DOE Hydrogen and Fuel Cells Program Record	
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Title: Hydrogen Production Cost From High Temperature Electrolysis – 2020	
Originators: David Peterson, James Vickers (DOE), Daniel DeSantis (Strategic Analysis)	
Peer reviewed by: Tony Leo, Joe Hartvigsen, Annabelle Brisse, Randy Petri	
Approved by: Katie Randolph, Ned Stetson, and Sunita Satyapal	Date: 9/29/20

Item

Rigorous stakeholder-vetted techno-economic analysis was performed to assess the cost of hydrogen produced using high-temperature electrolysis (HTE)[1] in the near- to long-term if manufactured at scale. Projected high-volume, untaxed hydrogen costs can range from approximately $2/kg H_2 to $6/kg H_2 based on industry input on HTE system performance as well as on capital, operational, and feedstock costs. The total installed high volume capital cost, for example, ranged from approximately $360/kW to $520/kW for different analysis scenarios.

Analysis Summary

The projected high-volume cost to produce hydrogen (untaxed, excluding delivery and dispensing) from high temperature electrolysis ranges from $2.27 to $5.71/kg based on case study results using the Hydrogen Production Analysis model, version 3.2018 (H2A v3.2018).[2] Two H2A cases were developed for Central hydrogen production plants (50,000 kg H_2/day): a *Projected Current* case based on 2019 state-of-the-art technology and a *Projected Future* case based on expected technology advancements by 2035.[3] The case studies assume an electrolyzer manufacturers' annual production capacity of 700 MW/yr in order to model a robust and mature production scenario. For reference, the HTE industry's production capacity at the time of publication is more than two orders of magnitude lower than this production capacity. Both cases are based on input from three high temperature electrolysis organizations regarding electrolyzer stack and system design, performance, and cost. The subsequent study parameters and results were reviewed by these same organizations to ensure relevance and accuracy. The analysis presented in this Record supersedes the 2016 H2A HTE case studies and Record.[4]

Table 1 - H_2 Production High-Volume Cost Projections for the HTE Cases.[5]

Central H_2 Production HTE Case Study	**Low Value** ($/kg H_2)	**Baseline** ($/kg H_2)	**High Value** ($/kg H_2)	**H_2 cost at 3¢/kWh$_{electric}$** ($/kg H_2)
Projected Current Case[6]	$2.50	**$4.16**	$5.71	$2.36
Projected Future Case[7]	$2.27	**$3.89**	$5.43	$2.00

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[1] In this Record, the term high temperature electrolysis (HTE) refers to solid oxide electrolysis (SOE). The Record updates prior Records and analysis by DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) in the Office of Energy Efficiency and Renewable Energy (EERE) which has been funding electrolysis R&D, including HTE, for over 2 decades.

[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] The H2A v3.2018 HTE cases are published at www.hydrogen.energy.gov/h2a_prod_studies.html. See Table 2 for a summary of case input parameters.

[4] Record #16014, https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf; See Supplemental Information for further details

[5] Hydrogen costs are reported in 2016$/kg, consistent with H2A v3.2018 methodology which uses data, including electricity cost, from the *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2019 Report* (where 2018$ is the cost basis).

[6] For this case the effective electricity price over the 40 year life of the plant is 7.35¢/kWh.

[7] For this case the effective electricity price over the 40 year 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 two cases studied. The Baseline cost projections in the table are derived from representative cost and performance inputs from manufacturer and researcher participants that were incorporated into the techno-economic analysis. Electricity prices for these baseline projections were taken from EIA AEO Reports with averages over the 40 year plant life in the range of $0.07-0.08/kWh. The *Low* and *High* values are included to reflect a projected cost spread (with 90% certainty) as determined by a Monte Carlo multi-variable analysis. An 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 hydrogen production.

Analytical Basis

Analyses to project the cost of producing hydrogen at a central facility by temperature 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 v3.2018 discounted cash flow model. The analysis presented in this Record supersedes the 2016 H2A SOE cases studies[4] and uses recent input from, and reviews by, three HTE organizations to ensure the relevance and accuracy of the study parameters and results. These case studies assume an electrolyzer manufacturers' annual production capacity of 700MW/yr in order to model a robust and mature production scenario. For reference, the HTE industry's production capacity at the time of publication is more than two orders of magnitude lower than this production capacity (i.e., less than 7 MW/yr)

Case studies were developed for two technology years, *Projected Current*[8] (2019) and *Projected Future*[9] (2035). Technology year is defined as the year in which a system design and electrolyzer cell/stack performance levels 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. Given the limited number of commercial HTE stacks or HTE systems in operation, and the limited long-term durability data at relevant operating conditions, the *Projected Current* case was extrapolated from technology demonstrated at the laboratory scale. Additional analysis and modeling were conducted to confirm case assumptions. 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.

Relevant techno-economic data for the two cases were solicited from three study participants, two companies and one research organization, via a questionnaire. 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 & operating parameters; (2) capital costs; (3) operating costs; (4) variable and fixed expenses; and (5) replacement costs. For each case, a generalized electrolyzer system 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®. The performance models were used

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[8] The *Projected Current* case is based on current 2019 state-of-the-art laboratory-demonstrated technology, with extrapolated scale-up to an industrial process that includes high-volume manufacturing, and market entry in 2015. (Market entry is maintained at 2015 to allow fair comparison to other case studies.)

[9] The *Projected Future* case uses advanced electrolyzer systems that will be technology-ready in 2035, with market entry assumed in 2040.

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, represents a system with a stack temperature of 800°C and an H_2 outlet pressure of 300 psi (the stack is assumed to run at ~73 psi but product H_2 is mechanically compressed to 300 psi prior to system exit). Heat to warm the reactants to stack inlet temperature is provided by hot stack outlet gases via recuperative heat exchange and topping heaters from a generic heat source, without judgment as to the heating source (see Table 2 for heating cost for each case). Air is used as a sweep-gas on the oxygen-generating side of the cells (anode).

