success of these pathways, primary cost drivers, and remaining R&D challenges.
- Assess technical progress, hydrogen costs, benefits and limitations, and the potential to meet U.S. DOE P&D cost goals of \$2 to 4/gasoline gallon equivalent (gge) (dispensed, untaxed) by 2020.

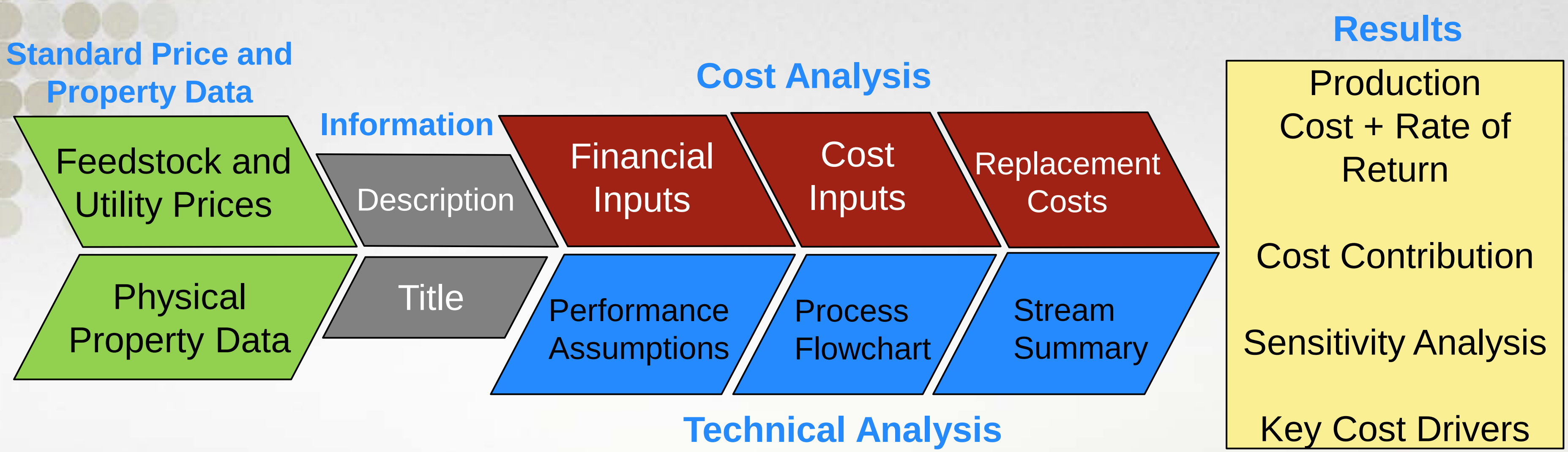
- Analyses assist DOE in setting research direction & priorities.

- H2A Production Model is used as the primary analysis tool for projection of \$/kgH2 production costs and cost sensitivities.

Technical Approach

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
    - 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 H2 Production Cost model
5. Initial results vetted with researchers/developers/DOE
6. Conduct sensitivity analysis based on feedback
7. Repeat steps 2-5 until team is confident in results

Overview of H2A Model

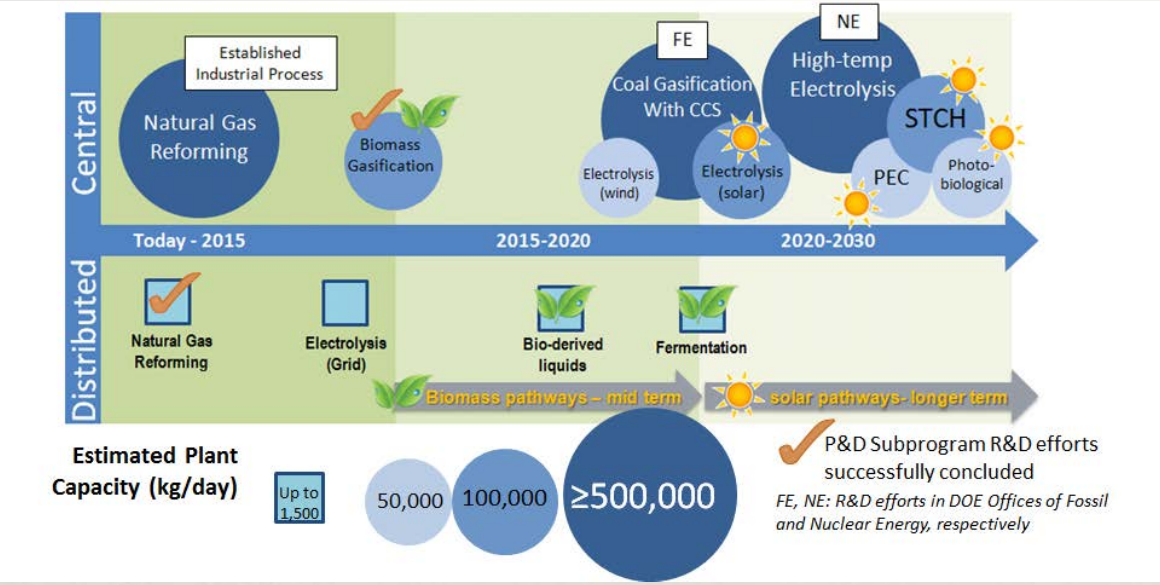


- H2A is a discounted cash flow analysis that computes the required price of H_2 for a desired after-tax internal rate of return (IRR)
- Developed by NREL and DOE EERE-FCTO
- Objective of H2A Analyses (production):
  - Establish a standard format for reporting the production cost of H_2, so as to compare technologies and case studies
  - Provide transparent analysis
  - Provide consistent approach
  - Prioritize research and development efforts

Different Technologies Analyzed using H2A

- **Past Production Case Studies**
  - Existing Technologies
    - Natural Gas Steam Methane Reforming (SMR) (Central/Forecourt)
    - Electrolysis (Central/Forecourt)
    - Ethanol Reforming (Forecourt)
    - Biomass (Central)
    - Coal Gasification (Central)
    - Nuclear Powered Water Splitting (Central)
  - Emerging Technologies
    - Photoelectrochemical (PEC) (Central)
    - Photo-Biological H_2 (Central)
    - Solar Thermochemical H_2 (STCH) (Central)

All production cases above can be found at:
http://www.hydrogen.energy.gov/h2a_prod_studies.html



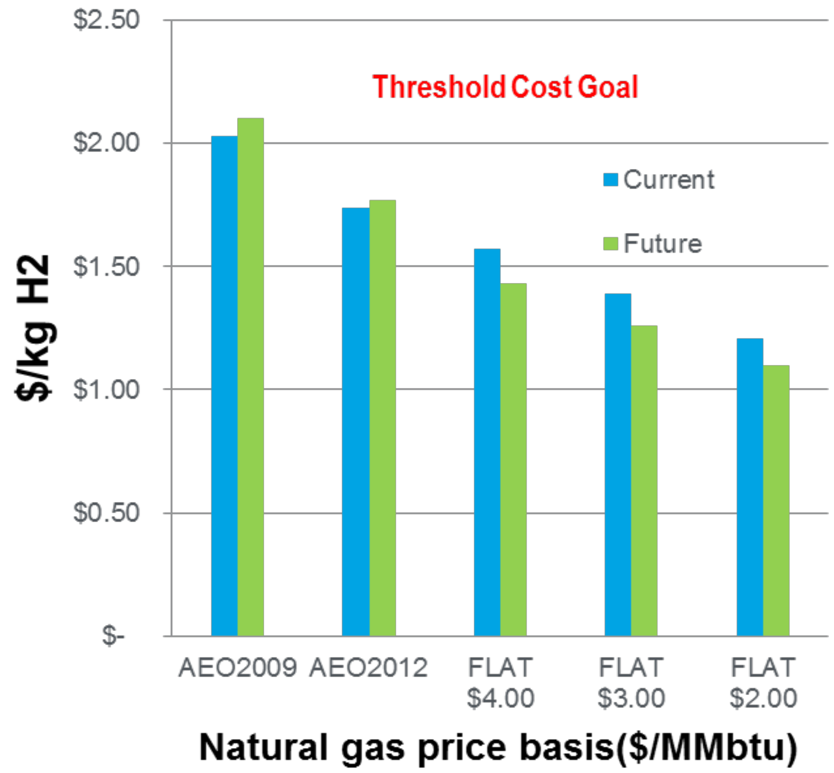
Next Generation of Pathway-Dependent Production Case Studies being Developed

Hydrogen Production from Natural Gas: Bridge to Longer-Term, Low-Carbon Technologies

Distributed H_2 Production from NG SMR (high volume/economies of scale, 1500 kg/day production)

- Cost of H_2 production not limiting factor
- Cost goals can be met by a wide range of NG prices*
- Focus shifting to longer term, renewable pathways:
  - Bio-feedstocks
    feedstock cost/availability
  - Renewable Electrolysis
    renewable electricity cost
  - Emerging Technologies

Projected $/kg H_2 (produced & untaxed, today's technology) for Varying Natural Gas Spot Prices – ***in line with market production costs***



*Production Cost Using Low-Cost Natural Gas, September, 2012, http://hydrogen.energy.gov/pdfs/12024_h2_production_cost_natural_gas.pdf

Based on H2A v3 Case Studies @ http://www.hydrogen.energy.gov/h2a_production.html
AEO2009 avg NG prices (HHV, $/MMBtu): $7.10 (Current, 2010-2030); $8.44 (Future, 2020-2040)
AEO2012 avg NG prices (HHV, $/MMBtu): $5.28 (Current, 2010-2030); $6.48 (Future, 2020-2040)

Case Overview

- Investigation of H2 production using a standalone grid-powered Polymer Electrolyte Membrane (PEM) Electrolyzer
- Four cases developed using the H2A v3 tool (for high volume projections of H_2 production costs incorporating economies of scale) :

Case	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

Existing Case (“if you were fabricating today at current volume”)

- Similar to performance & price quotes available now. Analyzed but not discussed here.

