DOE Hydrogen and Fuel Cells Program Record	
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Title: Hydrogen Production Cost from Fermentation	
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Item

The projected cost to produce hydrogen (H_2) from dark fermentation of biomass (corn stover) using techniques and strains currently in development at the laboratory scale is greater than $50/kg[1] (untaxed, high system production rates). However, it is expected to drop dramatically in the future to $5.65/kg by 2025, if assumed improvements in the technology and high volumes are realized. Two cases were considered, a *projected Current* year case based on 2015 technology using performance and design parameters that have been simultaneously demonstrated in the lab at low reactor volumes, and a *projected Future* case based on projected technological advancements by 2025. The cost analysis was performed using the Hydrogen Analysis version 3.101 (H2A Production v3.101) model and its associated assumptions[2] for a centralized production facility with a production capacity of 50,000 kg H_2/day.[3] The analysis utilizes a system design based on lab-demonstrated hydrogen production procedures[4] and using capital costs derived from a 2013 NREL report[5] on the production of hydrocarbons from lignocellulosic compounds.

Summary

The modeled costs (untaxed, delivery and dispensing not included) to produce hydrogen are summarized in **Table 1** for the two cases studied. The baseline costs are the projected costs to produce hydrogen for the *projected Current* and *projected Future* cases. The low and high values are included to reflect a range of uncertainty (±25%) in installed capital costs (with all other techno-economic inputs the same as in the baseline cases).

Table 1: High-volume cost projections for hydrogen production from a centralized facility with 50,000 kg H_2 /day production capacity using 2014 (*projected Current*) and 2025 (*projected Future*) technologies.[1]

Case Study	**Optimistic Value** (2007$/kg H_2)	**Baseline** (2007$/kg H_2)	**Conservative Value** (2007$/kg H_2)
Current Case (2015)	$59.76	**$67.71**	$75.67
Current Case (2015) with byproduct credit	$40.88	**$51.02**	$61.16
Future Case (2025)	$7.68	**$8.56**	$9.43
Future Case[6](2025) with byproduct credit	$3.40	**$5.65**	$7.91

Analytical Basis

Analyses of the cost to produce hydrogen at a central production facility with a plant capacity of 50,000 kg H_2/day were performed using the H2A Production v3.1 model. Two technology years were considered,[7] *projected Current*[8] (2015) and *projected Future* (2025).[9] The forecourt production capacity H2A model was not considered in this analysis.

There are no commercial dark fermentation hydrogen production facilities on which to base the system designs. Consequently, relevant techno-economic analysis inputs were derived for a hypothesized system. The process design for this projected hydrogen fermentation plant draws from two main sources: a hydrogen production fermentation plant previously conceptualized in 2009,[10] and a design and cost report for the production of lignocellulosic ethanol.[5] A 2013 National Renewable Energy Laboratory (NREL) report was supported and supplemented by data from previous versions of the report.[11,12] Data from these reports were adjusted to reflect recent technological progress and thinking (See **Figure 1**) and to adapt for hydrogen production. The alterations primarily consist of elimination of the distillation columns and scaling of the waste water system. The distillation columns are not required in the hypothesized system design as the system is not producing and purifying ethanol. The waste water treatment was scaled according to the size of the system and the content of the organic components in the waste stream. These organic compounds were modeled as being converted to biogas in the waste water treatment center. Consistent with the 2009 analysis and the laboratory data, hydrolysis pretreatment of cellulose and hemicellulose have been combined into one reactor, with combined saccharification and fermentation assumed to occur in a subsequent single reactor. In accordance with the 2009 analysis, *Clostridium thermocellum* converts cellulose to hydrogen and other byproducts in the *projected Current* case analysis. *Clostridium thermocellum* can also be combined with other microbes to create a microbial consortium that is capable of converting both cellulose and hemicellulose derivatives to hydrogen. This microbe consortium is modeled for the *projected Future* case as a technological improvement that will increase corn stover to hydrogen yield. Reaction parameters such as reaction rates, compound concentration, and product yields were provided by NREL.[13] Capital equipment design, cost, and performance data were gathered from the literature,[5] modified as appropriate to meet the hydrogen fermentation plant needs, and used to populate a set of baseline cases. Inputs to the H2A model fell into five primary categories:

1. Engineering system definition,
2. Capital costs,
3. Operating costs,
4. Variable and fixed expenses, and
5. Replacement costs.