The *Projected Current* case design (see Figure 1) features a feed water stream at low pressure and ambient temperature passing through multiple heat exchangers (HX) with the intention of recovering as much heat as possible, while raising the temperature and pressure to operating conditions (700-800°C and 73 psi). One heat exchanger is defined as the "heat source heat exchanger" and represents the inlet of an agnostic heat source. It is assumed for this study that the agnostic heat source provides low-grade heat (~300°C) and provides sufficient energy to raise the reactant steam to ~250°C. The price for an agnostic heat source is based on a 40-year average of industrial natural gas price as predicted by the EIA AEO 2009 Report and an 85.7% combustor efficiency. The stack is powered by DC current from the transformer/rectifier. An air sweep is used on the anode side of the stack to reduce O_2 gas concentration. Heat exchangers are placed to transfer heat from the air outlet stream to the air inlet stream where possible. The high temperature recuperators, the steam topping heaters, air topping heaters (*Projected Current* case only), and the stack are all inside a pressurized vessel kept at 73 psi. The pressure vessel minimizes stack mechanical stresses and H_2 leakage since there is no pressure gradient between the inside and outside of the stack nor across the cells in the stack. Further, the pressure vessel is an insulated unit, reducing heat loss for the high-temperature equipment and minimizing vessel cost by using carbon steel. It is sized for the operating pressure and expected temperature profile. After generation, H_2 and any unconverted water are passed through the H_2O/H_2 heat exchanger. At this point, the H_2 is either recycled into the stack feed or passed to a Temperature Swing Adsorber (TSA). After water removal, H_2 is passed to a compressor and the pressure is raised to 300 psi before exiting the system.

The generalized system design developed for the *Projected Future* baseline case is shown in Figure 2. While similar to the *Projected Current* baseline case, it represents a more technologically-advanced version with the following differences:

- Reduced stack operating temperature[11]
    - Assumes no loss in performance due to lower temperature operation
- Removal of air sweep of the oxygen side (anode)
    - Assumes no loss in stack performance without air sweep
- Stack pressure and H_2 outlet pressure are both 300 psi

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[10] The thermo-neutral operating point refers to a cell operating voltage where stack input energy (including activation, ohmic and concentration overpotentials), is all balanced with and consumed by the steam decomposition / splitting reaction. Thus the cell operates without a large temperature gradient between inlet and outlet streams. The thermo-neutral operating voltage is approximately 1.28 V at 800°C.

[11] For example 600°C – 650 °C. Temperatures as low as 500 °C through proton conducting electrolytes may also be an option in the future.

    - Absence of the air sweep allows the stack pressure to be increased without a large rise in parasitic power and eliminates the need for the hydrogen compressor (for 300 psi)
- Increased current density with no corresponding increase in degradation or other performance losses

For both cases, the questionnaire responses were used to derive system efficiency values (included in Table 2) that account for all losses associated with the stack efficiency, electrical inverter efficiency, and other balance of plant (BoP) loads. BoP electrical usages were further estimated using Aspen HYSYS® modeling software. The participating research organizations reviewed and vetted the generalized inputs and designs for both H2A baseline cases.

Cell current density (at the operating point) and area specific resistance (ASR) were used as inputs into the performance and cost analyses. These parameters were used to confirm stack capital cost, cell lifetime, and degradation rates. The electrical efficiency does not change much between the *Projected Current* and *Projected Future* cases because stacks from both systems operate at the same cell voltage. A modest increase in current density is expected between the *Projected Current* and *Projected Future* cases.

