STRATEGIC ANALYSIS INC

Techno-Economic Analysis of Hydrogen Production Pathways

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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.

DOE GOAL: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of \$2-\$4/gge H2 by 2020

Program Record (Offices of Fuel Cell Technologies)	
Record #: 11007	**Date:** March 25, 2011
Title: Hydrogen Threshold Cost Calculation	
Originator: Mark Ruth & Fred Joseck	
Approved by: Sunita Satyapal	**Date:** March 24, 2011

Description:

The hydrogen threshold cost is defined as the hydrogen cost in the range of \$2.00-\$4.00/gge (2007\$) which represents the cost at which hydrogen fuel cell electric vehicles (FCEVs) are projected to become competitive on a cost per mile basis with the competing vehicles [gasoline in hybrid-electric vehicles (HEVs)] in 2020. This record documents the methodology and assumptions used to calculate that threshold cost.

Principles:

The cost threshold analysis is a "top-down" analysis of the cost at which hydrogen would be competitive with gasoline in the light-duty vehicle (LDV) market. Because it is market-driven, it is pathway independent and provides a measure for assessing technology performance against market requirements. Projected improvements in vehicle technologies (both FCEVs and the competing HEVs) are included in the calculation through the incorporation of vehicle fuel economies and incremental costs.

Previous Target:

The previous hydrogen cost target of \$2.00-\$3.00/gge was calculated in 2005[1]. The previous cost target range was set in 2005 so the projected cost of the hydrogen FCEV was equivalent to the competing vehicle [HEVs were the competing vehicle for the lower end of the range and internal combustion engine (ICE) powered vehicles were the competing vehicle for its upper end]. The projected gasoline price (\$1.30/gal., untaxed) and the projected incremental ownership cost of the FCEV have significantly changed since then, thus requiring the cost target to be updated.

Calculation Methodology and Results:

The consumer's cost per mile for the FCEV is set to be equivalent to the cost of the competing technology (a gasoline HEV) on a per mile basis using the following equation:

$$\frac{\textit{Hydrogen threshold cost}\left(\frac{\$}{gge}\right)}{\textit{FCV fuel economy}\left(\frac{mile}{gge}\right)} + \textit{FCV's incremental cost}\left(\frac{\$}{mile}\right) = \frac{\textit{Projected gasoline cost}\left(\frac{\$}{gal}\right)}{\textit{HEV fuel economy}\left(\frac{mile}{gal}\right)}$$

Neither the hydrogen threshold cost nor the projected gasoline cost includes sales or gasoline taxes. The FCEV's incremental cost is the difference in non-fuel ownership costs between the FCEV and the HEV. The incremental cost includes vehicle depreciation, financing, maintenance, tires, repairs, insurance, and registration costs as well as taxes, fees, and tax credits with all terms converted to a \$/mile basis.

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DOE Hydrogen and Fuel Cells Program Record	
Record #: 12001	**Date:** May 14, 2012
Title: H_2 Production and Delivery Cost Apportionment	
Originator: Scott Weil, Sara Dillich, Fred Joseck, and Mark Ruth	
Approved by: Sunita Satyapal and Rick Farmer	**Date:** December 14, 2012

Item:

The hydrogen threshold cost is defined as the untaxed cost of hydrogen (H_2) (produced, delivered, and dispensed) at which hydrogen fuel cell electric vehicles (FCEVs) are projected to become competitive on a \$/mile basis with competing vehicles [gasoline in hybrid-electric vehicles (HEVs)] in 2020. As established in Record 11007 [1], this cost ranges from \$2.00-\$4.00/gge[a] of H_2 (based on \$2007). The threshold cost can be apportioned into its constituent H_2 production and delivery costs, which can then serve as the respective cost targets for multi-year planning of the Fuel Cell Technologies (FCT) Program H_2 Production and Delivery sub-programs. As described below, regardless of whether hydrogen is produced at central or distributed sites, the apportionment calculation approximates to a 50-50 split, or \$1.00 to \$2.00/gge for the cost of H_2 production and \$1.00 to \$2.00/gge for the cost of H_2 delivery (including CSD).

Data and Assumptions:

The following steps were used to establish the cost target apportionment between H_2 production and H_2 delivery based on the overriding hydrogen threshold cost of \$2.00 - \$4.00/gge:

1) Set a centralized hydrogen production target using cost projections based on the current lowest cost production technology because all other technologies will have to compete with that one on a cost basis.
2) Calculate a central delivery target (i.e. the threshold cost minus the production cost for the lowest cost technology for centralized H_2) and identify the appropriate delivery scenarios and parameters that can directly or approximately meet that target.
3) Use cost and efficiency information generated in the delivery scenarios identified in Step (2) to set the delivery target for distributed production; namely, the aggregate cost of compression, storage, and dispensing at the station. This step is based on the assumption that consistent technical targets should be used for delivery from both central and distributed production.
4) Calculate a distributed production target; i.e. the threshold cost minus the distributed delivery cost.

Discussed below are the details of this process.

[a] Where 1kg H_2 (LHV) is approximately equal to 1 gasoline gallon equivalent (gge).

