DOE Hydrogen and Fuel Cells Program Record	
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Title: Hydrogen Production Cost from Solid Oxide Electrolysis	
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Item

The projected cost to produce hydrogen from high-temperature solid oxide electrolysis cells (SOEC) in the near- to longer-term ranges from ~\$2.80 to ~\$5.80/kg H_2 at high volume (untaxed, excluding delivery and dispensing). The costs were projected using the Hydrogen Analysis version 3.1 (H2A v3.1) model.[1]

Background

Two H2A v3.1 cases were developed: a *projected current* case based on 2014 lab-scale technology and a *projected future* case based on expected technology advancements by 2025. Given that there are no commercial SOEC stacks or systems available, and that only limited long-term durability data exists for cells/stacks at relevant operating conditions, the *projected current* case was extrapolated from technology demonstrated at the laboratory scale. Both cases were based on input from, and were subsequently reviewed by six solid oxide electrolysis cell research organizations (laboratories and companies, four in the United States and two international) to ensure the study parameters and results were relevant and accurate. Based on consultations with the study participants, a central production capacity of 50,000 kg H_2/day was modeled (i.e., forecourt/distributed production scales ≤1,500 kg/day were not analyzed).

Results Summary

The modeled costs to produce hydrogen (untaxed, excluding delivery and dispensing) are summarized in Table 1 for the two cases studied. The *baseline* cost projections in the table were derived using inputs from study participants on the electrolyzer stack and balance of plant costs. The *low* and *high* values in the table were calculated based on a Monte Carlo analysis in which multiple input parameters were simultaneously varied to estimate the lower and upper bounds on hydrogen cost.

Table 1. H_2 Production High-Volume Cost Projections for the SOEC Cases[2]

Central H_2 Production SOEC Case Study	Low Value (\$/kg H_2)	Baseline (\$/kg H_2)	High Value (\$/kg H_2)
Projected Current Case[3]	\$3.73	**\$4.95**	\$5.84
Projected Future Case[4]	\$2.80	**\$3.83**	\$4.67

[1] 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: www.hydrogen.energy.gov/h2a_production.html. The H2A v3.1 SOEC cases are published at www.hydrogen.energy.gov/h2a_prod_studies.html. See Table 2 for a summary of case input parameters.

[2] Hydrogen costs are reported in 2007\$/kg, consistent with H2A v3.1 methodology which uses data from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2009 Report* (where 2007\$ is the cost basis).

[3] Levelized cost of hydrogen production in the *projected current* case assumes a 40-year plant life, 300 psi outlet pressure, and 6.24¢/kWh average electricity price (based on AEO projections for current pricing). See Table 2.

[4] Levelized cost of hydrogen production in the *projected future* case assuming a 40-year plant life, 700 psi outlet pressure, and 6.89¢/kWh average electricity price (based on AEO projections for future pricing). See Table 2.

Analytical Basis

Analyses to project the high-volume cost[5] of producing hydrogen at a central facility by solid oxide electrolysis with a plant capacity of 50,000 kg/day were performed by Strategic Analysis, Inc., in conjunction with the National Renewable Energy Laboratory using the H2A v3.1 model. Case studies were developed for two technology years,[6] *projected current*[7] (2014), and *projected future*[8] (2025). On-site forecourt production (assumed to be a maximum of 1,500 kg/day) was not analyzed for SOEC technology as the stakeholders from the six participating research organizations deemed this technology better suited for large, centralized production facilities (e.g., integrated with an industrial system, such as a nuclear reactor, where high-grade heat is available for use).

Relevant techno-economic data for the two cases were solicited from the six research organizations via questionnaire spreadsheets. The requested data included H2A input parameters needed to develop cases and supplemental documentation to support and vet 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. For each case, a generalized electrolyzer was defined based on representative input parameters derived from the solicited data and an engineering system performance design was developed and modeled using Aspen HYSYS.[9] The performance models were used to verify that the numerical values for the generalized electrolyzer were internally consistent and led to the expected level of overall system performance.

