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An Analysis of Hydrogen Production from Renewable Electricity Sources

Preprint

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AN ANALYSIS OF HYDROGEN PRODUCTION FROM RENEWABLE ELECTRICITY SOURCES

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ABSTRACT

To determine the potential for hydrogen production via renewable electricity sources, three aspects of the system are analyzed: a renewable hydrogen resource assessment, a cost analysis of hydrogen production via electrolysis, and the annual energy requirements of producing hydrogen for refueling. The results indicate that ample resources exist to produce transportation fuel from wind and solar power. However, hydrogen prices are highly dependent on electricity prices. For renewables to produce hydrogen at $2/kilogram, using electrolyzers available in 2004, electricity prices would have to be less the $0.01/kWh. Additionally, energy requirements for hydrogen refueling stations are in excess of 20.4 GWh/year, which may be challenging for dedicated renewable systems at the filling station to meet. Therefore, while plentiful resources exist to provide clean electricity for the production of hydrogen for transportation fuel, challenges remain to identify optimum economic and technical systems to provide renewable energy to distributed refueling stations.

1. INTRODUCTION

Solar and wind energy can be harnessed to provide clean electricity to hydrogen-generating electrolyzers. In this way, hydrogen production can be a pathway for using renewable domestic energy sources to contribute directly to reducing greenhouse gases and reliance on imported transportation fuels. Hydrogen is produced via electrolysis by passing electricity through two electrodes in water. The water molecule is split and produces oxygen gas at the anode and hydrogen gas at the cathode via the following reaction: $H_2O \rightarrow \frac{1}{2} O_2 + H_2$. In this paper, three aspects of the renewable electrolysis system are analyzed: a renewable hydrogen resource assessment, the cost of hydrogen production via electrolysis, and the annual energy requirements of producing hydrogen at refueling stations.

2. RESOURCE ASSESSMENT

Analysts at the National Renewable Energy Laboratory (NREL) completed a resource assessment to determine if the solar and wind resources in the United States can produce enough hydrogen to meet the vehicle fueling demands of this country. To make this determination, analysts determined the potential for hydrogen generation from photovoltaic (PV) and wind energy in the United States, and compared that to the United State's motor gasoline consumption in 2000. Geographical Information System (GIS) data on solar and wind resources across the country were collected and combined with PV, wind turbine, and electrolyzer efficiencies and capacity factors to determine the amount of hydrogen that can be produced from renewable resources.

2.1 PV and Wind Resource Analysis

The PV energy data were calculated from average yearly solar data based on 40 km^2 land area grids. The solar energy was converted to electricity via a PV non-tracking flat plate collector tilted at latitude. The study assumes any given 40 km^2 cell land area grid will have no more than 10% of its land area available for PV systems, and 30% of this area will actually be covered with PV panels yielding a total of 3% land coverage. In addition, the study excludes certain lands including all National Park Service areas; Fish and Wildlife Service lands; all federal lands with a specific designation (parks, wilderness, wilderness and study areas, wildlife refuge, wildlife area, recreational area, battlefield, monument, conservation areas, recreational areas, and wild and scenic rivers); conservation areas; water; wetlands; and airports/airfields. All of these land areas, plus a 3 km surrounding perimeter, are completely excluded: the water areas are excluded 100%. Furthermore it is assumed that solar energy can be converted to electricity at an average system efficiency of 10%. Current PV efficiencies range from 10-15%, and with cell/module and inverter efficiency improvements could reach 15-20% in the next decade.

The wind energy data provide an estimate of hydrogen potential from wind for the United States based on wind sites that are categorized as Class 3 or better. With current technology, Class 4 and greater are considered economically viable, but for this study, Class 3 is expected to be viable in the near future and is included. The analysis used updated wind resource data that were available for several states. Where updated wind resource data were not available, low-resolution 1987 U.S. wind resource data were used. The grid cell resolution of these data varies from 200 m – 1 km for the newer high-resolution data to 25 km for the 1987 low-resolution wind data. The wind class of each grid cell was used to calculate the potential electrical generation for that grid cell by assuming 5 MW of wind turbines could be installed on each square kilometer. The following table of wind class capacity factors was used to calculate the actual potential electricity generation from each grid cell.

TABLE 1: WIND CLASS CAPACITY FACTORS BASED ON YEAR 2000 TECHNOLOGY

Class	Capacity Factor
3	0.2
4	0.251
5	0.3225
6	0.394
7	0.394

As with the solar data, environmental exclusion areas were defined as federal and state lands where wind energy development would be prohibited or severely restricted. The land exclusions account for transportation right-of-ways, locally administered parkland, privately administered areas, and proposed environmental lands. In addition, the following classes of land were excluded:

- 100% excluded are all National Park Service areas; Fish and Wildlife Service lands; all federal lands with a special designation (parks, wilderness, wilderness and study areas, wildlife refuge, wildlife area, recreational area, battlefield, monument, conservation areas, recreational areas, and wild and scenic rivers); conservation areas; water; wetland; urban areas; and airports/airfields.
- 50% exclusions were applied to the remaining Forest Service, Department of Defense lands, and non – ridge crest forest.
- Entirely excluded is the 3 km area surrounding 100% environmental and land use exclusions: does not apply to water exclusion.