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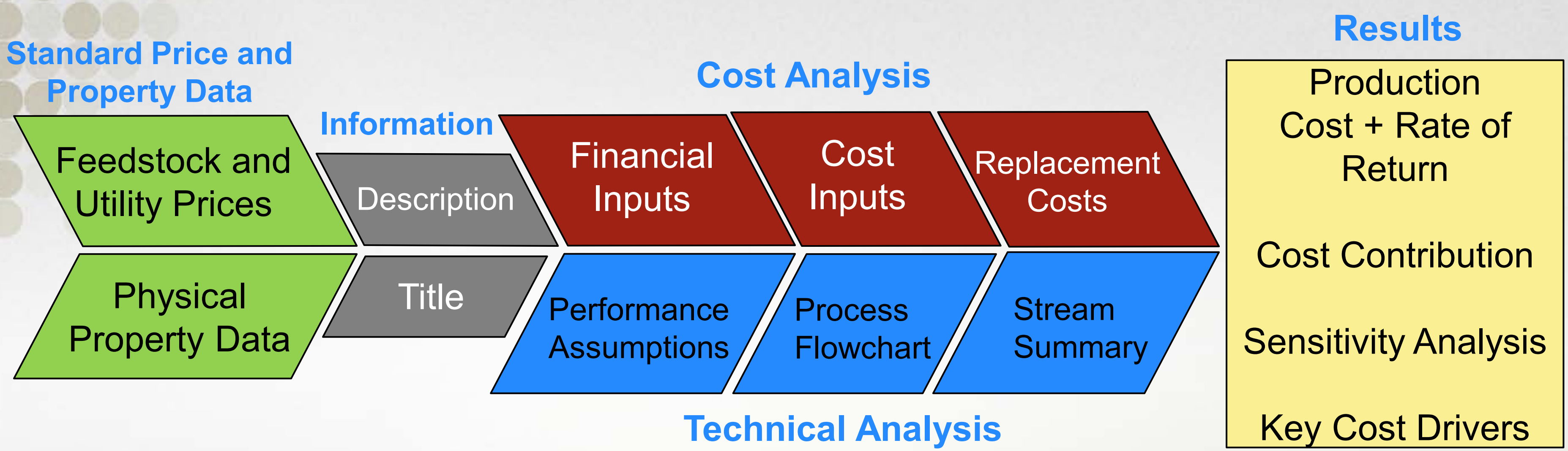
Cost Threshold and Apportionment Records:
http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf
http://www.hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

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

Types of H2A Production Case Studies

Distributed (forecourt/filling station): 1 to 5 metric tons H_2 per day
(also considering 200-500 kg/day for early roll-outs)
Central (large plant size): 100 to 500 metric tons H_2 per day
(also considering semi-central production in 50 metric ton range)

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

- Short term projection from current technology
  - demonstrated advances in technology are implemented
- Potential reduction in capital cost from currently accepted values
- Plant lifetimes consistent with measured or reported data.

Future Case

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

Ultimate Target Case

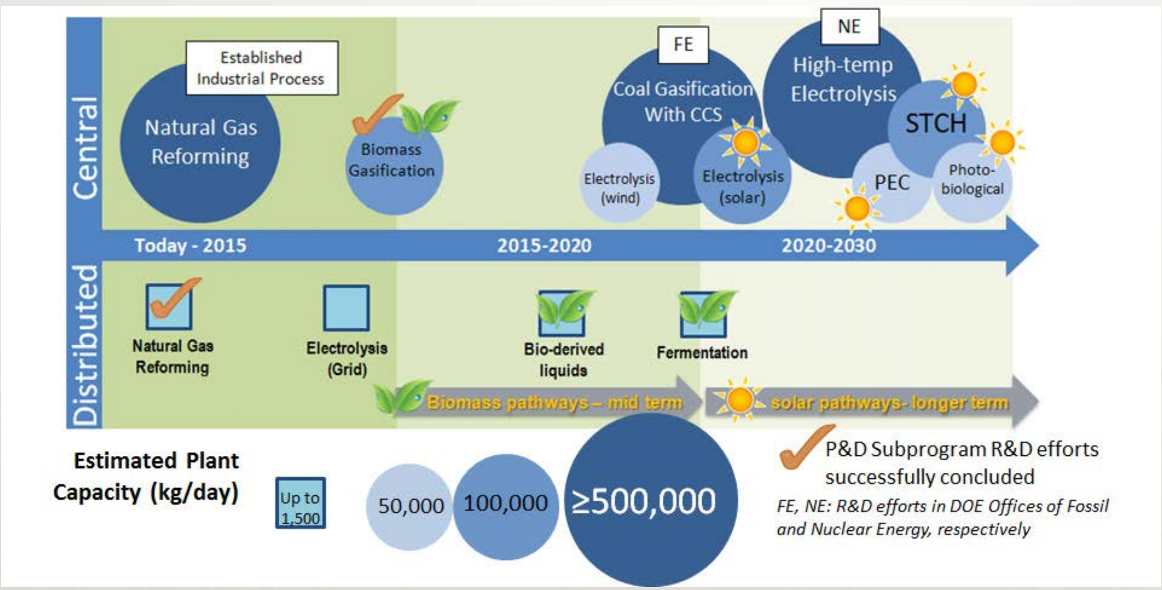
- Assumptions based on expected thermodynamic, physical, or economic limits of the technology.
- Generally expected to approach DOE production target of \$2/kg H_2

