NREL
NATIONAL RENEWABLE ENERGY LABORATORY

U.S. Geographic Analysis of the Cost of Hydrogen from Electrolysis

G. Saur and C. Ainscough

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-52640
December 2011

Contract No. DE-AC36-08GO28308

U.S. Geographic Analysis of the Cost of Hydrogen from Electrolysis

G. Saur and C. Ainscough

Prepared under Task No. H271.3710

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5600-52640
December 2011

Contract No. DE-AC36-08GO28308

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information

P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

1 Introduction

Wind-based water electrolysis represents a viable path to renewably-produced hydrogen production. It might be used for hydrogen-based transportation fuels, energy storage to augment electricity grid services, or as a supplement for other industrial hydrogen uses. This analysis focuses on the levelized production[1] *costs* of producing green hydrogen, rather than market *prices* which would require more extensive knowledge of an hourly or daily hydrogen market. However, the costs of hydrogen presented here do include a small profit from an internal rate of return on the system.

This analysis builds upon a previous study [1] which focused only on California, by expanding to a variety of sites and electricity markets across the country. The analysis deploys new tools such as an interactive web-based viewer to interpret the results. The previous paper focused only on sites in California and on one electricity market, California Independent System Operator (ISO). The new analysis is expanded to include:

- Midwest ISO,
- ISO New England,
- the Electric Reliability Council of Texas (ERCOT) and
- Pennsylvania, Jersey, Maryland (PJM) ISO.

In order to understand some of the regional variances of the cost of hydrogen produced by wind-based water electrolysis, five different grid pricing structures and 42 different wind sites were examined. Average yearly grid prices ranged from $0.034/kWh to $0.056/kWh and wind sites ranged from wind classes 3–(light wind)-6 (heavy wind) in each of the regional areas selected. Scenarios developed in a previous study [1] optimized the size of a wind farm to the size of the electrolyzer needed to produce a nominal 50,000 kg/day hydrogen. However, the results are scalable from about 1,000 kg/day to 50,000 kg/day as the capital costs of the electrolyzers are roughly linear in this range. The wind farm size would be scaled in proportion to the electrolyzer size.

The renewably-produced hydrogen was generated completely by wind electricity on either a cost or quantity basis. The base hydrogen costs ranged from $3.74kg to $5.86/kg. The base results show no wind sites that meet the centralized or distributed U.S. Department of Energy 2015 targets of $3.10/kg and $3.70/kg, respectively[2]; however, when considering the effects of the Production Tax Credit (PTC) and Investment Tax Credits (ITC) (reduction of $0.02/kWh), almost half the sites analyzed meet the distributed target and a few of the sites can meet the central target, see Figure 1. This small credit drops the cost of hydrogen by more than $1/kg, a significant reduction. Additional sensitivity to the wind turbine capital costs shows hydrogen cost reductions could be an additional $0.50/kg with only 20% decrease in wind farm capital cost. This puts some the wind-based hydrogen production within DOE targets.

[1] This analysis does not include costs for compression, storage or dispensing of hydrogen.
[2] 2015 U.S. DOE target is $3.10/kg for central hydrogen plants and $3.70/kg distributed plants in 2007$.

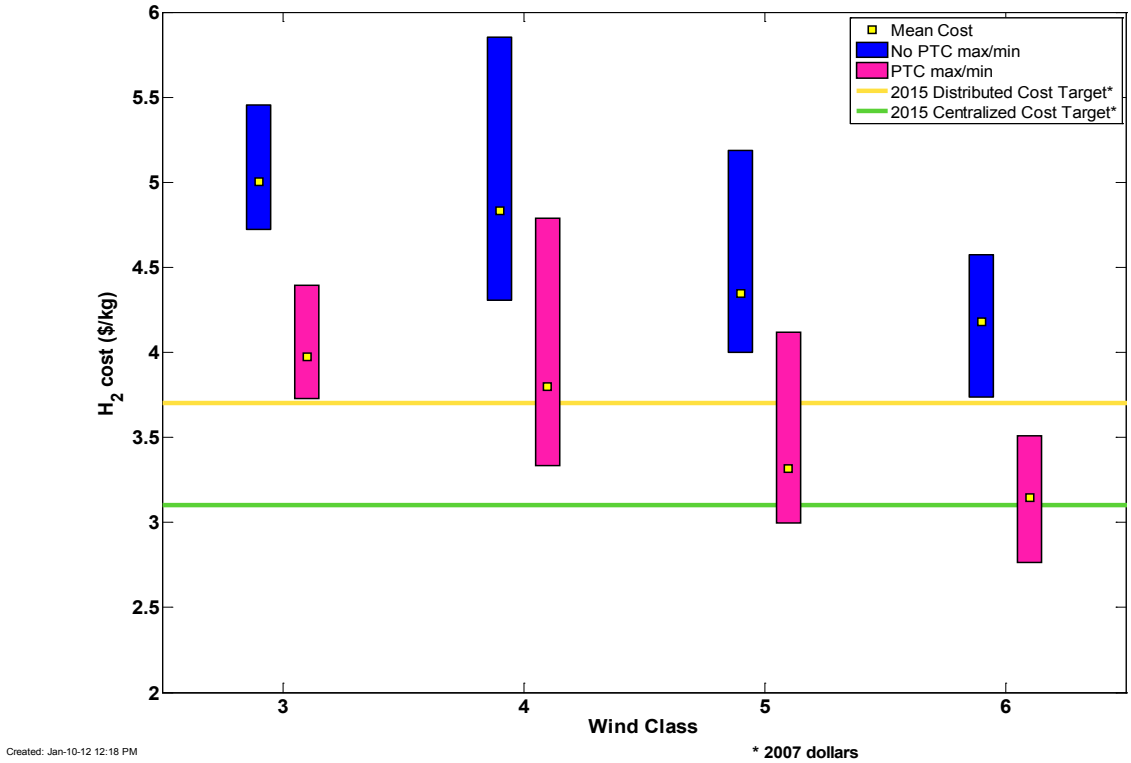

Figure 1. Range of Hydrogen Costs by Wind Class with and without the PTC/ITC and Treasury Grant

In order to allow better exploration of the results of this analysis, a new interactive map tool has been developed using the Google® Maps API v3. The tool lets users explore the entire set of results from this analysis interactively. It displays the results of each of the four scenarios, along with the site, amount of wind available (wind class), degree of capacity utilization (i.e., capacity factor), and cost of wind-generated electricity ($/kWh). This interactive tool is posted to NREL's Wind to hydrogen website. (http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html).

The interactive tool allows users to explore the data in a variety of ways by giving them full control over the map interface for zooming and panning, and allowing them to select specific sites from the list of sites analyzed. In addition, the tool also allows users to see the impact of a $0.02/kWh PTC/ITC, by turning that sensitivity on and off. Example outputs from the tool are shown in Figure 2 and Figure 3, below.