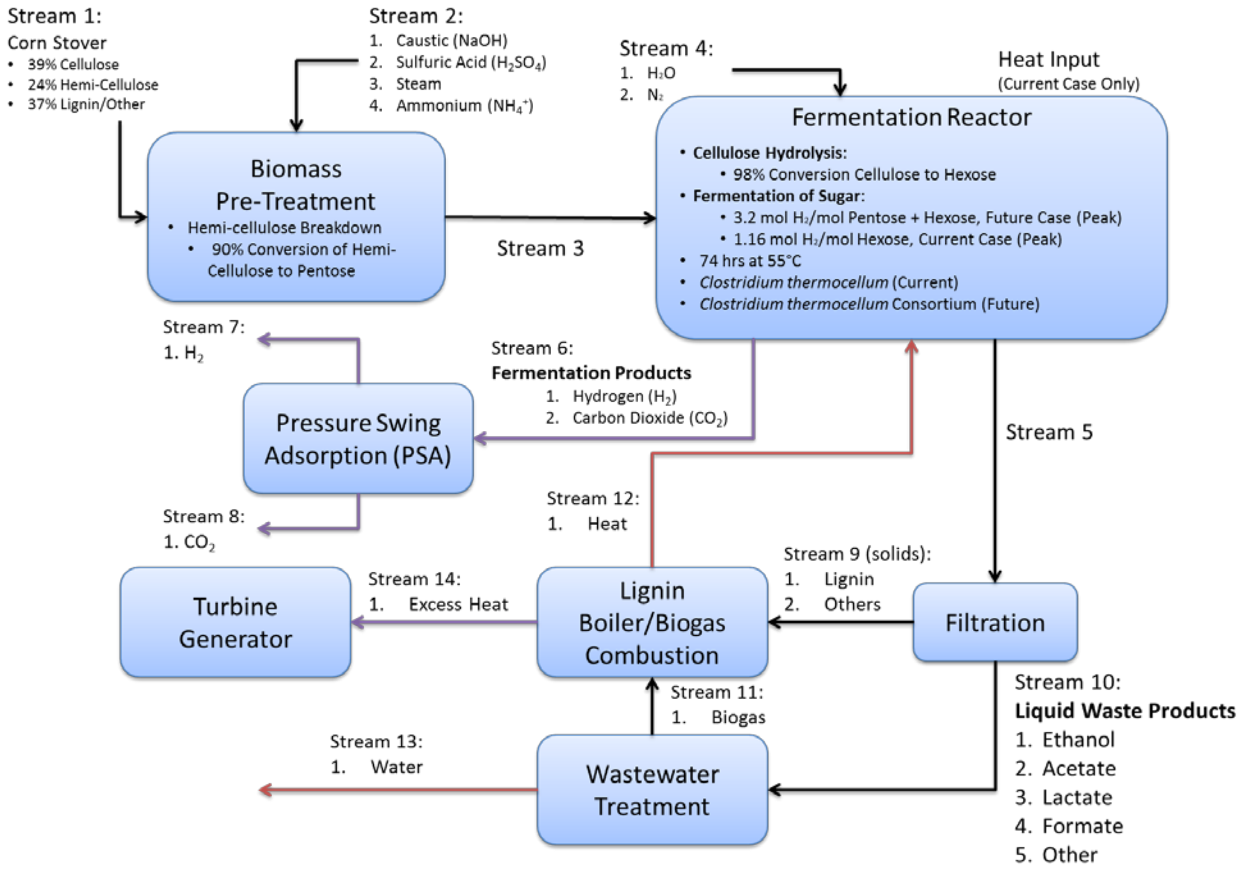

Figure 1: Process flow diagram used as the model system to project the cost to produce hydrogen via fermentation at a central production facility with a 50,000 kg/day capacity.