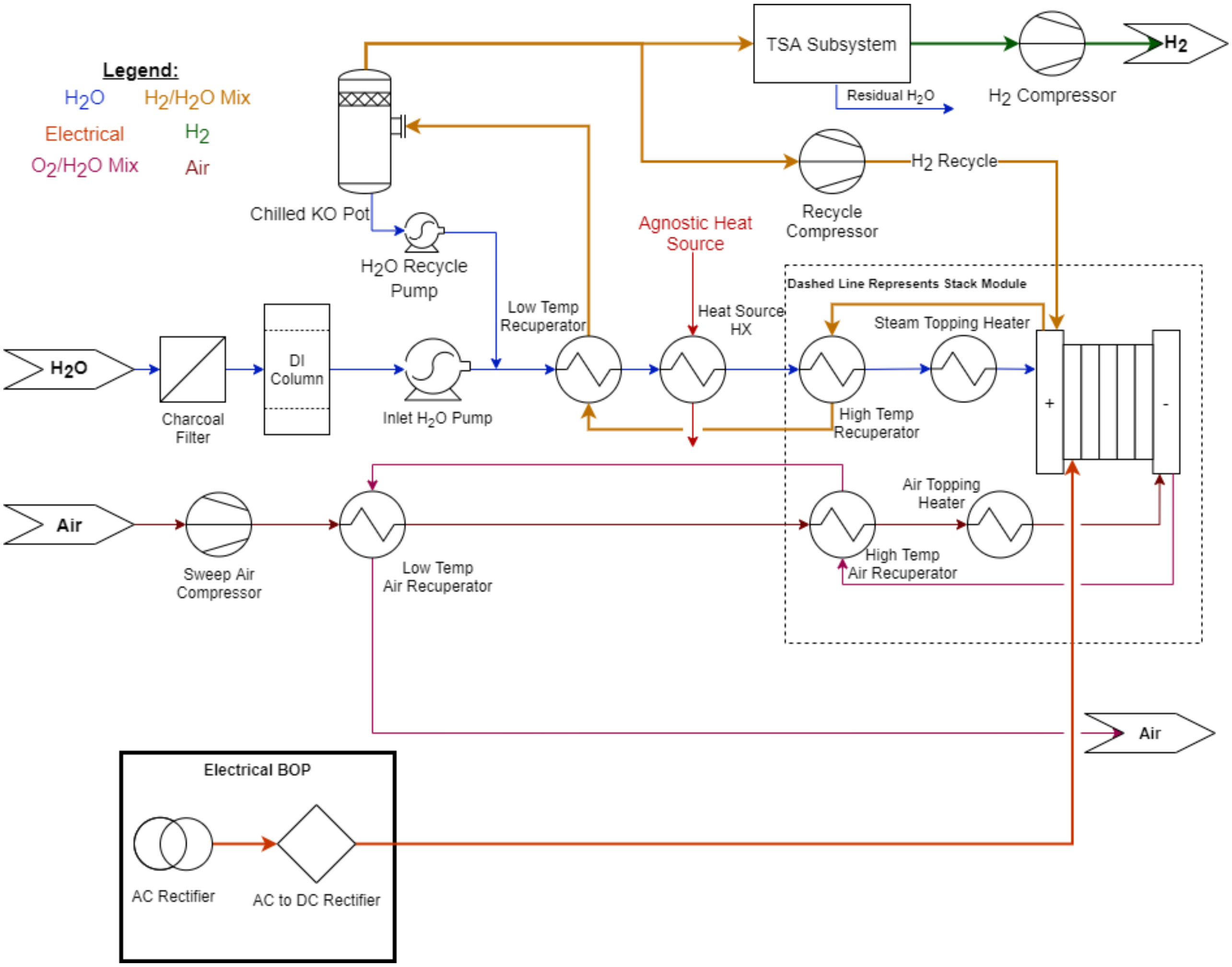

Figure 1 - Projected Current HTE Baseline Design.

The *Projected Future* case pressurizes water to greater than 320 psi at the feed water pump (Figure 2). The pressurized water is passed through a series of heat exchangers, as in the *Projected Current* case. One heat exchanger is defined as the “heat source heat exchanger” and represents the inlet of an agnostic heat source. It is assumed for this study that the heat source is low-grade heat (~300°C) and can provide sufficient energy to raise the outlet steam to ~ 250°C. No air sweep is used in the *Projected Future* case. In order to remove as much need for compression as possible, the electrolysis stack operates at approximately 320 psi. During electrolysis, the water is split into H_2 and O_2. The evolved O_2 is passed through heat exchangers with the inlet water, recovering more heat into the steam, before passing into a knock-out (KO) pot to remove any water. The relatively dry O_2 then exits the system. Simultaneously, produced H_2 passes through a chilled knock-out pot and is then either recycled to the stack (after passing through a compressor) or enters a TSA for water removal.[12]

Using the generalized inputs and designs vetted by the participants, baseline H2A v3.2018 case studies were prepared for the *Projected Current* and *Projected Future* cases, to project baseline H_2 production costs in the two technology years. H2A sensitivity analysis was also performed for each case based on vetted parameter limits, with results illustrated in the tables and tornado charts included in this Record.

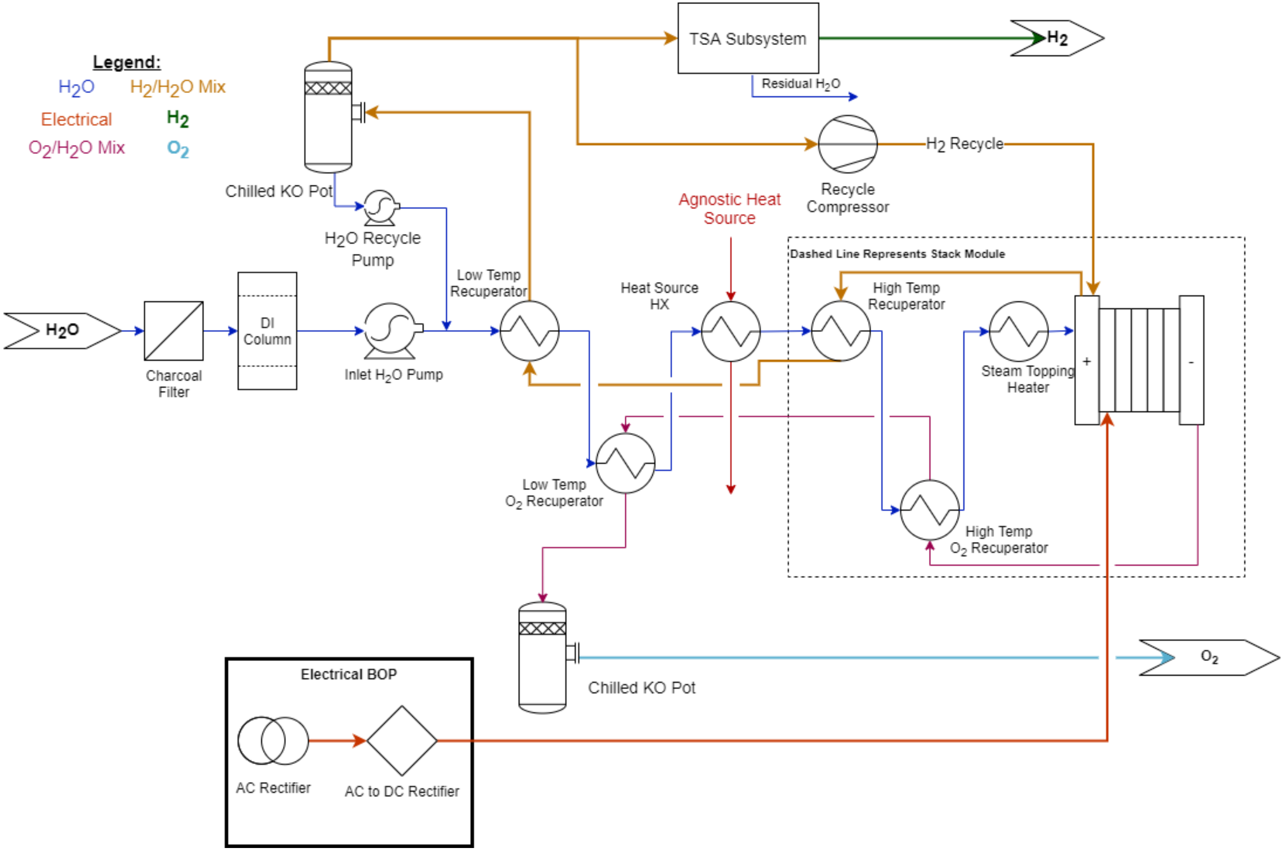

Figure 2 - Projected Future HTE Baseline Design.