This study also excludes areas with slope greater than 20% for the high-resolution data. These areas are considered too steep for siting wind turbines.

2.2 Hydrogen Potential from Renewable Electricity

Once the potential electricity production from wind and solar were determined, the hydrogen production potential could be calculated. The potential energy generation from PV and wind was combined with an electrolyzer system energy requirement to calculate the amount of hydrogen that could be produced from renewable resources across the United States. For this study 52.5 kWh/kg of hydrogen was assumed, which is a 75% efficient system based on the higher heating value of hydrogen. This efficiency is the entire efficiency of the system, including the electrolysis cell stack, any energy requirements from system auxiliaries, and system losses.

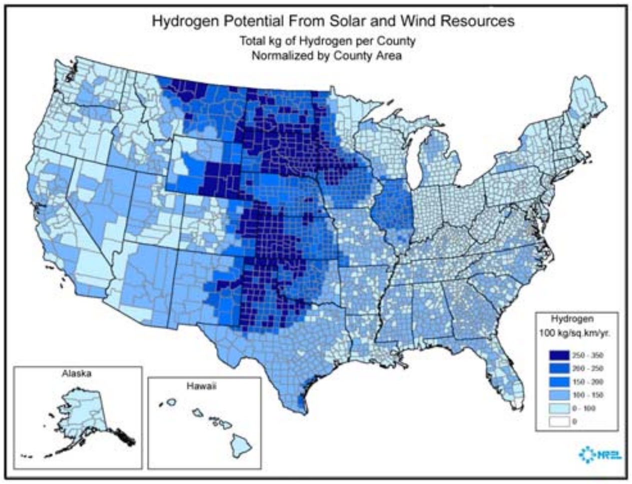

Fig. 1: Total kg of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from combined renewable resources - wind and solar.

Once the hydrogen potential for each county was calculated, a graphical representation was produced using GIS tools. This graphical representation of the resulting hydrogen production potential from wind and PV energy for each county can be seen in Figure 1.

2.3 Resource Analysis Results

The results verified that there are abundant solar and wind energy resources to meet hydrogen transportation fuel for the entire country. The gasoline consumption of the United States as a whole was 128 billion gallons of gasoline in 2000. The potential for hydrogen production from PV and wind for the entire country is 1,110 billion kilograms of hydrogen. As a kilogram of hydrogen is roughly equivalent to a gallon of gasoline in energy content, 8.6 times the year 2000 gasoline consumption in the United States can be met using hydrogen produced from PV and wind.

In addition, the data were broken down to state level to see if resources were available to meet each state's transportation fuel needs using renewable hydrogen. See Figure 2 for a graphical representation of these results.

The state with the highest potential production of hydrogen from PV and wind is Texas with 106,000 million kilograms of hydrogen. The state with the lowest potential production of hydrogen from PV and wind is Rhode Island with 213 million kilograms of hydrogen. Washington D.C. is even lower with the production potential of 5 million kilograms of hydrogen from PV and wind. All but 5 states, and Washington D.C., have enough renewable resources to meet transportation needs at the state level. New Jersey, Rhode Island, Massachusetts, Connecticut, Maryland and Washington D.C. are the exceptions. However, the New England region and the Mid-Atlantic region, where these states are located, can meet 240% and 160% of the transportation fuel needs of the region as a whole using hydrogen from wind and PV.