For each technology year considered, a model was created to determine the capital cost based on production volume, molar conversion of sugars to hydrogen, heat and energy requirements, and energy byproducts. Both *projected Current* and *projected Future* cases envision a hydrogen fermentation plant (**Figure 1**) in which feed material (modeled as corn stover, with cost of preparation for processing included) is delivered to the plant. Feedstock is first broken down via the pretreatment process.[14] The partially converted feedstock is then sent to a fermentation reactor in which two main reactions occur: (1) cellulose is hydrolyzed to hexose sugars, and (2) sugars are fermented into hydrogen and other products. For the *projected Current* case, *C. thermocellum* resides within the fermentation reactor and ferments only hexose sugars. For the *projected Future* case, a consortium of microbes, based on *C. thermocellum*, resides in the fermentation reactor and ferments both hexose and pentose sugars. The fermentation reactors are modeled as operating at 55°C for a given batch time. The fermentation batch time was determined through a cost optimization study, by plotting projected hydrogen cost as a function of fermentation time (see **Figure 2**). Maximum fermentation time was limited to 74 hours, as NREL data showed maximum conversion at that limit. The optimization curves, based on 2015 lab results, suggest the minimum cost of hydrogen corresponds to a fermentation time of 74 hours for both the *projected Current* and *projected Future* cases.[15]