H2A cost projections incorporate 'economies of scale' in all cases

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



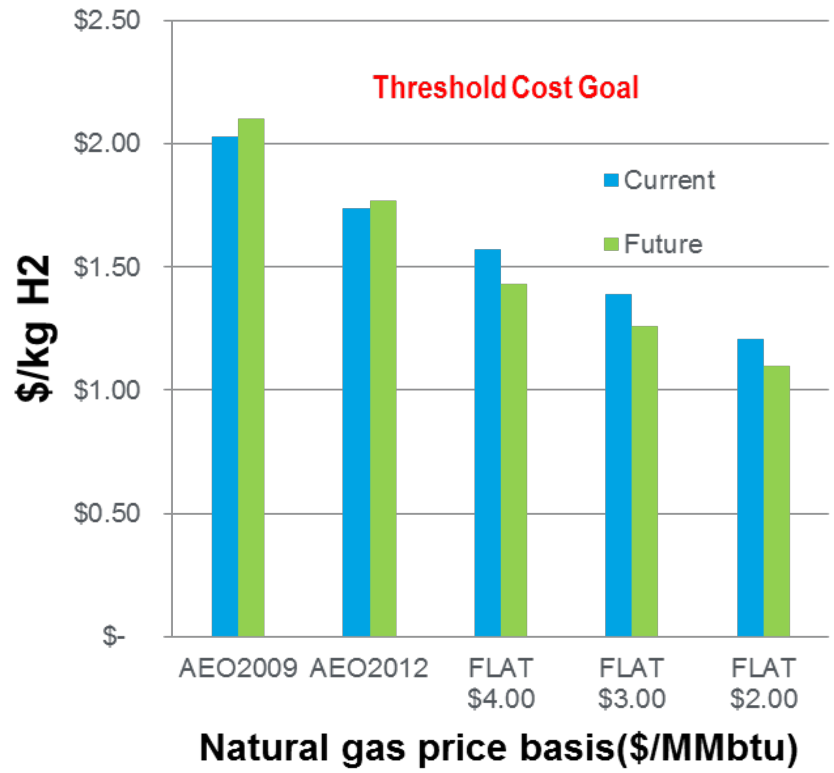
Next Generation of Pathway-Dependent Production Case Studies being Developed

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

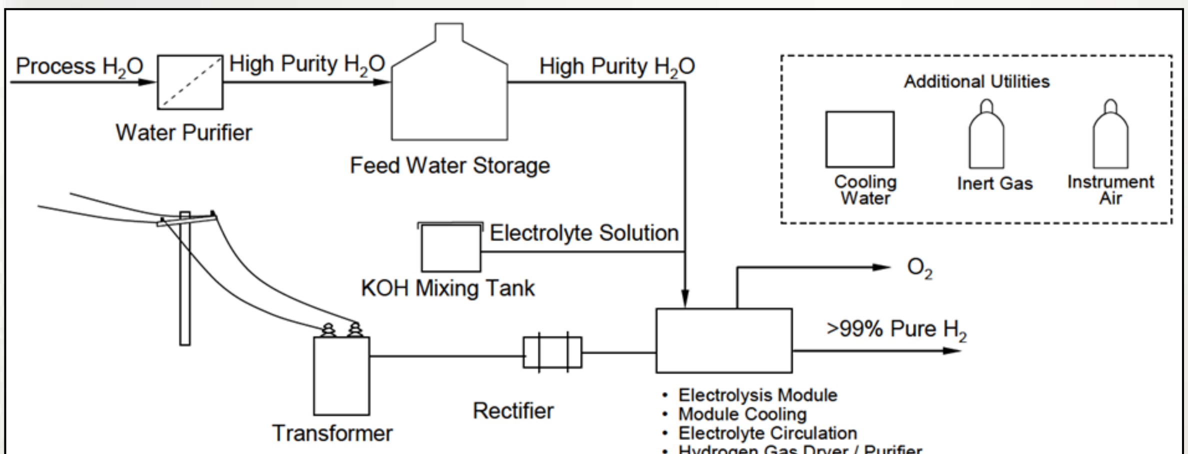
Based on H2A v3 Case Studies @ http://www.hydrogen.energy.gov/h2a_production.html
AEO2009 avg NG prices (HHV, $/MMbtu): $7.10 (Current, 2010-2030); $8.44 (Future, 2020-2040)
AEO2012 avg NG prices (HHV, $/MMBtu): $5.28 (Current, 2010-2030); $6.48 (Future, 2020-2040)

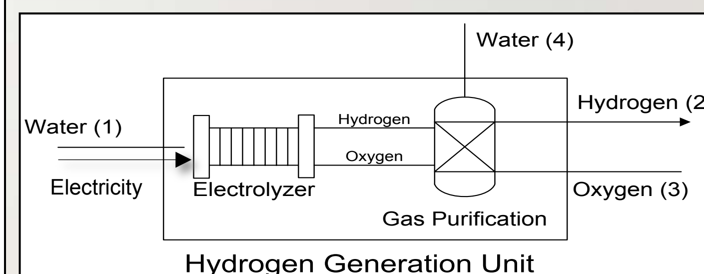
Nearer-Term, Low-Carbon Technologies

- 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

Previous Electrolysis H2A Case Studies

- Standalone grid powered electrolyzer system based on the Norsk Hydro bi-polar alkaline electrolyzer (Atmospheric Type No.5040 - 5150 Amp DC)
- Cases: Current (2015) and Future (2020) technology projection for Forecourt (1.5 metric tons/day) and Central (52.3 metric tons/day) plant sizes
- System Components:
  - Process water for electrolysis and system cooling
  - Transformer
  - Thyristor
  - Lye Tank
  - Feed Water Demineralizer
  - Hydrogen Scrubber
  - Gas Holder
  - 2 Compressor Units to 30 bar (435 psig)
  - Deoxidizer
  - Twin Tower Dryer