Baseline Input Parameters

The key parameters used to develop the two H2A v3.2018 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 AEO.[13] Additional parameter

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[12] The TSA sub-system recycles H_2 gas. The recycled gas loses pressure in the beds, so the TSA sub-system block includes a small compressor to make-up pressure losses for the recycled H_2 only.

[13] EIA AEO 2019 Report. https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf

values were drawn from standard H2A v3.1 default values[14] so as to create an overall assessment consistent with past H2A studies but also tailored to the unique attributes of the HTE system.

The stacks are modeled as operating at both constant voltage and current over their stack lifetime, despite performance degradation due to an increasing ASR. In order to maintain stack performance, the stack temperature is strategically increased to offset the degradation-induced rise in ASR. With this strategy, voltage, current density, ASR, and H_2 production rate are held constant over the life of the plant. Based on study participant input, stack degradation rates of 0.856%/1,000h and 0.311%/1,000h (% current density reduction at constant voltage) and stack effective service lifetimes of 4 and 7 years were used for the *Projected Current* and *Projected Future* cases, respectively.

Table 2 - Input Parameters for HTE H2A Central Production Baseline Cases (costs in 2016$).[5]

Parameter	Projected Current	Projected Future	Cost Basis
Technology Year	2019	2035	H2A Default Value
Start-up Year	2015	2040	H2A Default Value
Plant Capacity (kg/day)	50,000	50,000	H2A Default Value
Total Uninstalled Capital (2016$/kW)[15]	$522	$357	Eng. Calculation
Stack Capital Cost (2016$/kW)	$155	$100	Questionnaire Data
Balance of Plant (BoP) Capital Cost (2016$/kW)	$368	$257	Eng. Calculation
Total Energy Usage (kWh/kg)	46.6	44.2	Questionnaire Data
Net System Energy Efficiency[16]	71.4%	75.5%	Eng. Calculation
Stack Electrical Usage (kWh/kg)	34.0	34.0	Eng. Calculation
Stack Conversion Efficiency (% LHV H_2)	(98%)	(98%)	
System Electrical Usage (kWh/kg)	39.8	37.1	Eng. Calculation
System Conversion Efficiency (% LHV H_2)	(83.7%)	(89.8%)	
System Conversion Efficiency [% HHV]	[98.6%]	[105%][17]	
System Thermal Usage (kWh/kg)	6.86	7.10	Eng. Calculation
Cell Voltage (V)	1.285	1.285	Questionnaire Data
Current Density[18] **(A/cm^2)**	1.0	1.2	Questionnaire Data
Electrolyzer System Power Consumption (MW)	83	80	Eng. Calculation
Effective Elec. Price over Life of Plant (2016¢/kWh)	7.35	7.91	AEO/Eng. Calc.
Thermal Energy Cost (2016 ₵/kWh)	3.634	3.634	AEO/Eng. Calc.
Hydrogen Outlet Pressure (psi) (stack/system)	74/300	320/300	H2A standard
Installation Cost (% of uninstalled capital cost)	55%	63%	Eng. Calc./Question.Data
Stack Service Life[19] **(years)**	4	7	Questionnaire Data
H2A Plant Capacity Factor	90%	90%	H2A Default Value
Effective Annual Stack Service Replacement Cost[20] **(% of Stack Capital/year)**	22%	11%	Eng. Calculation
Balance of Plant (BoP) Lifetime (years)	20	20	Questionnaire Data
BoP Replacement Cost (% of BoP initial investment)	100%	100%	AEO/Eng. Calc

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

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

[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] The electrical conversion on a higher heating basis for the future case is expected to be above 100% due to the increased thermal input of the system. Taken on a complete energy basis, the total system efficiency is *not* above 100%.

[18] 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. A higher current density results in a smaller stack requirement.

[19] 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.

[20] 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 stacks taken off-line at the end of their service life.

Baseline Cost Projection Results

The H_2 production cost breakdown for the two H2A v3.2018 HTE baseline cases is shown in Table 3. Inputs from the study participants were used to determine the most likely parametric values at a production rate of 50,000 kg/day for the two different technology years (See Table 2). 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 and provided in Table 2) is seen to increase between the *Projected Current* and *Projected Future* cases. This electricity price increase is partially offset by the higher system electrical efficiency projected for *the Projected Future* case. Also, the capital cost projections for both *Projected Current* and *Projected Future* cases assume high volume manufacturing (700 MW/yr) has been achieved.

Table 3 - H_2 Production Cost Breakdowns in 2016\$/kg H_2 for HTE Baseline Cases.[21]

	Current		**Future**	
	Baseline Case	**3¢/kWh Case**	**Baseline Case**	**3¢/kWh Case**
Capital Costs	\$0.66	\$0.63	\$0.43	\$0.39
Decommissioning Costs	\$0.00	\$0.00	\$0.00	\$0.00
Fixed O&M Costs	\$0.23	\$0.23	\$0.19	\$0.19
Thermal Energy Feedstock Costs	\$0.25	\$0.25	\$0.26	\$0.26
Electricity Feedstock	\$3.01	\$1.24	\$3.01	\$1.15
Total Production Cost	**\$4.16/kg H_2**	**\$2.36/kg H_2**	**\$3.89/kg H_2**	**\$2.00/kg H_2**

Sensitivity Analysis

Table 4 details the range of parameter values used within the H2A v3.2018 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 three organizations. The range of sensitivity parameters was reviewed by the participating industry and research experts.

