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Sensitivity Study of the Economics of Photoelectrochemical Hydrogen Production

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Introduction

A 1998 study of the economic viability of photoelectrochemical (PEC) hydrogen production was revised to include advanced sensitivity analysis algorithms. Using Decisioneering's Crystal Ball, a Microsoft Excel add-in, probability distributions for the major variables were incorporated into the analysis to determine the most likely cost of hydrogen and the uncertainty in that value. This type of detailed sensitivity study presents a clearer picture of the important research elements for success of this technology. Furthermore, the likelihood of research success and progress can be more accurately measured once an analysis of this nature is performed and used as the baseline for future studies.

Methodology

This type of detailed sensitivity study is often referred to as risk analysis or stochastic modeling. Using various sampling techniques, numerous combinations of variable values can be tested to assess the most likely result. This differs from parametric sensitivity analyses, where only one parameter is varied at a time to assess its affect on the final result. Parametric analyses serve to highlight the most important variables, but do not present best or worse cases that would result from several parameters varying from the base case values. Additionally, the contribution to the uncertainty in the analysis cannot be determined. With parametric analysis, there's no opportunity for studying the likelihood that the final answer obtained in the base case will occur given uncertainty in the different inputs. In the context of a hydrogen research project, this type of economic analysis answers questions like: What is the probability that the cost of hydrogen will be less than a given amount? Which parameters contribute the most uncertainty to the final value? What are the likely best and worst cases that we could expect? What is the effect of research goals on the final hydrogen price?

To answer these questions, a risk analysis was performed using Crystal Ball, a software package offered by Decisioneering, Inc. Probability distributions, determined from research projections and historical data, were entered for most of the variables in the cost analysis. These distributions are given in Appendix A. The most common distribution used was the normal distribution with a 10% standard deviation. Distributions for variables for which there were more data or historical engineering practices available were constructed manually using the tools available in Crystal Ball. Notes regarding how some of these distributions were determined are given below. The order of distributions given by Crystal Ball (Appendix A) varies each time a report is generated; therefore, they are not in the same order as that given here.

> *Variable: average solar insolation*
> A suitable site for PEC hydrogen production would be close to the hydrogen load, spacious, warm, and of course, sunny. To determine the sensitivity of hydrogen selling price to the amount of sunlight that is received, a distribution curve was constructed based on solar insolation in various places in the Southwestern United States. The map on the following page shows annual average daily solar radiation for the U.S. The accompanying NREL data for each measurement site in the yellow and light-green areas of California, Nevada, New

Mexico, and Texas were obtained. The maximum and minimum values of the triangular distribution curve entered into Crystal Ball were set as the second highest and second lowest values in the data set. The mean value (5.80 $kWh/m^2/day$) was used as the most likely, and was only slightly higher than that used in the 1998 base case analysis (5.74 $kWh/m^2/day$). A normal distribution was not used for this parameter since the data set is not representative of a statistical sampling of sites within the geographic area of interest. Solar radiation data for a one-axis tracking, concentrating collector with North-South axis, tilted at an angle equal to the latitude was used for each site.

Variable: capacity factor
The base case PEC economic analysis assumes that the average capacity factor is 95%. A higher-than-usual value is appropriate because maintenance can take place when the sun is not shining. Furthermore, the solar insolation data already takes into account down-time. For the risk assessment, the mean was set at 100%, with a standard deviation of 10%. The minimum and maximum values were limited to 0% and 110%. A capacity factor greater than 110% is possible in the event of higher solar insolation, over-design, and slightly higher cell efficiencies.

Variable: contingency
Because this was a detailed study, the project contingency was set in a triangular distribution at 10% to 25%, with 15% being the most likely. The long-term nature of this research makes it unlikely that the contingency factor for this analysis will be lower than this.

Variable: electrolyte membrane cost
Data on this parameter are limited and based on future projections of PEM fuel cell membrane costs. The base case uses a value of $\$50/m^2$, but because of the higher uncertainty, a 20% standard deviation was assumed. The maximum was limited to 30% greater than the base case. Final results showed that the membrane did not contribute greatly to the overall uncertainty in the analysis, so further data were not pursued.