H2A Alkaline Electrolysis Model: http://www.hydrogen.energy.gov/h2a_prod_studies.html

H2A Alkaline Electrolysis Report (2009 Independent Review): http://www.hydrogen.energy.gov/pdfs/46676.pdf

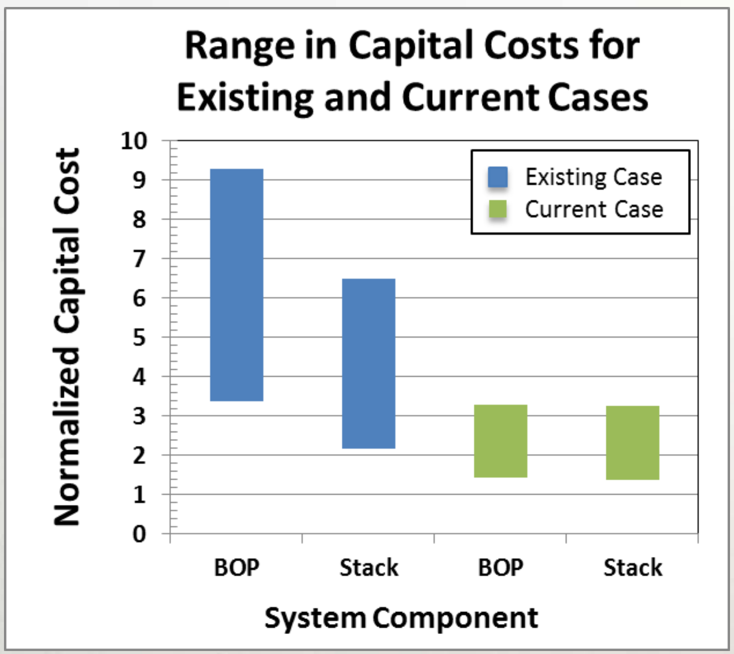
Methodology for New PEM Electrolysis Case Study

		Size of Plant	
		Forecourt	Central
Time Frame for Technology	Existing	Existing Forecourt	
	Current	Current Forecourt	Current Central
	Future	Future Forecourt	Future Central

- Examined four main cases:
  - Forecourt and Central
  - Current and Future
  - (plus company-sensitive information collected for "Existing" cases)
- Solicited information from four electrolyzer companies
  - Proton Onsite, Hydrogenics, Giner, and ITM Power Ltd. (UK)
- Requested relevant detailed information on:
  - Existing/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
  - Current/Future cases for Forecourt/Central