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 4, and Figure 5).

2) Two Variable Contour Plots in which electricity cost and either capital cost or system electrical usage were varied within the bounded ranges and the resulting hydrogen cost plotted in a contour graph (Figure 6 and Figure 7).

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 and as error bars in Figure 3. The Monte Carlo analysis uses the same high and low parameter values as those found in the single parameter sensitivity analysis (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).

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[21] 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

Table 4 - Sensitivity Analysis Results for the Two HTE Central Cases (H_2 production cost results reported in 2016$).

Projected Current Central Baseline H_2 Production Cost=$4.16	*Parameter Low[22] Value*	*Production Cost (2016$/kg H_2)*	*Parameter Baseline Value*	*Parameter High[23] Value*	*Production Cost (2016$/kg H_2)*
Constant Electricity Price over life of the plant (2016$/kWh)	$0.015	$1.74	$0.0735	$0.12	$6.08
System Electrical Usage (kWh/kg H_2)	34.0	$3.72	39.8	50	$4.94
Thermal Energy Cost (2016$/kW)	$0.00	$3.90	$0.0364	$0.07	$4.40
Stack Capital Cost[24] ($/$cm^2$) [$/kW]	$0.10 [$78]	$3.97	$0.20 [$155]	$0.30 [$233]	$4.36
Electrical BoP Cost ($/kW)	$50	$4.13	$85	$150	$4.22
Mechanical BoP Cost ($/kg H_2/day) [$/kW]	$301 [$216]	$4.08	$402 [$282]	$502 [$360]	$4.24
Thermal Energy Usage (kWh/kg H_2)	5	$4.09	6.86	8.5	$4.22
Stack Replacement Interval (years)	7	$4.06	4	1	$4.91
Operating Capacity Factor	97%	$4.10	90%	83%	$4.23

Projected Future Central Baseline H_2 Production Cost=$3.89	*Parameter Low[22] Value*	*Production Cost (2016$/kg H_2)*	*Parameter Baseline Value*	*Parameter High[23] Value*	*Production Cost (2016$/kg H_2)*
Constant Electricity Price over life of the plant (2016$/kWh)	$0.015	$1.42	$0.079	$0.12	$5.47
System Electrical Usage (kWh/kg H_2)	34.0	$3.64	37.1	50	$4.95
Thermal Energy Cost (2016$/kW)	$0.00	$3.62	$0.0364	$0.07	$4.14
Stack Capital Cost[24] ($/$cm^2$) [$/kW]	$0.10 [$65]	$3.83	$0.15 [$100]	$0.30 [$195]	$4.07
Electrical BoP Cost ($/kW)	$50	$3.88	$65	$150	$3.98
Mechanical BoP Cost ($/kg H_2/day) [$/kW]	$206 [$145]	$3.83	$273 [$192]	$343 [$241]	$3.95
Thermal Energy Usage (kWh/kg H_2)	5	$3.81	7.10	8.5	$3.94
Stack Replacement Interval (years)	11	$3.86	7	3	$4.01
Operating Capacity Factor	97%	$3.85	90%	83%	$3.94

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[22] "Low" reflects the most optimistic parameter value, resulting in a lower H_2 production cost.

[23] "High" refers to the least optimistic parameter value, resulting in a higher H_2 production cost.

[24] 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 active area. To convert from $/$cm^2$ to $/kW, the following formula can be used:

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

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 "error bars" provided with the total costs reflect 90% confidence limits of the Monte Carlo analysis.[25] Since electricity price is the key driver of hydrogen cost, hydrogen cost results are also shown for a single-point, constant electricity price of $0.03/kWh.

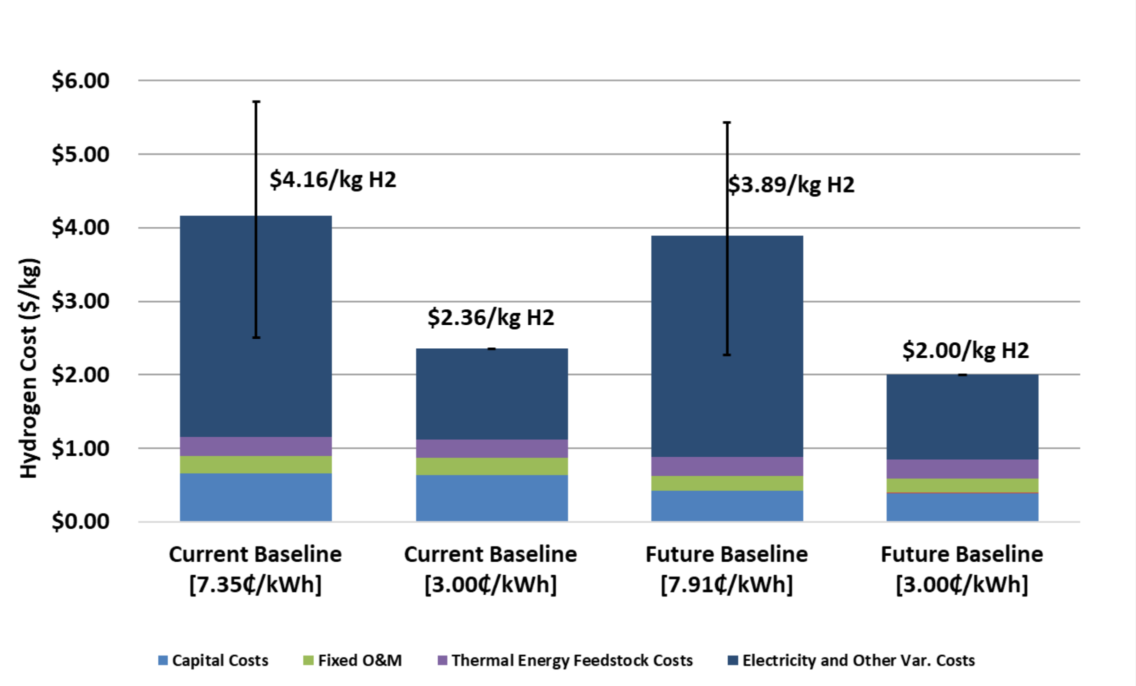

Figure 3 - HTE H_2 Production Cost Contributions (2016$/kg) for the two Baseline Case Studies with supplemental cost breakdowns for cases with constant $0.03/kWh electricity over the life of the plant.