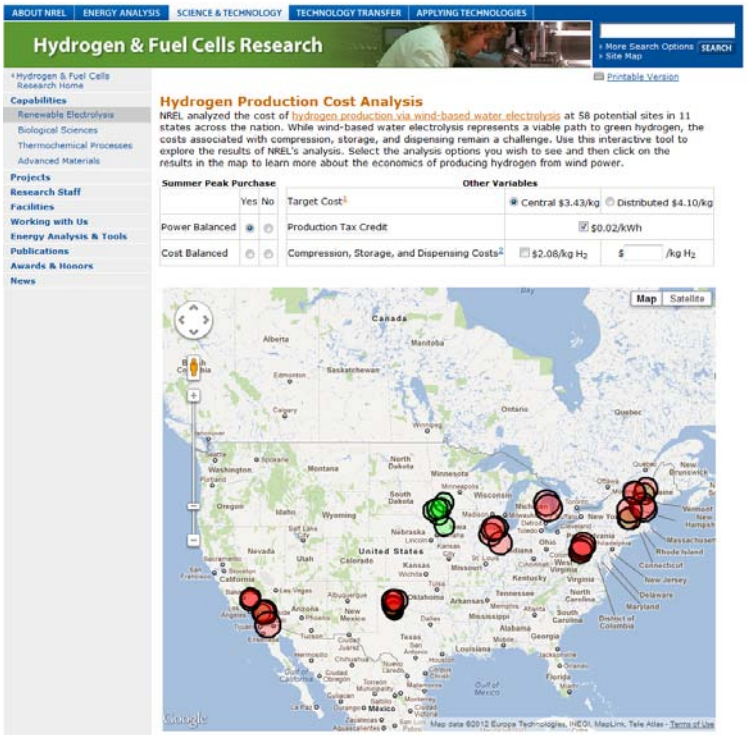

Figure 2 - Opening screen of the interactive tool, showing the entire set of analysis results, with the PTC effect turned on. Green sites meet DOE's 2015 target for centralized electrolysis ($3.10/kg)

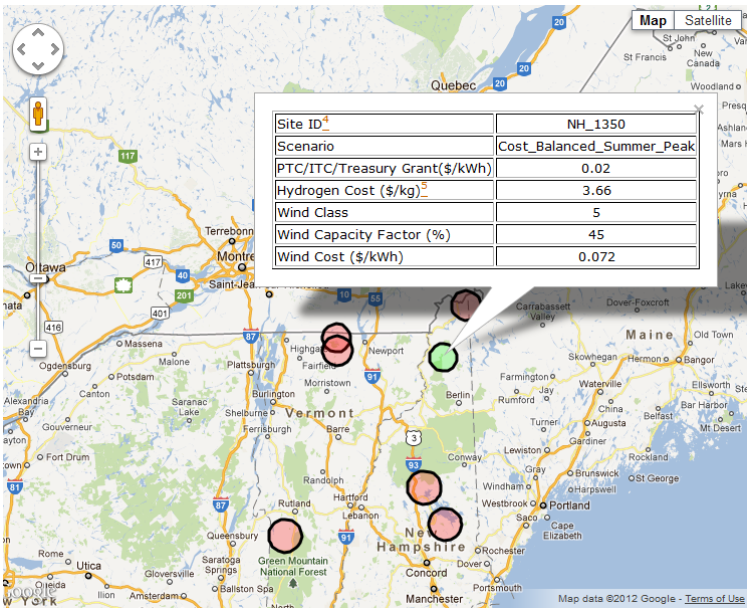

Figure 3 - Interactive tool showing wind sites in New England, with the effect of the PTC

2 Background

This project builds on a previous analysis [1] to develop a regional analysis of hydrogen production cost from wind-based water electrolysis. Based in part on the H2A Production Model [3] and the H2A FCPower Model, an hourly model was written in MATLAB to be used in conjunction with the H2A Production Model. The hourly model and data were expanded to include five regional grid-pricing structures, and 42 wind sites spanning the five regional grids. The regional variations were used to highlight some similarities and differences between sites and how these might affect overall economics. Model outputs include a range of techno-economic results to help with future systems analysis.

This analysis assumes a relatively constant nominal hydrogen demand of 50,000 kg/day and uses four scenarios to find the relative size of the wind farm needed to meet that. The plant size is scalable from about 1,000 kg/day to the 50,000 kg/day with the wind farm size directly proportional. The electrolyzer could be co-located with the wind farm or downstream of a group of wind farms closer to a specific demand. The scenarios provide a basis for achieving renewable hydrogen production.

This analysis assumes that the electrolyzer is co-located with the wind farm in order to isolate the production cost of hydrogen. It does not address the business case for other configurations such as electrolyzers downstream of a wind farm which adds complexities of ownership, markets for product, and primary business. We are analyzing the basic cost of wind hydrogen production as a core business. For a central plant the cost accounts for only the production of the hydrogen, additional cost would include transportation, compression, storage, and dispensing. The results are also applicable among a subset of distributed refueling stations located outside of urban areas where there is sufficient inexpensive, open land along roadways. For instance a single 3-MW turbine could provide sufficient power in the scenarios discussed in the paper for a 1000-1500 kg/day hydrogen station depending on wind quality. These distributed refueling stations could provide valuable interconnection along the hydrogen network for vehicles. However, as with the central plant, only production costs are examined, not additional storage, compression, and dispensing.

The scenarios provide a basis for achieving renewable hydrogen that is not subsidized by any other part of the system. Grid power supplements the wind-based power to run electrolyzers. In all scenarios wind power is sold to the grid to meet a net balance by either cost or quantity of the grid electricity bought to run the electrolyzers.

NREL researchers are expanding the analysis to include a greater breadth of geographic information, and to better understand regional variations and factors that may improve the system.

3 Model Configurations

The model was configured to accommodate more geographic locations. The regional additions have five grid pricing structures, including the original used in the prior analysis [1], and expanded wind profiles from Classes 3–6.

Costs were updated where possible. Wind costs include data from 2010 [4] and all costs were updated to 2007$ using the GDP Implicit Deflator Price Index from the U.S. Energy Information Administration's Short Term Energy Outlook 2011 [2]. Electrolyzer cost and overall performance had no regional variations, and costs remain consistent with the previous analysis.

3.1. Electrolyzer

Electrolyzer performance and costs were taken from an independent review panel report on low-temperature electrolysis [5]. A 51,020 kg/day electrolyzer was modeled with a peak capacity factor of 98%/year for an adjusted output of 50,000 kg/day, the nominal hydrogen demand. The electricity requirement of the electrolyzer was 106 MW. The electrolyzer size and capital costs are linearly scaleable from 1,000 kg/day to 50,000 kg/day as per the independent review panel [5].