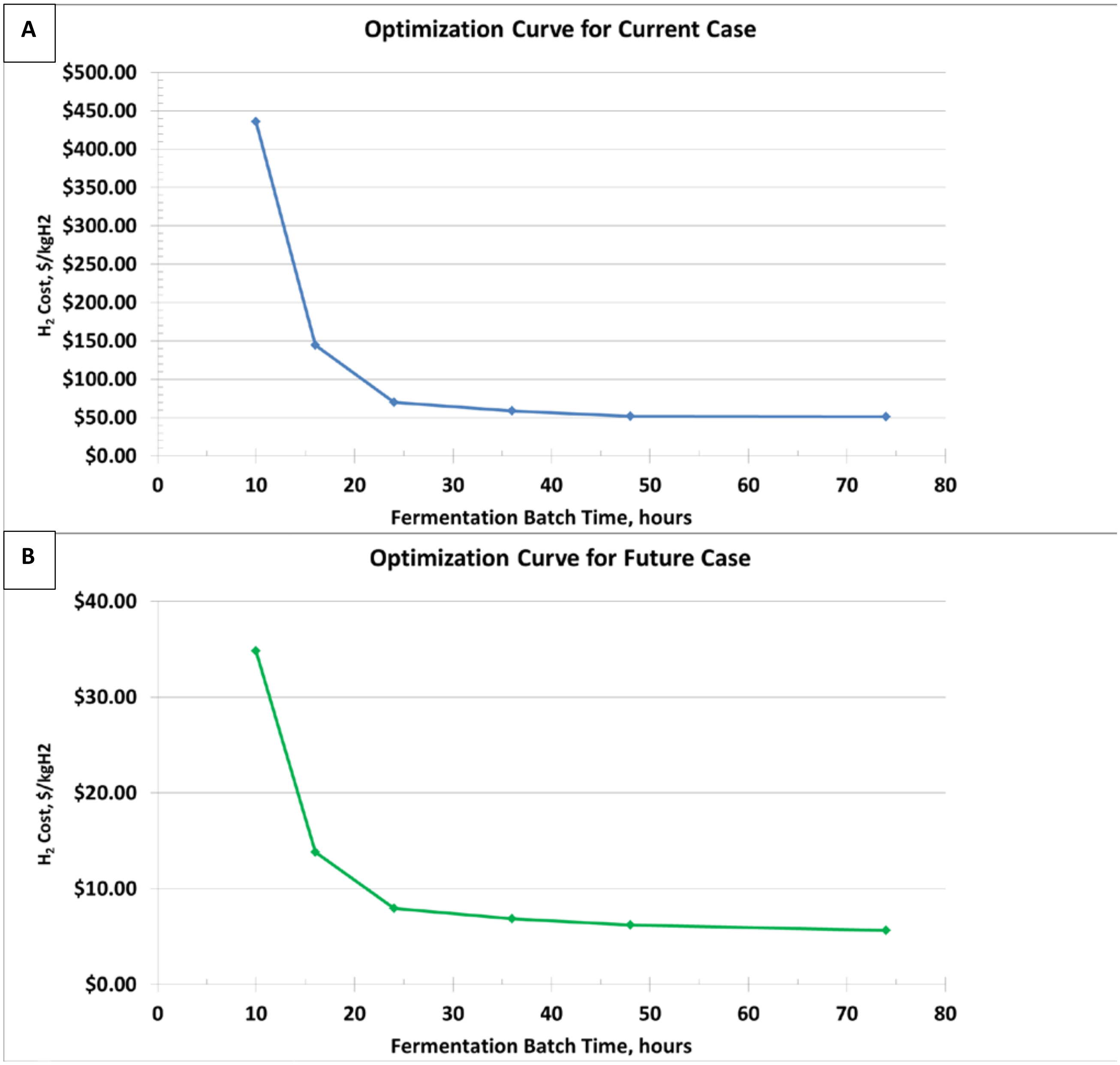

Figure 2: Optimization Curves for Fermentation Cases A) *projected Current* case and B) *projected Future* case based on the modeled corn stover loadings and other variables.

The H_2 and CO_2 gaseous products are vented from the fermentation reactor and separated from one another via Pressure Swing Adsorption (PSA). After fermentation, the broth is filtered, with the solids fraction (mostly lignin) used for energy recovery, and the liquid fraction (a dilute mixture of ethanol, acetate, and other organic acids) sent to waste water treatment. The waste water treatment plant is based on anaerobic digestion to create a byproduct gas of mostly methane. The byproduct gases, as well as the lignin, are combusted to generate thermal energy to heat the system.[16] The excess thermal energy is converted to electricity in a gas turbine electrical generator and sold to the grid for byproduct credit equivalent to $11.93 and $8.19 per kg of hydrogen produced for the *projected Current* and *projected Future* cases, respectively.[17] In the cases without byproduct credit, the hydrogen cost is higher since there is no revenue collected from electricity sales, but the cost increase is partially offset by a reduction in system capital cost as there is no need for the gas turbine. Fuel cell conversion of the byproduct gases into electricity was considered but ultimately rejected due to a desire to focus the cases on fermentation technology and to leave them unencumbered by uncertainty of fuel cell capital cost projections.

Key differences between the *projected Current* and *projected Future* case are:

1) A change in fermentation broth concentration[18] from 12.8 g/L (*projected Current*) to 175 g/L (*projected Future*).[19,20]
2) A change from *C. thermocellum* (capable of converting only hexose sugars) in the *projected Current* case to a microbial consortium (capable of converting both hexose and pentose sugars) in the *projected Future* case.
3) An increase in peak molar conversion of sugars to H_2 from 1.16 mol H_2/mol sugar (*projected Current*) to 3.2 mol H_2/mol sugar (*projected Future*). [21]

The yields were determined based on experimental data from NREL. NREL ran fermentation studies with acid hydrolysis pre-treated corn stover (PCS) and Avicel[22] feed stocks, creating fermentation broth with cellulose concentrations of 1 g, 2.5 g, and 5 g cellulose/L.[23] The peak molar yields ranged from approximately equivalent to 1.16 mol H_2/mol hexose to approximately 3.2 mol H_2/mol hexose, at 74 hours.[21] The selected operating points for lowest system cost are 1.16 mol H_2/mol hexose at 74 hours for a 12.8 gram corn stover/L[24] broth concentration for the *projected Current* case, and, for the projected *Future* Case, 3.2 mol H_2/mol sugar (pentose and hexose) at 74 hours for a 175 g corn stover/L broth concentration. The *projected Future* case model used the highest yield demonstrated by NREL. Note, however, that this yield occurred at the lowest fermentation broth concentration tested (1 g cellulose/L) while the *projected Future* case is based on achievement of this high molar yield at the *projected Future* broth concentration of 175 g/L. This is a substantial projected performance improvement, but one deemed reasonable and appropriate for the 2025 timeframe of the *projected Future* case.

Byproduct sales of the ethanol and acetate produced during fermentation were considered, but they were ultimately not included due to the unfavorable economics associated with concentrating and isolating the products to levels required for the marketplace.

