DOE Hydrogen and Fuel Cells Program Record	
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Title: Hydrogen Production Cost From PEM Electrolysis	
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Item

The projected high volume untaxed cost of hydrogen production from polymer electrolyte membrane (PEM) electrolysis ranges from ~$4 to $5.80/kg[1], based on Hydrogen Analysis version 3 (H2A v3) model[2] case study results. Four cases were analyzed, comprising two technology years (Current [2013] and Future [2025]), and two production capacities (Distributed Forecourt [500-1,500 kg/day] and Centralized [50,000 kg/day])[3]. The analysis used input from, and reviews by, four independent manufacturers of PEM electrolysis systems to ensure the relevance and accuracy of the study parameters and results.

Summary

Table 1 summarizes the cost projection results for hydrogen production (untaxed, delivery and dispensing not included) for the four cases. The Baseline Projections shown in the table incorporate averages of the manufacturer-supplied electrolyzer stack and balance of plant (BOP) costs; while the Low and High Values are included to reflect an expected spread in uninstalled capital costs (with all other technoeconomic inputs the same as in the Baseline cases), as vetted by the manufacturers. The Baseline, Low, and High values in the table for the Forecourt cases represent a standard 1,500 kg/day production capacity; as a variation on the standard Current Forecourt case, an analysis of early market stations (500 kg/day capacity) was performed with inputs from the manufacturers. The result is also included in Table 1.

Table 1. H_2 production high-volume cost projections for the PEM Electrolysis cases[4]

Case Study	Low Value ($/kg H_2)	Baseline ($/kg H_2)	High Value ($/kg H_2)	Early Market[5] ($/kg H_2)
***Forecourt**: Current Case*[6]	$4.79	**$5.14**	$5.49	$5.79
Future Case[7]	$4.08	**$4.23**	$4.37	-
***Central:** Current Case*[8]	$4.80	**$5.12**	$5.45	-
Future Case[9]	$4.07	**$4.20**	$4.33	-

[1] Costs per kg of produced hydrogen using 2007 dollars as the cost basis (i.e., reported as 2007$/kg H_2).
[2] H2A is a discounted cash-flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for H_2 production at central and forecourt facilities: http://www.hydrogen.energy.gov/h2a_production.html.
[3] H2A v3 PEM Electrolysis Cases published at: http://www.hydrogen.energy.gov/h2a_prod_studies.html: See Table 2 for a summary of case input parameters.
[4] Hydrogen costs reported in 2007$/kg, consistent with H2A v3 methodology which utilizes data from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2009 Report* (where 2007$ is the standard cost basis).
[5] Current Forecourt analysis at the 500 kg/day production level, more representative of early market stations.
[6] Uses 6.12¢/kWh average electricity price (levelized over 20 yr. life); with 450psi outlet pressure. See Table 2.
[7] Uses 6.88¢/kWh average electricity price (levelized over 20 yr. life); with 1000psi outlet pressure. See Table 2.
[8] Uses 6.22¢/kWh average electricity price (levelized over 40 yr. life); with 450psi outlet pressure. See Table 2.
[9] Uses 6.89¢/kWh average electricity price (levelized over 40 yr. life); with 1000psi outlet pressure. See Table 2.

Analytical Basis

Four case studies centered on PEM-based electrolysis were performed using the H2A v3 model[10]. The four cases comprised two technology years[11]: Current[12] (2013) and Future[13] (2025); and two production capacities: distributed Forecourt (500 -1,500 kg/day) and Centralized (50,000 kg/day).

Relevant technoeconomic data and information for the cases were solicited from four independent electrolyzer companies via questionnaire spreadsheets. The requested data included H2A input parameters needed for developing cases; as well as supplemental information for the documentation and vetting of the underlying technology assumptions. Data collected fell into the following five primary categories: (1) engineering system definition; (2) capital costs; (3) operating costs; (4) variable and fixed expenses; and (5) replacement costs.

The data and information were used as inputs for the four H2A case studies. For each case, an engineering system performance model was developed from the baseline inputs, so as to create a generalized electrolyzer system engineering design based on the diverse industry input from the electrolyzer manufacturers. The generalized electrolyzer system schematic is shown in Figure 1.