Current Case (“if you were fabricating today at production volume”)*

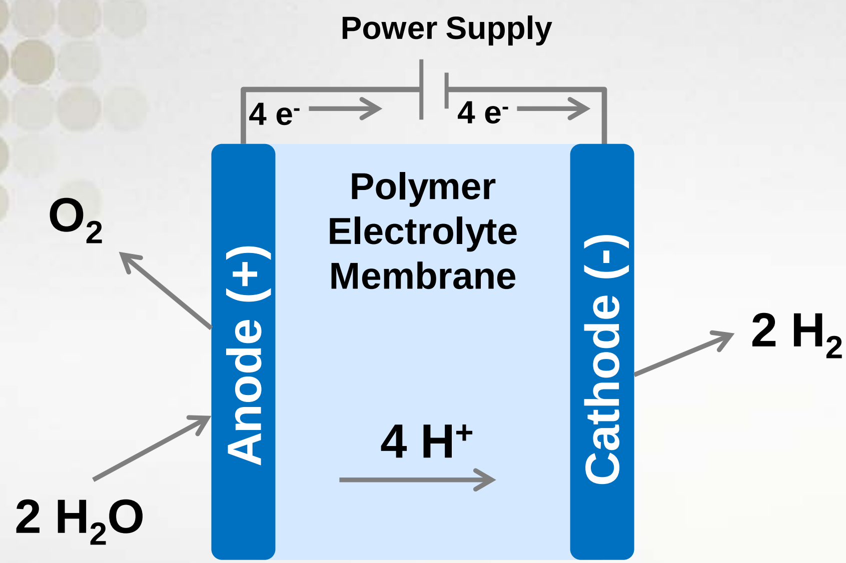
- Demonstrated advances in technology are implemented
- Potential reduction in capital cost from existing values
- Plant lifetimes consistent with measured or reported data

Future Case

- New materials and systems with increased H_2 production efficiency and longer plant lifetimes
- Improved replacement cost schedule
- Greater reductions in capital cost

**not to be confused with existing costs based on low production commercially available electrolyzers*

PEM Electrolysis Technology



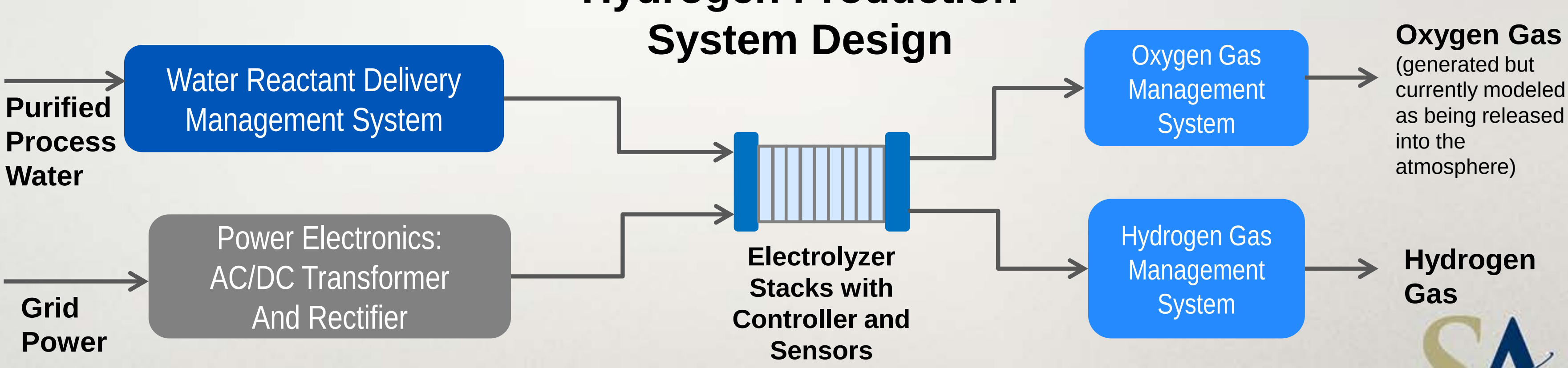
$2H_2O \rightarrow 4H^+ + 4e^- + O_2$

$4\ H^+ + 4\ e^- \rightarrow 2\ H_2$

PEM water electrolysis uses electrical power to split water into oxygen (O_2) and hydrogen (H_2).

- Positive terminal (anode): water (H_2O) reacts with catalyst to form oxygen molecules, electrons (e^-), and hydrogen protons (H^+).
- Electrolyte: Hydrogen protons are conducted across the polymer electrolyte membrane.
- External Circuit: electrons flow through an external power supply to produce an electric current.
- Negative terminal (cathode): the electrons combine with the hydrogen protons to produce H_2.

Hydrogen Production System Design



Key Analysis Modeling Assumptions and Basis for Assumptions

- **Summary:** PEM Electrolysis H2A case models based on a generic system using input from several key industry collaborators with commercial experience in PEM electrolysis.
- **Methodology:**
- Solicited information from four electrolyzer companies
- Requested relevant detailed information on:
  - Current/Future cases for Forecourt/Central
  - Followed H2A sheet input format:
    - System definition
    - Operating conditions
    - Variable and fixed expenses
    - Capital costs
    - Replacement costs
- Data synthesized, amalgamated into base parameters for cases
- Base parameters & sensitivity limits vetted by the four companies
- Four H2A Cases Populated and models run to predict H_2 cost
  - Current/Future cases for Forecourt/Central Production

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Basic Parameters Used for the Four Public H2A Cases

	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 study is a synthesis of the views of several companies. These numbers can be referenced against specific company viewpoints.
- Companies verified the basic parameters assumed.
- No sensitive information was disclosed to companies.

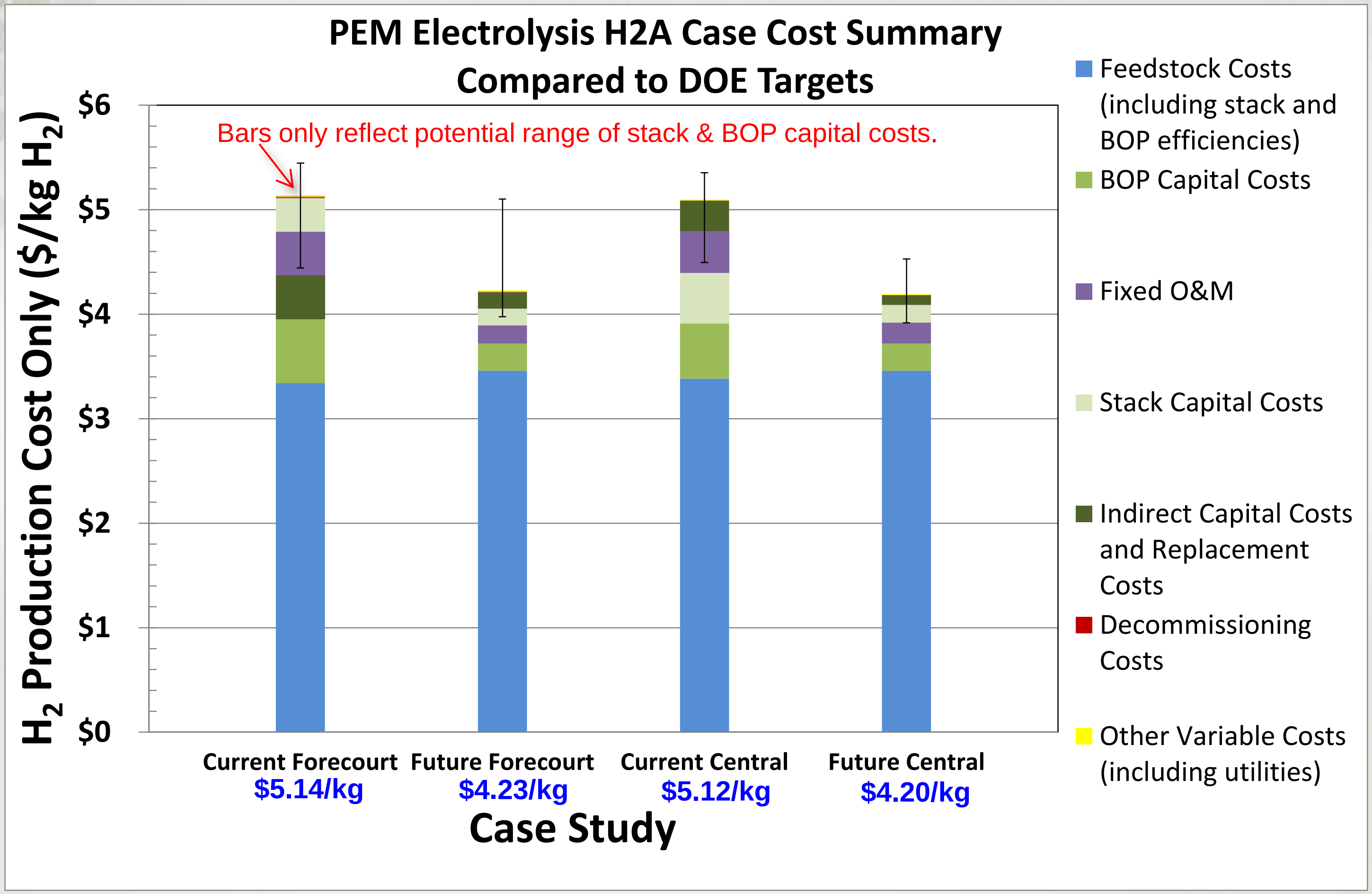
PEM Electrolyzer System Performance Parameters

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	\$173	\$421	\$150
BOP Capital Cost (2012\$/kW)	\$555	\$277	\$479	\$250
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	46.7	49.2	46.7
BOP Electrical Usage (kWh/kg)	5.4	3.7	5	3.5
Electrolyzer Power Consumption (MW)	3.4	3.1	113	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.

PEM Electrolysis H2A Case Production Cost Results*

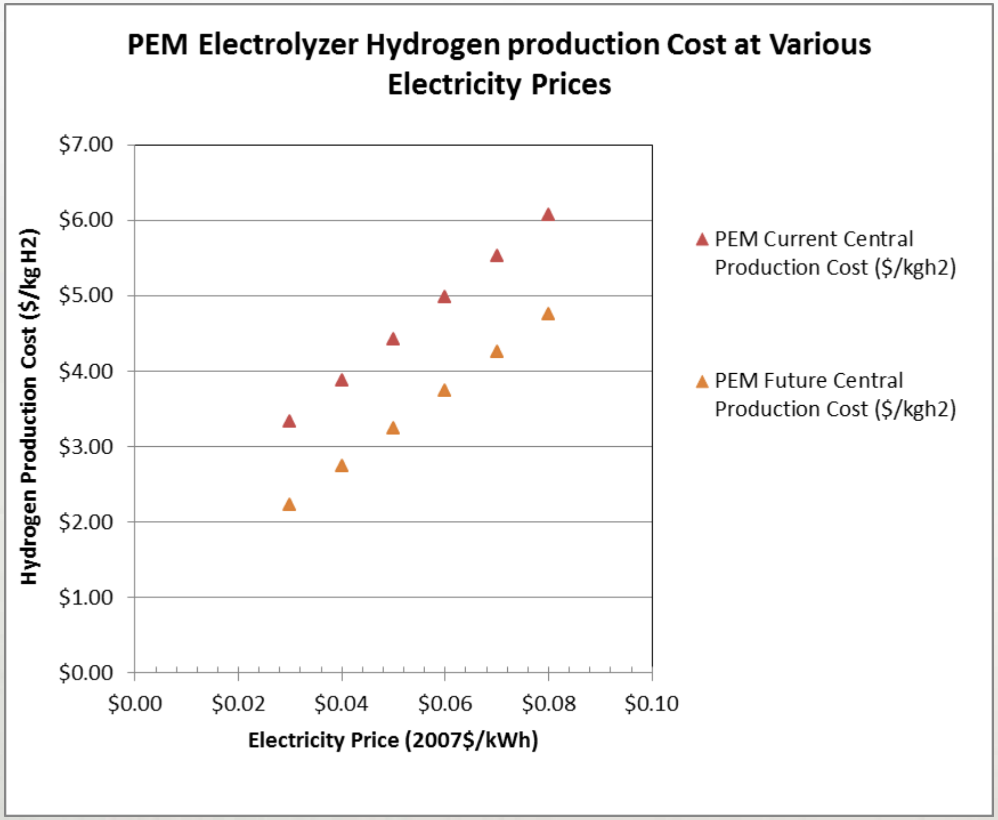


** In a 2007 dollar cost basis, standard to the H2A v3 tool (reflecting production costs only)*

- All cases reflect a $4-5/kg cost for H_2 production. The current cases ($5.14 vs. $5.12) and the future cases ($4.23 vs. $4.20) are similar in cost.
- The H_2 cost reduction is greater 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 decrease electricity price.