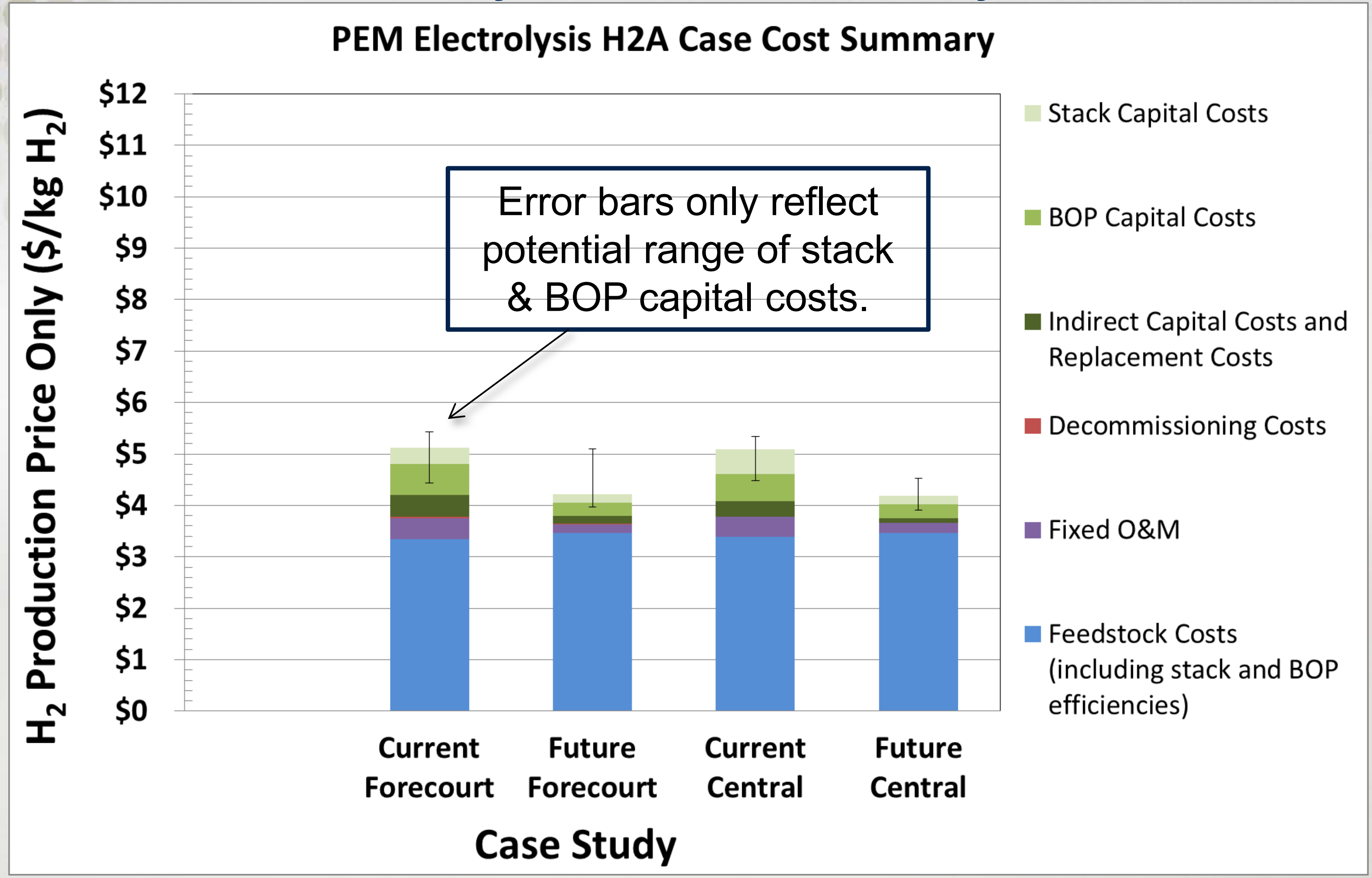
Existing PEM Electrolyzer Technology

- Existing Case refers to largest/best currently available commercial product.
- Current Case refers to technology:
  - already offered as a product or demonstrated in the laboratory
  - projected to high/Nth-quantity production rates
  - sufficient confidence that it could be turned into a commercial product with relatively little development risk
  - only requires a relatively standard/rapid product development cycle.



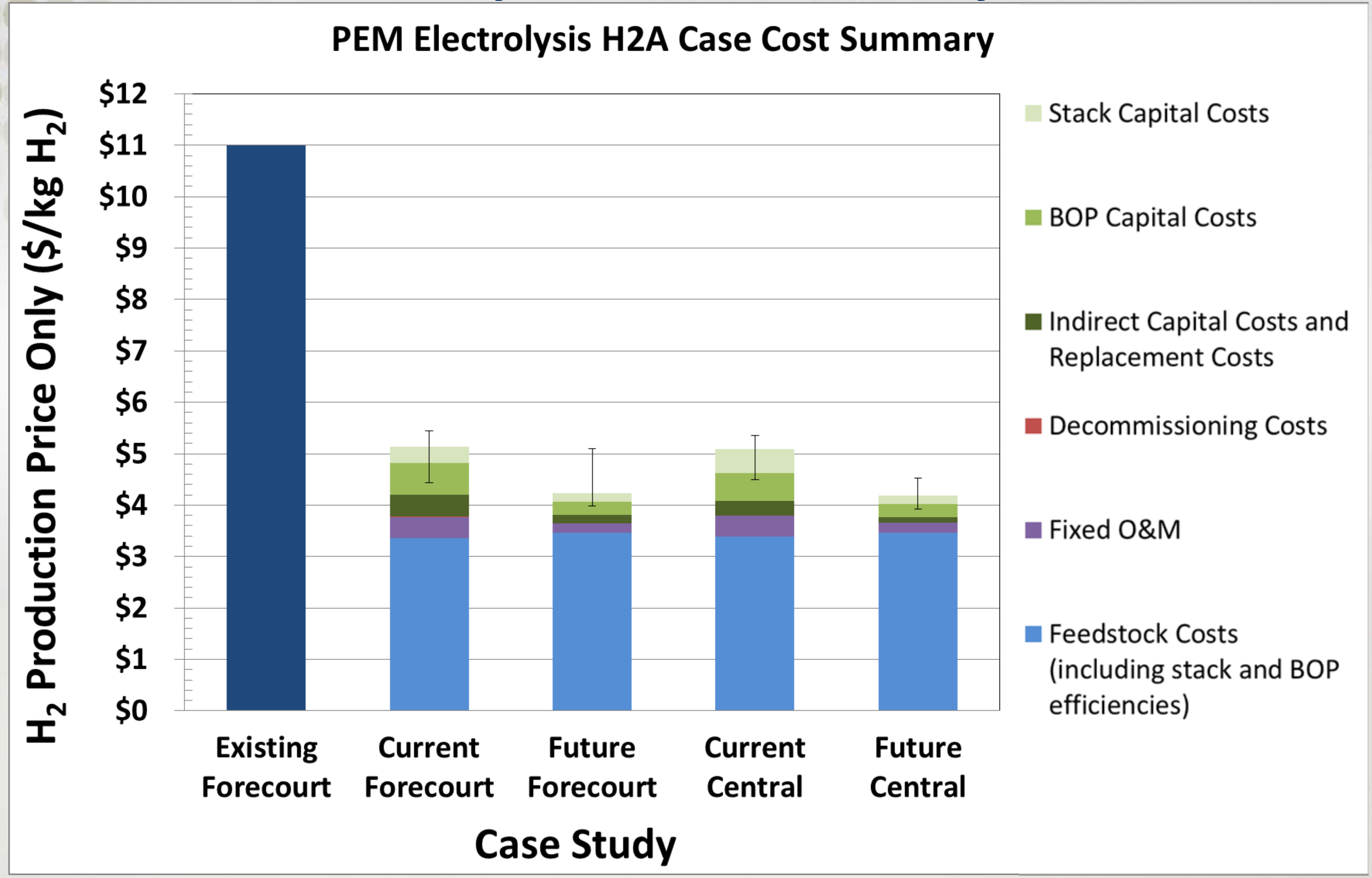
- **Large variation in industry cost estimates.**
  - Existing: +- 45% (for both Stack and BOP)
  - Current: +- 40% (for both Stack and BOP)
- **Large cost reduction moving from "Existing" to "Current"**
  - Existing Stack: 1.5 – 4x "Current"
  - Existing BOP: 1.25- 3x "Current