Many standard H2A economic assumptions [6, 7] were used to calculate the electrolyzer costs. These included a 10% internal rate of return and a 40-year plant life. Table 1 shows the capital cost, operations and maintenance (O&M), and several other technical parameters taken from the review panel report to represent the electrolyzer [5]. Uninstalled costs used were $408/kW ($850/kg/day and 50 kWh/kg). Costs are shown in 2007$.

Table 1. Electrolyzer Economic Parameters Based on the Independent Review Panel Report[a]

Parameter	Review Panel Baseline Value
Total Depreciable Capital Cost	$53.2 million[a]
Electrolyzer Efficiency	50 kWh/kg
Replacement Cost	25% of direct installed capital
Replacement Interval	7 years
Operating Capacity Factor	98%
Working Capital	5%
Other Material Costs	$0
Land Costs	$53,100/acre and 5 acres
Labor	10 full time equivalents
Production Maintenance Costs	2% of direct installed capital

[a] The review panel [5] gave a value of $50 million for total depreciable capital costs in 2005$. The value listed reflects a close approximation that separated the costs into direct and indirect costs, and then converted to 2007$.

3.2. Wind Farm

Wind-based electricity was used to produce hydrogen; when wind-based electricity supply was higher than the electrolyzer demand, it was sold to the grid. The wind was modeled as a wind farm composed of multiple 3-MW turbines. The cost was related to the capital and O&M costs of the turbines. The hourly electricity production was modeled from real wind profiles taken from wind Classes 3–6 and used in the analysis. Figure 4 and Figure 5 show the wind electricity costs and some characteristics of wind profiles used.

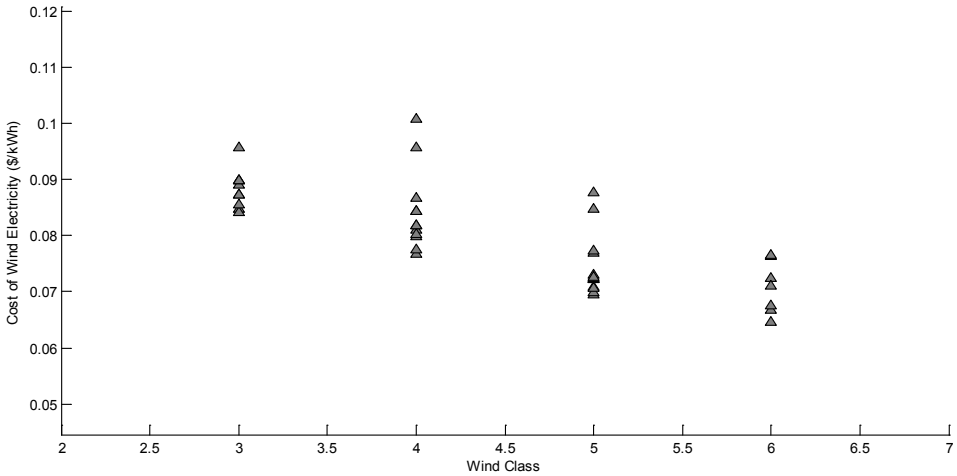

Figure 4. Wind electricity cost versus wind class

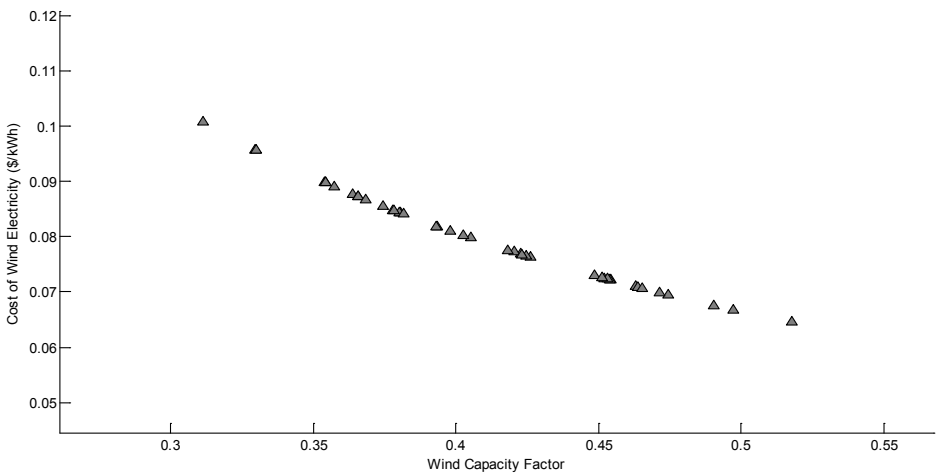

Figure 5. Wind electricity cost versus capacity factor

3.2.1. Wind Farm Costs

The wind-based electricity was characterized as a wind farm using turbine performance and costs. The wind farm performance was modeled as a multiple of 3-MW turbines using an efficiency curve to determine the electricity output at different wind speeds. The costs were derived from Wiser and Bolinger [4].

A fixed charge rate of 12.05% was used for the capital costs. This includes a 10% internal rate of return, 35% federal tax rate, and 6% state tax rate. Costs were divided simply into capital and O&M (see Table 2).

Table 2. Case 1 Wind Cost Parameters [3]

Parameter	Value (2007$)
Installed Turbine Capital Cost	$2067/kW
O&M (includes replacement costs)	$0.0087/kWh

3.2.2. Wind Profiles

Wind profiles were gathered for five regions from NREL's Western Wind and Eastern Wind datasets [8, 9]. These included wind resources from Classes 3–6. Lower class sites were excluded because they are unlikely to be used in large-scale hydrogen production; however, results from the previous analysis show their trends [1]. The datasets provide yearly data in 10-min intervals, which were then converted into an hourly profile spanning one year. These 8,760 hourly profiles were used to run the model simulations.

3.3. Grid

This analysis expands on the previous analysis by extending the modeling of wind-based hydrogen production to other geographic locations. The initial analysis focused on locations served by the California ISO electricity grid. ISO New England, PJM, and a limited Texas (ERCOT) dataset were added. Texas data are limited because the ERCOT electricity market switched from zonal to nodal pricing on December 1, 2010. Market clearing price was replaced by locational marginal price (LMP), which is used in the remainder of the ISO markets analyzed.

Figure 6 shows sample electric utility data and the results of typical usage spikes in the summer and winter. This is an average of prices in Day Ahead Market and the LMP.

