DOE Hydrogen and Fuel Cells Program Record	
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Title: Hydrogen Production Cost From PEM Electrolysis - 2019	
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Item

Rigorous stakeholder-vetted technoeconomic analysis was performed to assess the cost of hydrogen produced using state-of-the-art polymer electrolyte membrane (PEM) electrolyzers if manufactured at scale. Projected high-volume, untaxed hydrogen costs can range from approximately \$2/kg-H_2 to \$7/kg-H_2 based on industry input on PEM system performance as well as on capital, operational and feedstock costs. The total uninstalled capital cost, for example, ranged from approximately \$230/kW to \$600/kW for different analysis scenarios.

Analysis Summary

The projected high-volume, untaxed cost of hydrogen production from polymer electrolyte membrane electrolysis ranges from ~\$2.16 to \$7.22/kg[1], based on case study results using the Hydrogen Production Analysis model[2], version 3.2018 (H2A v3.2018). Four cases were analyzed, comprising two technology years (*Projected Current* [2019] and *Projected Future* [2035]), and two production capacities (*Distributed* [1,500 kg/day] and *Central* [50,000 kg/day])[3]. The case studies assume an electrolyzer manufacturers' annual production capacity of 700MW/yr in order to model a robust and mature production scenario. For reference, industry's production capacity at the time of publication is approximately 10MW/yr. The analysis presented in this Record supersedes the 2014 H2A PEM cases studies[4], and uses recent input from, and reviews by, four independent manufacturers of PEM electrolysis systems to ensure the relevance and accuracy of the study parameters and results.

Table 1- H_2 production high-volume cost projections for the PEM Electrolysis cases.[5]

Case Study	Low Value (\$/kg H_2)	Baseline (\$/kg H_2)	High Value (\$/kg H_2)	H_2 cost at 3₵/kWh$_{electric}$
***Distributed**: Projected Current Case*[6]	\$2.93	**\$4.98**	\$7.22	**\$2.54**
Projected Future Case[7]	\$2.16	**\$4.48**	\$6.07	**\$1.92**
***Central:** Projected Current Case*[8]	\$2.67	**\$4.83**	\$6.99	**\$2.31**
Projected Future Case[9]	\$2.16	**\$4.48**	\$6.14	**\$1.86**

[1] Costs per kg of produced hydrogen using 2016 dollars as the cost basis (i.e., reported as 2016\$/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 distributed facilities

[3] H2A v3.2018 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] Record #14004, https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf; See Supplemental Information for further details

[5] All costs reported in 2016\$/kg, consistent with H2A v3.2018 methodology which utilizes data from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2017 Report* (where 2016\$ is the standard cost basis)

[6] For this case, the effective electricity price over the life of the plant is 7.27 ₵/kWh

[7] For this case, the effective electricity price over the life of the plant is 7.87 ₵/kWh

[8] For this case, the effective electricity price over the life of the plant is 7.35 ₵/kWh

[9] For this case, the effective electricity price over the life of the plant is 7.91 ₵/kWh

Table 1 summarizes the cost projection results for hydrogen production (untaxed, delivery, & dispensing not included) for the four cases. The baseline projections shown in the table capture representative system cost and performance based on averages of the manufacturer-supplied input incorporated into the technoeconomic analysis. Electricity prices for these baseline projections were taken from EIA AEO Reports with averages >$0.07/kWh. The Low and High Values are included to reflect an expected cost spread (with 90% certainty) as determined by Monte Carlo multi-variable analysis. Special assessment of the system assuming a constant electricity price of $0.03/kWh, in line with the recent development of low cost electricity from renewable energy, is also shown in Table 1 and highlights the importance of electricity price on electrolysis-based H_2 production.

Analytical Basis

Four case studies centered on PEM-based electrolysis were performed using the H2A v3.2018 model.[10] The four cases comprise two technology years: *Projected Current* (2019) and *Projected Future* (2035); and two production capacities: *Distributed* (1,500 kg H_2/day) and *Central* (50,000 kg H_2/day). Technology year is defined as the year in which a system design and electrolyzer cell/stack performance level have been demonstrated in the laboratory with high confidence that it can be translated to and developed into a full-scale system able to achieve the stated performance, durability, and cost targets. *Projected Current* cases reflect demonstrated state-of-the-art 2019 technology but manufactured at high production volume. This differs from the existing commercial systems which are manufactured at significantly lower production rates using slightly older technology. *Projected Future* cases use advanced electrolyzer systems that will be technology-ready in 2035, with market entry assumed in 2040. Compared with the *Projected Current* cases, the *Projected Future* cases incorporate expected reductions in capital cost, electricity usage, and site preparation cost as well as increases in the stack replacement interval.

Relevant technoeconomic data and information for the cases were solicited from four independent electrolyzer companies via questionnaire. Requested data included H2A input parameters needed for developing the cases as well as supplemental information for the documentation and vetting of the underlying technology assumptions. Data collected fell into 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 study, an engineering system performance model was developed from the baseline inputs to create a generalized electrolyzer system engineering design consistent with the diverse industry input from electrolyzer manufacturers. The engineering model was supplemented with a detailed ASPEN® based model including economic analysis. The generalized electrolyzer system schematic is shown in Figure 1.

Based on the manufacturer inputs, literature review, and ASPEN design model, generalized system designs were developed for the *Projected Current* baseline cases that model electrolyzers operating at 2,000 mA/cm^2 with a H_2 outlet pressure of 300 psi. The generalized system designs developed for the *Projected Future* baseline cases were based on technologically-advanced electrolyzers operating at 3,000 mA/cm^2 with a H_2 outlet pressure of 700 psi. Capital costs[11] for each case assume a production rate of 700 MW/yr

[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 distributed 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] All capital costs in this record are inclusive of markup

and were developed through a combination of questionnaire responses, quoted equipment costs, and ASPEN model economic adviser. The ASPEN Economic Adviser projects costs for single item purchases of equipment. To align these equipment costs with manufacturing economies of scale of PEM operation (building enough production sites to handle a sum total of 700 MW/yr of input power), a cost reduction formula was applied to lower cost of equipment. For equipment in which 2-5 units are purchased in achieving the annual production rate, a 5% discount is applied to the single unit cost. For any equipment in which more than 5 units would be purchased to achieve the annual production rate, a cost reduction equation was used, lowering cost 10% for every 10x unit purchases. A high production rate is critical for achieving stack and balance of plant (BoP) cost reductions necessary for electrolyzers to achieve cost-competitiveness with other H_2 generation technology. The four companies vetted the generalized inputs and designs for all H2A baseline cases, and participated in selection of reasonable parameter limits for H2A sensitivity analysis.