Tornado charts based on the parameter spreads summarized in Table 4 were developed for the *Projected Current* and *Projected Future* HTE cases 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. 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 (blue) in the baseline hydrogen cost from the change in input parameter.

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

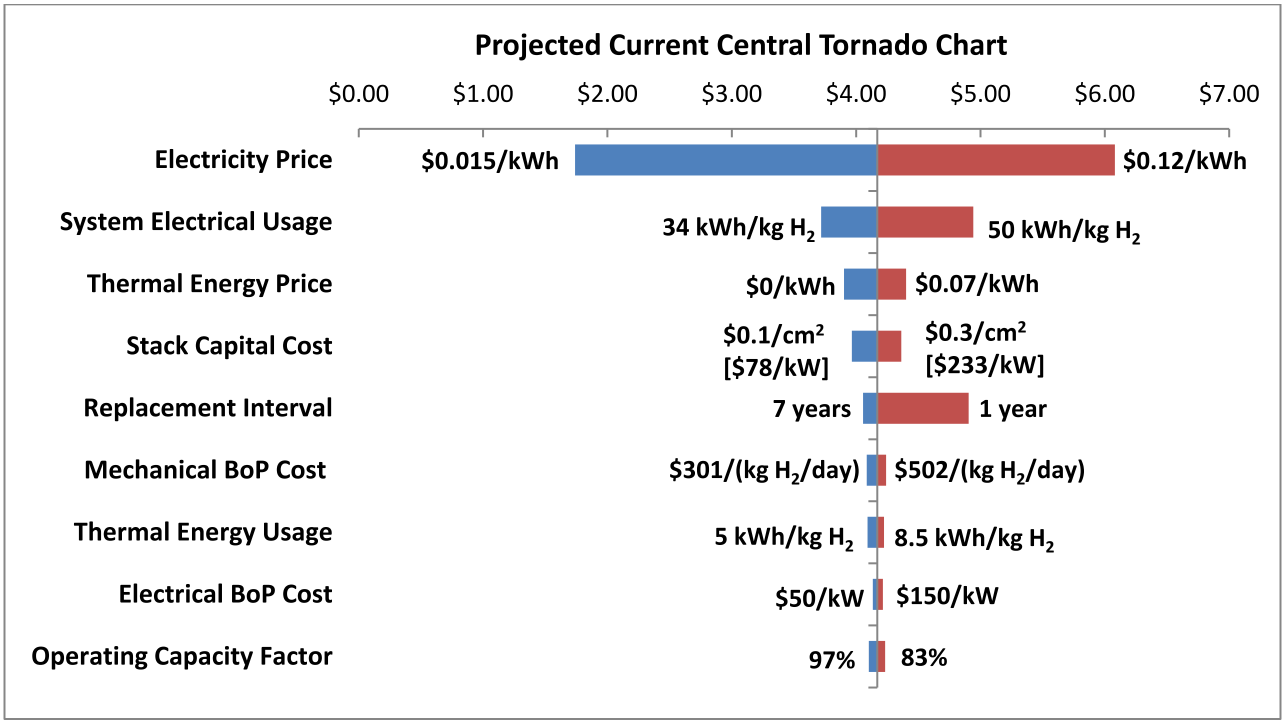

Figure 4 - Tornado chart showing parameter sensitivities for the Projected Current HTE case.