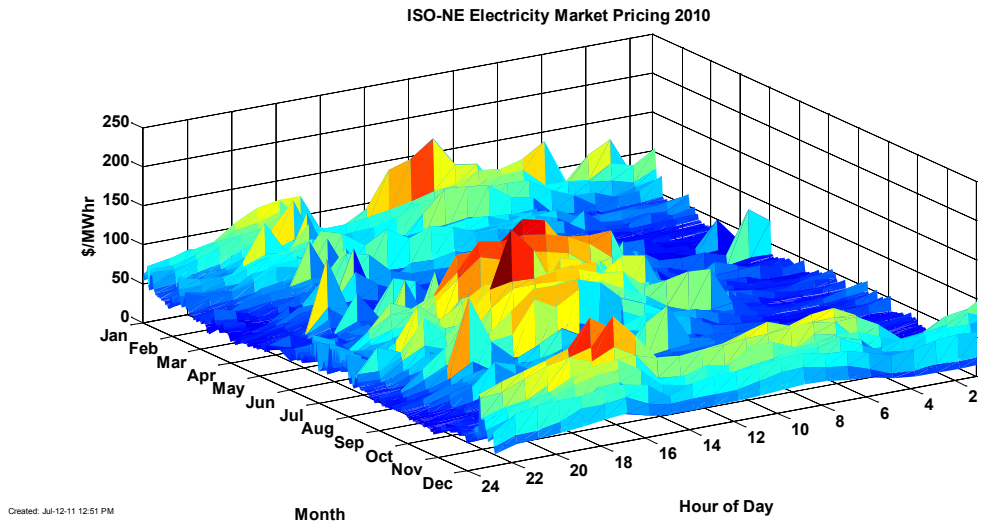

Figure 6. ISO New England 2011 electricity pricing

Raw Data Source, FERC (/www.ferc.gov/market-oversight/mkt-electric/overview.asp), Accessed June 2011.

For the hydrogen production model, data are classified as peak, partial peak, and off-peak. The edge of the peak, partial peak, and off-peak bins are calculated from the mean and standard deviation of all the data available for a particular market to determine the boundaries.

P = vector of all hourly 2010 price data.

- Off-peak: All prices ≤ mean(p) + stdev(p) are classified as off-peak.
- Partial peak: All prices ≤ mean(p)+2*stdev(p), but > mean(p) + stdev(p) are classified as partial peak.
- Peak: All prices > mean(p)+2*stdev(p) are classified as peak.

The mean price of each bin is assigned as the price for all hours that fall into that bin. This smoothes the data somewhat, and makes the analysis less specific to the exact circumstances of a particular year. Further, these bins are calculated for the summer period of June 1 to September 30; the winter period is defined as the balance of the year. Two of these results are shown in Figure 7 and Figure 8.

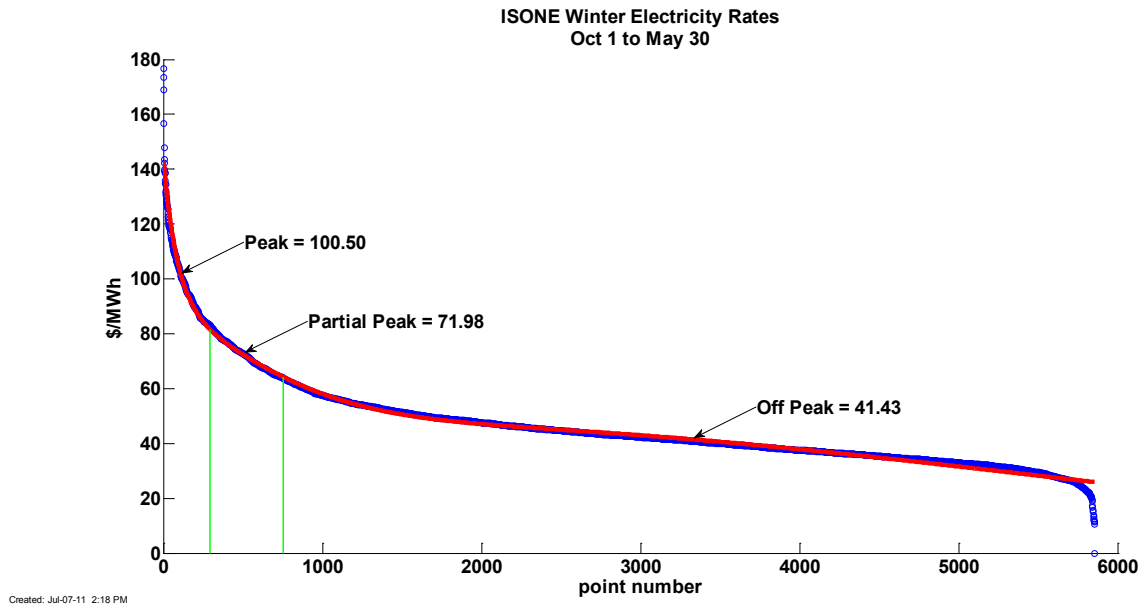

Figure 7. ISO New England winter electricity price classification

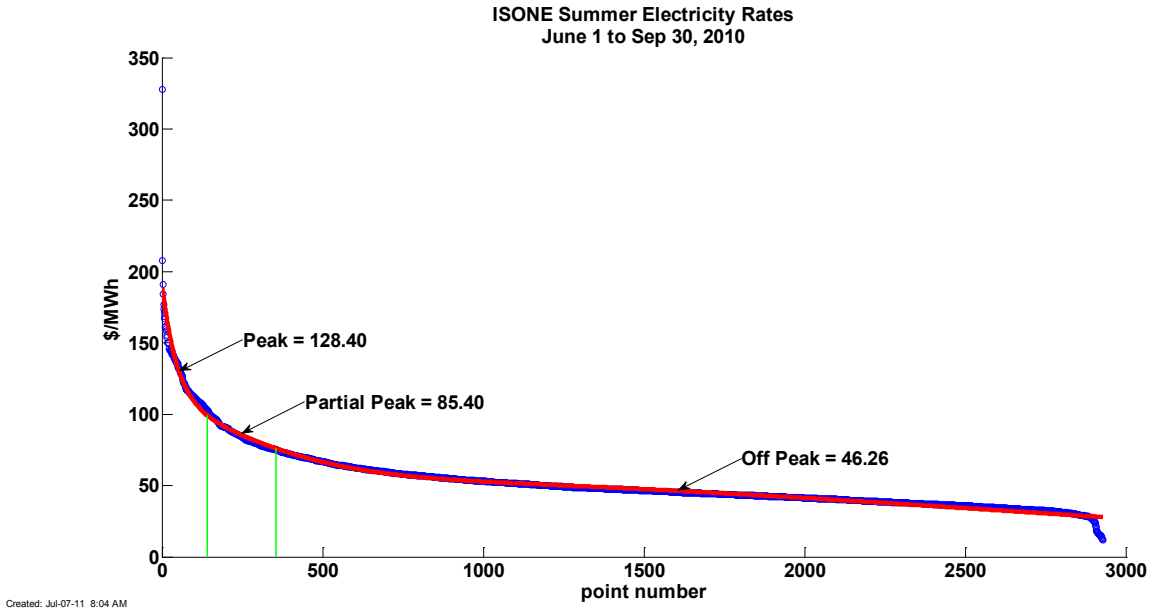

Figure 8. ISO New England 2011 summer electricity pricing classification

Raw Data Source, FERC (www.ferc.gov/market-oversight/mkt-electric/overview.asp),
Accessed June 2011.