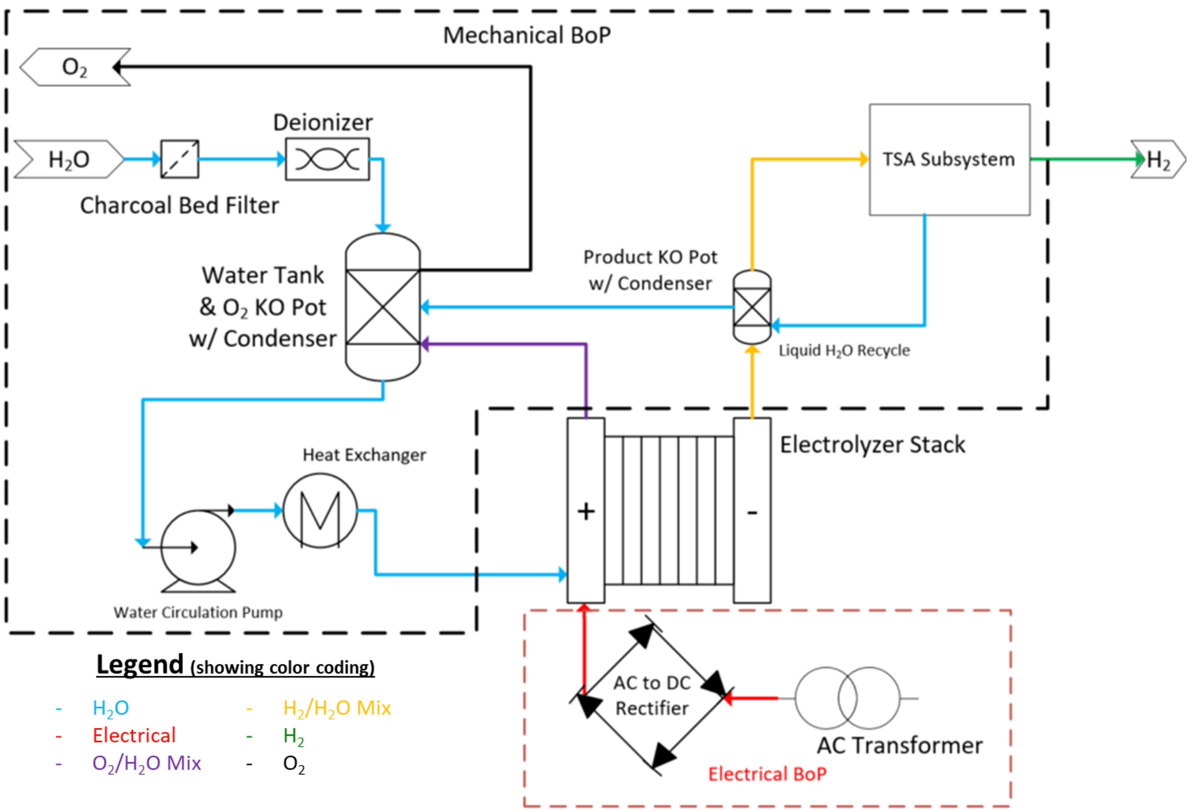


Figure 1- Generalized PEM Electrolyzer System.[12]

H2A v3.2018 specifies a standard outlet H_2 pressure of 300 psi to allow cost comparisons across different production technologies. Since the electrolyzer system *Projected Future* case outlet pressure is 700 psi, a "credit" is applied to the H_2 cost to account for the higher outlet pressure compared to the nominal H2A value (300 psi). The credit is based on the power and capital cost of a notional compressor conducting

[12] KO: Knock-out pot, generally used for separation of water from H_2
TSA: Temperature Swing Adsorption
The rectifier-transformer equipment quote includes internal cooling equipment for heat rejection

added compression. Compressor cost was calculated based on the compressor cost equations in Hydrogen Delivery Scenario Analysis Model[13] and compressor power was calculated based on flow rate, pressure ratio (700 psi/300 psi), and efficiency (75%). The compressor credits amounted to \$0.09/kg H_2 and \$0.05/kg H_2 for the distributed and central cases, respectively. Using the generalized inputs and designs vetted by manufacturers, four baseline H2A v3.2018 case studies were performed (i.e., *Projected Current Distributed*, *Projected Current Central*, *Projected Future Distributed*, and *Projected 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 v3.2018 baseline case studies are shown in Table 2 (all other H2A input parameters not cited in the table used standard H2A v3.2018 default values[14]).

[13] Hydrogen Delivery Scenario Analysis Model website: https://hdsam.es.anl.gov/index.php?content=hdsam

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

Table 2 - Input parameters for H2A Production cases for PEM electrolysis (costs in 2016$).

Parameter	**Current Distributed** *1,500 kg/day*	**Future Distributed** *1,500 kg/day*	**Current Central** *50,000 kg/day*	**Future Central** *50,000 kg/day*
Technology Year	2019	2035	2019	2035
Start-up Year	2015	2040	2015	2040
Total Uninstalled Capital (2016$/kW)[15]	$599	$379	$460	$233
Stack Capital Cost (2016$/kW)	$342	$143	$342	$143
BoP CapEx (2016$/kW)	$257	$236	$118	$91
Mechanical BoP Cost (2016$/kW)[16]	$136	$140	$36	$23
Electrical BoP Cost (2016$/kW)	$121	$97	$82	$68
Total Electrical Usage (kWh/kg) [% LHV] (% HHV)	55.8 [59.7%] (70.6%)	51.4 [64.8%] (76.6%)	55.5 [60.1%] (71.0%)	51.3 [65.0%] (76.8%)
Stack Electrical Usage (kWh/kg) [% LHV] (% HHV)	50.4 [66.1%] (78.2%)	47.8 [69.8%] (82.4%)	50.4 [66.1%] (78.2%)	47.8 [69.8%] (82.4%)
BoP Electrical Usage (kWh/kg)	5.4	3.66	5.04	3.54
Stack Current Density (A/cm^2)	2.0	3.0	2.0	3.0
Cell Voltage (V)	1.9	1.8	1.9	1.8
Electrolyzer Power Consumption at Peak Production (MW)	3.56	3.53	119	118
Effective Electricity Price over Life of Plant[17] (2016¢/kWh)	7.27	7.87	7.35	7.91
Outlet Pressure from Electrolyzer (psi)	300	700	300	700
Installation Cost (% of uninstalled capital cost)	12%	10%	12%	10%
Stack Replacement Interval (years)	7	10	7	10
Stack Replacement Cost Percentage (% of installed capital cost)[18]	15%	15%	15%	15%
Plant Life (years)	20	20	40	40
Stack Degradation Rate (mV/khrs)	1.5	1	1.5	1
Cell Active Area (cm^2)	700	700	1,500	1,500
Capacity Factor (%)	97%	97%	97%	97%