Variable: housing unit cost
Crystal Ball constructed a probability distribution based on data obtained from the literature and plastics manufacturers for the 1998 study. Unfortunately, the sample size was small, so the accuracy of this approach is limited. However, the range was sufficiently broad to take into account the possibility of all of the quotes we received.

Variable: linear concentrator assembly cost
Because the cost of the linear concentrator assembly for PV systems was obtained from a vendor, the error in this parameter was assumed to be small, and the distribution normal. Only a portion (20-30%) of the cost shown with the probability distribution would be incurred in the PEC system since some of the cost is relevant only to PV systems. This reduction is taken into account in the main body of the analysis spreadsheet.

Variable: number of laborers required
Because the PEC system will not require constant maintenance or attention, it is feasible to assume that workers will visit the site on a regular basis but will not be required to be on staff full-time. Additionally, because the PEC system operates only when the sun is shining, workers will not need to be present during the night. For this variable, it was assumed that the most likely staffing requirement was one-quarter of a man-year, with the minimum and maximum required set at 10% and 50%, respectively.

Variable: photocatalyst cost
Information from Dr. John Thornton at NREL's National Center for Photovoltaics predicts that future photocatalyst cost will be in the range of \$0.50 to \$1.00 per watt at 1000 W/m^2. This is for a-silicon cells without the interconnects and wiring required for PV systems. Dr. Thornton felt that a good base case assumption would be \$0.75/W. A normal distribution was constructed, with a mean of \$0.75/W and a 20% standard deviation to account for the larger uncertainty. The minimum was set at \$0.50/W, with the maximum allowed to go to infinity.

Variable: system efficiency
System efficiency, calculated on a lower-heating-value basis, was determined from discussions with Dr. John Turner of NREL. The cell assumed in this analysis is a-silicon, which in a PEC setting has a theoretical efficiency limit of 24%. Dr. Turner believes that the system efficiency could be as high as 17%, with 14% most likely in the mid- to long-term. A minimum value of 10% was entered, based on current cell performances.

Crystal Ball offers two sampling methods for determining which combinations of parameter values to test in each iteration. The first is Monte Carlo sampling, which randomly selects values. This is a brute-force approach, and depends on running a large number of cases to obtain a smooth results curve. The second sampling method, Latin hypercube, is more precise than Monte Carlo. This technique divides an assumption's probability distribution into intervals of equal probability, where the number of intervals corresponds to a specified minimum sample size. This allows the entire range of the distribution to be sampled in a more even, consistent manner than with Monte Carlo sampling. The increased precision comes at the expense of more computing requirements, although with today's advanced PCs, tens of thousands of runs take only a few minutes.

The desired output is the hydrogen selling price for a specified after-tax internal rate of return (IRR). Because a manually-constructed Excel macro was used to calculate this value after each iteration of the analysis, the IRR could not be varied in the simulation. Rather, four analyses were made to study the expected hydrogen selling price versus IRR. The base case analysis assumes that the return required by the investor would be 15%, based on conversations with industrial contacts, literature data, and conventional chemical engineering practice. Cases were also tested at 20% (since this is a new and unproven technology), 10%, and 0%. The 0% case represents the *pre-tax* break-even point for this project.

Rather than setting the number of trials to a large number and hoping that a smooth results curve is obtained at the end of the run, the base case 15% IRR analysis was set to continue until the mean standard error reached 0.08. This measure is the estimate of the deviation of the calculated mean to the true mean. Approximately 5,000 trials were required for this to occur. In watching the frequency charts as the analysis proceeds, it's clear that the simulation changes little well before this mean standard error is reached. The other cases, particularly the 0% pre-tax IRR case, reach this point very quickly, and changes were still occurring in the statistical results; these cases were then run at least 5,000 times.

Results

Table 1 shows the major results for the cases tested, with results in terms of $/kg of hydrogen sold. Table 2 shows the same results for $/GJ of hydrogen on a higher heating value basis. Appendix 2 contains the Crystal Ball reports for each run. Included in these reports are the results curves, the sensitivity curves, and percentile rankings.