Electricity Cost is a Key Factor in Hydrogen Cost

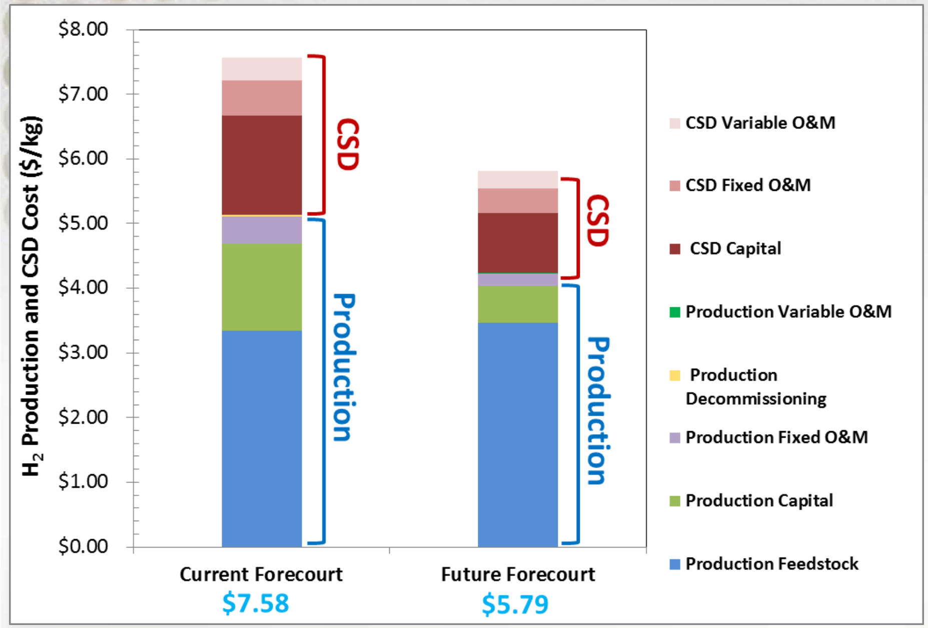
	Forecourt		Central	
	Current	Future	Current	Future
Electricity Price (2007$/kWh) Constant Price Over Life of Plant				
PEM	0.061	0.069	0.062	0.069
Published H2A Case	0.061	0.069	0.062	0.069



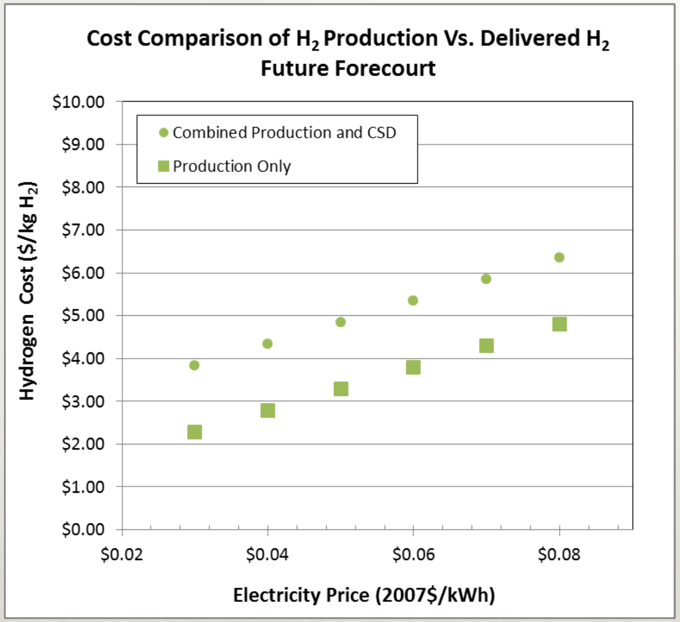
- Varying electricity cost while keeping all other variables (efficiency and capital cost) constant.
- H_2 cost varies linearly with Electricity Price.

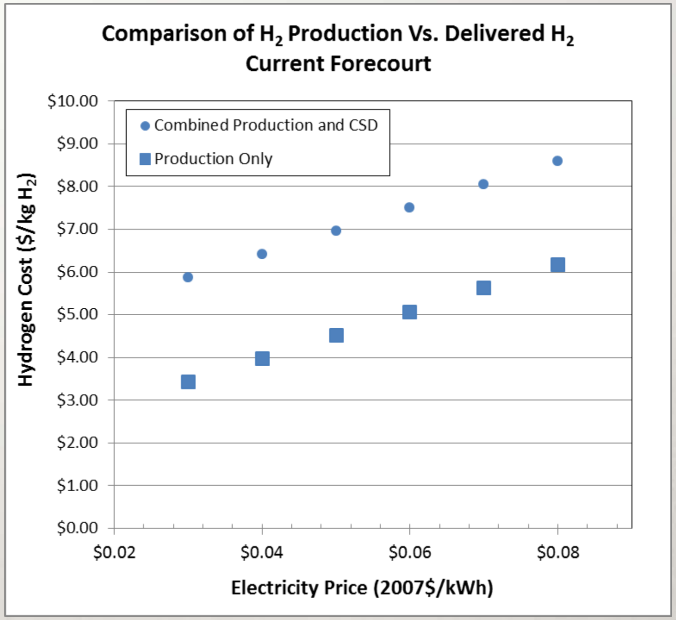
Electricity price is the most volatile and also the most impactful parameter.

Compression Storage and Dispensing (CSD)



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	$0.01	$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	$1.57	Not Applicable	
Capital	$1.53	$0.92		
Fixed O&M	$0.54	$0.38		
Variable O&M	$0.36	$0.27		
Total Cost (2007$/kg)	$7.58 (Prod. & CSD)	$5.79 (Prod. & CSD)	$5.12 (Prod. only)	$4.20 (Prod. only)