[15] All capital costs in this table assume manufacturing at volumes such that economies of scale have been achieved.

[16] Mechanical BoP costs increase slightly between the *Projected Current* and *future* cases due to increased system operating pressure. Costs between the *Distributed* and *Central* cases decrease substantially due an assumption of increased reliability leading to decreased number of Mechanical BoP modules and hence increased unit size with benefit from economies of scale.

[17] Effective electricity price over life of plant (20 years for *Distributed* cases and 40 years for *Central* cases)

[18] Stack Replacement Cost Percentage is estimated at 15% of the installed capital cost based on questionnaire responses. This cost is meant to capture the net expense of stack replacement, inclusive of old stack residual value and installation cost.

Baseline Cost Projection Results

The hydrogen production cost breakdown for the four H2A v3.2018 PEM electrolysis baseline cases is shown in Table 3. As shown in the table, the primary cost driver for H_2 production is the electricity cost. The system electrical efficiency increases between the *Projected Current* and *Projected Future* cases (as seen in Table 3), while the average electricity price between the *Projected Current* case and *Projected Future* case rises. As a result of these two changes between the cases, the overall electricity cost contribution to the price of H_2 is slightly lower for the *Projected Future* than the *Projected Current* cases in Table 3. The cost contribution of electricity on the cost of H_2 from *Central* production sites is slightly higher than the cost contribution of electricity in *Distributed* production sites due to the longer life of the *Central* plants. The electricity price during the last 20 years of the *Central* plants is higher than the electricity price of the life of the *Distributed* plants, which raises the overall effective electricity price of the plant over the course of its life. Overall, there is only a small cost reduction in moving from small *Distributed* plants to large *Central* plants, and only a modest (~10%) cost reduction between *Projected Current* and *Projected Future* plants.

Table 3- H_2 production cost breakdowns in 2016$/kg H_2 for PEM electrolysis baseline cases.

Component	*Current Distributed* 1,500 kg/day	*Future Distributed* 1,500 kg/day	*Current Central* 50,000 kg/day	*Future Central* 50,000 kg/day
Capital Costs	$0.55	$0.31	$0.40	$0.23
Decommissioning Costs	$0.01	$0.01	$0.00	$0.00
Fixed O&M	$0.35	$0.19	$0.24	$0.15
Electricity Feedstock	$4.09	$4.06	$4.18	$4.15
Credit for outlet pressure>300psi	$0.00	-$0.09	$0.00	-$0.05
Total H_2 Production Cost[19]	***$4.98***	***$4.48***	***$4.83***	***$4.48***

While the above projections correspond to state-of-the-art electrolysis systems produced at 700MW/year, existing commercial systems available for sale rationally have higher costs as they are produced with slightly older manufacturing technology (due to the engineering design cycle) and lower rates of production. Currently available commercial systems are approximately $800/kW-$1,500/kW with a 10MW/year production capacity. The analysis is meant to illustrate the potential cost, should these advanced technologies be implemented in fully-functional integrated systems at full-scale production; they should not be interpreted to represent pricing in today's limited PEM market.

Sensitivity Analysis

Table 4 details the range of parameter values used within the H2A v3.2018 sensitivity analysis. The parameters and the upper and lower limits of each parameter were selected by the analysis team, and are meant to capture the potential range of parameter variation rather than to report company-sensitive minimum and maximum values from the four participating electrolyzer manufacturers.

[19] The summations in Table 3 may vary slightly from the Total H_2 Production Cost listed due to small rounding differences between the subcategory costs listed in the table and the actual H2A projected total costs

Three sensitivity analyses were conducted:

1) Single Variable Tornado Charts in which one parameter was varied, all others were held fixed at the baseline case values, and the new cost was recorded (Table 4, Figure 3 and Figure 5).

2) Two Variable Contour Plots in which electricity cost and stack electrical usage were varied within the bounded ranges and the resulting hydrogen cost plotted in a contour graph (Figure 4 and Figure 6).

3) Monte Carlo Analysis in which all Table 2 parameters were stochastically and simultaneously varied over their full range to create a probability distribution function of potential hydrogen costs (Table 1).

Tabular results of the Monte Carlo results appear in Table 1 as the upper and lower bounds of the projected H_2 production cost. The Monte Carlo analysis uses the same high and low parameter values as those found in the single parameter sensitivity analysis[20] (shown in Table 4), a sampling size of 10,000 iterations, and reports the middle 90% range ($\alpha = 0.90$) of cost results (i.e. there is a 90% chance of H_2 cost falling between the low and high cost estimates).

Table 4- Sensitivity Analysis Results for the four PEM electrolysis cases.