Baseline Input Parameters

The parameters used in the two H2A v3.1 baseline case studies are summarized in **Table 2.** Parameter values are based on the hypothetical plant shown in **Figure 2** and conversations with industry researchers. They are supported by standard H2A v3.1 default values,[25] engineering judgment and calculations, and utility pricing information from the Annual Energy Outlook (AEO). [26]

While broth concentration is not an input parameter for H2A, it is included in **Table 2** because of the large impact it has on fermenter heating requirements and the overall system capital cost. The concentration of the broth directly adjusts the volume of the fermentation broth, which in turn adjusts the quantity of reactors required, total reactor capital cost, and the total heating requirements. In the *projected Current* case, 2.7 billion liters of broth per total batch (requiring 728 individual reactors) are required to produce 50,000 kg H_2/day while only 43.5 million liters of broth (12 reactors) are needed per batch in the *projected Future* case, due to the higher broth concentration and higher molar conversion. This directly affects the system capital cost and energy balance that are critical to hydrogen cost. Broth concentration contributes to an electrical energy surplus of 179kWh/kg H_2 and 116 kWh/kg H_2 in the *projected Current* and *projected Future* cases, respectively.

Table 2: Input parameters and other key parameters for H2A Production cases for fermentation of corn stover.

Parameter	*Projected Current* Central	*Projected Future* Central
Plant Capacity (kg/day)	50,000	50,000
Fermentation Broth Concentration[27] (g/L)	12.8	175
Broth volume per batch (L)	2.7 billion	43.5 million
Number of reactors required	728	12
Total Uninstalled Capital (2010$)	$1,773M	$386M
Total Feedstock Required (kg/kg H_2)	229.2	49.47
Hemi-Cellulose to Pentose Conversion (%) **(in pretreatment reactors)**	90	90
Pentose Conversion (%) **(in fermentation reactor)**	0	100
Cellulose to Hexose Conversion (%)[5,28] **(in fermentation reactor)**	98	98
Hexose Conversion (%) **(in fermentation)**	100	100
Molar Conversion (mol H_2/mol Sugar) **(in fermentation reactor)**	1.16 molH_2/mol Hexose 74h batch time	3.2 molH_2/mol (Pentose & Hexose) for 74h batch time
Energy Byproduct Recovery	Energy Excess	Energy Excess
Electrical Energy Purchased (kWh/kg H_2)	5.4	2.6
Electrical Energy Byproduct (kWh/kg H_2)[29,30]	179	116
Repair And Maintenance Costs **(% of capital cost/year)**	0.5	0.5

Baseline Cost Projection Results

The hydrogen production cost breakdown for the two H2A v3.1 fermentation cases is shown in **Table 3.** Large differences in capital cost are observed between the *projected Current* and *projected Future* cases and result primarily from the low concentration of the fermentation broth in the *projected Current* case, which leads to a large number of high volume reactors and supplemental equipment. Electrical energy costs required to run the fermentation plant appear on the “Variable O&M” line of the cost breakdown. The excess electrical energy generated in both cases can be sold back to the grid. The revenue generated by this byproduct appears on the “Byproduct Credits” line of the cost breakdown; the effective electricity byproduct selling price is 6.40¢/kWh and 6.60¢/kWh (levelized over the 40 year analysis period) for the *projected Current* and *projected Future* cases, respectively.

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

Component	*Projected Current* Central *50,000 kg/day*	*Projected Future* Central *50,000 kg/day*
Installed Capital Cost	$36.07	$7.86
Decommissioning	$0.05	$0.01
Fixed operations and maintenance (O&M)	$5.67	$1.49
Feedstock Costs[31]	$18.01	$3.82
Byproduct Credits	-$11.93	-$8.19
Variable O&M (including electrical utilities)	$3.15	$0.65
Total H_2 Production Cost (2007$/kg H_2) with byproduct credits	**$51.02**	**$5.65**[32]
Total H_2 Production Cost (2007$/kg H_2 without steam generator or energy byproduct[33]	**$67.71**	**$8.56**