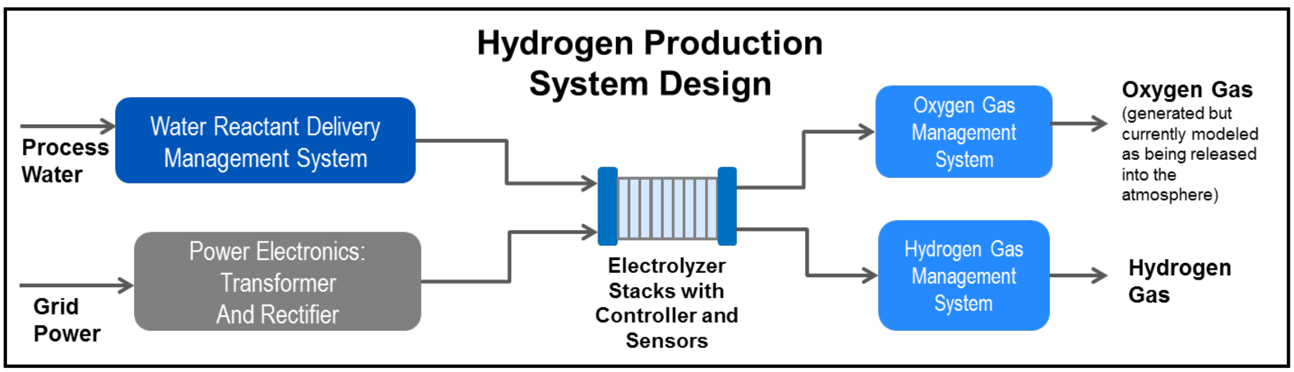

Figure 1. Generalized PEM electrolyzer system.

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[10] H2A is a discounted cash-flow model providing transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and forecourt facilities. H2A addresses cost scenarios where sufficiently high annual and cumulative volumes have been reached so that economies of scale for capital and unit costs have been achieved. Additional information can be found at: http://www.hydrogen.energy.gov/h2a_production.html.

[11] Technology development year is defined as the year in which a system design and performance level have been demonstrated in the laboratory with high confidence that it can be developed into a full-scale system able to achieve performance, durability, and cost targets.

[12] Current Cases reflect demonstrated state-of-the-art technology manufactured at production volume (different from existing costs based on low production commercially available electrolyzers).

[13] Future Cases use advanced electrolyzer systems that will be technology-ready in 2025, with market entry assumed in 2030. Compared with the Current Cases, the Future Cases incorporate expected reductions in capital cost, electricity usage, and site preparation cost as well as increases in replacement interval. The expected levels of improvement were vetted by the manufacturers.

Based on the manufacturers' inputs, generalized system designs were developed for the Current baseline cases that incorporate electrolyzers operating at 1,500 mA/cm^2 with an outlet pressure of 450 psi. The generalized system designs developed for the Future baseline cases were based on technologically-advanced electrolyzers operating at 1,600 mA/cm^2 with an outlet pressure of 1000 psi. For all the cases, the manufacturer's inputs were used to derive system efficiency values (included in Table 2 below under the heading of *Total Electrical Usage*) that account for all losses associated with the stack efficiency, H_2 permeation, the H_2 dryer, and the electrical inverter efficiency as well as other balance-of-plant (BOP) loads. The four companies reviewed and vetted the generalized inputs and designs for all the H2A baseline cases, and also participated in the selection of reasonable parameter limits for the H2A sensitivity analysis.

Using the generalized inputs and designs vetted by the manufacturers, four baseline H2A v3 case studies were performed (i.e., Current Forecourt, Current Central, Future Forecourt, and Future Central), to project baseline hydrogen production costs. In addition, H2A sensitivity analysis was performed for each case, and illustrated in tornado charts, based on the vetted parameter limits.

Baseline Input Parameters

The major parameters used to develop the four H2A v3 baseline case studies are shown in Table 2 (all other H2A input parameters not cited in the table used standard H2A v3 default values[14]).

Table 2. Input parameters for H2A Production cases for PEM electrolysis (costs in 2007$[15] and in 2012$[16])

Parameter	**Current Forecourt** *1,500 kg/day*	**Future Forecourt** *1,500 kg/day*	**Current Central** *50,000 kg/day*	**Future Central** *50,000 kg/day*
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[17]	$171	$423	$148
Balance of Plant (BOP) Capital Cost (2012$/kW)	$555[18]	$279	$477	$252

[14] Default values described at: http://www.hydrogen.energy.gov/h2a_analysis.html#assumptions.