Projected Current Distributed Baseline H_2 Production Cost=$4.98	*Parameter Low[21] Value*	*Production Cost (2016$/kg H_2)*	*Parameter Baseline Value*	*Parameter High[22] Value*	*Production Cost (2016$/kg H_2)*
Electricity Price ($/kWh)	$0.015	$1.70	$0.0727	$0.12	$7.65
Stack Electrical Usage (kWh/kg H_2)	40.3	$4.20	50.4	60.5	$5.77
Stack Cost[23] ($/cm^2) [$/kW]	$1.00 [$263]	$4.87	$1.30 [$342]	$2.20 [$579]	$5.32
Electrical BoP Cost($/kW)	$94.4	$4.95	$121	$282	$5.22
Mech. BoP Cost ($/(kg H_2/day)	$231.2	$4.95	$286	$347	$5.02
Stack Replacement Cost Percentage (% per 7 years)	10%	$4.97	15%	75%	$5.13
Capacity Factor	98%	$4.98	97%	40%	$6.17
Stack Replacement Interval	11	$4.96	7	3	$5.13

[20] An exception to this statement occurs in that the Capacity Factor lower bound for the Monte Carlo analysis was restricted to 85% rather than 40%, as a 40% capacity factor is unlikely to occur with a fully operational plant operating on grid electricity. However, a 40% capacity factor is selected for the single variable sensitivity analysis as it is a practical value when considering intermittent plant operation using low-cost renewable (wind) electricity.
[21] "Low" reflects the most optimistic parameter value, resulting in a lower H_2 production cost
[22] "High" refers to the least optimistic parameter value, resulting in a higher H_2 production cost
[23] While stack cost is frequently listed in ($/kW), the various industry respondents had very different power densities. In order to decouple stack cost from the stack operating point, the stack cost was converted to $/cm^2 where cm^2 is square centimeters of stack membrane active area. To convert from $/cm^2 to $/kW, the following formula can be used:

$$Cost\left(\frac{\$}{kW}\right) = \frac{Cost\left(\frac{\$}{cm^2}\right)}{Power\ Density\left(\frac{kW}{cm^2}\right)} = \frac{Cost\left(\frac{\$}{cm^2}\right) * 1000\left(\frac{W}{kW}\right)}{Cell\ Voltage_{BOL}(V) * CurrentDensity_{BOL}\left(\frac{A}{cm^2}\right) * \left(\frac{1\,W}{V * A}\right)}$$

Table 4 cont. - Sensitivity Analysis Results for the four PEM electrolysis cases

Projected Future Distributed Baseline H_2 Production Cost=\$4.48	*Parameter Low[24] Value*	*Production Cost (2016\$/kg H_2)*	*Parameter Baseline Value*	*Parameter High[25] Value*	*Production Cost (2016\$/kg H_2)*
Electricity Price (\$/kWh)	\$0.015	\$1.14	\$0.0787	\$0.12	\$6.63
Stack Electrical Usage (kWh/kg H_2)	40	\$3.82	47.8	57.4	\$5.26
Stack Cost[23] (\$/cm²) [\$/kW]	\$0.21 [\$38.9]	\$4.35	\$0.77 [\$143]	\$0.90 [\$167]	\$4.51
Electrical BoP Cost(\$/kW)	\$75	\$4.45	\$97	\$226	\$4.62
Mech. BoP Cost (\$/(kg H_2/day)	\$243	\$4.45	\$278	\$365	\$4.50
Stack Replacement Cost Percentage (% per 10 years)	10%	\$4.47	15%	75%	\$4.54
Capacity Factor	98%	\$4.46	97%	40%	\$5.08
Stack Replacement Interval	15	\$4.46	10	5	\$4.51

Projected Current Central Baseline H_2 Production Cost=\$4.83					
Electricity Price (\$/kWh)	\$0.015	\$1.45	\$0.0735	\$0.12	\$7.50
Stack Electrical Usage (kWh/kg H_2)	40.3	\$4.04	50.4	60.5	\$5.62
Stack Cost[23] (\$/cm²) [\$/kW]	\$1.00 [\$263]	\$4.74	\$1.30 [\$342]	\$2.20 [\$579]	\$5.09
Electrical BoP Cost(\$/kW)	\$66	\$4.81	\$82	\$197	\$4.96
Mech. BoP Cost (\$/(kg H_2/day)	\$61	\$4.81	\$76	\$91	\$4.84
Stack Replacement Cost Percentage (% per 7 years)	10%	\$4.82	15%	75%	\$5.06
Capacity Factor	98%	\$4.83	97%	40%	\$5.65
Stack Replacement Interval	11	\$4.80	7	3	\$4.94

Projected Future Central Baseline H2 Production Cost=\$4.48					
Electricity Price (\$/kWh)	\$0.015	\$1.07	\$0.0791	\$0.12	\$6.66
Stack Electrical Usage (kWh/kg H_2)	40	\$3.82	47.8	57.4	\$5.27
Stack Cost[23] (\$/cm²) [\$/kW]	\$0.21 [\$38.9]	\$4.37	\$0.77 [\$143]	\$0.90 [\$167]	\$4.50
Electrical BoP Cost(\$/kW)	\$53	\$4.46	\$66	\$158	\$4.57
Mech. BoP Cost (\$/(kg H_2/day)	\$37	\$4.47	\$46	\$55	\$4.48
Stack Replacement Cost Percentage (% per 10 years)	10%	\$4.47	15%	75%	\$4.55
Capacity Factor	98%	\$4.46	97%	40%	\$4.92
Stack Replacement Interval	15	\$4.47	10	5	\$4.50

[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

Cost Plots and Tornado Charts

Figure 2 plots the H_2 production cost breakdown results for the four baseline cases. Vertical bars around each of the baseline total costs reflect the 90% confidence limits of the Monte Carlo analysis.[26] Since electricity price is key driver of hydrogen cost, results are also shown for a constant electricity price of $0.03/kWh, representative of a low-cost electricity source.