Generalized system designs were developed for both the *projected current* and *projected future* baseline cases using inputs and guidance from the study participants. Both cases envision the electrolysis cells operating very close to the thermo-neutral operating point.[10] The system flow schematic for the *projected current* baseline shown in Figure 1 is based on a stack temperature of 800°C with an outlet gas pressure of 300 psi. Byproduct oxygen is not captured. Heat to warm the reactants to the stack inlet temperature is provided from a generic heat source, without judgment as to the heating source. (See Table 2 for the heating cost[11] for each case.) Steam is used as a sweep-gas on the oxygen-generating side of the cells (cathodes) to lower the oxygen partial pressure and thereby enhance performance and limit corrosion. (Alternatively, air may be used as a sweep-gas and to reduce potential chromium migration.) The generalized system design developed for the *projected future* baseline case is shown in Figure 2. While

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[5] H2A high-volume cost projections are based on 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 www.hydrogen.energy.gov/h2a_production.html.

[6] 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.

[7] The *projected current* case is based on current state-of-the-art laboratory-demonstrated technology, with extrapolated scale-up to an industrial process that includes high-volume manufacturing.

[8] The *projected future* case uses advanced electrolyzer systems that will be technology-ready in 2025, with market entry assumed in 2030. Compared with the *projected current* case, the *projected future* case incorporates expected reductions in capital cost as well as increases in net system energy efficiency, decreases in degradation rates, and increases in the stack service lifetime. The expected levels of improvement were vetted by study participants.

[9] Aspen HYSYS is commercially available software used to simulate the material and energy balances of chemical processing plants.

[10] The thermo-neutral operating point refers to a cell operating voltage where ohmic losses within the cell (which releases heat) are balanced by the water splitting heat of reaction (which consumes heat). Thus the cell operates without a large temperature gradient between inlet and outlet streams. The operating voltage is 1.28 V.

[11] Heat price is based on the 40-year average of industrial natural gas price as predicted by the *EIA AEO 2009 Report*, beginning in the start-up year (2015 for Current, 2025 for Future), and an 85.7% combustor efficiency.

similar to the *projected current* baseline case, it represents a more technologically advanced version with the following differences:

- 700 psi product gas pressure
- Inclusion of an exhaust gas expander to generate electrical power (resulting in a nominally higher system electrical efficiency)
- Reduced thermal losses (due to tighter thermal integration)
- Improvement in electrical rectification efficiency (nominally 95% for the *projected current* case and 97% for the *projected future* case).

For both cases, the participating research organizations' inputs were used to derive system efficiency values (included in Table 2 under the parameter *Total Energy Usage*) that account for all losses associated with the stack efficiency, electrical inverter efficiency, and other balance of plant (BOP) loads. The participating research organizations reviewed and vetted the generalized inputs and designs for both H2A baseline cases. Parameter values are meant to be representative but alternative configurations (such as arrangement of heat exchangers, use of inline electrical heating in lieu of a high temperature burner, use of low-grade waste heat, and air versus steam sweep) are expected to lead to system performance differences.

Cell current density (at the operating point) and area specific resistance (ASR) were not primary inputs into the performance or cost analysis. Rather these parameters were used by the participants to estimate stack capital cost, which was then used within the H2A model. While electrical efficiency does not change much between the *projected current* and *projected future* cases, a large increase in current density is expected (at the same operating voltage) which is expected to reduce the stack footprint, thereby decreasing the stack cost per kW.