Four PEM Electrolysis H2A Case Study Results



- "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)

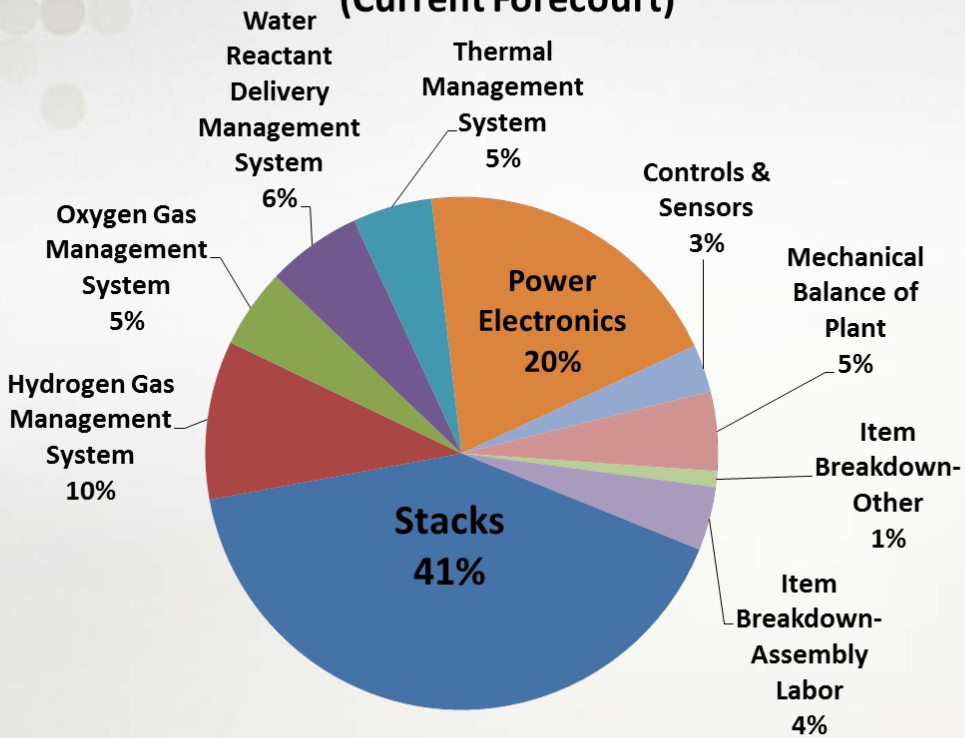
Four PEM Electrolysis H2A Case Study Results



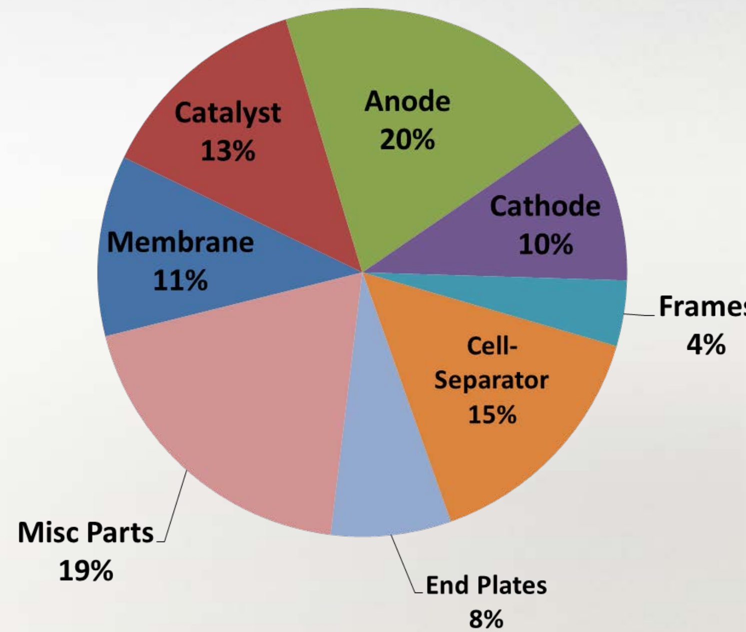
- Substantial H_2 cost difference between “existing” and “current” cases
- Existing Forecourt computed using most conservative assumptions for existing capital cost and existing efficiency