3.4. Scenarios

We again chose four balancing scenarios to determine the size of wind farm needed to produce a nominal 50,000 kg/day of hydrogen. The scenarios represent different visions of how renewable hydrogen might be produced without being particularly subsidized by other pieces of the energy system. Two scenarios meet the full hydrogen demand; the other two show the ramifications of not making hydrogen during summer peak hours when the electricity grid must meet its highest demand. Not buying summer peak electricity often results in slightly lower hydrogen production costs because expensive electricity is not bought, but some hydrogen demand is not met. The four scenarios follow:

- Scenario A: cost balanced—the cost of the grid electricity that is purchased is balanced to the wind electricity sold at grid rate.
- Scenario B: power balanced—the amount of grid electricity purchased (in megawatt-hours) is balanced with the amount of wind electricity sold.
- Scenario C: same as scenario A, cost balanced, but no grid electricity is purchased during summer peak periods.
- Scenario D: same as scenario B, power balanced, but no grid electricity is purchased during summer peak periods.

The scenarios show the minimum wind farm size versus electrolyzer size that would meet a hydrogen demand. In power balanced scenarios, the amount of wind energy sold to the grid equals the grid electricity bought for the electrolyzer. Enough wind electricity is produced at the wind farm to fully meet electrolyzer demand. Cost balanced scenarios do the same, but based on the cost of the electricity bought and sold. Both follow the hourly grid pricing structures.

4 Results

The cost of wind electricity mostly depends on the cost of the wind turbines and the quality of the wind resource at a particular site. Each site has unique characteristics based on average yearly wind speed and capacity factor, which then correspond to a particular wind electricity cost for each site. The cost of hydrogen based on these unique sites is related to the wind electricity cost and the grid pricing (see Figure 4). Regional grid pricing structures cause some variation; while lower grid prices equal lower hydrogen prices, there is still a strong correlation to the cost of the wind electricity also.

Figure 9 shows one way the regional variation affects the cost of hydrogen. Two sites are circled in green, with wind electricity cost about $0.095/kWh. The site in red is in California (CA-ISO); the site in purple is from the Midwest ISO (MISO) region. These two sites show how the regional grid pricing affected the cost of hydrogen. MISO has a lower average grid price and correspondingly lower hydrogen costs. This particular result seems obvious, but higher grid price does not always correspond to higher hydrogen cost.

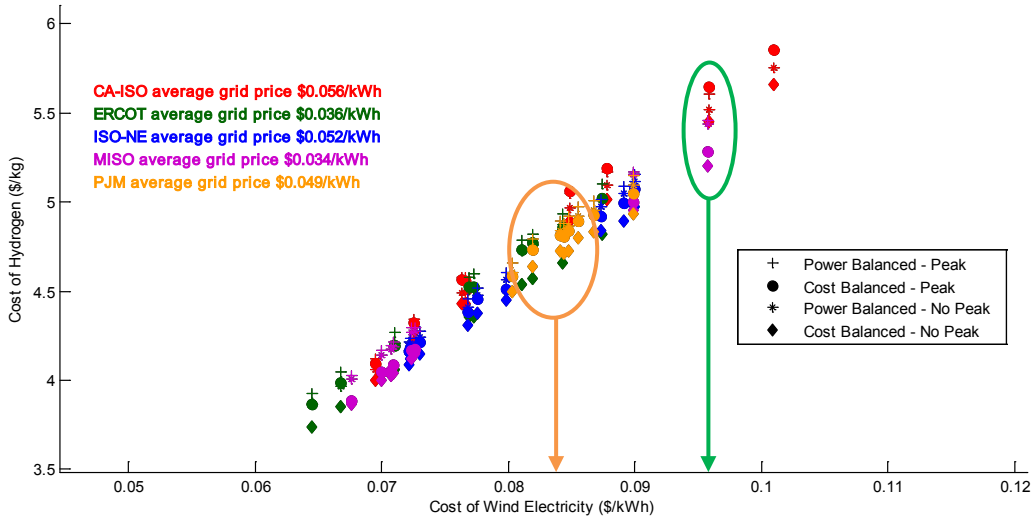

Figure 9. Hydrogen cost (2010$) versus wind electricity cost

Figure 9 also shows several sites that fall into the $0.08–$0.09/kWh for wind electricity (circled in orange). Sites from the PJM region have orange markers, with an average yearly grid cost of $0.049/kWh; sites in Texas (ERCOT) have green markers, with an average yearly grid cost of $0.036. All these sites show hydrogen costs in the same range, even though the grid costs are fairly different.

These scenarios show a trend that the higher percentage of wind electricity used directly by the electrolyzer, rather than sold back to the grid to achieve the required power or cost balance, reduces the cost of hydrogen even when the average cost of grid electricity is less than the cost of wind electricity (see Figure 10 and Figure 11). Furthermore, each site has an associated wind electricity cost based on the wind profile and lower wind costs are generally better wind production sites (Figure 11). Thus, the electrolyzer is using higher percentages of wind electricity.

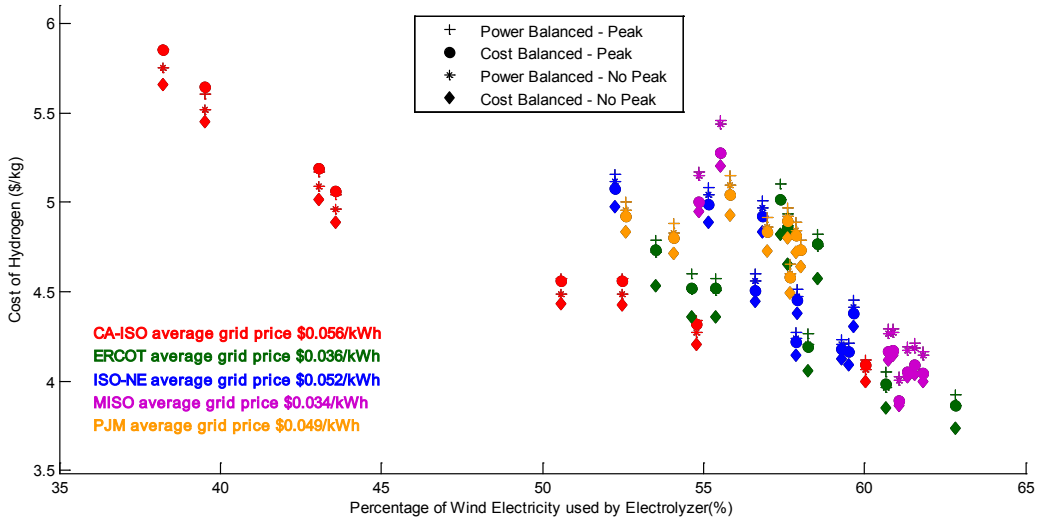

Figure 10. Percentage of wind electricity used by electrolyzer to cost of hydrogen