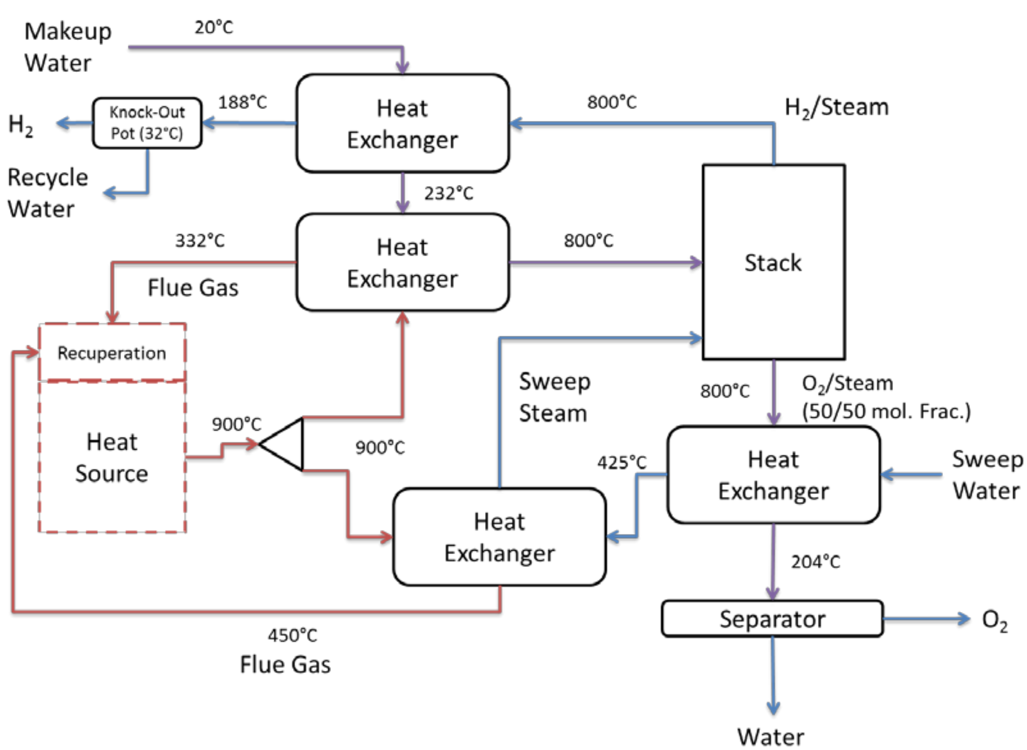

Figure 1. Projected Current SOEC Baseline Design

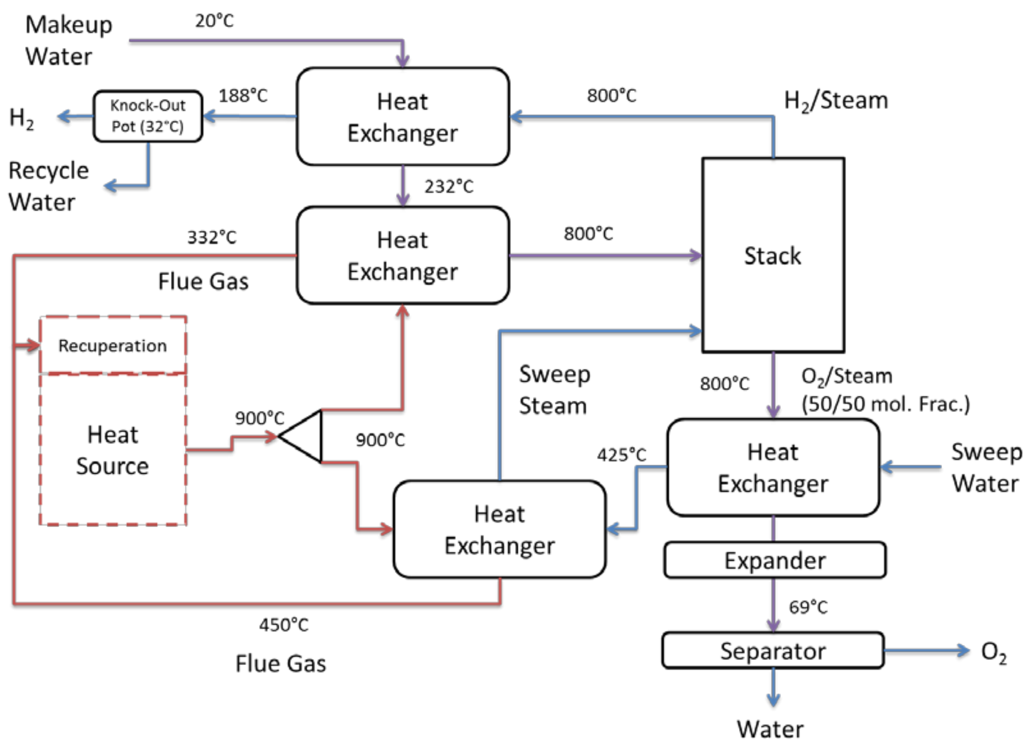

Figure 2. Projected Future SOEC Baseline Design

The source of the high-grade heat required for SOEC operation is an important consideration for SOEC technology. Although, it should be noted that some system configurations do not require high-grade waste heat. For modeling and cost estimation purposes, a natural gas combustion system was selected as a representative generic heat source for SOEC systems as it provides a well-established and convenient analysis baseline. The capital and maintenance costs estimated for the burner system are dramatically less than the natural gas fuel costs by roughly three orders of magnitude. Consequently, changes in burner system capital cost are unlikely to have an appreciable impact on the effective overall cost of heat supplied by the system.

Using the generalized inputs and designs vetted by the participants, baseline H2A v3.1 case studies were prepared for the *projected current* and *projected future* cases, establishing baselines for the projected hydrogen production costs in the two technology years. In addition, H2A sensitivity analysis was performed for each case, with results illustrated in the tables and tornado charts included in this Record.