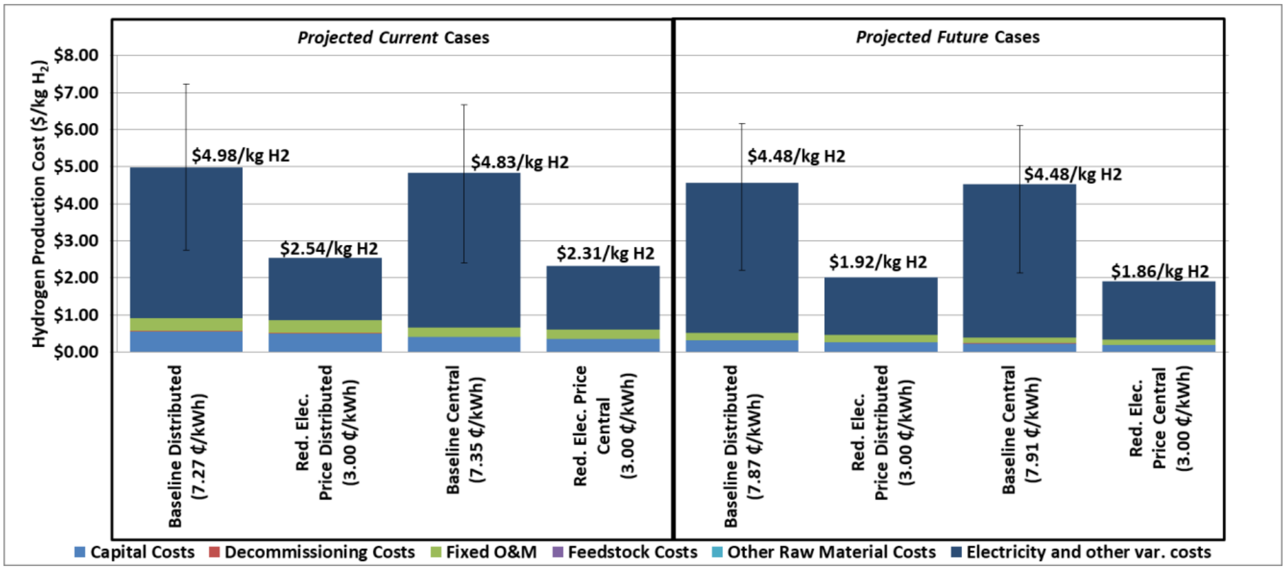


Figure 2 - PEM electrolysis H_2 production cost contributions (2016$/kg) for four case studies with effective electricity prices listed for each case. Further, a cost is listed for each case study at a reduced electricity price of $0.03/kWh.

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 Figure 3 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) average electricity price over life of plant; (2) electricity usage; (3) stack cost; (4) stack replacement interval; (5) electrical BoP cost; (6) mechanical BoP cost; (7) stack replacement cost percentage; and (8) capacity factor. Each tornado chart is organized from top to bottom to represent the most to least sensitive input parameters, respectively. The colored shading indicates either an increase (red) or a decrease (blue) in the baseline hydrogen cost from the change in input parameter.

Important input parameters influencing hydrogen cost include the electricity usage of the electrolyzer (which is proportional to electrolyzer net system electrical efficiency) and the 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.

The provided contour plots (Figure 4 and Figure 6) can be used to determine the cost of H_2 resulting from various combinations of the input parameters highlighted in the single parameter sensitivity study. Two

[26] Sensitivity studies were not run for the $0.03/kWh cases. As such, these cases do not have vertical bars displayed for bounding purposes

contour plots are provided for each case study. One plot shows the cost relationship of H_2 to electricity price and the uninstalled system capital cost ($/kW) while the other contour plot shows the cost relationship of H_2 to electricity price and stack electrical usage (stack efficiency). The contour plots provide a quick and efficient way to target H_2 price for a system with a given electrical price.

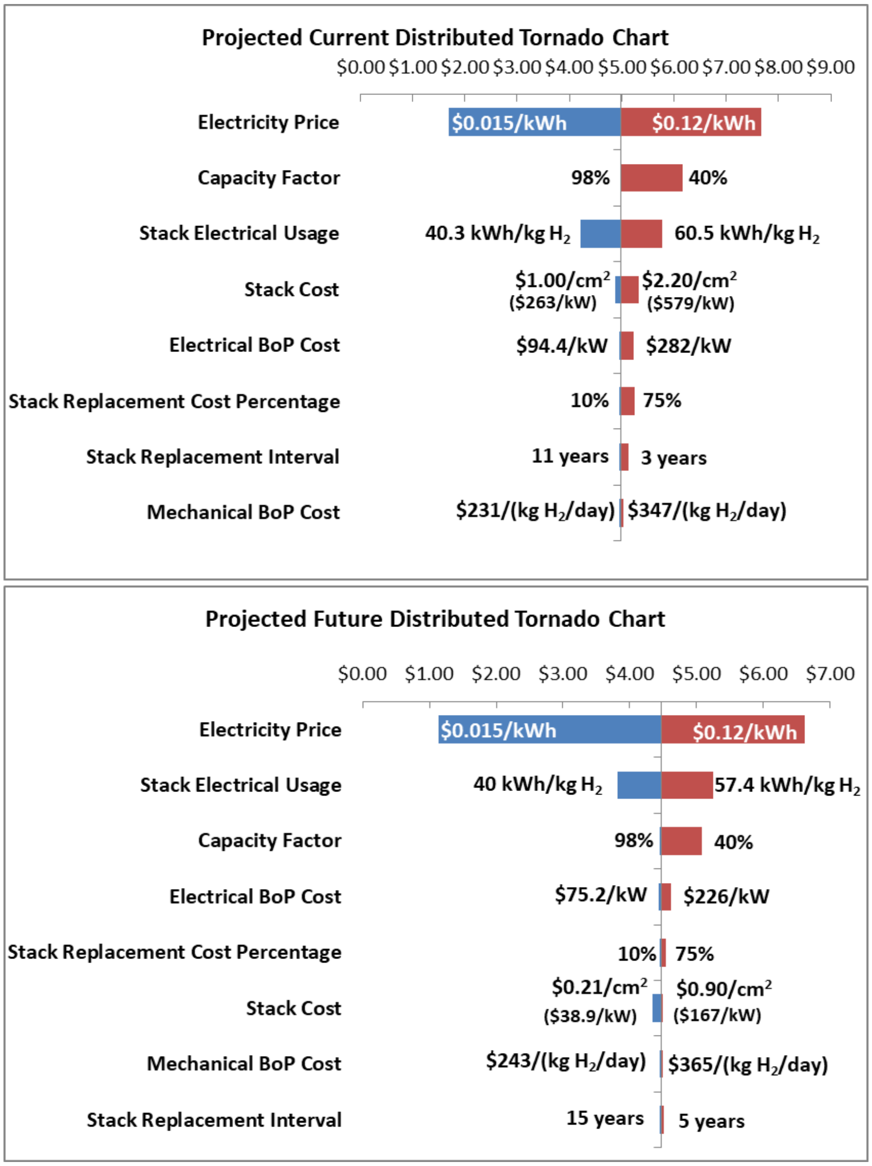


Figure 3 - Tornado chart showing parameter sensitivities for Projected Current and Projected Future Distributed PEM Electrolysis cases.