Sensitivity Analysis

A single parameter sensitivity study was conducted for the *projected Future*[34] case (including the aforementioned energy byproduct). **Table 4** details the range of parameter values used within the H2A v3.1 sensitivity analysis for those parameters which were varied: all other parameters were fixed at their baseline case values. As stated in **Table 3**, the use of a byproduct credit offers an overall cost reduction of almost $3.00/kg H_2. This reduction identifies the use of the byproduct credit as one of the largest cost drivers. In fact, the byproduct credit is such a large cost driver, it becomes appropriate to examine the case without a byproduct credit so as to disentangle the cost impacts. Results from **Table 4** are graphically displayed in the **Figure 3** tornado chart, with projected hydrogen cost variations on the x-axis plotted against single input parameters along the y-axis. Specifically, the plots illustrate the H_2 production cost sensitivities to variations in:

1. Feedstock cost,
2. Total installed capital cost,
3. Broth concentration,
4. Electrical turbine generator efficiency, and
5. Reduced fermentation time due to an increased reaction rate.[35]

The tornado chart is organized from top to bottom to represent the most to least sensitive of the analyzed input parameters. The colored shading indicates either an increase (red) or a decrease (green) from the baseline hydrogen cost due to the change in input parameter value. The y-axis labels list the low, baseline, and high values for each input parameter.

Table 4: Sensitivity analysis results for the *projected Future* case (with byproduct credit). Results of H_2 production cost for parameters varied are reported in 2007$ below the adjusted parameter.

***Projected Future* Central**	**Units**	**Parameter Values for Lower Bound Cost**	**Baseline Parameter Value ($5.65/kg)**	**Parameter Values for Upper Bound Cost**
Installed Capital Cost	$ millions	470 ($3.39/kg H_2)	627	784 ($7.90/kg H_2)
Feedstock Cost	$/dry metric ton	56.53 ($4.67/kg H_2)	75.37	94.21 ($6.63/kg H_2)
Broth Concentration	g/L	300 ($5.42/kg$H_2$)	175	100 ($6.14/kg H_2)
Electrical Generator Efficiency	%	55 ($4.85/kg H_2)	50	45 ($6.52/kg H_2)
PSA Recovery	%	96 ($5.34 /kg H_2)	88	80 ($6.06/kg H_2)
Fermentation Time	hours	24 ($5.34/kg H_2)	74	74 ($5.65/kg H_2)