[15] A cost basis of 2007 dollars (2007$) is used for electricity price data which is derived from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2009 Report* which uses 2007$ as its standard cost basis.

[16] Electrolyzer capital costs are listed in U.S. 2012 dollars (2012$) because that is the reporting year for the four electrolyzer companies. However, hydrogen cost results ($/kg) are reported in 2007 dollars (2007$), according to the standard H2A v3 methodology approved by DOE.

[17] Corresponding value of $516 for the 500 kg/day analysis.

[18] Corresponding value of $618 for the 500 kg/day analysis.

Table 2 continued

Parameter	**Current Forecourt** *1,500 kg/day*	**Future Forecourt** *1,500 kg/day*	**Current Central** *50,000 kg/day*	**Future Central** *50,000 kg/day*
Total Electrical Usage kWh/kg Conversion Efficiency (LHV of H_2)	54.6[19] (61%)	50.3 (66%)	54.3 (61%)	50.2 (66%)
Stack Electrical Usage (kWh/kg) Conversion Efficiency (LHV of H_2)	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 at full power (MW)	3.4	3.1	113	105
Average Electricity Price over Life of Plant[20] (2007¢/kWh)	6.12	6.88	6.22	6.89
Electricity Price in Startup Year[21] (2007¢/kWh)	5.74	6.59	5.74	6.59
Outlet Pressure from Electrolyzer (psi)	450	1,000	450	1,000
Installation Cost (% of uninstalled capital cost)	12[22]	10	12	10
Replacement Interval (years)	7	10	7	10
Replacement Cost of Major Components (% of installed capital cost)	15	12	15	12
Plant Life (years)	20	20	40	40
Stack Current Density (mA/cm^2)	1,500	1,600	1,500	1,600
Capacity Factor (%)	86	86	97	97

[19] Value unchanged for the 500 kg/day analysis.

[20] Average electricity price over life of plant (20 years for Forecourt cases and 40 years for Central cases). Note that the average Current Forecourt electricity price (6.12¢/kWh) is less than the average Current Central electricity price (6.22¢/kWh) because of the different time horizons for the investment (20 years versus 40 years). The same pattern holds for the Future cases.

[21] Based on Energy Information Administration (EIA) Annual Energy Outlook (AEO) data.

[22] Corresponding value of 17.5% for the 500 kg/day analysis.

Baseline Cost Projection Results

The hydrogen production cost breakdown for the four H2A v3 PEM electrolysis baseline cases is shown in Table 3. These cases used inputs from the OEMs to determine the most likely parametric values for a given scale of the technology within a given timeframe. This is in contrast to the sensitivity analysis which looks at the effects of deviations from those baseline inputs. As shown in the table, the primary cost driver for production is the electricity feedstock cost for the electrolysis. Although the electrolyzer electrical efficiency increases between the Current and Future cases (as seen in Table 3), the electricity price also rises (also shown in Table 3), and, as a result of this combined effect and other factors, electricity feedstock costs are slightly higher for the Future versus Current cases in Table 3.

Table 3. H_2 production cost breakdowns in 2007$/kg H_2 for PEM electrolysis baseline cases

Component	Current Forecourt *1,500 kg/day*	Future Forecourt *1,500 kg/day*	Current Central *50,000 kg/day*	Future Central *50,000 kg/day*
Stack Capital Cost	$0.42	$0.16	$0.48	$0.17
BOP Capital Cost	$0.61	$0.25	$0.53	$0.26
Indirect Capital Cost and Replacement Cost	$0.32	$0.16	$0.32	$0.10
Decommissioning	$0.02	$0.01	$0.00	$0.00
Fixed operations and maintenance (O&M)	$0.42	$0.18	$0.40	$0.20
Electricity Feedstock	$3.34	$3.46	$3.38	$3.46
Variable O&M	$0.01	$0.01	$0.01	$0.01
Total H_2 Production Cost (2007$/kg H_2)	**$5.14**[23]	**$4.23**	**$5.12**	**$4.20**

Sensitivity Analysis

Table 4 details the range of parameter values used within the H2A v3 sensitivity analysis. The four electrolyzer companies vetted these sensitivity limits, which were suggested by the analysis team, and which are meant to capture the potential range of parameter variation rather than to report the company-sensitive minimum and maximum values from the four participating electrolyzer manufacturers. As one parameter was varied, all others were held fixed at the baseline case values. Analysis of the electricity usage sensitivity shown in Table 4 shows that hydrogen costs can be reduced by $0.08-0.09/kg for every decrease of 1 kWh/kg in net energy usage.