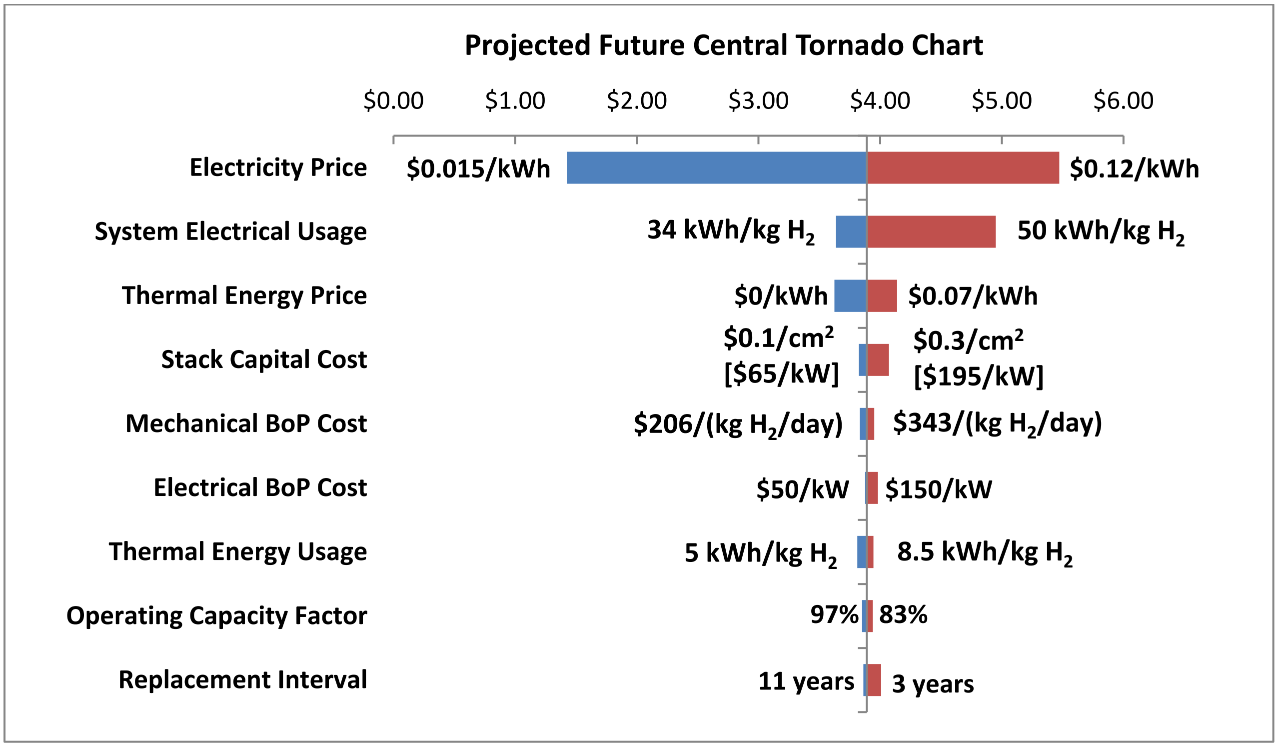

Figure 5 - Tornado chart showing parameter sensitivities for the Projected Future HTE case.

The tornado charts show that for the HTE process investigated, for both *Projected Current* and *Projected Future* cases, hydrogen production cost is primarily impacted by, and most sensitive to, changes in the price of electricity. This result is consistent with PEM electrolysis, where electricity price is also the main cost driver.[26] Other important input parameters influencing hydrogen cost include the electricity usage of the electrolyzer system (which is proportional to electrolyzer net system electrical efficiency) and the capital cost of the electrolyzer (including stack and BoP) 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.

Two-parameter sensitivity studies were conducted for both *Projected Current* and *Projected Future* cases and can be used to determine the cost of H_2 resulting from various combinations of two input parameters. The results of these studies are reflected in contour plots, presented in Figure 6 and Figure 7, with two contour plots provided for each case study. One set of input parameters is electricity price and thermal energy price and the other is electricity price and capital cost ($/kW). The contour plots provide a quick and efficient way to target H_2 price for a system with a given electrical price.

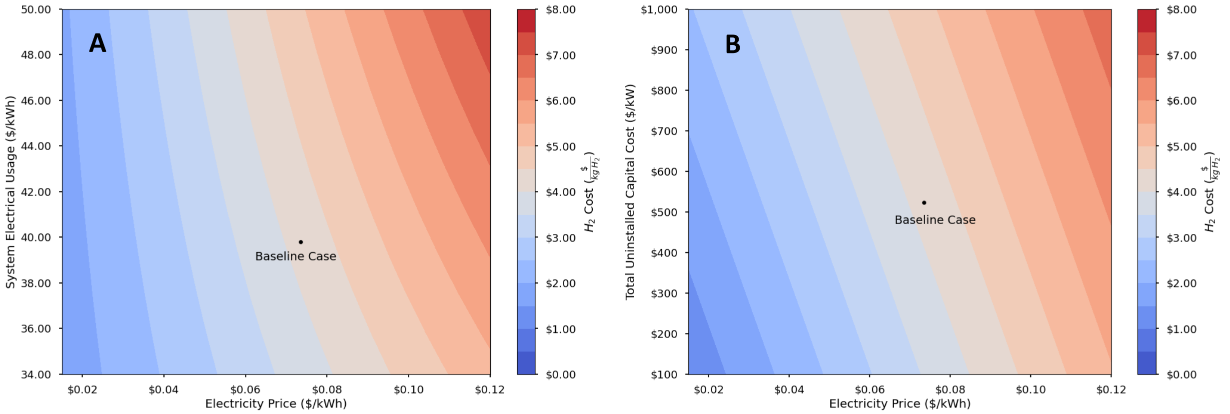

Figure 6 – Contour plots depicting results of the two-parameter sensitivity studies for the Projected Current case. The dependency of H_2 cost based on electricity price and System Electrical Usage is shown in (A). The dependency of H_2 cost based on electricity price and uninstalled capital cost ($/kW) is shown in (B).

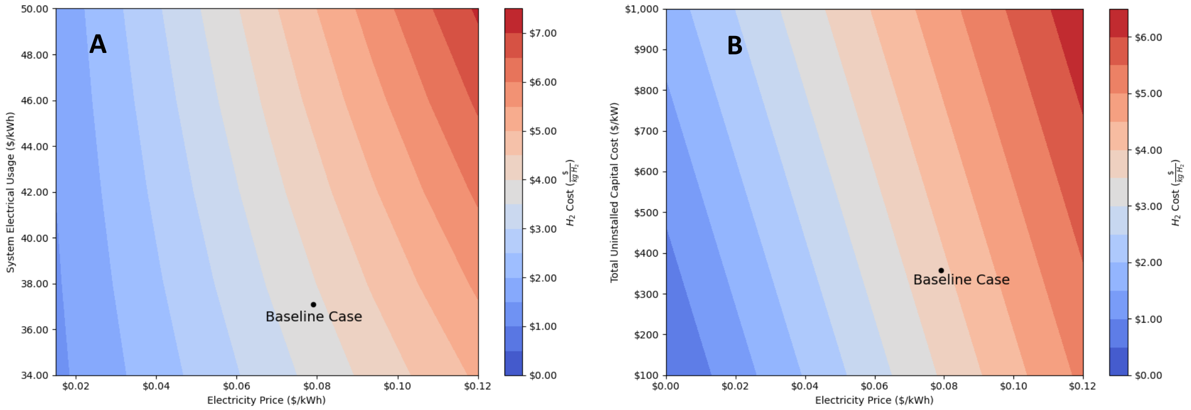

Figure 7 – Contour plots depicting results of the two-parameter sensitivity studies for the Projected Future case. The dependency of H_2 cost based on electricity price and System Electrical Usage is shown in (A). The dependency of H_2 cost based on electricity price and uninstalled capital cost ($/kW) is shown in (B).