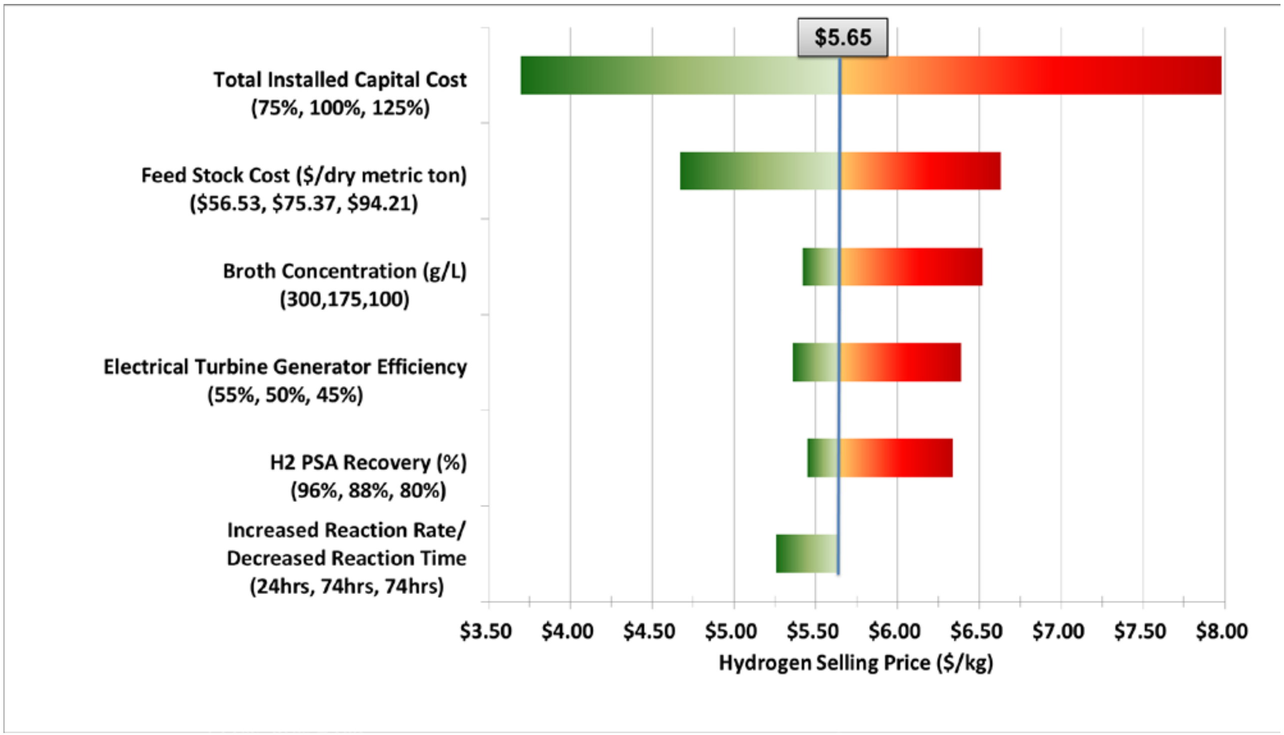

Figure 3: Tornado chart showing parameter sensitivities for the *projected Future* central fermentation case (with byproduct credit).

The tornado chart shows that the fermentation process investigated is highly dependent on the system capital cost which was varied +/-25% based on the perceived accuracy of the capital cost estimates. Hydrogen cost is also sensitive to changes in the price of the feedstock. Broth concentration appears to be only a modestly sensitive parameter but this result is only valid because the broth concentration parameter is limited to the lower bound of 100g/L. Were broth concentration evaluated at the *projected*

Current case value of 12.8g/L, it would be the dominant parameter in a sensitivity analysis due to its impact on the energy balance and capital equipment costs (see above for complete description.

Conclusions

Hydrogen produced via fermentation will require advances in technology to become a feasible production technology. The molar yield of the conversion of biomass to hydrogen will need to be improved, and the operating fermentation broth concentration will need to be substantially higher than currently demonstrated in the lab. Even with these advances, the cost of hydrogen is projected to be approximately $8.56/kg prior to consideration of any byproduct credits. Byproduct credits offer a significant opportunity to reduce the cost of hydrogen. However, the production of the byproducts (electrical or chemical) must not reduce hydrogen production as this would be counter to the primary goal of the H_2 plant. Further cost reduction to approximately $3/kg H_2 may be achievable by lowering equipment capital cost, further increasing the molar yield, increasing electrical byproduct generation, increasing PSA recovery, and raising the fermentation broth concentration above 175 g/L. Further research is needed to explore the potential, feasibility, and extent of these improvements.

Endnotes

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[1] 2007 dollars are used as the cost basis (i.e., reported as 2007$/kg H_2), consistent with H2A v3.1 methodology and assumptions.

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

[3] H2A Production v3.1 Dark Fermentation Cases are at http://www.hydrogen.energy.gov/h2a_prod_studies.html. See Table 2 for a summary of case input parameters.

[4] Personal communication with NREL researchers Pin-Ching Maness and Lauren Magnusson.

[5] Davis, R. *et al. Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons : Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons Process Design and Economics for the Conversion*. (2013). doi:10.2172/1107470

[6] Uses 6.89¢/kWh effective electricity price (levelized over 40 yr. life) as electricity byproduct selling price.

[7] 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.

[8] *Projected Current* Cases reflect demonstrated laboratory results.

[9] *Projected Future* Cases use molar conversions that will be feasible by 2025, with market entry assumed in 2030. It is possible that these molar yields will be available much sooner than 2025. The expected levels of improvement were vetted by industry input.

[10] B.D. James, G. N. Baum, J. Perez and K. N. Baum. *Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production*. (2009). http://energy.gov/eere/fuelcells/downloads/technoeconomic-boundary-analysis-biological-pathways-hydrogen-production.

[11] Aden, A. *et al.* Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. (2002). doi:NREL/TP-510-32438

[12] Wooley, Robert, Mark Ruth, John Sheehan, Kelly Ibsen, Henry Majdeski, and Adrian Galvez. *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis Current and Futuristic Scenarios*. (1999).