[23] In the early market 500 kg/day analysis, the total projected H_2 production cost is increased to **$5.79/kg** including a total capital cost contribution increase to $1.75/kg, and an O&M cost contribution increase to $0.66/kg.

Table 4. Sensitivity Analysis Results for the four PEM electrolysis cases (H_2 production cost results reported in 2007$; sensitivity limits reported in 2007$ and 2012$, as appropriate)

Current Forecourt	Low[24] Value	Production Cost (2007$/kg)	Baseline Value	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Average Electricity Price over Life of Plant (2007¢/kWh)	3.06	$3.47	6.12	$5.14	9.18	$6.81
Electricity Usage (kWh/kg) (% LHV H_2)	50 (67%)	$4.71	54.6 (61%)	$5.14	65 (51%)	$6.11
Uninstalled Capital Costs[26] (2012$/kW)	752	$4.79	940	$5.14	1,128	$5.49
Site Prep (% of installed capital)	1%	$4.95	19%	$5.14	40%	$5.36
Replacement Interval (years)	20	$5.04	7	$5.14	4	$5.25
Replacement Costs (% of installed capital)	10%	$5.11	15%	$5.14	25%	$5.20

Future Forecourt	Low[24] Value	Production Cost (2007$/kg)	Baseline Value	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Average Electricity Price over Life of Plant (2007¢/kWh)	3.44	$2.50	6.88	$4.23	10.31	$5.96
Electricity Usage (kWh/kg) (% LHV H_2)	45 (74%)	$3.79	50.3 (66%)	$4.23	55 (61%)	$4.62
Uninstalled Capital Costs[26] (2012$/kW)	360	$4.08	450	$4.23	540	$4.37
Site Prep (% of installed capital)	1%	$4.14	18.85%	$4.23	40%	$4.32
Replacement Interval (years)	20	$4.21	10	$4.23	4	$4.28
Replacement Costs (% of installed capital)	10%	$4.22	12%	$4.23	25%	$4.24

[24] "Low" reflects the most optimistic parameter value, resulting in a lower H_2 production cost.
[25] "High" refers to the least optimistic parameter value, resulting in a higher H_2 production cost.
[26] "Low" and "High" values from the sensitivity analysis of uninstalled capital costs determine are the basis for the "Low" and "High" values summarized for each case in Table 1.

Table 4 continued

Current Central	Low[24] Value	Production Cost (2007$/kg)	Baseline Value	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Average Electricity Price over Life of Plant (2007¢/kWh)	3.11	$3.41	6.22	$5.12	9.33	$6.82
Electricity Usage (kWh/kg) (% LHV H_2)	50 (67%)	$4.72	54.3 (61%)	$5.12	65 (51%)	$6.12
Uninstalled Capital Costs[26] (2012$/kW)	720	$4.80	900	$5.12	1080	$5.45
Site Prep (% of installed capital)	1%	$5.11	2%	$5.12	40%	$5.49
Replacement Interval (years)	20	$5.03	7	$5.12	4	$5.24
Replacement Costs (% of installed capital)	10%	$5.09	15%	$5.12	25%	$5.20

Future Central	Low[24] Value	Production Cost (2007$/kg)	Baseline Value	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Average Electricity Price over Life of Plant (2007¢/kWh)	3.45	$2.46	6.89	$4.20	10.34	$5.95
Electricity Usage (kWh/kg) (% LHV H_2)	45 (74%)	$3.77	50.2 (66%)	$4.20	55 (61%)	$4.59
Uninstalled Capital Costs[26] (2012$/kW)	320	$4.07	400	$4.20	480	$4.33
Site Prep (% of installed capital)	1%	$4.19	2%	$4.20	40%	$4.35
Replacement Interval (years)	20	$4.18	10	$4.20	4	$4.24
Replacement Costs (% of installed capital)	10%	$4.19	12%	$4.20	25%	$4.22

Cost Plots and Tornado Charts

Figure 2 plots the H_2 production cost breakdown results for the four baseline cases shown in Table 3. The vertical bars around each of the baseline total costs reflect the low and high projections for each case based on the sensitivities to uninstalled capital costs (as seen in Table 4 and summarized in Table 1).