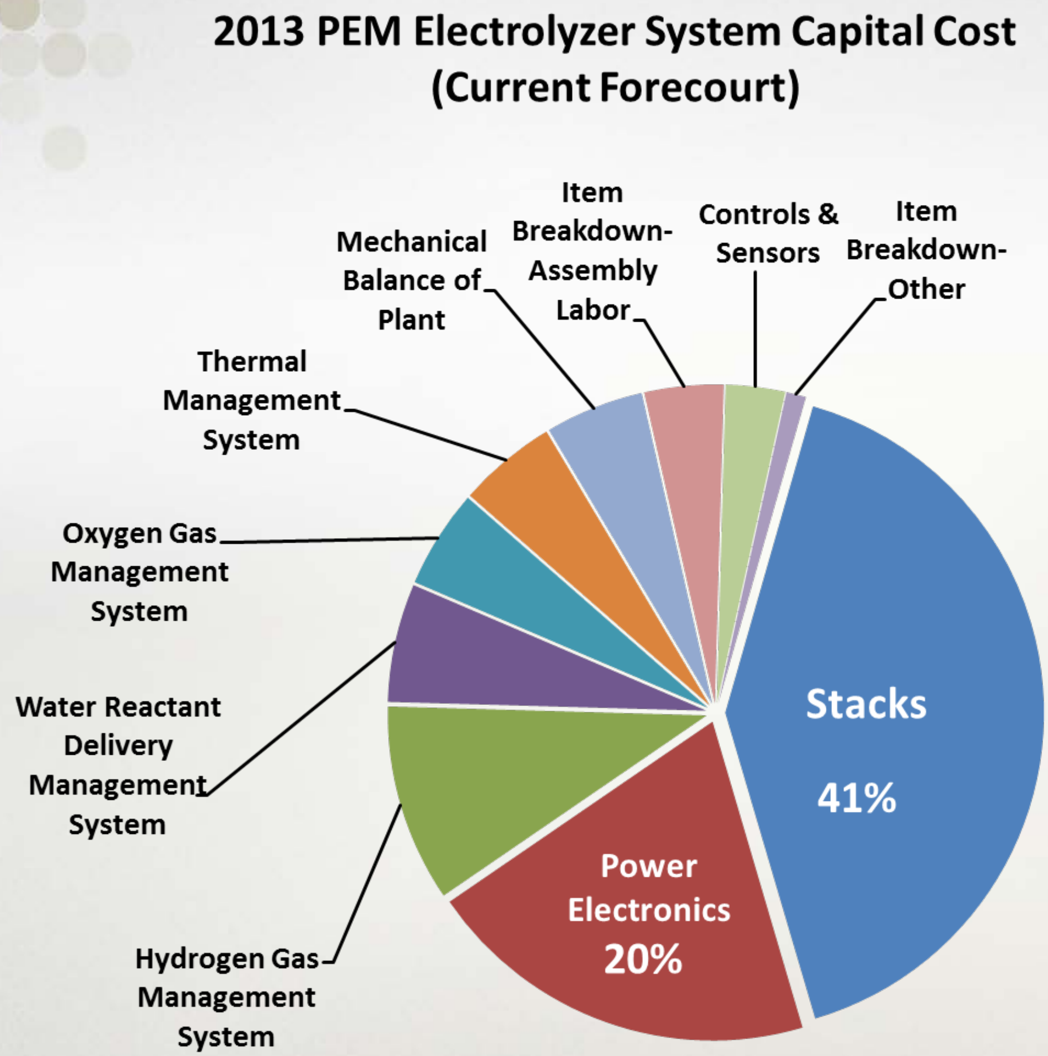


Calculated system electrical usage using models and industry feedback

H2A Case		Forecourt Current	Forecourt Future	Central Current	Central Future	Basis for Assumptions
H_2 Outlet Pressure	psi	450	1000	450	1000	Industry feedback
Stack Electrical Usage						
Cell voltage	volts/cell	1.75	1.66	1.75	1.66	Based on literature and industry input. 5% improvement for Future Cases.
Voltage Efficiency	% LHV	70.3%	74.0%	70.3%	74.0%	Equation: 1.23/cell voltage
Dryer Loss	% of gross H_2	3.0%	1.5%	3.0%	1.5%	The 3% Dryer loss comes from industry ("3-4%"). The reductions (1.5%) are estimates based on a lower flow of water required for full saturation at higher outlet pressures in future cases.
Permeation Loss	% of gross H_2	0.7%	2.0%	0.7%	2.0%	Based on back diffusion model (1.85x10-7cm^2/s back diffusion coefficient): Industry input is 0.7% at 450psi, model says 0.5% at 450psi/3μm thick membrane, 2.02% at 1,000psi/2μm thick membrane.
Total Stack Energy Usage per mass net H_2	**$kWh_{elec}/kg_{Net\ H2}$**	**49.23**	**46.67**	**49.23**	**46.67**	
BOP Loads						
Power Inverter Efficiency	%	94%	97%	95%	97%	Based on industry input (with improvement to 97% for future performance and to 95% for current/Central to reflect larger size).
Inverter Electrical Load	$kWh_{elec}/kg_{Net\ H2}$	2.95	1.44	2.59	1.44	
Dryer Thermal Load	$kWh_{therm}/kg_{Net\ H2}$	0.34	0.31	0.34	0.31	Based on Hysys Simulation.
Dryer Efficiency	kWh_{elec}/kWh_{therm}	3.67	3.49	3.67	3.30	Based on industry input for the ratio of net electrical energy for the chiller. 5% efficiency improvement for Future Forecourt, 10% improvement for Future Central.
Dryer Electrical Load	$kWh_{elec}/kg_{Net\ H2}$	1.25	1.08	1.25	1.02	
Misc Electrical Load	$kWh_{elec}/kg_{Net\ H2}$	1.2	1.14	1.2	1.08	Based on industry input for current. 5% improvement for future/forecourt. 10% improvement for future/central.
Total BOP Electrical Load	**$kWh_{elec}/kg_{Net\ H2}$**	**5.40**	**3.66**	**5.04**	**3.54**	
Total System Electral Usage per mass net H_2	$kWh_{elec}/kg_{Net\ H2}$	**54.6**	**50.3**	**54.3**	**50.2**	

- Additional performance parameters defined to corroborate industry reported values.
- While not used in H2A models, inclusion allows
  - H2A documentation
  - Discern changes as technology advances

Breakdown of Electrolyzer System Capital Cost



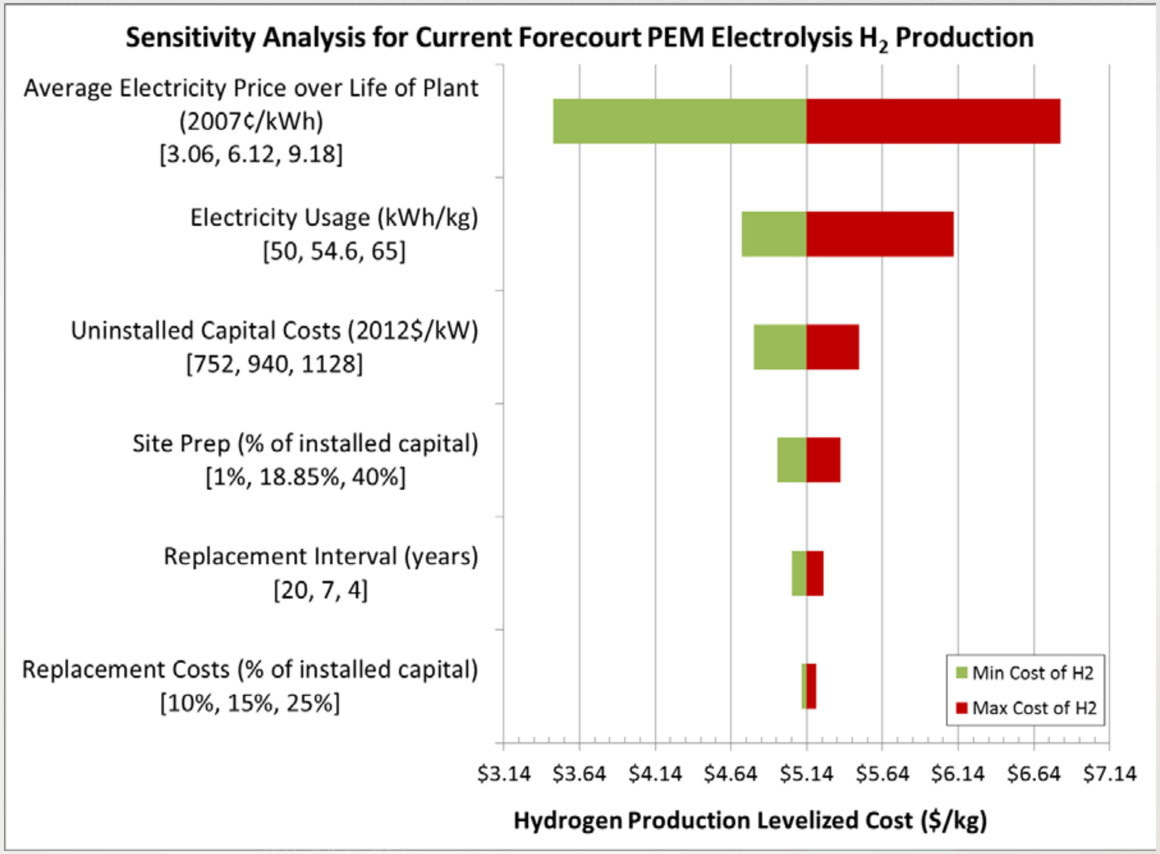
- Power electronics, hydrogen gas management, and the stacks sum to a combined 71% of total system cost.
- Within the stack capital cost, combined membrane, catalyst, anode and cathode make up ~60%.

Discussion of Cost Drivers

- H2A PEM Electrolysis cases show production costs are highly dependent on (1) electricity cost, (2) electrolyzer 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 (although relates to electrical efficiency)
2. Electrical Efficiency (kWh/kg H_2)
   a. Stack efficiency based on operating voltage and 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: 1.75V at 1500 mA/cm^2 (Current) and 1.65V at 1600 mA/cm^2 (Future)
3. 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 higher capital cost for PEM electrolyzers than in previous published H2A electrolyzer analyses.

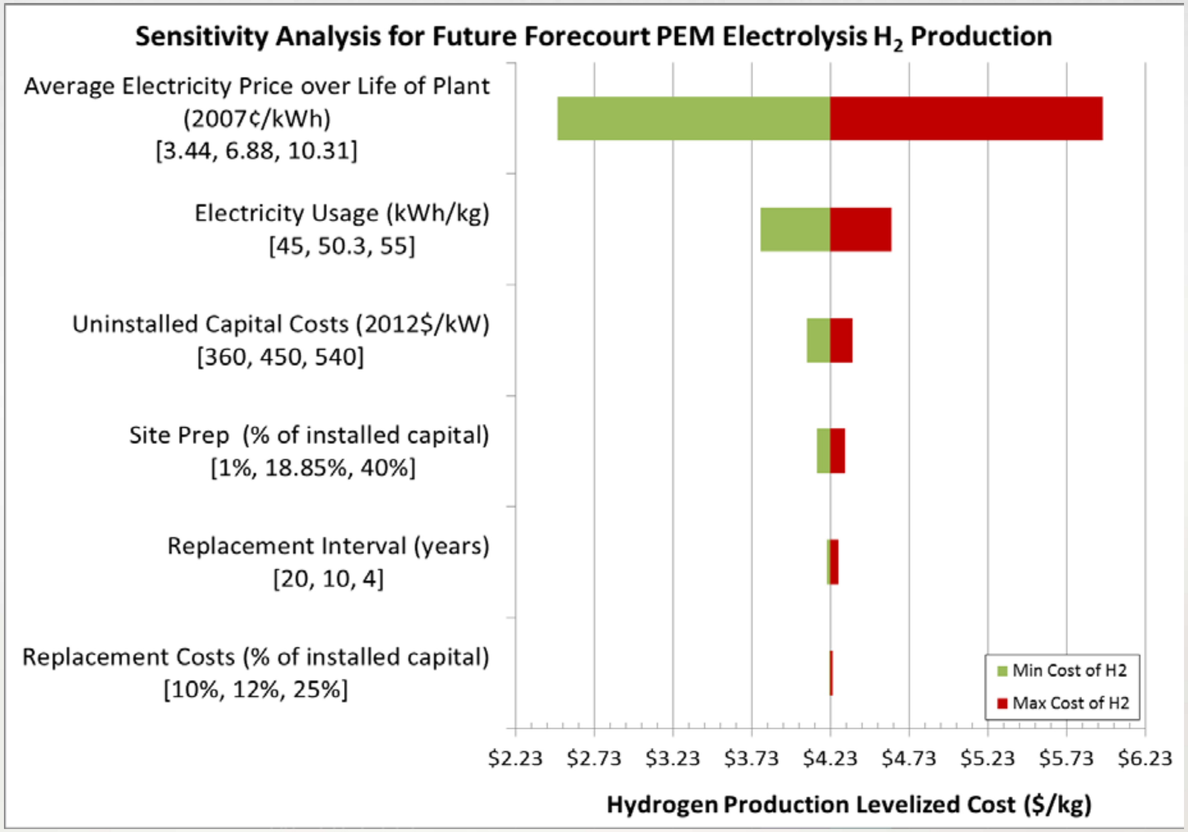
Sensitivity Analysis: Current 2010 Forecourt Technology Projection



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	3.06¢/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

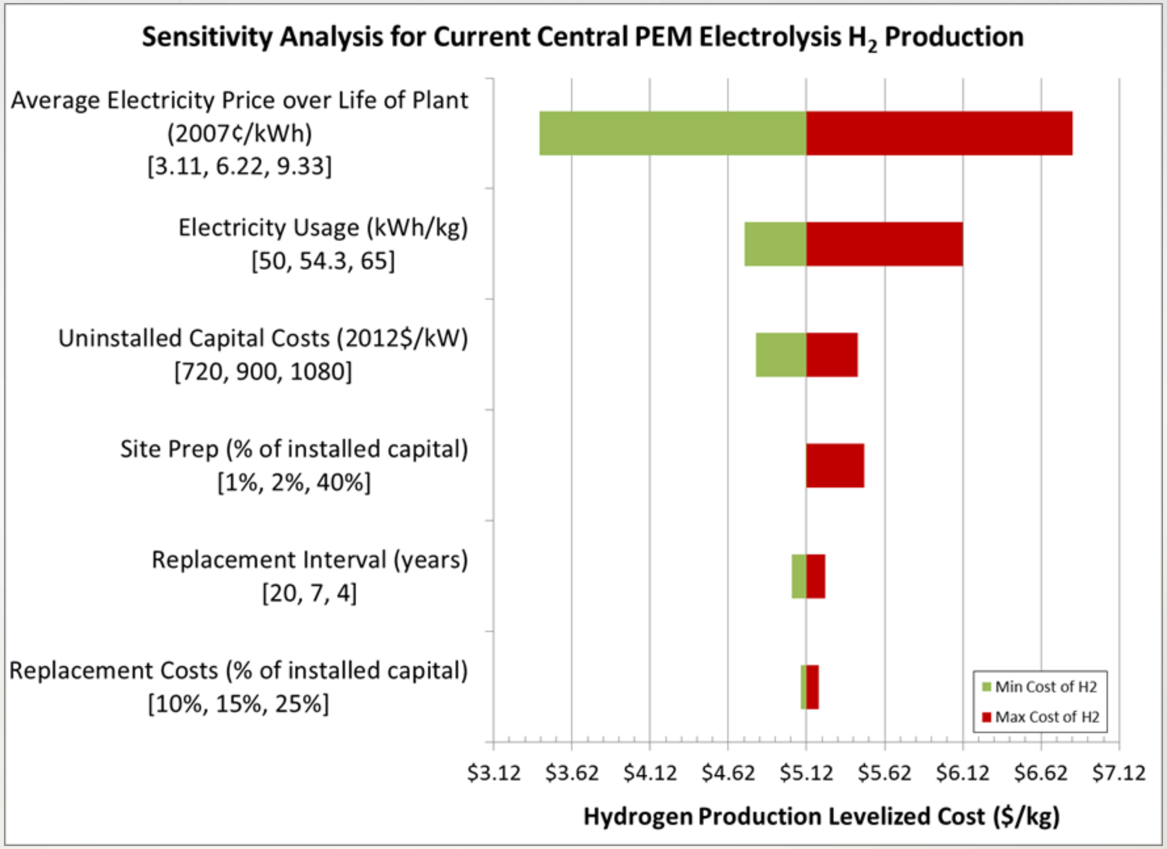
Sensitivity Analysis: Future 2025 Forecourt Technology Projection