[13] Maness, P., Logan, B. 'Fermentation And Electrohydrogenic Approaches To Hydrogen Production'. Annual Merit Review (2015). Presentation. https://www.hydrogen.energy.gov/pdfs/review15/pd038_maness_2015_o.pdf

[14] Alternate processing steps are feasible. For instance, the lignin can be filtered prior to entering the fermentation reactor. This would reduce the size of the fermentation reactors and preclude lignin inhibition of the reaction. However, it would also possibly lower yield by introducing reactable feedstock losses as part of the lignin filtration process.

[15] Modeled assuming the rates of hydrogen production are proportionally increased to reach the specified final molar yield (1.16 for *projected Current*, 3.2 for *projected Future*) at the cost optimum time for batch fermentation. There exists the possibility to improve the fermentation rate and reduce the fermentation time in future systems. Such a scenario is demonstrated in the sensitivity analysis shown in **Table 4.**

[16] The lignin is still wet after filtration (modeled as 30 wt% water) and is dried prior to burning. The energy for drying is included in the system energy balance.

[17] Electricity byproduct selling price is set at 6.89¢/kWh average electricity price (levelized over 40 year life). Similar byproduct credit systems have been used in previous analyses completed by NREL.

[18] Broth concentration is defined as grams of feedstock (corn stover) per liter of slurry within the fermentation reactor.

[19] 175 g/L was chosen to align with BETO's target value of 17.5% loading in the fermentation reactor.
Davis, Ryan. 'DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review'. 2015. Presentation.
http://energy.gov/sites/prod/files/2015/04/f21/biochemical_conversion_davis_0315.pdf

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[20] The increased broth concentration poses several processing challenges. Handling of the broth may be difficult due to increased viscosity and may require extra capital equipment to transport the slurry. Additionally, the high broth concentration may inhibit the fermentation reaction or require the use of high levels of pre-treatment chemicals which could be costly or toxic if they are not neutralized before entering the fermentation reactor. Achieving the targeted yields with high broth concentration is a significant research challenge.

[21] Maness, P.C., Logan, B. Fermentation and Electrohydrogenic Approaches to Hydrogen Production. Annual Merit Review (2015). Presentation, Slide 6. https://www.hydrogen.energy.gov/pdfs/review15/pd038_maness_2015_o.pdf

[22] Avicel is a pure cellulose product commercially available and typically used in laboratory testing.

[23] For the purpose of calculations, biomass, Avicel, and other complex compounds were compared based on equivalent cellulose loadings.

[24] NREL studies were conducted with a loading based on cellulose content. In order to match the cellulosic loading used by NREL for the *projected Current* case, 12.8 g Corn Stover/L are envisioned for the fermentation loading (Corn Stover is assumed to have 39% cellulosic content. Thus, 12.8 g Corn Stover contains 5 g Cellulose).

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

[26] *Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2009 Report.*

[27] Broth concentration is not an actual input to the H2A model but is listed here because it is a defining parameter in determining capital cost and energy use.

[28] Varanasi, S., Rao, K., Relu, P. A. & Yuan, D. Methods for Fermentation of Xylose and Hexose Sugars. (2013).

[29] Electrical purchases and byproducts are reported separately for clarity but in practice only a net electrical transaction would occur.

[30] Energy purchase and byproduct are book-kept separately to ensure clarity of energy distribution. In reality, most facilities would likely use the generated energy onsite to run the plant equipment.

[31] 2009 AEO Projections for Corn Stover Feedstock.

[32] While the sum of the *projected Future* Case subcategory costs in **Table 3** is \$5.64/kg H_2, this is due to rounding of the subcategory costs and the actual H2A projected total cost is \$5.65/kg H_2

[33] Removal of the byproduct energy credit also considers removing the associated steam-turbine generator from the system, reducing the total capital cost. As such, the price adjustment is not a simple subtraction of the byproduct credit.

[34] A sensitivity analysis for the *projected Current* case was not conducted because any significant changes to the broth concentration dominated all other parameters to a degree that made the results of the sensitivity analysis immaterial

[35] The examined reduction of the fermentation time is a result of an increased reaction rate that produces the same amount of hydrogen as the baseline case. The only change to the system is the fermentation broth time and the resulting capital cost changes.