<u>Baseline Input Parameters</u>

The key parameters used to develop the two H2A v3.1 baseline case studies are shown in Table 2. Parameter values were drawn chiefly from responses to the questionnaire, but also were supported by engineering judgment/calculations and by utility pricing information from the Annual Energy Outlook (AEO).[12] Additional parameter values were drawn from standard H2A v3.1 default values[13] so as to

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[12] *EIA AEO 2009 Report.*

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

create an overall assessment that is consistent with past H2A studies, but which is tailored to the unique attributes of the SOEC system.

To account for stack performance degradation, the analysis modeled stack operation at a constant voltage of 1.28V with the H_2 production rate (i.e., stack current density) decreasing over the course of a year. Based on study participant input, stack degradation rates of 0.9%/1,000h and 0.25%/1,000h and stack service lifetimes of 4 and 7 years were used for the *projected current* and *projected future* cases, respectively. A stack replacement schedule was developed where stacks reaching end of service life are removed and where stack capacity is added to bring the total H_2 production of the plant back to 100% at the beginning of each year. This process is repeated for the 40-year life span of the plant. The overall effective plant capacity (i.e. actual annual H_2 production divided by plant design annual H_2 production) represents the combined effect of diminishing H_2 production due to stack performance degradation during the year and the plant capacity factor due to planned/unplanned shutdowns.

Baseline Cost Projection Results

The hydrogen production cost breakdown for the two H2A v3.1 SOEC baseline cases is shown in Table 3. These cases used inputs from the study participants to determine the most likely parametric values at a central scale for the two different technology years. The effects of deviations from these baseline inputs are considered separately in the *Sensitivity Analysis* section which follows. Table 3 shows that the primary cost driver for H_2 production is the electricity required to run the electrolysis process. Unlike other cost categories, the price of electricity (as projected by AEO) is seen to increase between the *projected current* and *projected future* cases. This electricity price increase is partially offset by the higher electrical efficiency projected for the *projected future* case.

Table 2. Input Parameters for SOEC H2A Central Production Baseline Cases
(costs in 2007$[14] and 2012$[15])

Parameter	Projected Current	Projected Future	Cost Basis
Plant Capacity (kg/day)	50,000	50,000	H2A
Total Uninstalled Capital (2012$/kW)	$820	$430	Ind. Questionnaire
Stack Capital Cost (2012$/kW)	$287	$99	Ind. Questionnaire
Balance of Plant (BOP) Capital Cost (2012$/kW)	$533	$331	Ind. Questionnaire
Total Energy Usage (kWh/kg)	50.9	46.6	Ind. Questionnaire
Net System Energy Efficiency[16]	66%	72%	Ind. Questionnaire
Stack Electrical Usage (kWh/kg) Stack Conversion Efficiency (% LHV H_2)	34.0 (98.0%)	34.0 (98.0%)	Ind. Questionnaire
System Electrical Usage (kWh/kg) System Conversion Efficiency (% LHV H_2)	36.8 (90.5%)	35.1 (94.9%)	Ind. Questionnaire
System Heat Usage (kWh/kg)	14.1	11.5	Ind. Questionnaire
Cell Voltage (V)	1.28	1.28	Ind. Questionnaire
Current Density[17] (mA/cm^2)	1,000	1,500	Ind. Questionnaire
Electrolyzer Power Consumption (MW)	76.6	73.1	Eng. Calculation
Effective Elec. Price over Life of Plant (2007¢/kWh)	6.24	6.89	AEO/Eng. Calc.
Electricity Price in Start-up Year[18] (2007¢/kWh)	5.74	6.59	AEO/Eng. Calc.
Thermal Energy Cost ($2007/GJ)[19] (2007¢/kWh)	10.1 (3.64)	11.5 (4.13)	AEO/Eng. Calc.
Hydrogen Outlet Pressure (MPa)	2.1 (300 psi)	4.8 (700 psi)	Ind. Questionnaire
Installation Cost (% of uninstalled capital cost)	12%	10%	H2A
Stack Service Life[20] (years)	4	7	Ind. Questionnaire
H2A Plant Capacity Factor	90%	90%	H2A
Percent Stack H_2 Production Rate due to degradation at end of first service year	83.2%	94.5%	H2A Calculation
Overall Effective Plant Capacity[21]	82.4%	87.5%	Eng. Calc
Effective Annual Stack Service Replacement Cost[22] (% of Stack Capital/year)	27.3%	12.8%	Eng. Calculation
Balance of Plant (BOP) Lifetime (years)	20	20	Ind. Questionnaire
BOP Replacement Cost (% of BOP initial investment)	100%	100%	AEO/Eng. Calc

[14] A cost basis of 2007 dollars (2007$) is used for electricity price data, which is derived from the *EIA AEO 2009 Report*, which uses 2007$ as its standard cost basis.