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	3.44¢/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

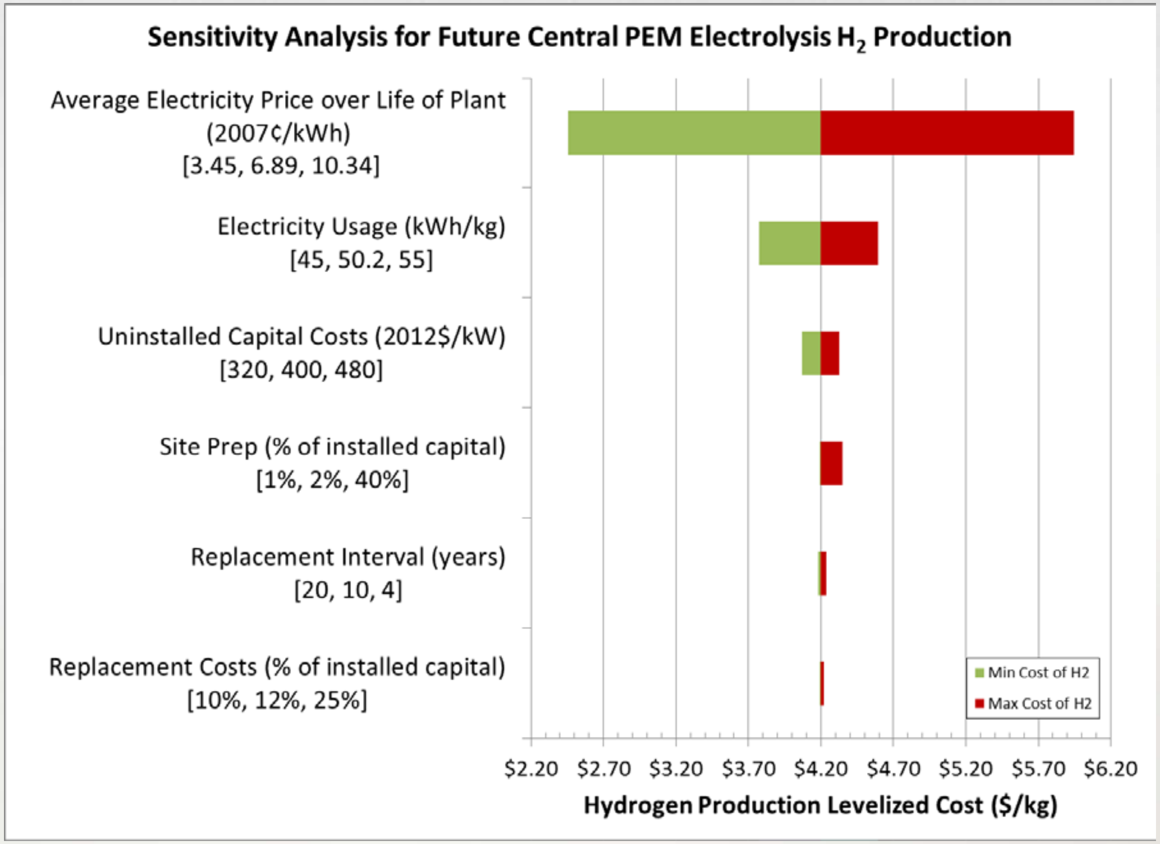
Sensitivity Analysis: Current 2010 Central Technology Projection



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

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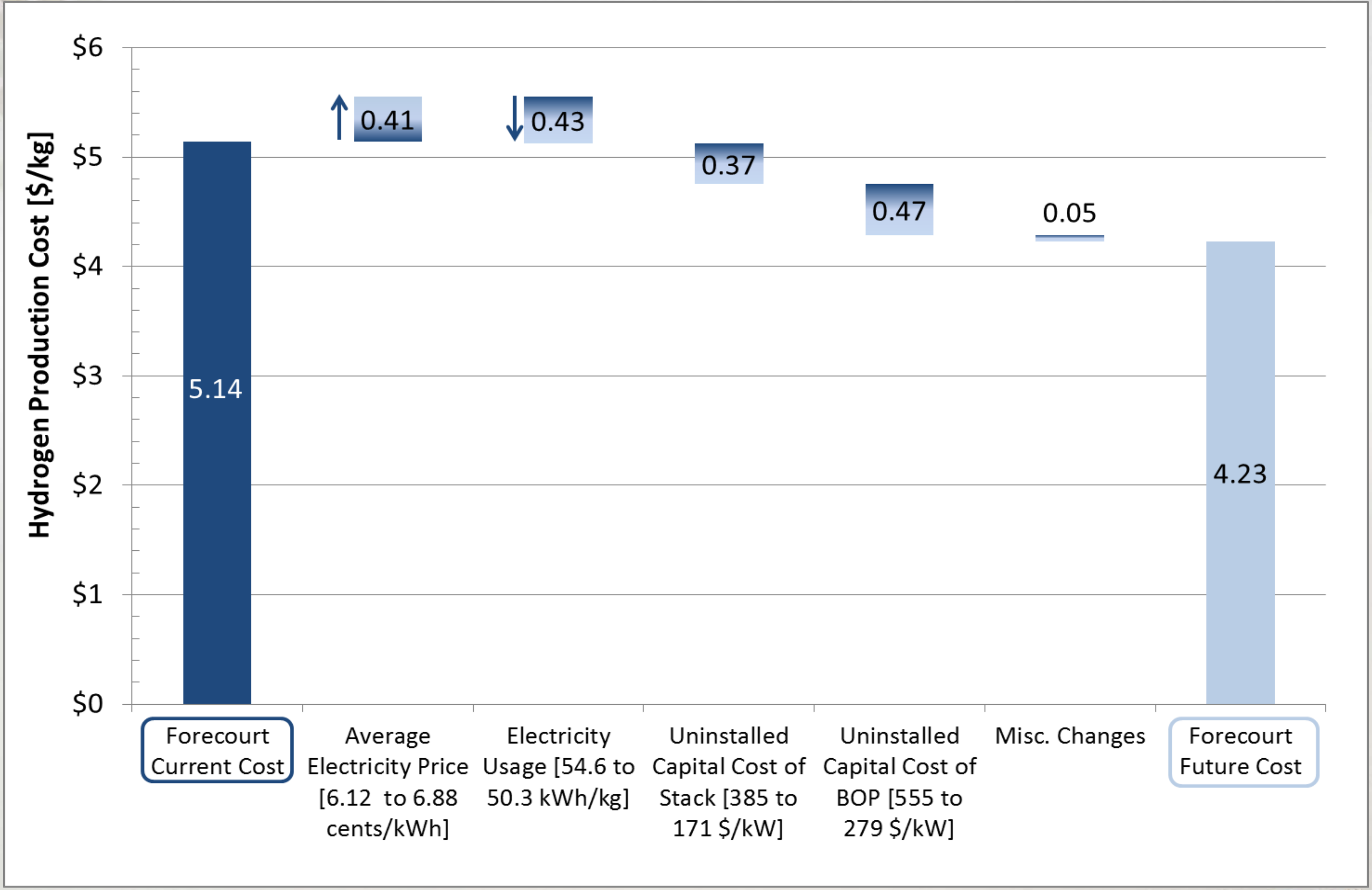
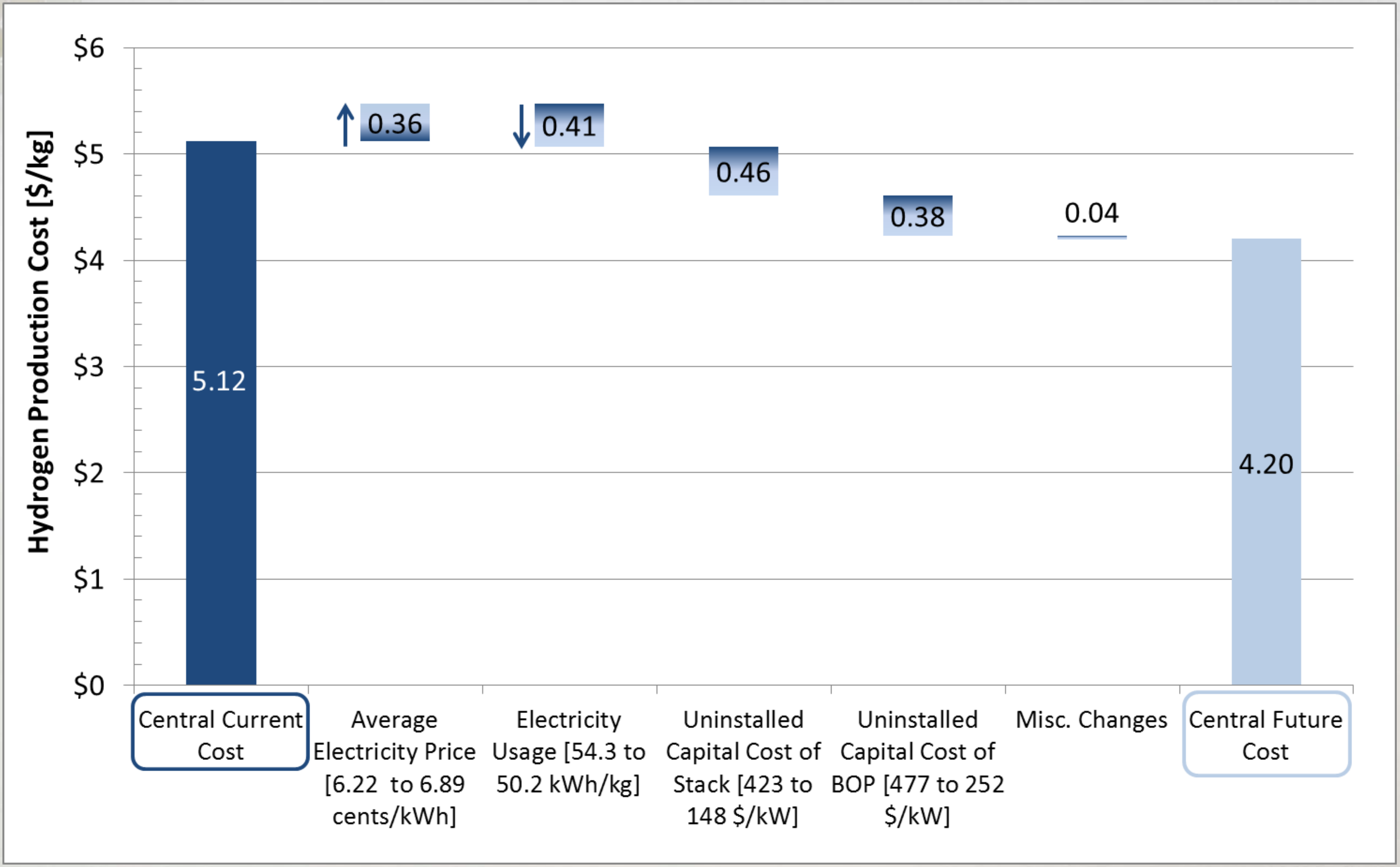
Waterfall Chart: Forecourt Current to Future