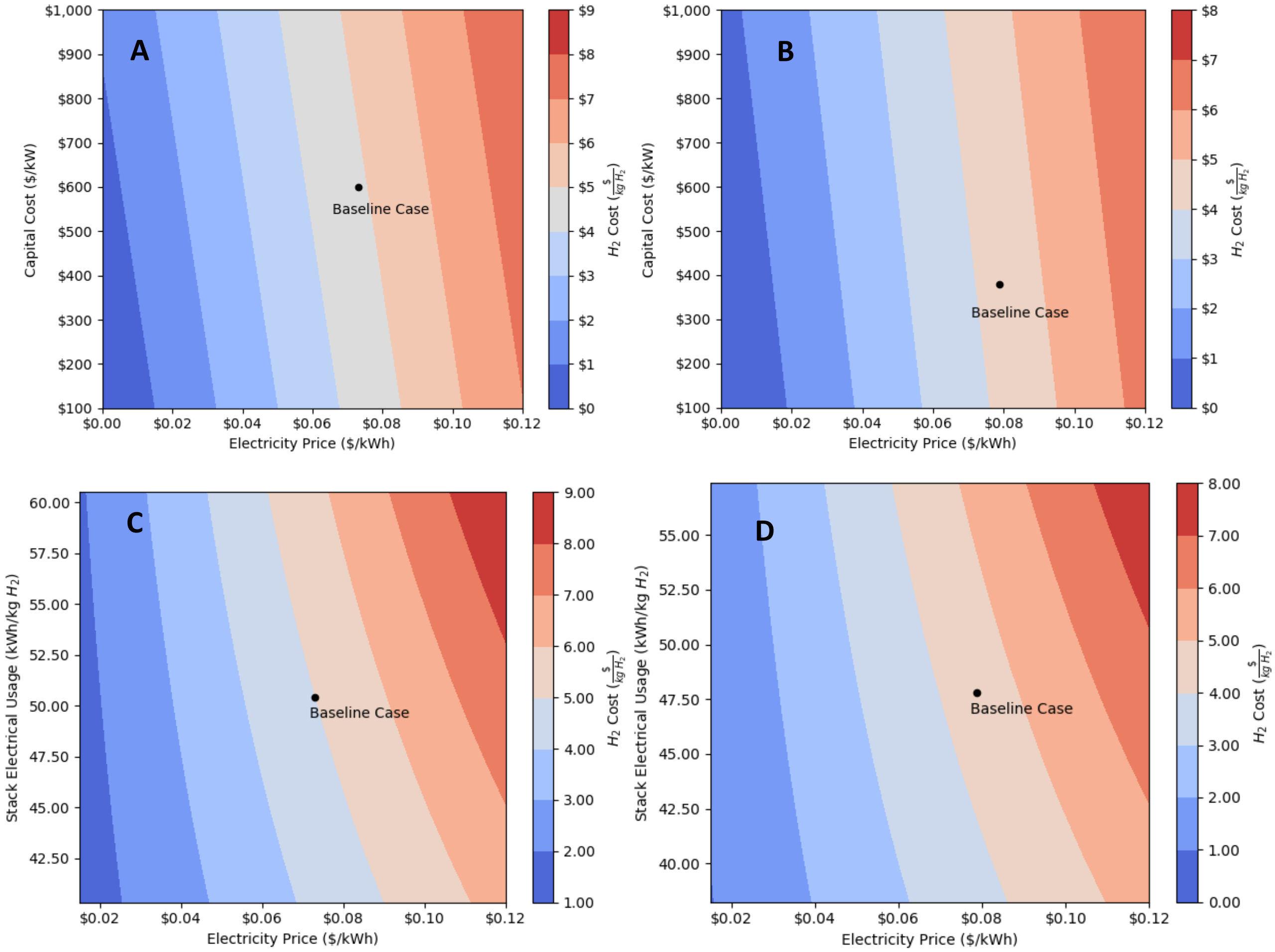


Figure 4 - Contour plots depicting cost variation for H_2 production with changes to electrolyzer system capital cost and electricity price and for: (A) Projected Current and (B) Projected Future Distributed PEM cases. Contour plots depicting cost variation for H_2 production with changes to stack electrical usage and electricity price for: (C) Projected Current and (D) Projected Future Distributed PEM cases.