[15] Electrolyzer capital costs are listed in U.S. 2012 dollars (2012$) because that is the reporting year for the six research organizations. However, hydrogen cost results ($/kg) are reported in 2007 dollars (2007$), according to the standard H2A v3.1 methodology approved by DOE.

[16] Efficiency is defined as H_2 Product Output Energy/Input Electrical and Heat Energy. H_2 Product Output Energy is based on the lower heating value (LHV) of H_2.

[17] Current density is not used directly within the H2A analysis but is included here as a representative value to allow comparison between the *projected current* and *projected future* cases.

[18] H2A default values from EIA AEO 2009 data.

[19] The thermal energy cost is based on the average EIA AEO 2009 reference case costs for natural gas over the plant life, a combustion efficiency of 85.7%, and burner capital costs over the plant lifetime of ~$0.01/GJ.

[20] Stack service life represents the duration of the stack's plant operational use producing hydrogen. It differs from stack lifetime in that the stack may still have H_2 production capacity at the end of its service life.

[21] Product of plant capacity factor and linear average of % stack H_2 production rate at beginning of service year (i.e. 100%) and end of service year.

[22] Effective annual stack service replacement cost represents the constant average (over 40-year plant life) annual cost incurred to replace H_2 production capacity lost to performance degradation and to stacks taken off-line at the end of their service life.

Table 3. H_2 Production Cost Breakdowns in 2007$/kg H_2 for SOEC Baseline Cases

Component	Projected Current *50,000 kg/day*	Projected Future *50,000 kg/day*
Stack Capital Cost	$0.24	$0.09
BOP Capital Cost	$0.45	$0.29
Indirect Capital Cost and Replacement Cost	$1.00	$0.24
Decommissioning	$0.00	$0.00
Fixed Operations and Maintenance (O&M)	$0.38	$0.23
Thermal Energy Feedstock	$0.53	$0.49
Electricity Utility	$2.34	$2.49
Variable O&M	$0.01	$0.00
Total H_2 Production Cost (2007$/kg H_2)	**$4.95**	**$3.83**

Sensitivity Analysis

Table 4 details the range of parameter values used within the H2A v3.1 sensitivity analysis. These ranges are meant to capture the probable range of parameter variations rather than to report the company-sensitive minimum and maximum values from the six organizations. The range of sensitivity parameters was reviewed by the participating industry and research stakeholders. 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 would decline by $0.08–$0.09/kg for every decrease of 1 kWh/kg in net electricity usage.

Table 4. Sensitivity Analysis Results for the Two SOEC Central Cases
(H_2 production cost results reported in 2007$; sensitivity limits reported in 2007$ and 2012$, as appropriate)

Projected Current	Low[23] Value	Production Cost (2007$/kg)	Baseline Value[24]	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Effective Electricity Price over Life of Plant (2007¢/kWh)	3.12	$3.74	6.24	$4.95	9.36	$6.16
System Electricity Usage (kWh/kg) Conversion Eff. (%LHV H_2)	36.1 (92%)	$4.91	36.8 (91%)	$4.95	37.5 (89%)	$5.00
Uninstalled Capital Costs (2012$/kW)	410	$4.02	820	$4.95	1230	$5.88
Thermal Energy Usage (kWh/kg)	7	$4.68	14.1	$4.95	15	$4.99
Thermal Energy Cost (2007¢/kWh)	0.00[26]	$4.41	3.64	$4.95	5.46	$5.22
Plant Capacity due to Operational Downtime[27]	95%	$4.85	90%	$4.95	80%	$5.15
Stack Service Lifetime (yrs)	7	$4.87	4	$4.95	1	$6.16