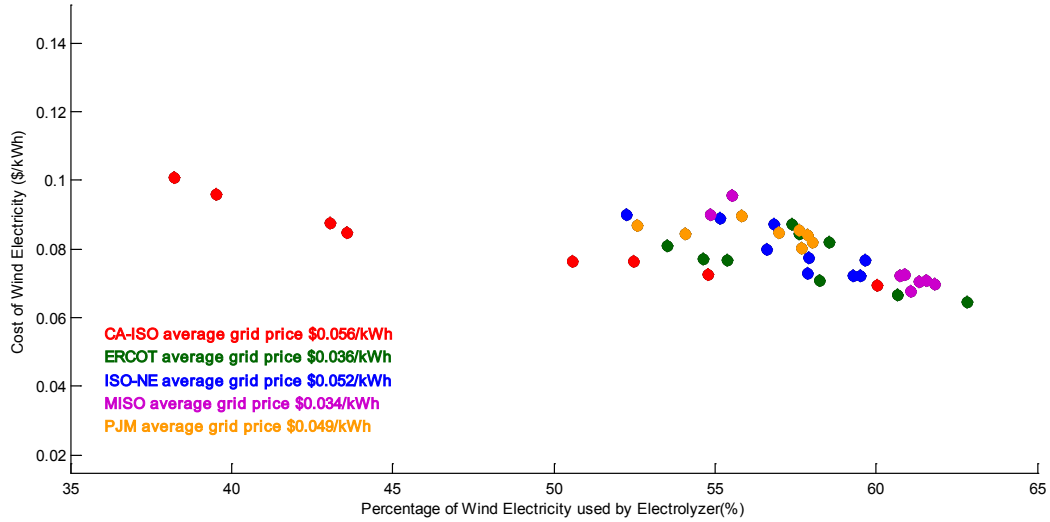

Figure 11. Percentage of wind electricity used by electrolyzer to cost of wind

The wind capital cost dominated the total cost of hydrogen (see Figure 12) for New England (ISO-NE). The example is for the power balanced scenario, which buys summer peak power; however, other scenarios and grids also displayed similar trends. For the wind sites in ISO-NE, the hydrogen production costs were $4.09–$5.15/kg. For the scenario displayed (power balanced, buying summer peak grid electricity), the cost contribution of the grid is not equal, though the grid electricity bought and sold is along the same order. For cost balanced scenarios, the grid cost contributions would be equal.

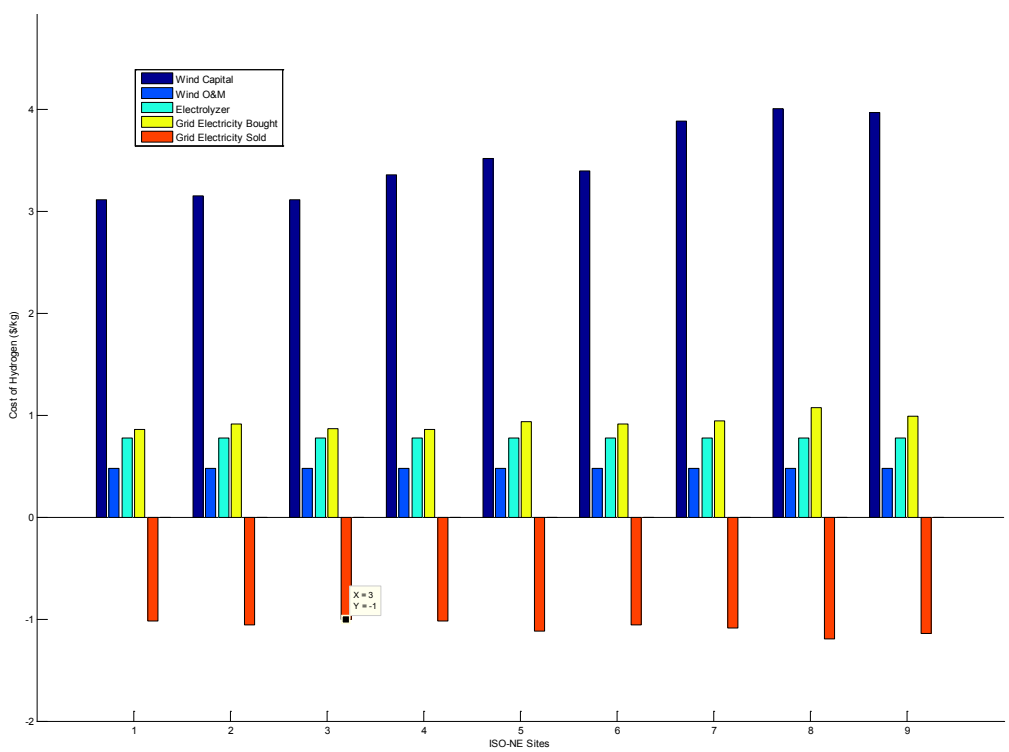

Figure 12. Cost of hydrogen breakdown for ISO-New England

Figure 13 shows disposition of the electricity for a New England wind site. The figure also shows the wind variability and how this is used in conjunction with the grid to power the electrolyzer. The electrolyzer runs at a relatively steady 106 MW throughout the year. The only downtime would be planned and unplanned maintenance, which is assumed to be less than 2% of the time. The grid would pick up wind farm maintenance downtime.