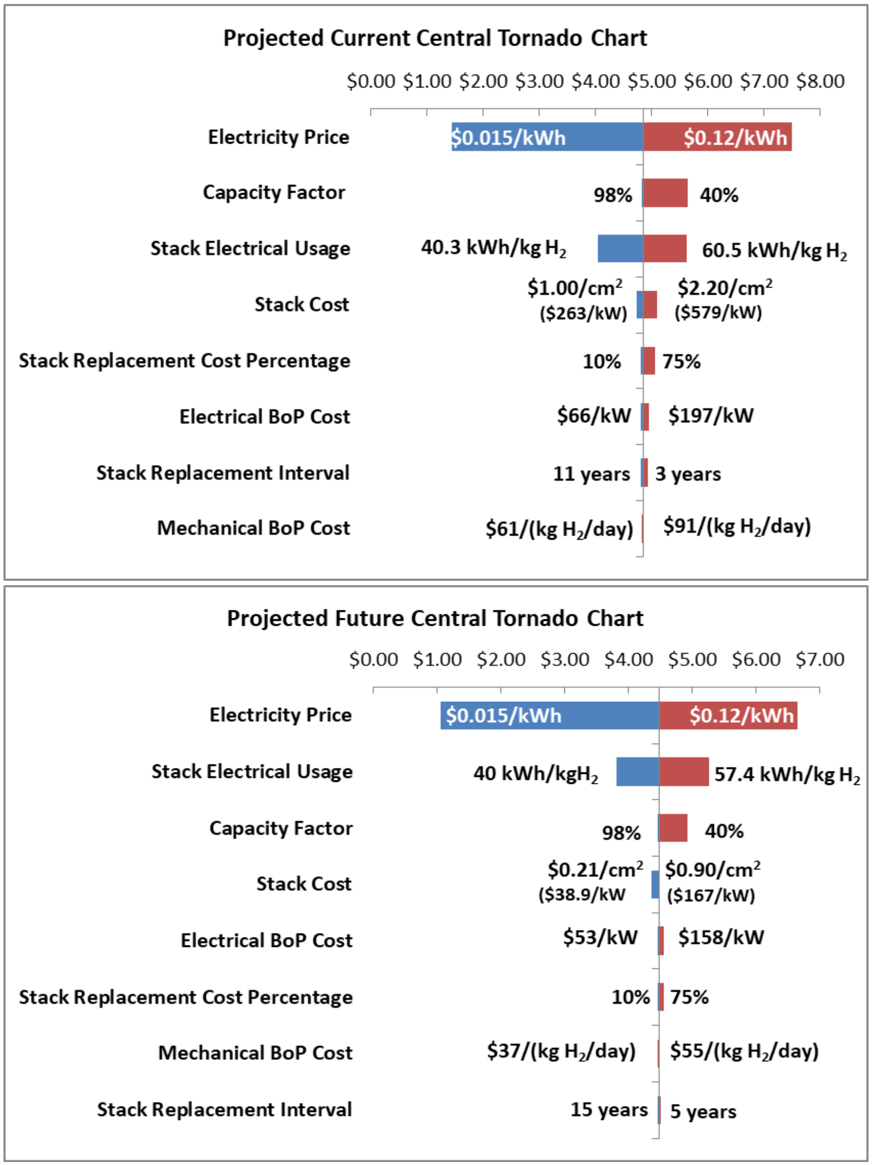


Figure 5 - Tornado chart showing parameter sensitivities for Projected Current and Projected Future Central PEM Electrolysis cases.

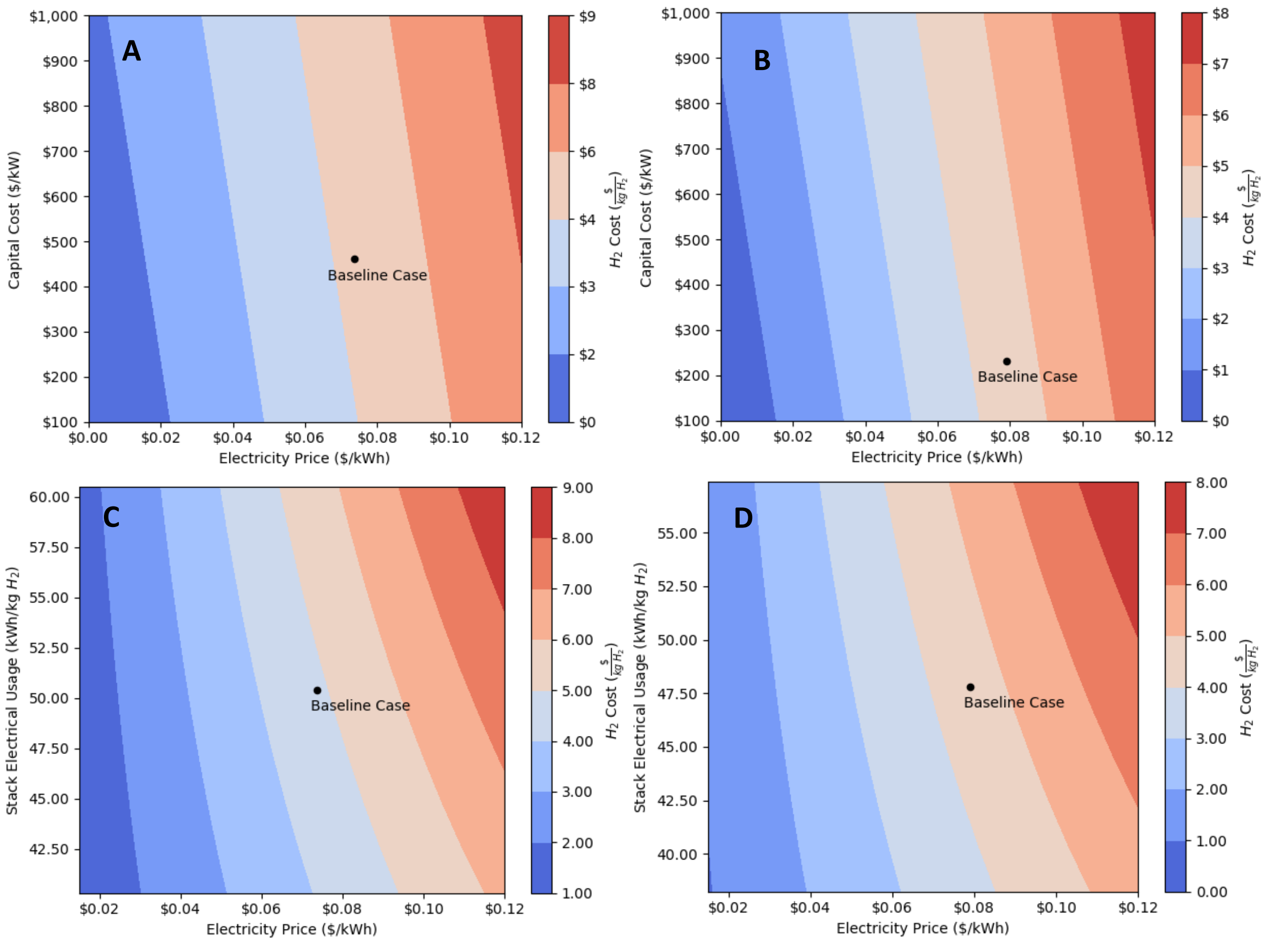


Figure 6 - Contour plots depicting cost variation for H_2 production with changes to electrolyzer system capital cost and electricity price for: (A) Projected Current and (B) Projected Future Central PEM cases. Contour plots depicting cost variation for H_2 production with changes to stack electrical usage and electricity price for: (C) Projected Current and (D) Projected Future Central PEM cases.