Projected Future	Low[23] Value	Production Cost (2007$/kg)	Baseline Value[24]	Production Cost (2007$/kg)	High[25] Value	Production Cost (2007$/kg)
Effective Electricity Price over Life of Plant (2007¢/kWh)	3.45	$2.55	6.89	$3.83	10.34	$5.10
System Electricity Usage (kWh/kg) Conversion Eff. (% LHV H_2)	34.4 (97%)	$3.78	35.1 (95%)	$3.83	35.8 (93%)	$3.88
Uninstalled Capital Costs (2012$/kW)	215	$3.50	430	$3.83	645	$4.16
Thermal Energy Usage (kWh/kg)	7	$3.63	11.5	$3.83	15	$3.98
Thermal Energy Cost (2007¢/kWh)	0.00[26]	$3.33	4.13	$3.83	6.18	$4.08
Plant Capacity due to Operational Downtime[27]	95%	$3.79	90%	$3.83	80%	$3.92
Stack Service Lifetime (yrs)	10	$3.80	7	$3.83	4	$3.89

[23] The *Low Values* reflect the most optimistic parameter value, resulting in a lower H_2 production cost.
[24] The *Baseline Values* reflect the baseline case parameters from Table 2.
[25] The *High Values* refer to the least optimistic parameter value, resulting in a higher H_2 production cost.
[26] "Free" heat is included in the sensitivity analysis to quantify the H_2 cost impact of the use of near-zero-cost co-produced process heat.
[27] The Plant Capacity Factor is a measure of how often the plant is running relative to 100% operation. This parameter is only affected by plant shutdowns, whether planned or unplanned. There is no accounting for stack degradation in this parameter. Stack degradation is accounted for in the Stack Service Lifetime and Effective Annual Stack Service Replacement Cost parameters.

Results Summary: Baseline Cost Breakdown Plots and Tornado Sensitivity Charts
Figure 3 plots the H_2 production cost breakdown results for the two baseline cases shown in Table 3. The contribution for electricity is seen to be the dominant cost contributor. The significant decrease in *indirect capital costs and replacement costs* between the *projected current* and *projected future* cases is primarily related to the decrease in direct capital (due to indirect capital costs being a ratio of the direct capital costs) and the decrease in the SOEC stack degradation rate. Uncertainty analysis was performed to determine the most likely range of hydrogen costs using the Monte Carlo method and variation of the parameters shown from Table 4. The H2A cost computation was repeated 500,000 times with each parameter independently and simultaneously varied. The resulting set of hydrogen cost projections allows assessment of the hydrogen cost range and probability of occurrence. The ranges of potential hydrogen costs corresponding to the middle 90% of projections are displayed as dashed "error bars" in Figure 3.[28] As a comparison, the solid "error bars" in the figure represent the effect of ±50% variation in the capital cost components for each case.