Breakdown of Electrolyzer System Capital Cost

2013 PEM Electrolyzer H2A Case Study (Current Forecourt)



2013 PEM Electrolyzer Stack Breakdown

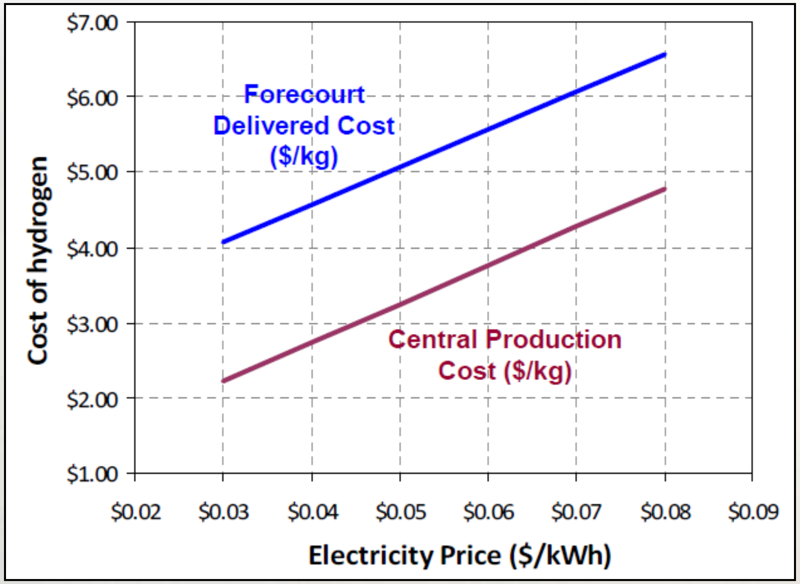


- Power electronics, hydrogen gas management, and the stacks sum to a combined 71% of total system cost.
- Misc. parts of stack includes sealing, tie rods, current collectors, etc.
- Combined membrane, catalyst, anode and cathode make up 54% of stack cost.

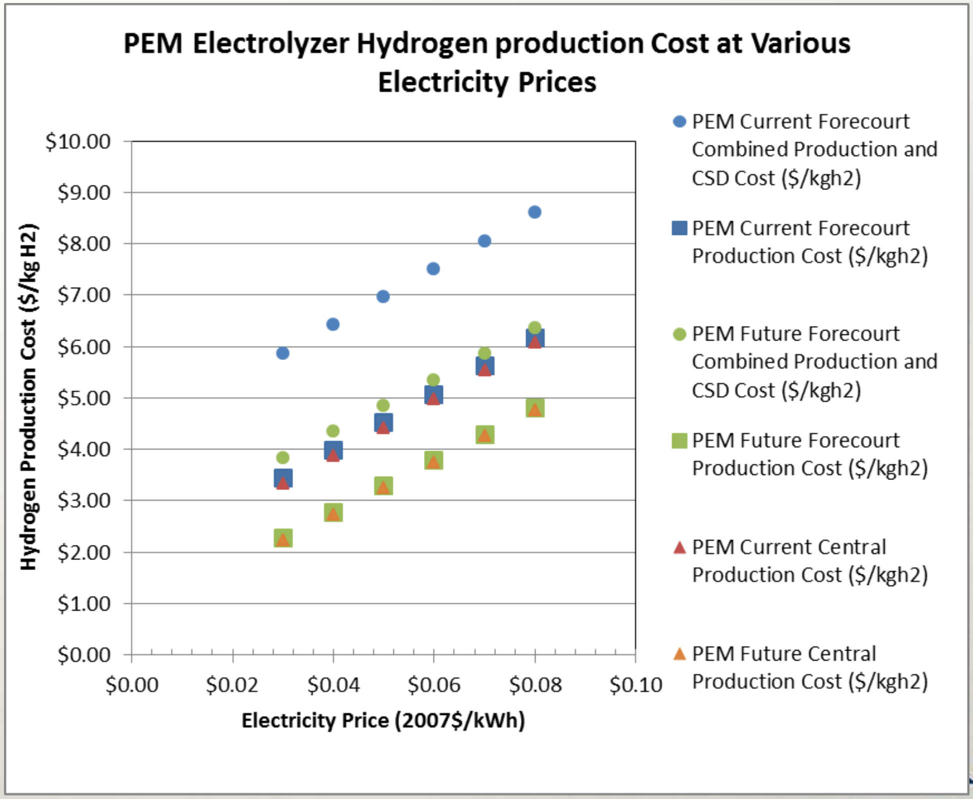
Electricity Cost is a Key Factor in Hydrogen Cost

	Forecourt		Central	
	Current	Future	Current	Future
Electricity Price (2007$/kWh) Constant Price Over Life of Plant				
PEM	0.0612	0.0688	0.0622	0.069
Published H2A Case	0.0612	0.0688	0.0622	0.069

- Varying electricity cost while keeping all other variables (efficiency and capital cost) constant