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

Waterfall Chart: Central Current to Future



Similar results are seen for the Central Cases between current to future.

Incorporating Degradation into H2A Model

H2A Model Sizes	Forecourt		Central	
H2A Model Technology Time Frame	Current	Future	Current	Future
H2A Model Stack Lifetime (yrs)	7	10	7	10

- Degradation: 2-6mV/1,000hr for modern systems, degradation has historically been higher.
- Two possible system design types to handle degradation:
  1. **Design of PEM system: produce required amount of gas over lifetime.** The power supply is oversized to compensate for the voltage increase over time such that the system can maintain the same input current (and hence H_2 production) over its lifetime.
  2. **Design of PEM system: produce less gas over lifetime.** Could operate so that maintain the same power input (reduction of current density = reduction in capacity of system).
- Degradation is minor and for the H2A cases, it was assumed to be addressed within the range of sensitivities limits for the system capital costs (specifically, the assumed electrolyzer stack and DC power supply capital costs).

Higher H_2 Outlet Pressure Systems

H2A Model Sizes	Forecourt		Central	
H2A Model Technology Time Frame	Current	Future	Current	Future
H2A Model System Pressure (psi)	450	1,000	450	1,000

Disadvantages of Operating at Higher Pressure

- Operating at high pressures places limitations on increasing electrolyzer stack size because of pressure containment issues and the need to reduce cell diameter at high pressures.
- Higher stack cost (SA projects a 20% increase in capital cost when double pressure based on prior SA cost models for electrochemical hydrogen compression.)
- There is a tradeoff with higher (differential) pressure operation in that it results in increased H_2 back-diffusion in the PEM stack. As a result, the marginal cost of mechanical compression may be less expensive than pressurized electrolyzers for delivering higher pressure H_2.
- (Currently) lower demonstrated compressor efficiency than mechanical compression, and
- Higher electrical input required (for overcoming Nernst effects and back-diffusion).

Advantages of Operating at Higher Pressure

- Simpler design with fewer moving parts and lower noise than mechanical compression,
- Potentially better compression efficiency than mechanical compression (projected in the future but not currently demonstrated), and
- Potential storage cost savings if outlet pressure >3 kpsi due to an altered dispensing paradigm.
- Mechanical compressors are one of the largest sources of unscheduled maintenance at hydrogen refueling stations.

Higher H_2 Outlet Pressure Systems

a. Not all manufacturers agree that pressure will be higher in future
b. Analysis assumes stack operation at 450psi(current) and 1,000psi (future)
c. Advantages of less mechanical compression and potential of storage cost savings if outlet pressure > 3kpsi due to an altered dispensing paradigm
d. Disadvantages of higher stack pressure include higher stack cost and higher electrical input required for overcoming Nernst effects and back-diffusion
e. Based on this analysis, it is not a clear advantage to operate at high pressures

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How does Pressure affect H_2 Cost?

There is no clear cost advantage to higher pressure based on this initial analysis.

- Analysis compares the cost of H_2 delivered at 1,000 psi via either higher electrolyzer pressure outlet or mechanical compression.
- Estimated capital cost (stack only) and electrical usage changes only.
- Applied to Forecourt Current H2A case
- Computed $/kgH_2$ change between 450 psi and 1,000 psi

5% increase in stack cost

- Based on Electrochemical Hydrogen Compression (EHC) model

5% increase in energy use

- Based on feedback from industry

H_2 Outlet Pressure (psi)	Stack Cost ($/sys)	Energy Usage (kWh/kg)	Total Production and Compression, Storage, and Dispensing (CSD) Cost ($/kg H_2)
450 psi	$1,315,178	54.6	$7.58
1,000 psi	$1,380,936	57.33	$7.67

Δ +$0.09/kg$_{H2}$

H_2 cost appears to be relatively insensitive to pressure over this pressure range.

Comparison Details:

Cost Component	Cost of H_2 ($/kg$_{H2}$): Production Cost 450psi	Production Cost 1,000psi	Production Cost Net	Compression, Storage, and Dispensing Cost 450psi	CSD Cost 1,000psi	CSD Cost Net
Capital Costs	$1.35	$1.45	$0.10	$1.53	$1.44	-$0.09
Decommissioning Costs	$0.02	$0.02	$0.00			$0.00
Fixed O&M	$0.42	$0.44	$0.03	$0.54	$0.52	-$0.03
Feedstock Costs and Other Variable Costs (including utilities)	$3.35	$3.52	$0.17	$0.36	$0.28	-$0.08
Total	**$5.14**	**$5.43**	**+$0.29**	**$2.44**	**$2.24**	**-$0.20**

The increase in capital cost associated with pressure only considers the stack. BOP capital cost adjustments were not considered. More detailed analyses could be beneficial.

SUMMARY

- H2A software used to assess current & future PEM electrolysis systems.
- Four PEM electrolysis companies surveyed for input information. Collected data represent general trends/consensus values but not any one particular PEM electrolysis system.
  - large difference in capital cost observed between the four companies
- Large capital cost reductions predicted between Existing and Current systems, and between Current and Future systems.
- Most recent H2A electrolysis cases predict a significant reduction in H_2 production cost, highly dependent on:
  - electrolyzer capital cost
  - electricity price and
  - increased electrolyzer efficiency
- The price of production for H_2 from PEM electrolysis is estimated to be between $4-5/kg for both forecourt and central size plants based on an average cost of electricity of 6.12¢-6.89¢/kWh .
- Different ways to handle degradation, depending on the required availability of the H_2 gas output capacity.
- Operating at higher outlet pressure is not a clear avenue for currently reducing H_2 cost, according to this analysis.

Publicly Available Sources/References

- 2009 Alkaline/PEM "Independent Review"H2A Cases
  - http://www.hydrogen.energy.gov/pdfs/46676.pdf
- Microsoft™ PowerPoint™ Overview of Cases
- Microsoft™ Word™ Document Overview of Cases
  - Includes data questionnaire sent to the Four Companies
  - Includes base parameters and sensitivity limits of Four Cases
- Four H2A Cases

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Backup Slides

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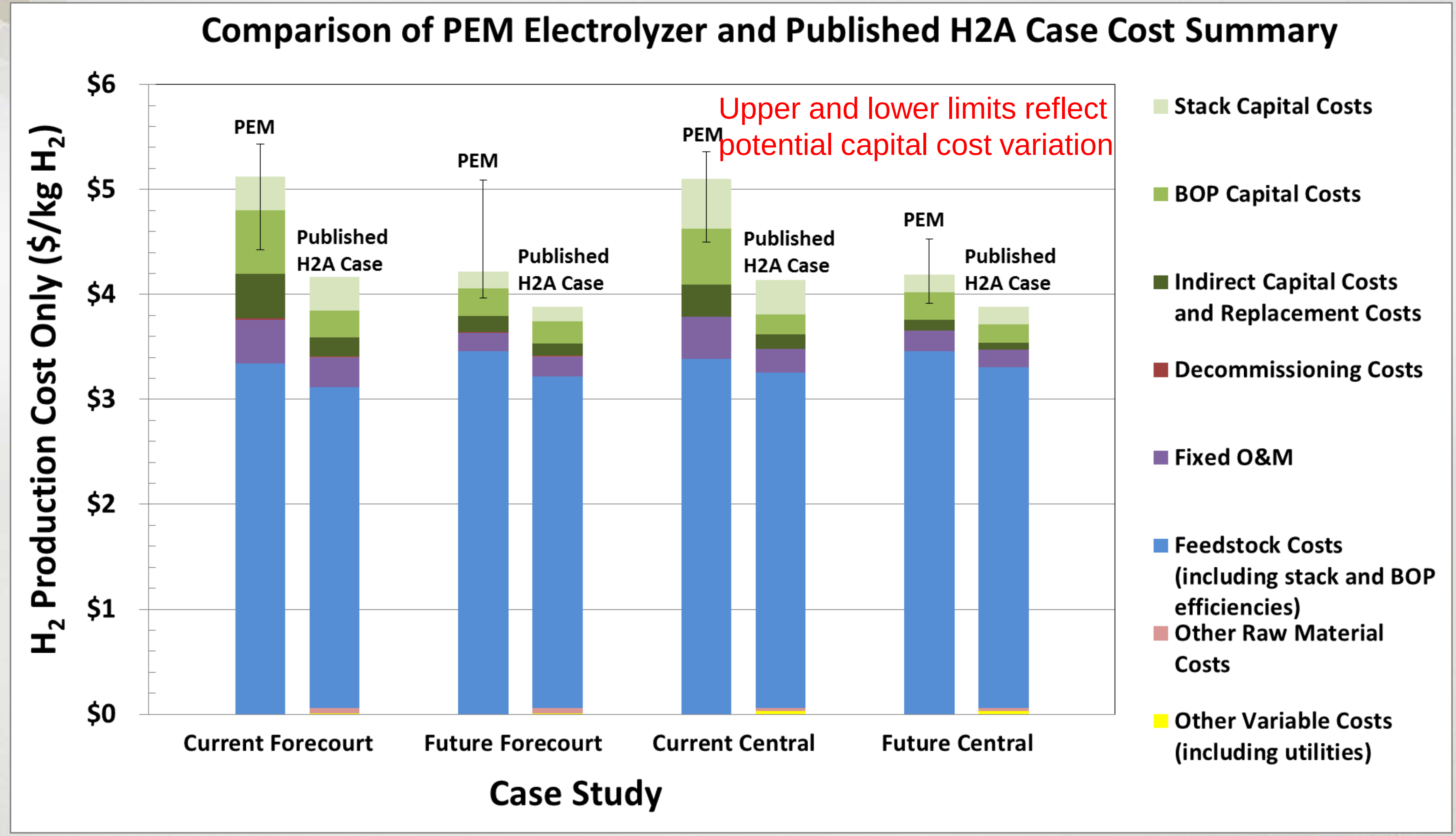
Comparison of four PEM case studies with 2010 Published H2A Case