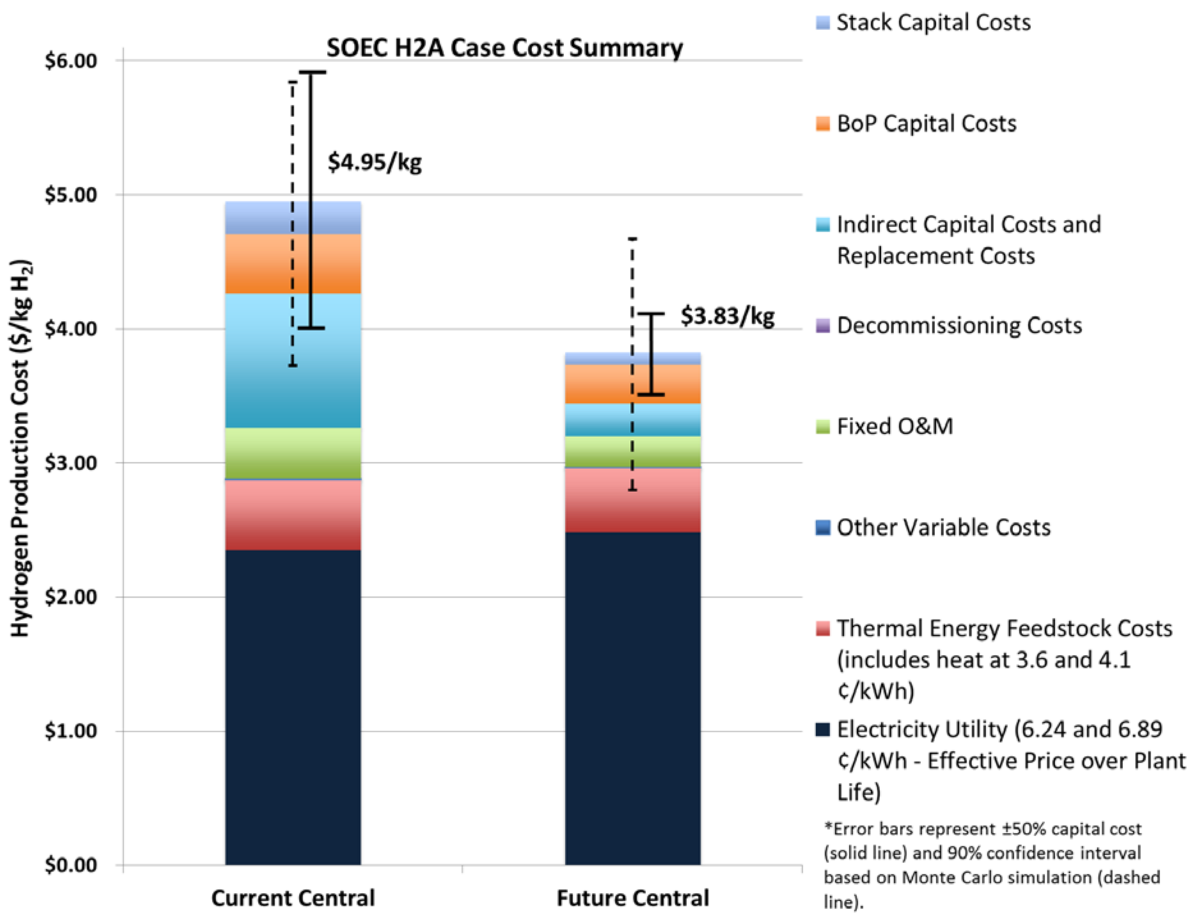

Figure 3. SOEC H_2 Production Cost Contributions (2007$/kg) for the two Case Studies[29]

[28] The range of hydrogen cost is based on simultaneous probabilistic variation of the parameters (and values) shown in Table 4. A triangular probability distribution is assumed for each parameter. Results are shown for the middle 90% of cost predictions.
[29] Based on case-dependent electricity prices of 6.24¢/kWh and 6.89¢/kWh for *projected current* and *projected future* cases, respectively, as per Table 2.

Tornado charts based on the parameter spreads summarized in Table 4 were developed for the *projected current* and *projected future* cases for centralized SOEC hydrogen production to examine the impact of individual parameters on hydrogen cost in a single variable sensitivity analysis. These tornado charts, shown in Figure 4 and Figure 5, 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) effective electricity price over life of plant; (2) uninstalled capital cost; (3) stack service lifetime; (4) average price of heat over life of plant; (5) thermal usage; (6) plant capacity due to operational downtime; and (7) electrical usage. 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 (red) or a decrease (green) 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).