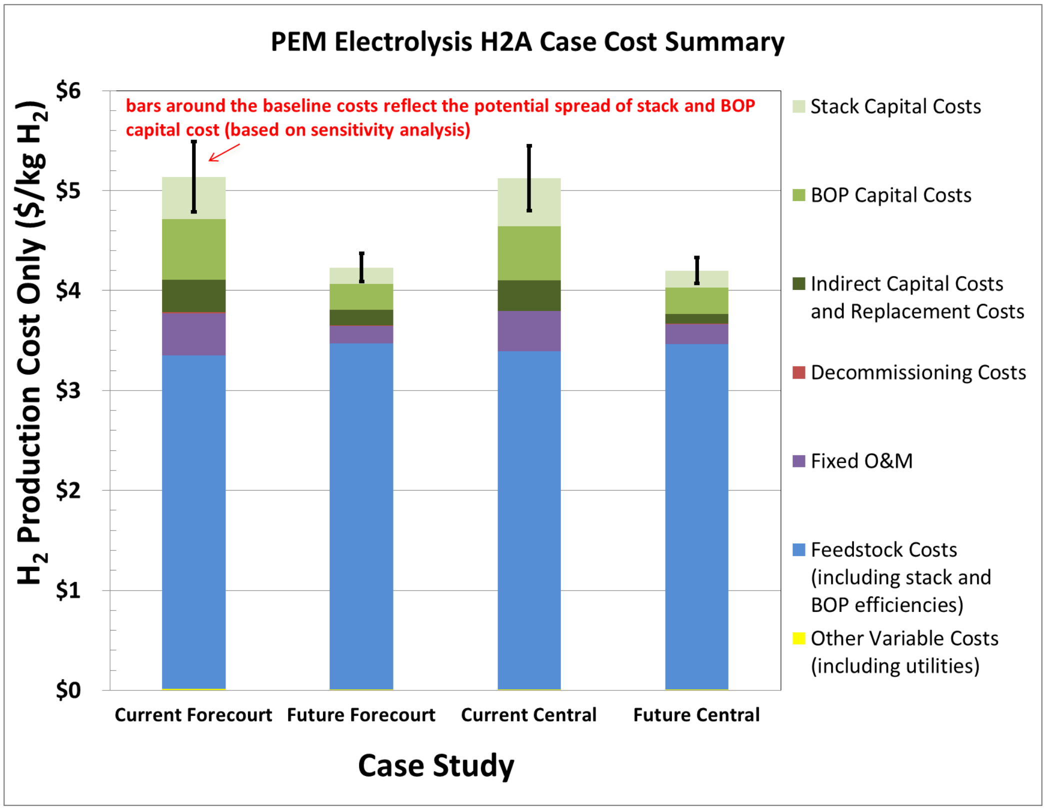

Figure 2. PEM electrolysis H_2 production cost contributions (2007$/kg) for four case studies.[27]

Tornado charts based on the parameter spreads summarized in Table 4 were developed for the four cases to examine the impact of individual parameters on hydrogen cost in a single variable sensitivity analysis. These tornado charts, shown in Figures 3-6, plot the projected hydrogen cost variations on the x-axis against different single input parameters arranged along the y-axis. Specifically, the plots illustrate the H_2 production cost sensitivities to variations in: (1) average electricity price over life of plant; (2) electricity usage; (3) uninstalled capital cost; (4) site preparation cost; (5) stack replacement interval; and (6) stack replacement cost. Each tornado chart is organized from top to bottom to represent the most to least sensitive of the analyzed input parameters, respectively. The colored shading indicates either an increase or a decrease in the baseline hydrogen cost from the change in input parameter. The y-axis lists the low, baseline, and high values for the input parameters (which are also shown in Table 4).

[27] Based on case-dependent electricity prices of 6.12¢/kWh, 6.88¢/kWh, 6.22¢/kWh and 6.89¢/kWh, respectively, as per Table 2.