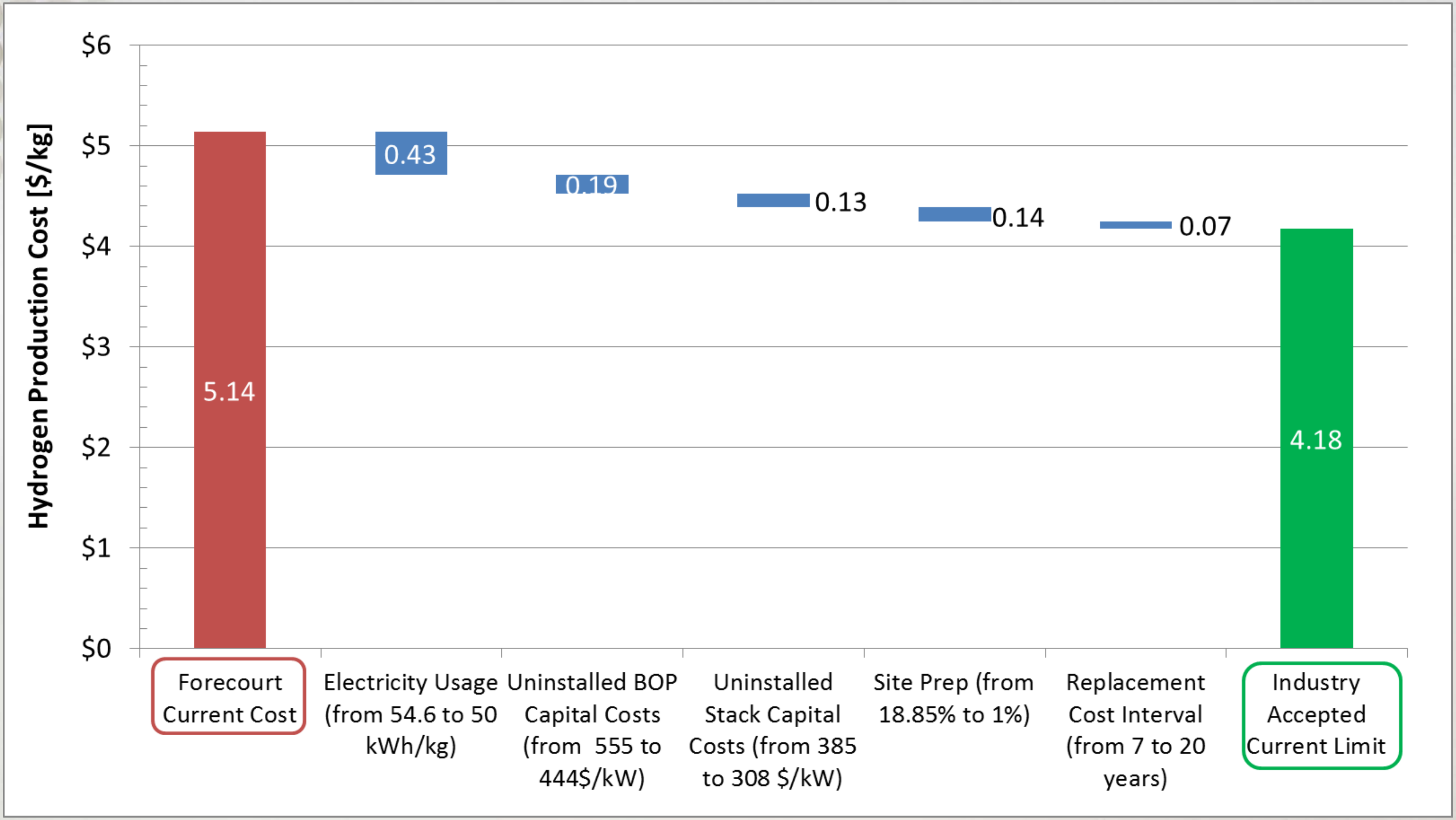
Consistent increases over published cases due largely to BOP capital costs and BOP efficiency losses (affecting feedstock costs)



- "Byproduct Costs" are zero for all cases
- Feedstock costs highly dependent on efficiency and the cost of electricity ($0.057/kWh in startup year for current cases and $0.066/kWh in startup year for future cases)

Waterfall Chart

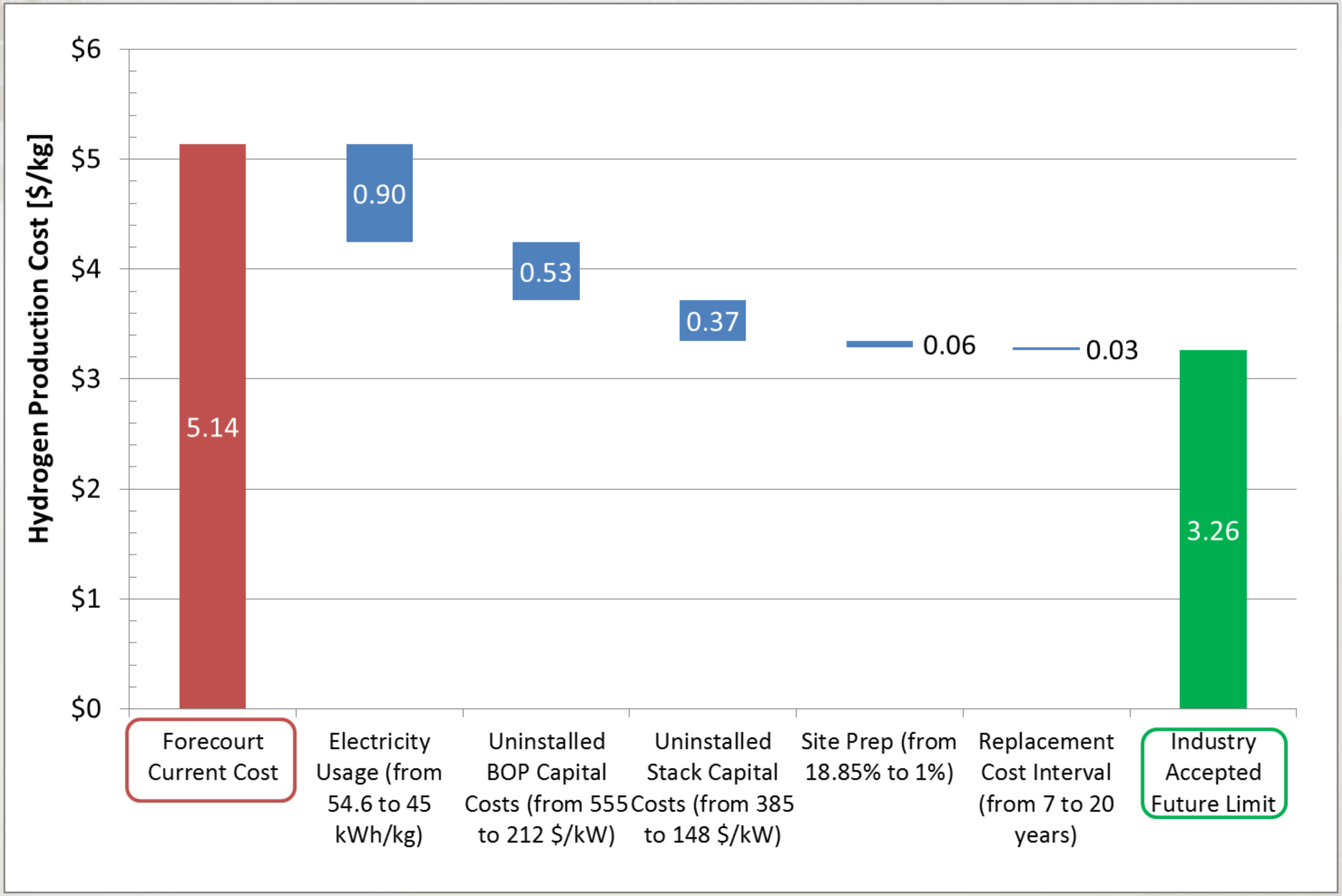
PEM Electrolysis Case (starting at Current Forecourt Cost)



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 future forecourt case. The final low cost is not a 'target,' but a result of applying these changes to model input values.

Target Tables for Water Electrolysis H_2 Production from DOE 2012 Multi-Year Research, Development, & Demonstration (MYRD&D) Plan

DOE Forecourt Targets

Table 3.1.4 Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Production [a, b, c]

Characteristics		Units	2011 Status	2015 Target	2020 Target
Hydrogen Levelized Cost[d] (Production Only)		$/kg	4.20[d]	3.90[d]	2.30[d]
Electrolyzer System Capital Cost		$/kg $/kW	0.70 430[e, f]	0.50 300[f]	0.50 300[f]
System Energy Efficiency[g]		% (LHV)	67	72	75
		kWh/kg	50	46	44
Stack Energy Efficiency[h]		% (LHV)	74	76	77
		kWh/kg	45	44	43
Electricity Price		$/kWh	From AEO 2009[i]	From AEO 2009[i]	0.037[j]

DOE Central Targets

Table 3.1.5 Technical Targets: Central Water Electrolysis Using Green Electricity[a,b]

Characteristics	Units	2011 Status[c]	2015 Target[d]	2020 Target[e]
Hydrogen Levelized Cost (Plant Gate)[f]	$/kg H_2	4.10	3.00	2.00
Total Capital Investment[b]	$M	68	51	40
System Energy Efficiency[g]	%	67	73	75
	kWh/kg H_2	50	46	44.7
Stack Energy Efficiency[h]	%	74	76	78
	kWh/kg H_2	45	44	43
Electricity Price[i]	$/kWh	From AEO '09	$0.049	$0.031

Table 3.1.4.A Distributed Electrolysis H2A Example Cost Contributions [a, b, c]

Characteristics		Units	2011 Status	2015	2020
Electrolysis System	Cost Contribution[a, b, e]	$/kg H_2	0.70	0.50	0.50
	Production Equipment Availability[c]	%	98	98	98
Electricity	Cost Contribution	$/kg H_2	3.00[i]	3.10[i]	1.60[j]
Production Fixed O&M	Cost Contribution	$/kg H_2	0.30	0.20	0.20
Production Other Variable Costs	Cost Contribution	$/kg H_2	0.10	0.10	<0.10
Hydrogen Production	Cost Contribution	$/kg H_2	4.10	3.90	2.30
Compression, Storage, and Dispensing[k]	Cost Contribution	$/kg H_2	2.50	1.70	1.70
Total Hydrogen Levelized Cost (Dispensed)		$/kg H_2	6.60	5.60	4.00