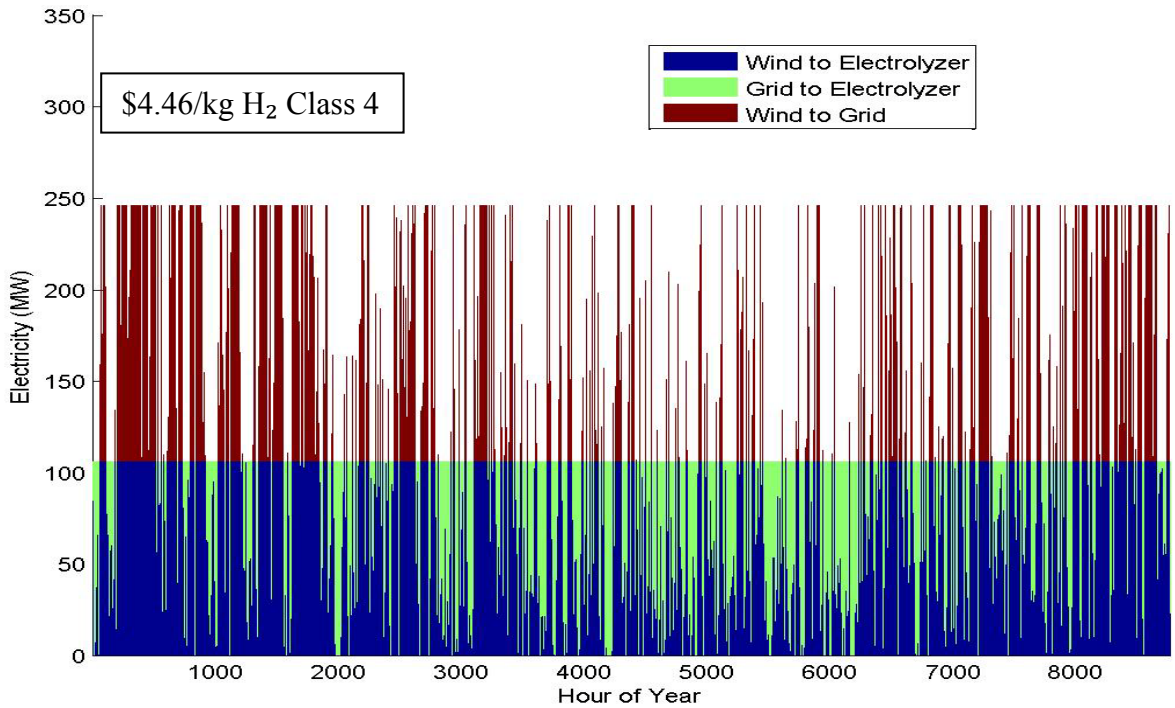

Figure 13. Detailed profile of wind site in New England

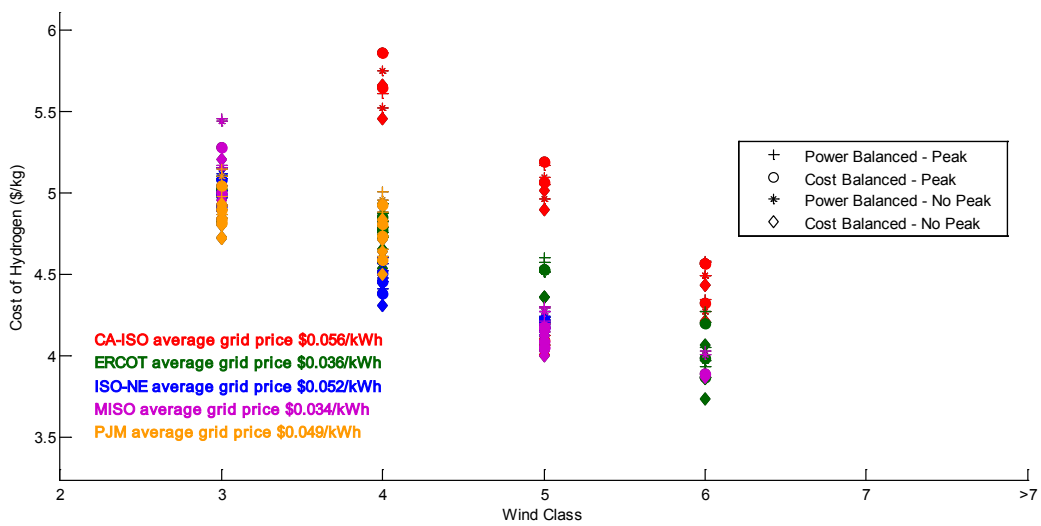

Figure 14. Range of hydrogen costs by wind class

Sensitivity analysis was run to see what effect several variables had on the cost of hydrogen. Table 3 shows the variable, base value, and the high and low values used. All costs are in 2007$. The low value reduces hydrogen cost; the high value increases it.

Table 3. Sensitivity Values for High and Low Hydrogen Costs

Variable Name	Base Case Value	Low Value	High Value
Wind Turbine Capital Cost ($/kW)	2067	1654	2481
Electrolyzer Energy Use (kWh/kg)	50	47.5	60
Electrolyzer Capital Cost ($/kW)	408	326	489
Wind Farm Availability (%)	88	90	86
Electrolyzer Capacity Factor (%)	98	99.5	96

Figure 15 shows the results of the sensitivity analysis. The wind turbine capital cost, which dominated the hydrogen cost in the breakdown (Figure 12), also shows the greatest sensitivity to the cost of the hydrogen with all other factors held constant. A 20% difference in wind turbine capital cost can change the cost of hydrogen by more than $0.50/kg. The electrolyzer cost and performance can also have a significant effect on the cost of hydrogen. The maintenance downtime for the electrolyzer and the wind farm are much less significant. Other sites and scenarios showed similar ranges as that in Figure 15.