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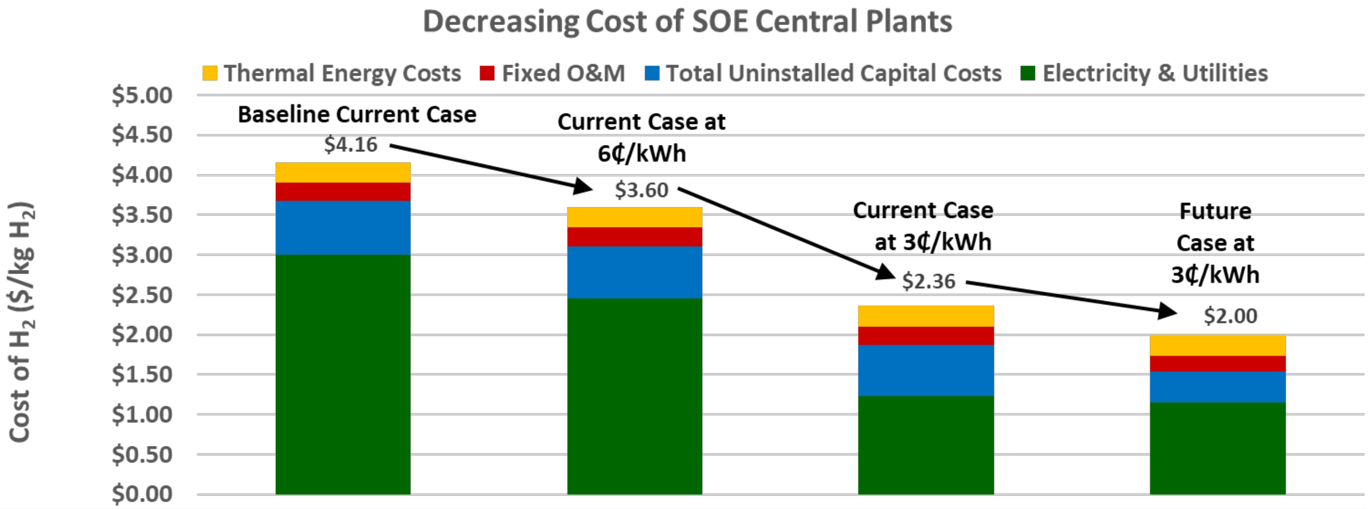
[26] Peterson, D., Vickers, J., and DeSantis, D., "Hydrogen Production Cost from PEM Electrolysis," 2019. https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf

Pathway to reduced H_2 cost

Further cost reductions are needed to achieve the DOE H_2 production target cost of \$2.00/kg H_2 and to be competitive with H_2 production from steam methane reforming. Figure 8 expands on the previous sensitivity studies and 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. Some renewable energy prices are currently averaging approximately \$0.06/kWh, with the potential to move to \$0.03/kWh as is being seen with some power purchase agreements (although generally at low capacity factors currently).[27] Consequently, Figure 8 graphs the hydrogen production price for sequentially reduced electricity costs and *Projected Current* case assumptions. The final step in the pathway to reduced H_2 cost applies the *Projected Future* case assumptions for capital cost, stack lifetime, and improved stack efficiency. The resulting H_2 cost for these combined changes is about \$2.00/kg H_2.



Capacity Factor	90%	90%	90%	90%
Total Electrical Efficiency [%LHV]	83.7%	83.7%	83.7%	89.8%
Total Uninstalled Capital Cost	\$522/kW	\$522/kW	\$522/kW	\$360/kW
Effective Electricity Price	\$0.074/kWh	\$0.060/kWh	\$0.030/kWh	\$0.030/kWh
Degradation Rate	11 mV/khrs	11 mV/khrs	11 mV/khrs	4 mV/khrs
Stack Lifetime	4 years	4 years	4 years	7 years

Figure 8 - Waterfall chart describing a pathway towards low-cost H2 production via high temperature electrolysis.

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[27] Wiser, R. *et al. 2018 Wind Technologies Market Report*. 103 (2018).

Supplemental Information

There are numerous differences between the previous 2016 H2A HTE case studies (Record 16014) and this update resulting from both input parameter changes and revisions to the H2A model. Table 5 provides a summary comparison of these differences. The change in reference year from 2007$ to 2016$ alone increases the hydrogen production cost by approximately $0.50/kg H_2.

Table 5 – Supplemental Information: Key differences between 2016 and 2019 H2A Case Studies for H_2 production via HTE.

Parameter	Units	*Projected Current*		*Projected Future*	
Production Scale		Central		Central	
Case Publication Year		2016 Case Study	2019 Case Study	2016 Case Study	2019 Case Study
H_2 Production Cost	$/kg H_2	$4.95	$4.16	$3.83	$3.89
H2A Version[28]	-	H2A v3.101	H2A v3.2018	H2A v3.101	H2A v3.2018
Assumed plant startup year	-	2010	2015	2020	2040
Current Density	A/cm^2	1	1	1.5	1.2
Cell Voltage	V	1.28	1.285	1.28	1.285
Total Uninstalled Capital Cost[29]	2016$	$820	$522	$448	$326
H_2 Outlet Pressure	psi	300	300	1,000	300
Stack Degradation	mV/khrs	11	11	3.15	4
Effective Electricity Price	2016₵/kWh	7.22	7.35	7.98	7.91
System Electrical Efficiency	kWh/kg H_2	36.8	39.8	35.1	37.1

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[28] The change from H2A v3.101 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%.

[29] All 2016 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.