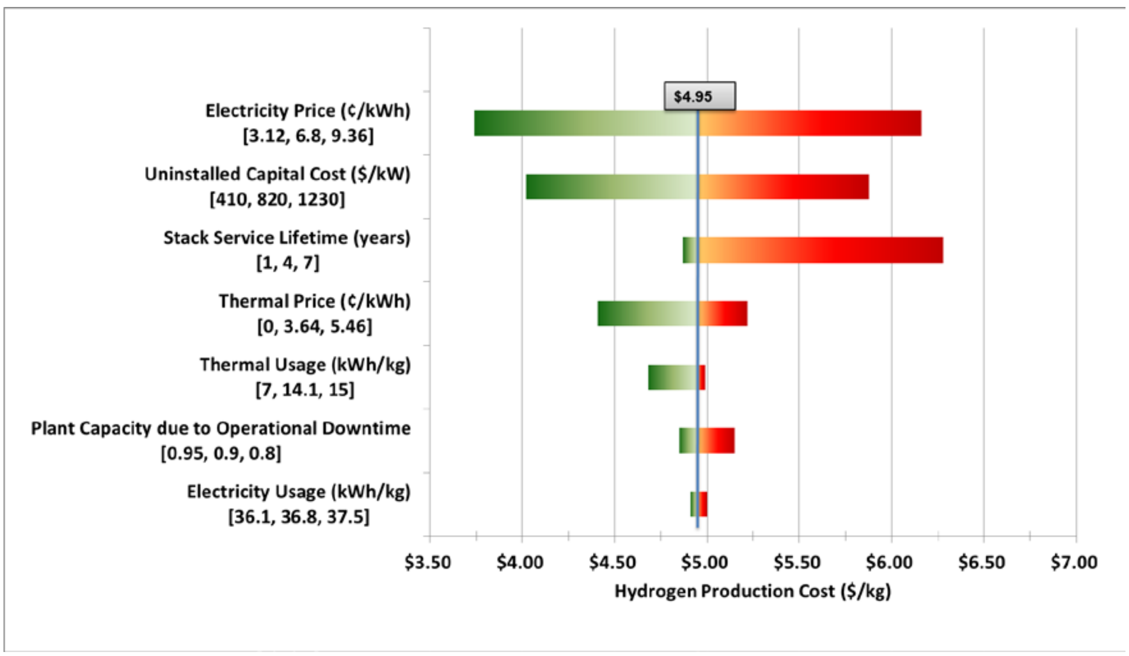

Figure 4. Tornado Chart Showing Parameter Sensitivities for the *Projected Current* SOEC Case

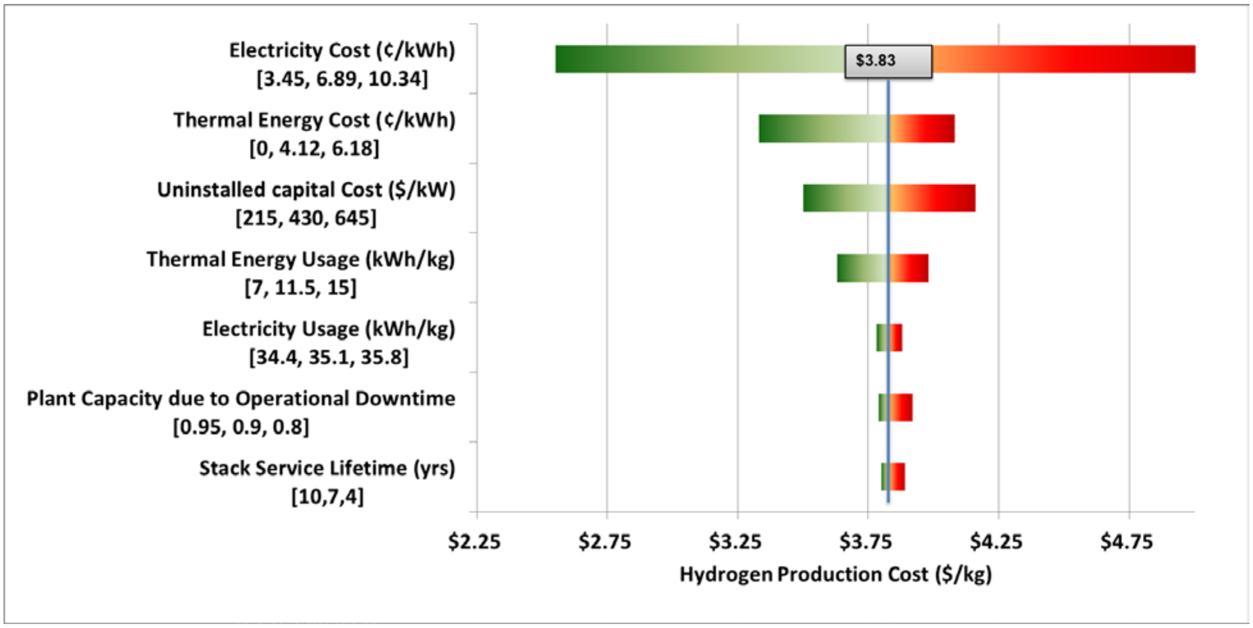

Figure 5. Tornado Chart Showing Parameter Sensitivities for the *Projected Future* SOEC Case

The tornado charts show that for the SOEC process investigated, for both *projected current* and *projected future* cases, hydrogen production cost is primarily dependent on and most sensitive to changes in the price of electricity. This result is consistent with both alkaline electrolysis and PEM electrolysis, where electricity price is also the main cost driver. Also, especially for the *projected current case*, the hydrogen production cost is sensitive to changes in the uninstalled capital cost and stack service lifetime. Note that electricity usage is comparatively far down the tornado graph as a direct result of the narrow range of usage values used within the sensitivity analysis. That narrow range is attributable to the narrow band of responses received for both the *projected current* and *projected future* cases from the industry respondents. Finally, the lower bound on heat price is set at zero to reflect the scenario where heat is available to the electrolyzer system at no cost.

This record was peer reviewed by industry, national laboratories and DOE representatives including: Annabelle Brisse of the European Institute for Energy Research, Joseph Hartvigsen of Ceramatec, Inc., Randy Petri of Versa Power Systems, and Greg Tao of Materials and Systems Research Inc.