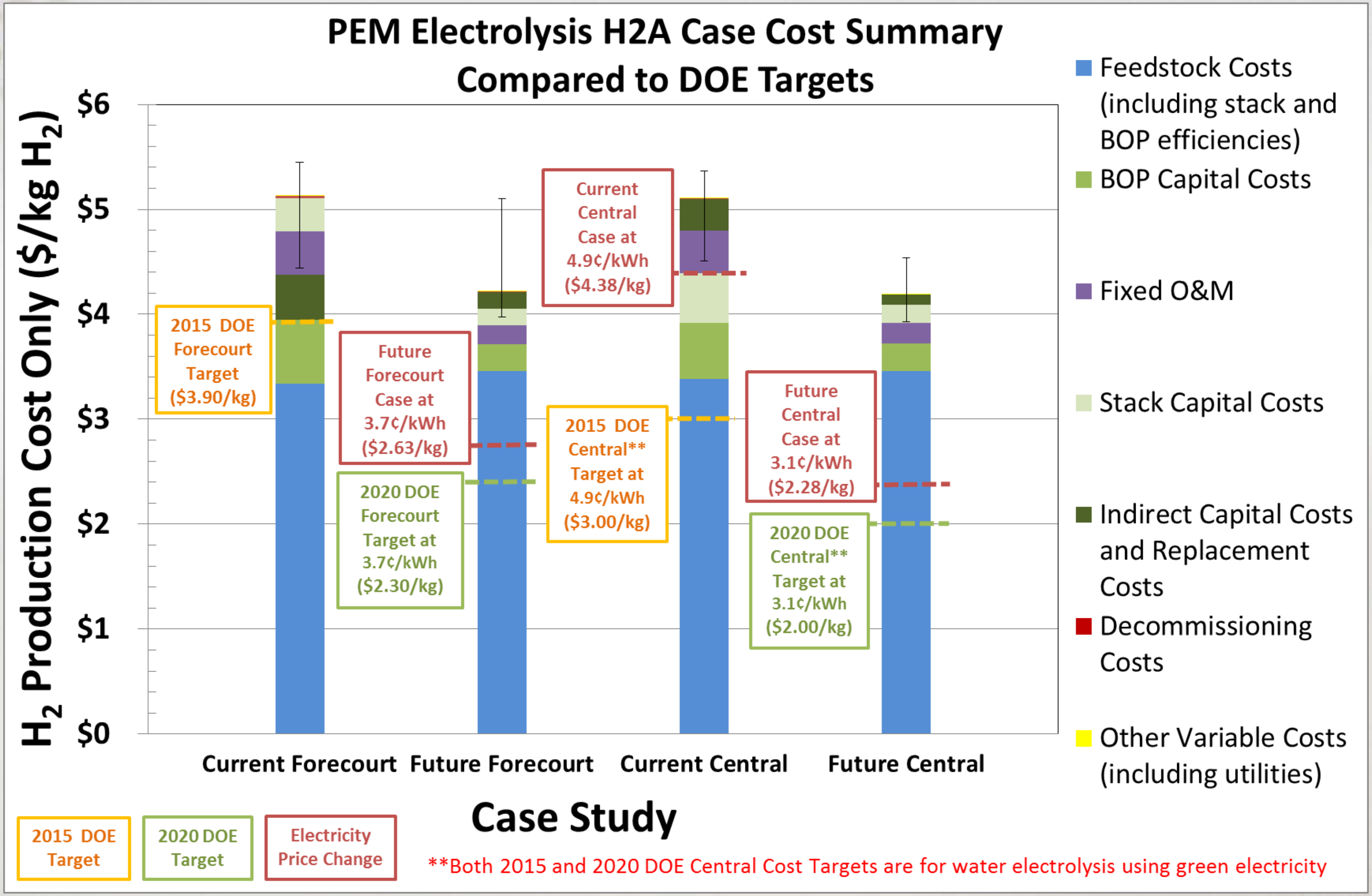
Table 3.1.5.A Central Water Electrolysis H2A Example Cost Contributions [a,b]

Characteristics	Units	2011 Status[c]	2015[d]	2020[e]
Capital Cost Contribution	$/kg	0.60	0.50	0.40
Feedstock Cost Contribution	$/kg	3.20	2.30	1.40
Fixed O&M Cost Contribution	$/kg	0.20	0.10	0.10
Other Variable Cost Contribution	$/kg	0.10	0.10	0.10
Total Hydrogen Levelized Cost (Plant Gate)	$/kg	4.10	3.20	2.00

DOE Targets assume low electricity prices: 3.7¢/kilowatt (kW) for forecourt in 2020; 4.9¢/kW for central in 2015 and 3.1¢/kW for central in 2020.

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

Case Cost Results Compared to DOE Targets[2]



Future PEM system H_2 cost (both Forecourt & Central) is within ~10% of DOE 2020 Targets when electricity price is adjusted to DOE assumptions.

[2] *http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf*

Target Tables for Water Electrolysis H_2 Production from DOE 2012 Multi-Year Research, Development, & Demonstration (MYRD&D) Plan

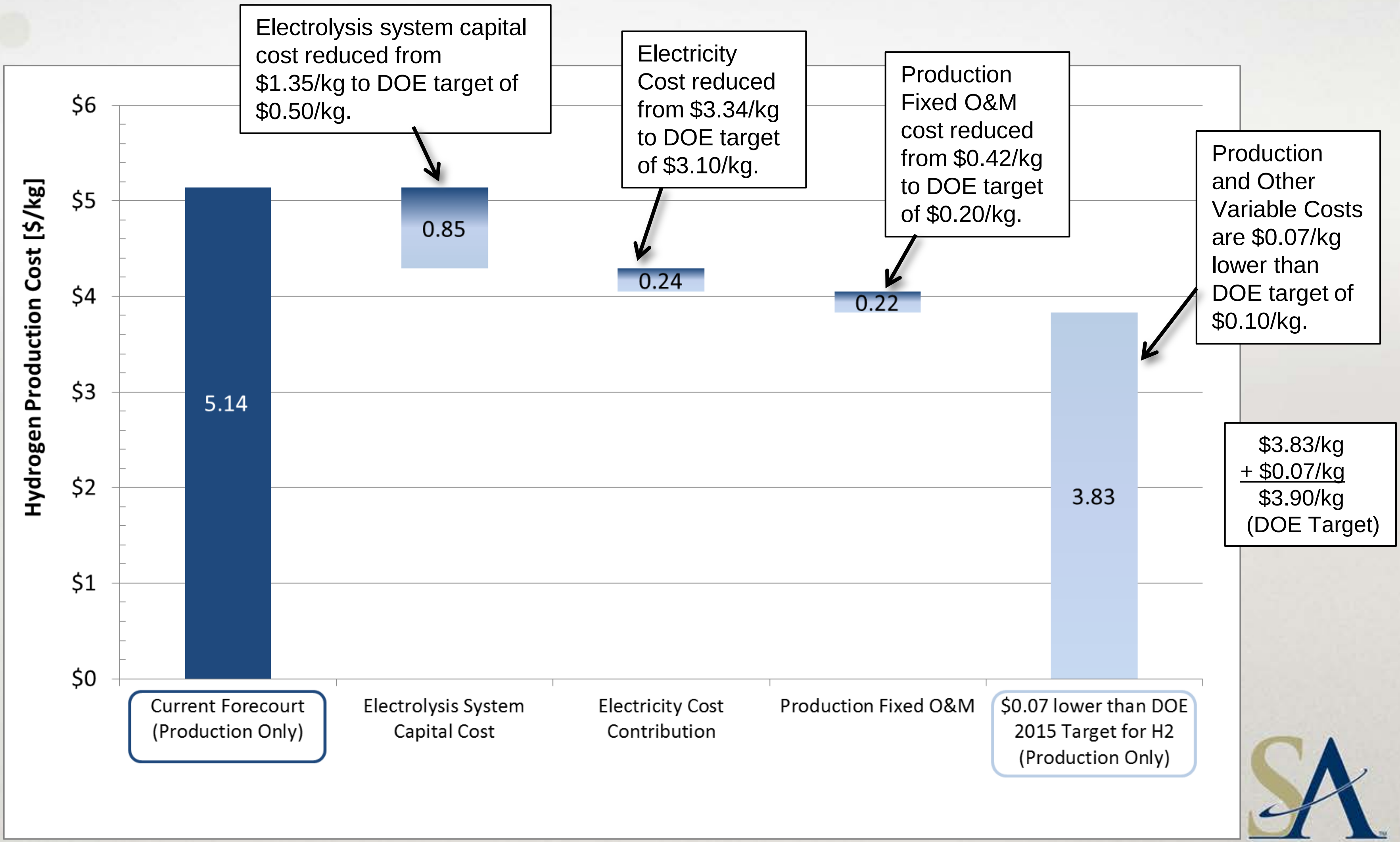
Table 3.1.4.A Distributed Electrolysis H2A Example Cost Contributions [a, b, c]						Distributed Forecourt PEM Water Electrolysis Hydrogen Production	
Characteristics		Units	2011 Status	2015	2020	2013 Current Forecourt Case	Changes Required to Achieve Target
Electrolysis System	Cost Contribution [a, b, e]	$/kg H_2	0.70	0.50	0.50	1.35	(0.85)
	Production Equipment Availability [c]	%	98	98	98	97	(1)
Electricity	Cost Contribution	$/kg H_2	3.00 [i]	3.10 [i]	1.60 [j]	3.34	(0.24)
Production Fixed O&M	Cost Contribution	$/kg H_2	0.30	0.20	0.20	0.42	(0.22)
Production Other Variable Costs	Cost Contribution	$/kg H_2	0.10	0.10	<0.10	0.03	Target Met
Hydrogen Production	Cost Contribution	$/kg H_2	4.10	3.90	2.30	5.14	(1.24)
Compression, Storage, and Dispensing [k]	Cost Contribution	$/kg H_2	2.50	1.70	1.70	2.46	(0.76)
Total Hydrogen Levelized Cost (Dispensed)		$/kg H_2	6.60	5.60	4.00	7.60	(2.00)

Graphical comparison of Current Forecourt to DOE 2015 target on next slide.

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

Waterfall Chart from Current Forecourt Case to DOE 2015 Target for Production Only

Reductions in cost required to meet DOE 2015 Target for production cost of H_2



Nearer-Term, Low-Carbon Technologies

- Reforming of Biogas
  - Uses mature reforming processes
  - Gas clean-up and feedstock cost/availability are issues
  - Can be modeled by modifying existing H2A cases

- Water Electrolysis using Renewable Electricity
  - Uses commercial technologies
  - Electricity cost is primary cost driver
  - Stack and BOP efficiencies can be improved
  - Stack and BOP capital costs can be reduced
  - Detailed H2A cases under development
  - High priority in EU energy strategies

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