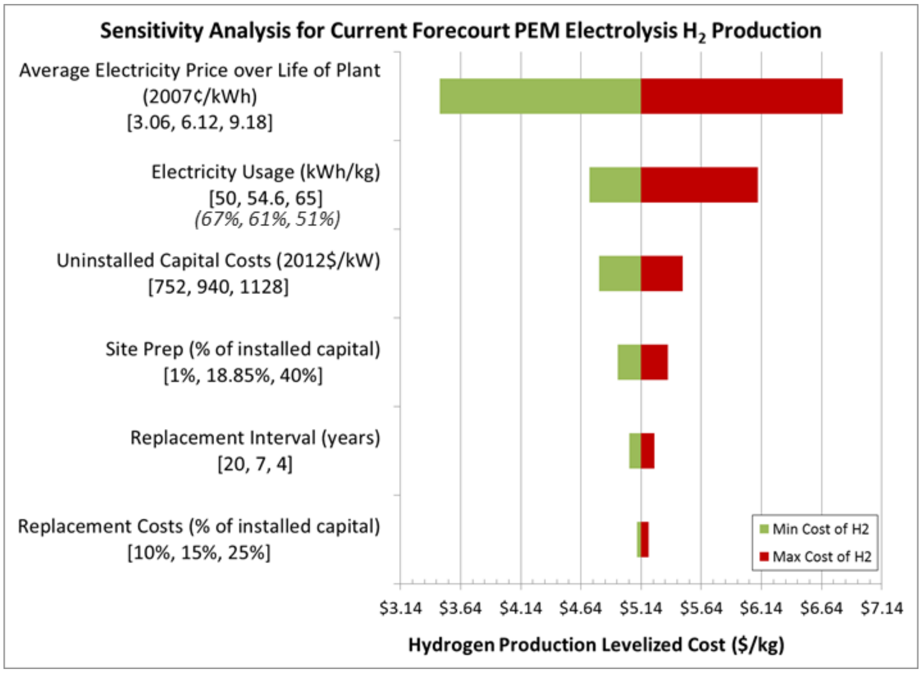

Figure 3. Tornado chart showing parameter sensitivities for Current Forecourt PEM Electrolysis case.

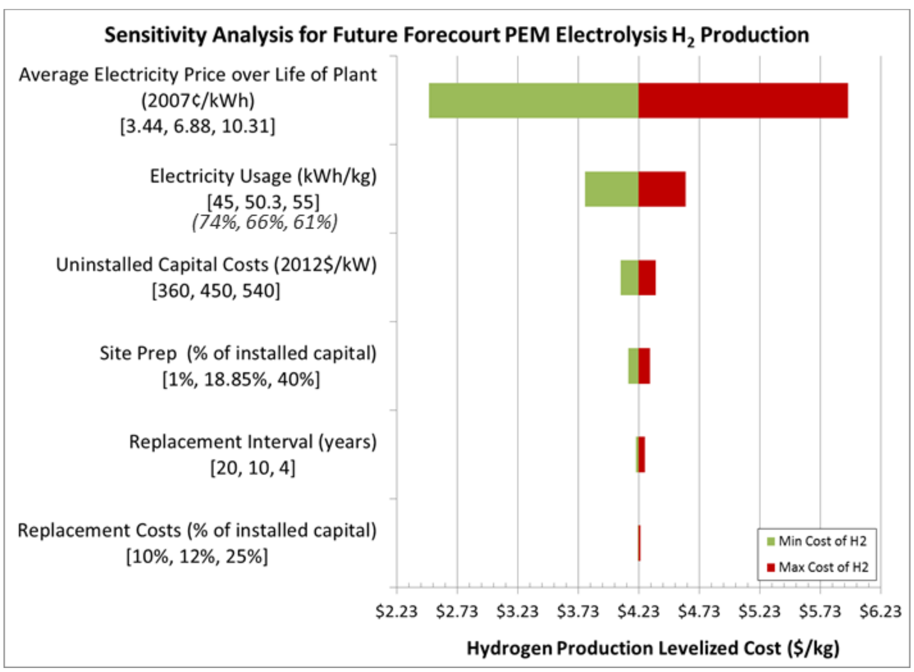

Figure 4. Tornado chart showing parameter sensitivities for Future Forecourt PEM Electrolysis case.