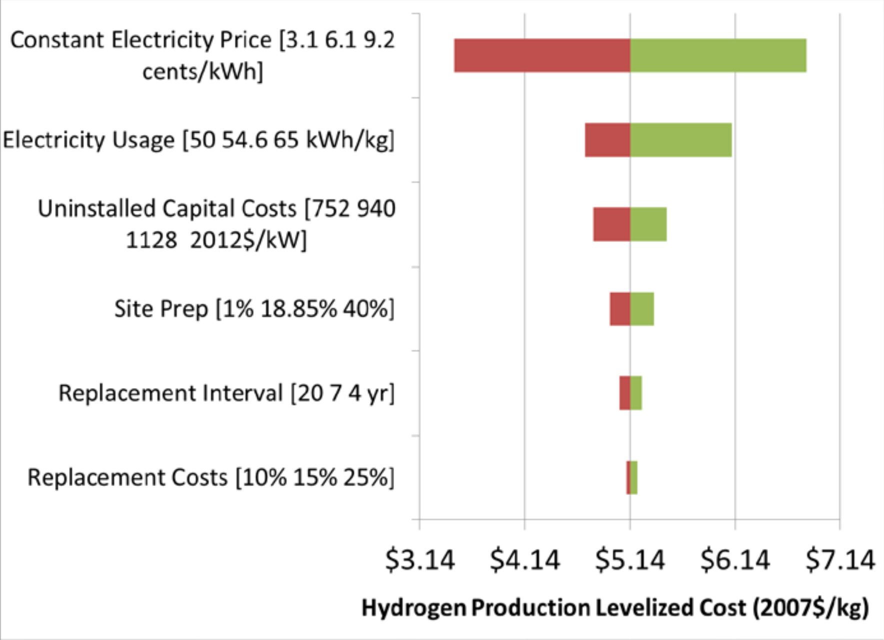


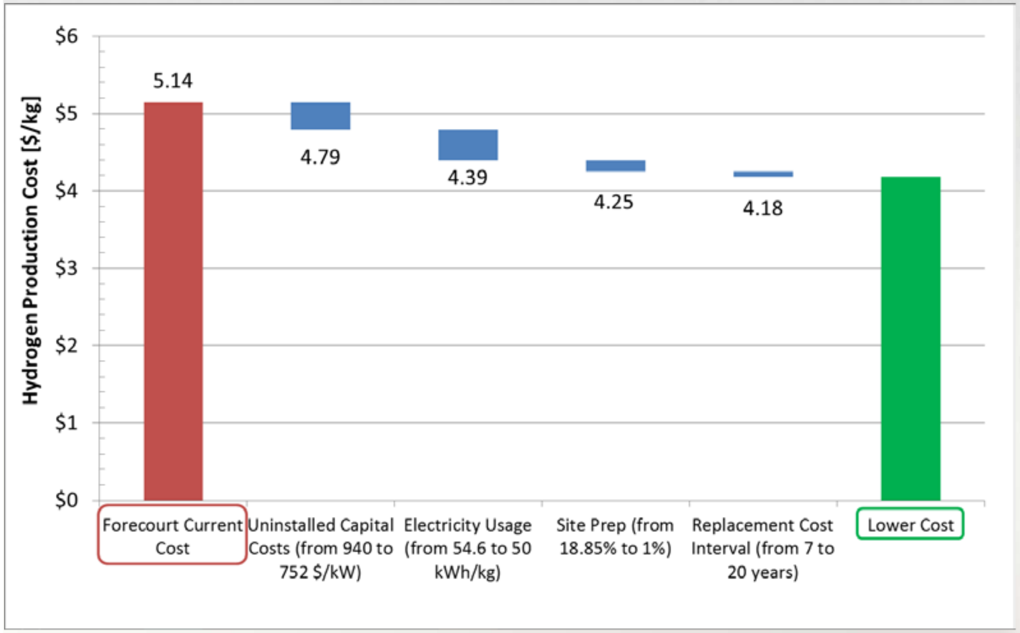
Graph taken from 2009 H2A Electrolyzer Case Study Report
http://www.hydrogen.energy.gov/pdfs/46676.pdf



Sensitivity study for H2A cases

Current Forecourt PEM Electrolysis Case





Sensitivity	Current			Future		
	Default (Forecourt /Central)	High Value	Low Value	Default (Forecourt /Central)	High Value	Low Value
Electricity Cost ($/kWh)	$0.061	+50%	-50%	$0.069	+50%	-50%
Electricity Usage (kWh/kg)	54.6/54.3	65	50	50.3/50.2	55	45
Uninstalled capital Cost ($/kW)	940/900	+20%	-20%	450/400	+20%	-20%
Site Prep (% installed capital)	18.85%/2%	40%	1%	18.85%/2%	40%	1%
Replacement Interval (yr)	7	20	4	10	20	4
Replacement Costs (% installed costs)	15%	25%	10%	12%	25%	10%

Sensitivity limits approved by manufacturers used in analysis.

Important Input Parameters Influencing PEM Electrolysis Hydrogen Production Cost

1. 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: 1.75 at 1500 mA/cm^2 (Current) and 1.65V at 1600 mA/cm^2 (Future)

2. Capital Cost ($)
   a. Methodology: Compared & contrasted industry data. Then used a weighted average of individual components based on company stack/system production experience
   b. More recent feedback shows more detail in cost breakdown for systems and reflects a higher capital cost for PEM electrolyzers than in previous published H2A electrolyzer analysis.

3. Operating pressure (psi)
   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

SUMMARY

- H2A software has been a collaborative tool for techno-economic analyses of H_2 production and delivery pathways to support DOE decisions in research direction and priorities and setting US targets for the price of hydrogen $2/gge by 2020
- NG Steam Methane Reforming is a bridge to nearer-term low-carbon renewable pathways such as biogas reforming and electrolysis using renewable electricity
- Most recent H2A electrolysis cases predict a significant reduction in H_2 production cost, highly dependent on electrolyzer capital cost, electricity cost and increased electrolyzer efficiency
- Emerging renewable energy technologies (i.e. photoelectrochemical (PEC), solar-thermochemical (STCH), and biological production of hydrogen) offer long term advantages
- Techno-economic tools are critical to identifying key costs of promising hydrogen production pathways

Funding Source

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