Table 1: Risk Analysis Results in terms of $/kg Hydrogen

Case	Base case 15% IRR	20% IRR	10% IRR	0% IRR (pre-tax)
Trials	5000	9450	5000	5000
Mean ($/kg)	4.98	6.74	3.45	1.16
Median ($/kg)	4.90	6.64	3.41	1.15
Mode ($/kg)	4.43	5.97	3.59	1.16
Standard Deviation ($/kg)	0.72	0.99	0.49	0.14
Variance	0.52	0.99	0.24	0.02
Skewness	0.64	0.62	0.64	0.52
Kurtosis	3.84	3.81	3.84	3.38
Coeff. of Variability	0.14	0.15	0.14	0.12
Range Minimum ($/kg)	3.11	4.17	2.19	0.78
Range Maximum ($/kg)	9.27	12.65	6.33	1.81
Range Width ($/kg)	6.16	8.48	4.14	1.03
Mean Std. Error	0.01	0.01	0.01	0.00

Table 2: Risk Analysis Results in Terms of $/GJ (HHV) of Hydrogen

Case	Base case 15% IRR	20% IRR	10% IRR	0% IRR (pre-tax)
Trials	5000	9450	5000	5000
Mean ($/GJ)	36.95	50.01	25.64	8.62
Median ($/GJ)	36.41	49.30	25.30	8.53
Mode ($/GJ)	32.86	44.34	26.62	8.62
Standard Deviation ($/GJ)	5.35	7.37	3.61	1.05
Variance	28.65	54.32	13.03	1.10
Skewness	0.64	0.62	0.64	0.52
Kurtosis	3.84	3.81	3.84	3.38
Coeff. of Variability	0.14	0.15	0.14	0.12
Range Minimum ($/GJ)	23.09	30.99	16.28	5.83
Range Maximum ($/GJ)	68.80	93.91	47.01	13.46
Range Width ($/GJ)	45.71	62.92	30.73	7.63
Mean Std. Error	0.08	0.08	0.05	0.02

The statistical parameters shown in these tables, as well as the shape of the curves shown in Appendix B, serve to describe the variability in this analyses. The standard deviation, or distribution of values around the mean, was about 15% of the mean. This indicates a fair amount of uncertainty. The kurtosis, or shape of the curve, was 3.84. This is slightly higher than what would be expected of a normal distribution, meaning that the curve is more narrow than the standard. It's important to note that the accuracy of this risk analysis is only as good as the assumptions used to construct the probability distributions. Efforts were made to choose conservative assumptions, but results will be affected by distributions that were made too narrow.

The sensitivity curves shown in Appendix 2 demonstrate which parameters contribute most to the uncertainty in this analysis. As expected, system efficiency, which has the largest impact on hydrogen selling price is the most important variable, at 30% contribution to variance. Capacity factor holds second place, and demonstrates that the reliability of the system to operate when the sun is shining is crucial to success. Siting the PEC units where there is good solar insolation is important, as demonstrated by its 17.5% contribution to variance. The housing unit, while ranked as fourth, still contributes a very significant 12.4% to the uncertainty of this analysis. Contingency and photocatalyst cost each account for less than 5% of the uncertainty. The support structure, or linear concentrator assembly, is responsible for less than 2%. Other variables accounted for less than 1% each, and 1.3% combined.

Inside of Excel, the frequency curves can be used to determine the probability that the final result will fall below a certain value. Using this tool, it is possible to say that there is an 80% certainty that the hydrogen will cost less than $41.3/GJ with a 15% after-tax IRR. For 95% confidence, the hydrogen will cost less than $46.4/GJ.

Conclusions and Implications

Risk analysis has been demonstrated to be a useful tool for identifying the key contributors to uncertainty in a technoeconomic analysis of a long-term research project. The major research objectives according to this analysis should focus on improving PEC cell efficiency. During engineering design and scale-up, attention should be directed toward improving the reliability of the system so that the capacity factor is high, designing a low-cost housing unit, and siting the system in locations where there is good solar insolation. The final hydrogen selling price according to this analysis contains a fair amount of uncertainty, which should be taken into account in the determination of the feasibility of this system.

Future Work

As research continues, the assumptions entered into the probability distributions should be updated, and the risk analysis re-calculated. Additionally, progress in research efforts can be measured as a reduction in the uncertainty in this analysis.

Appendix A
Variable Probability Distributions

Appendix B
Crystal Ball Reports