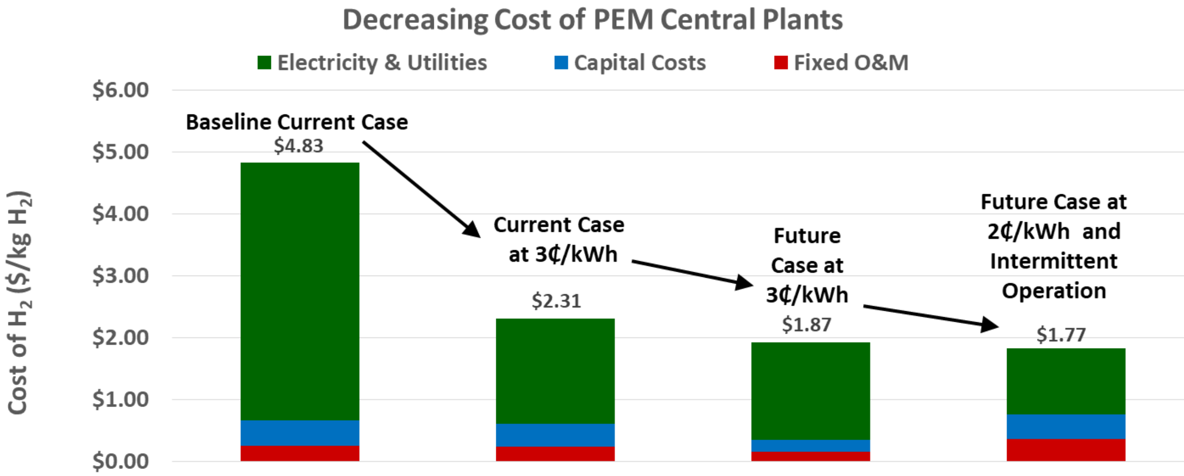
Pathway to reduced H_2 cost

In order to meet the goal of producing H_2 for less than \$2.00/kg H_2 and to be competitive with H_2 production from steam methane reforming, further cost reductions are needed.[27] To expand on the previous sensitivity studies, Figure 7 highlights a possible pathway to reduce production costs of H_2 to below \$2.00/kg. Given the significant dependence of H_2 cost on electricity price, a low electricity price is the key aspect of the pathway to reduced H_2 cost. With the continued decrease in electricity cost from renewable energy sources, power purchase agreements at ≤\$0.03/kWh are becoming more common. The next step in the pathway to reducing H_2 cost is to use the capital cost, stack lifetime, and improved stack efficiency, as well as the other assumptions for the *Projected Future* case with an electricity price of \$0.03/kWh.[28] The combination of cost reductions then predicts a H_2 cost of less than \$2.00/kg H_2. One final scenario examined in Figure 7 predicts the cost of H_2 if the price of electricity were reduced to \$0.02/kWh

[27] https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis

[28] Includes the \$0.05/kg H_2 pressure credit discussed in the Analytical Basis

while the electrolysis operation is run with an intermittent schedule that amounts to a 40% capacity factor on the plant. In this case, the projected cost of producing H_2 drops to $1.77/kg H_2. This last scenario is a good example of how the price of H_2 could be reduced by using an electrical source that has a variable pricing schedule during periods when the electricity is inexpensive. A real world example would be running the electrolyzer from a grid supply while the local grid is underutilized.



Capacity Factor	97%	97%	97%	40%
Stack Electrical Efficiency	66.1%	66.1%	69.8%	69.8%
System Cap Cost	$460/kW	$460/kW	$233/kW	$233/kW
Effective Electricity Cost	7.4¢/kWh	3.0¢/kWh	3.0¢/kWh	2.0¢/kWh
Degradation Rate	1.5 mV/khrs	1.5 mV/khrs	1 mV/khrs	1 mV/khrs
Stack Lifetime	7 yrs	7 yrs	10 yrs	10 yrs

Figure 7- Waterfall chart describing a pathway towards low cost H2 production via PEM electrolysis. The analysis presumes a Central size facility. A Distributed facility is likely to see similar reductions in cost.

Supplemental Information

There were many changes between the previous 2014 H2A PEM case studies (Record 14004) and this update from both the H2A model revision as well as the input parameters. Table 5 provides a summary comparison of the differences. The change in reference year from 2007$ to 2016$ alone resulted in an increase in the hydrogen production cost of approximately $0.85/kg H_2 between the 2014 and 2019 cases.

Table 5 – Supplemental Information: Key differences between 2014[4] and 2019 H2A Case Studies for H_2 production via PEM Electrolysis

Parameter	***Units***	***Current***				***Future***			
Production Scale		Distributed		Central		Distributed		Central	
Case Publication Year		2014 Case Study	2019 Case Study	2014 Case Study	2019 Case Study	2014 Case Study	2019 Case Study	2014 Case Study	2019 Case Study
H_2 Production Cost	\$/kg H_2	\$5.14	\$4.98	\$5.12	\$4.83	\$4.23	\$4.48	\$4.20	\$4.48
H2A Version[29]	-	H2A v3.1	H2A v3.2018	H2A v3.1	H2A v3.2018	H2A v3.1	H2A v3.2018	H2A v3.1	H2A v3.2018
Assumed plant startup year	-	2010	2015	2010	2015	2020	2040	2020	2040
Current Density	A/cm^2	1.5	2	1.5	2	1.6	3	1.6	3
Cell Voltage	V/cell	1.84	1.9	1.84	1.9	1.7	1.8	1.7	1.8
Total Uninstalled Capital Cost[30]	2016\$	\$1,053	\$599	\$504	\$460	\$1,008	\$379	\$448	\$233
H_2 Outlet Pressure	psi	450	300	450	300	1,000	700	1,000	700
Compression Credit	-	No	No	No	No	No	Yes	No	Yes
Stack Degradation Rate	mV/khrs	2	1.5	2	1.5	1	1	1	1
Effective Electricity Price	2016₵/kWh	7.25	7.27	7.36	7.35	7.25	7.87	7.90	7.91
Electrical Efficiency	kWh/kg H_2	54.6	55.8	54.3	55.5	50.3	51.4	50.2	51.3

[29] The change from H2A v3.1 to v3.2018 includes: Increasing the basis dollar year from 2007 to 2016, reducing the equity financing from 100% to 40%, lowering the After Tax Real IRR from 10% to 8%, switching from a declining debt balance to a constant debt balance, specifying a 3.7% interest rate on debt, and reducing the federal tax rate from 35% to 21%

[30] All 2014 capital costs and electrical efficiencies are taken from the results of the questionnaires submitted to industry experts. All 2019 capital costs and electrical efficiencies are taken from the results of the questionnaires submitted to industry experts, as well as internal engineering design and analysis