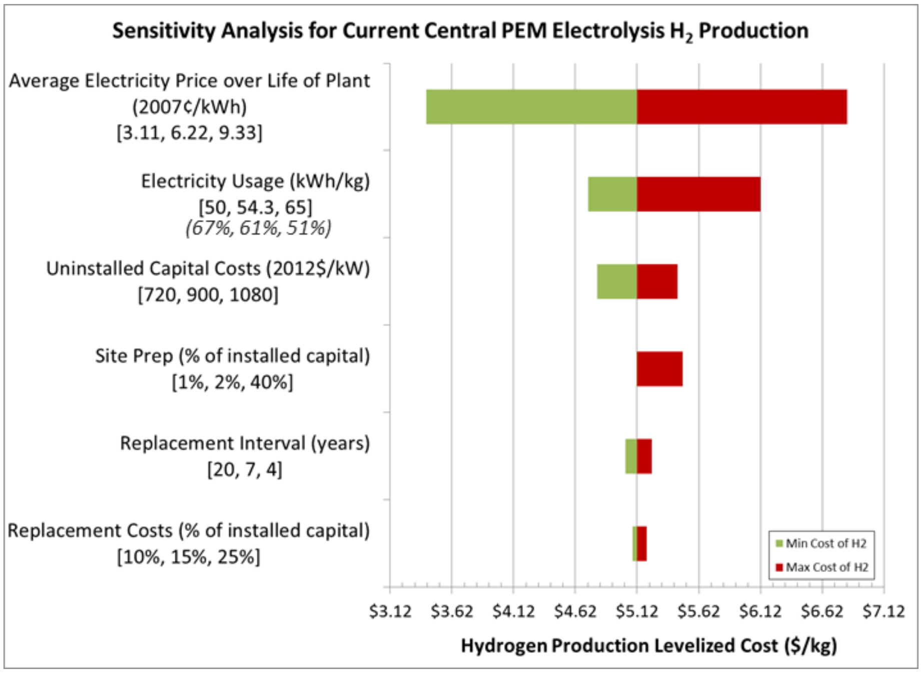

Figure 5. Tornado chart showing parameter sensitivities for Current Central PEM Electrolysis case.

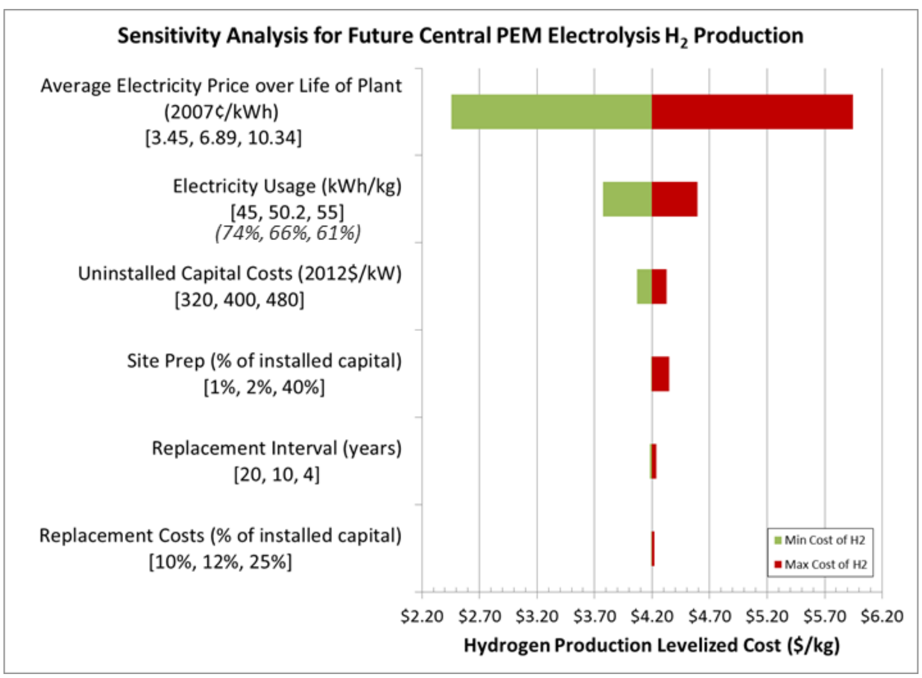

Figure 6. Tornado chart showing parameter sensitivities for Future Central PEM Electrolysis case.

Important input parameters influencing hydrogen cost include the electricity usage of the electrolyzer (which is proportional to electrolyzer net system electrical efficiency) and the uninstalled capital cost of the electrolyzer (including stack and BOP). For all four cases over the range of values and parameters investigated, the tornado charts clearly show that the most sensitive input parameter impacting hydrogen cost is the electricity price.

This Record was peer reviewed by industry, national laboratories and DOE representatives including: Giner Inc., Hydrogenics Corp., ITM Power, and Proton OnSite. Industry stakeholder participants voluntarily furnished relevant confidential commercial information to the government in support of the PEM electrolysis case studies represented in the Record. This confidential commercial information is not publicly available and is customarily held in confidence.