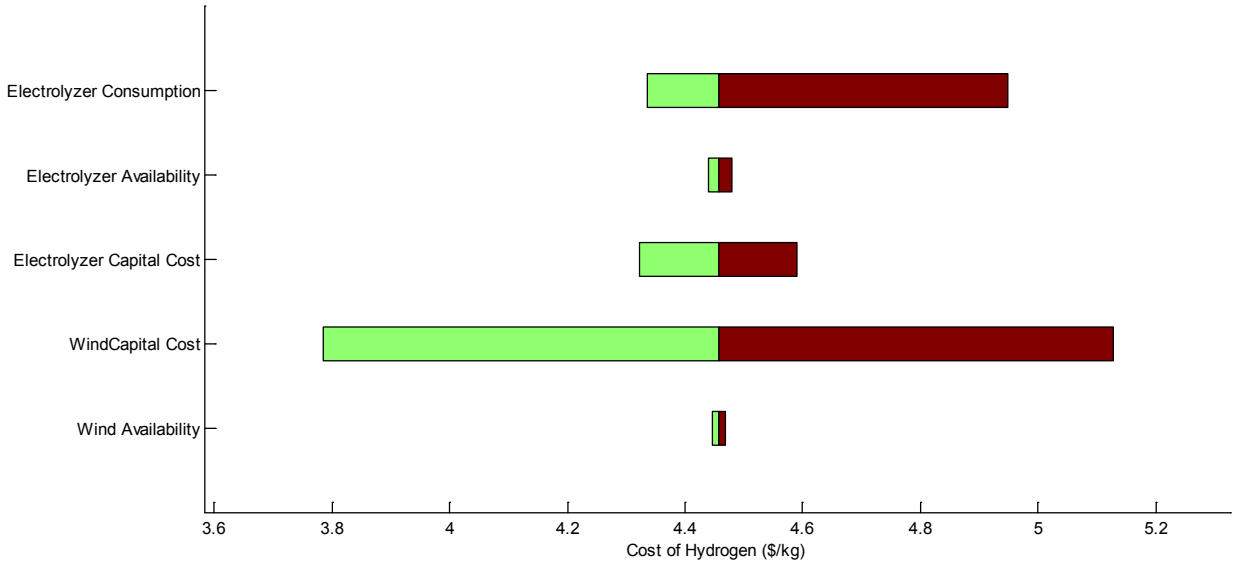

Figure 15. Example cost sensitivity for a wind site in New England

Finally, sensitivity to a PTC, ITC and Treasury Grant for wind power was analyzed. These combined credits reduce the wind electricity cost by $0.02/kWh for the life of the plant, consistent with Wiser and Bolinger [4]. All wind electricity was given the credit, both what was sold to the grid and what was used by the electrolyzer. This may not apply to electricity sent to the electrolyzer, depending on the economic system setup. The cost of hydrogen was reduced by more than $1/kg in most sites and scenarios (see Figure 16). This figure also shows the DOE

targets for distributed and central hydrogen production, both converted to 2007$. Some sites could meet the DOE centralized target if the credits can be used. This hydrogen is a renewable alternative to other fossil fuel-based methods of hydrogen production, and suggests that hydrogen production from renewable electricity could provide a viable alternative.

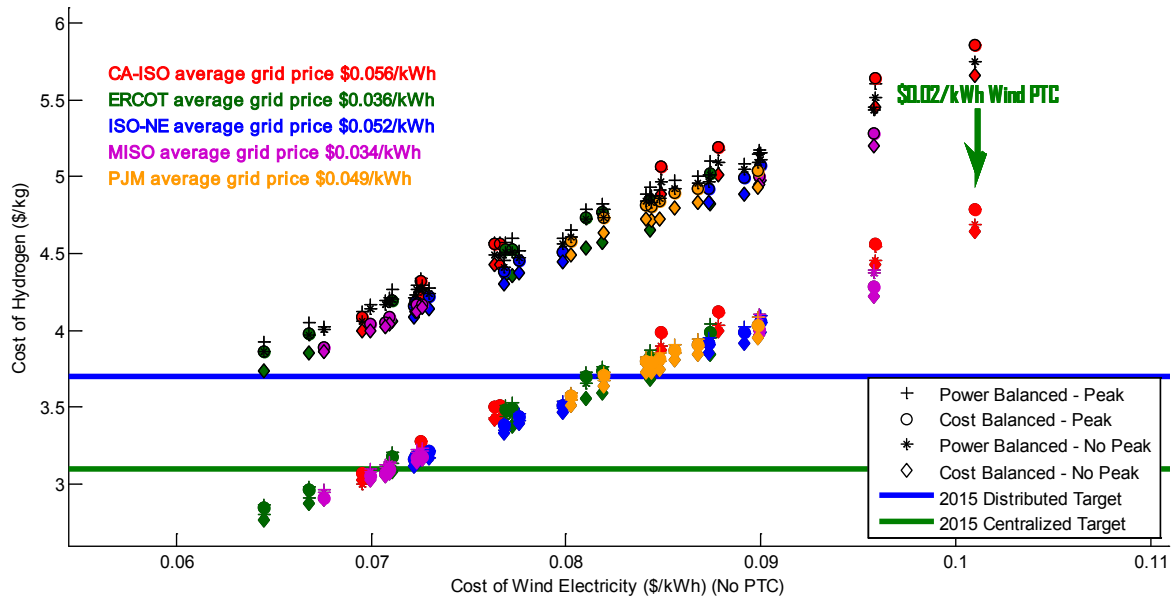

Figure 16. Cost of hydrogen with and without the PTC and ITC effects.

5 Conclusion

The cost of renewable wind-based hydrogen production is very sensitive to the cost of the wind electricity. Using differently priced grid electricity to supplement the system had only a small effect on the cost of hydrogen; because wind electricity was always used either directly or indirectly to fully generate the hydrogen. Wind classes 3–6 across the U.S. were examined and the costs of hydrogen ranged from $3.74kg to $5.86/kg. These costs do not quite meet the 2015 DOE targets for central or distributed hydrogen production ($3.10/kg and $3.70/kg, respectively), so more work is needed on reducing the cost of wind electricity and the electrolyzers. If the PTC and ITC are claimed, however, many of the sites will meet both targets. For a subset of distributed refueling stations where there is also inexpensive, open space nearby this could be an alternative to central hydrogen production and distribution.

Sensitivity shows that the electricity price, based upon the wind turbine capital cost, can affect the cost of hydrogen more than even the electrolyzer capital cost and performance. This is most visible when the combined effect of the PTC and ITC of $0.02/kWh is applied to the wind electricity. Cost of hydrogen drops by more than $1/kg with a PTC to $2.76-$4.79/kg.

All wind electricity is not equivalent, but even a range of wind class sites can provide renewable, green hydrogen at a cost close to current DOE targets. The use of this renewable fuel could then be used to supplement introduction of fuel cell electric vehicles, energy storage for increased variable renewable electricity penetration, or other industrial uses currently dependent on fossil fuels.

6 References

1. Saur, G. and T. Ramsden. *Wind Electrolysis: Hydrogen Cost Optimization*. NREL/TP-5600-50408. Golden, CO:NREL, 2011.
2. EIA, U.S. *Short Term Energy Outlook (August 9, 2011)*. 2011 [cited 2011 August 15]; Available from: http://www.eia.gov/emeu/steo/pub/cf_tables/steotables.cfm?tableNumber=5.
3. *DOE Hydrogen Program: DOE H2A Production Analysis*. 2008 August 23, 2011]; Available from: http://www.hydrogen.energy.gov/h2a_production.html.
4. Wiser, R. and M. Bolinger. *2010 Wind Technologies Market Report*. DOE/GO-102011-3322. 2011.
5. Genovese, J., et al. *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis: Independent Review*. Golden, CO:NREL, 2009.
6. Ramsden, T., *Current (2008) Hydogen Production from Central Grid Electrolysis v 2.0.1*, U. DOE, Editor. 2008.
7. *DOE Hydrogen Program: DOE H2A Analysis*. 2008 March 11, 2008]; Available from: http://www.hydrogen.energy.gov/h2a_analysis.html.
8. *NREL: Wind Integration Datasets - Eastern Wind Dataset*. [cited 2011 August 1]; Available from: http://www.nrel.gov/wind/integrationdatasets/eastern/methodology.html.
9. *NREL: Wind Integration Datasets - Western Wind Dataset*. [cited 2010 July 15]; Available from: http://www.nrel.gov/wind/integrationdatasets/western/methodology.html.