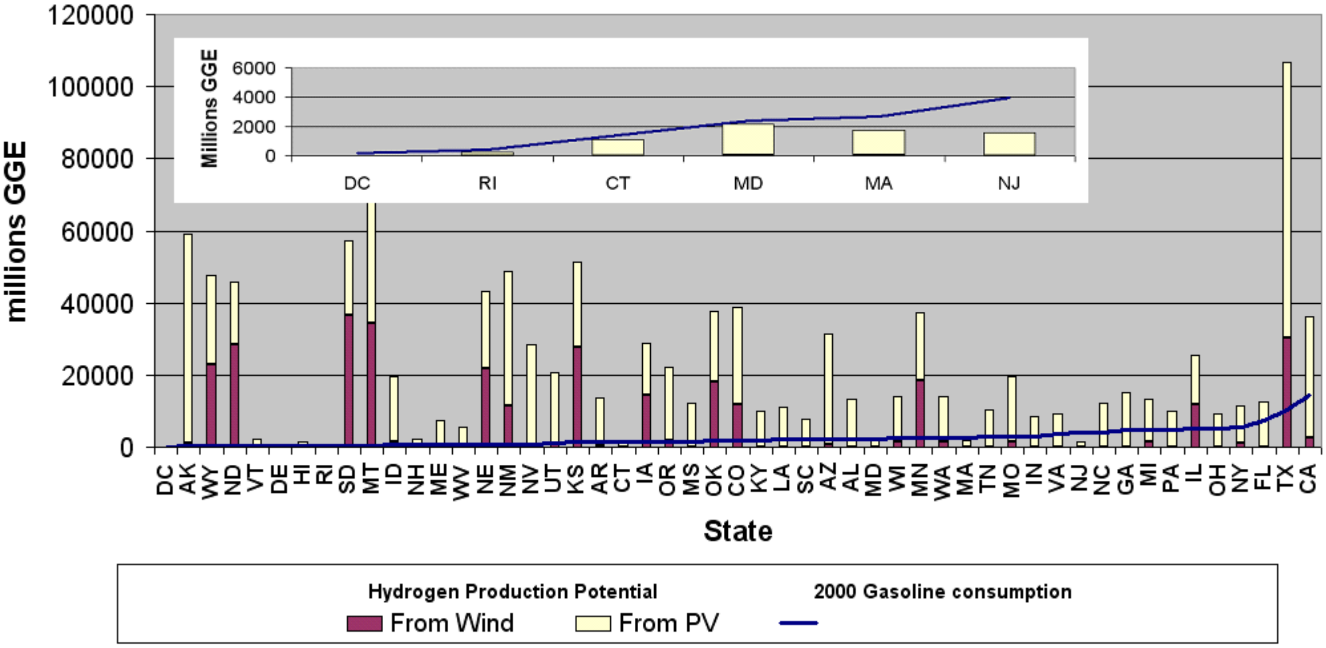

Fig. 2: Gasoline Usage vs. Renewable Hydrogen Potential. Gasoline consumption is plotted on the solid line in terms of gallons of gasoline consumed in the year 2000. The potential for hydrogen production is plotted in the dark bars (wind potential) and the light bars (PV potential). The inset shows a more detailed view of the states where gasoline consumption is not met by renewable hydrogen production. The y-axis units of GGE stand for Gallon of Gasoline Equivalent and are equal to a gallon of gasoline or a kilogram of hydrogen.

3. HYDROGEN FROM ELECTROLYSIS COST ANALYSIS

The resource analysis determined that ample resources exist to create transportation fuel from wind and solar power. However, that study did not quantify how much hydrogen from renewable electricity sources will cost. In order to determine the cost of hydrogen, other analysis methodologies need to be employed.

3.1 Boundary Analysis

The cost analysis began with a boundary analysis to establish the effects of electricity price on hydrogen costs. The analysis focused on five companies' electrolysis units: Stuart IMET; Teledyne HM and EC; Proton HOGEN; Norsk Hydro HPE and Atmospheric; and Avalence Hydrofiller, all available in 2004. For each electrolyzer, the system energy requirement was used to determine how much electricity is needed to produce hydrogen. The results of this study can be seen in Figure 3.

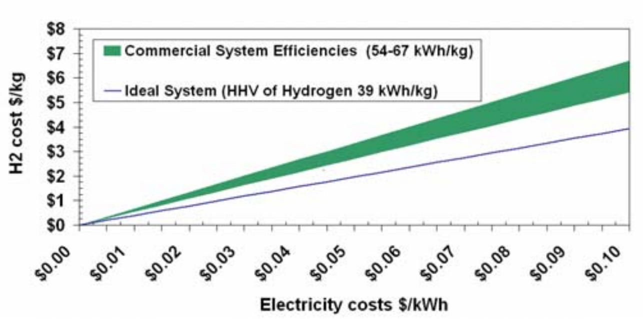

Fig. 3: Hydrogen costs via electrolysis with electricity costs only. The cost of hydrogen production using only electricity costs. No capital, operating or maintenance costs are included. This analysis demonstrates that regardless of any additional cost elements, electricity costs will be a major price contributor to the price of hydrogen produced via electrolysis.

This analysis demonstrated that at electrolyzer energy requirements from 54-67 kWh/kg (72-58 efficient HHV of hydrogen respectively), electricity costs must be lower than \$0.04 - \$0.055/kWh respectively to produce hydrogen at lower than \$3.00/kg. For an ideal system operating at 100% efficiency (39 kWh/kg), electricity costs must be less than \$0.075/kWh to produce hydrogen at lower than \$3.00/kg. These results show that regardless of any additional cost elements, electricity costs have a major impact on hydrogen price if produced via electrolysis. This analysis also shows that there is a limit to the hydrogen cost improvement that increasing the efficiency of the electrolyzer can provide. Thermodynamically, electrolyzers cannot be more efficient than the ideal line shown in Figure 3. Thus, the only way to decrease the amount of electricity needed below that line is to provide energy to the system in another form, such as heat, which may or may not provide a cost savings, depending on the system. This suggests that it would be worth examining in detail the cost and feasibility of designing solar-electrolysis systems that utilize both the electricity the heat from concentrating photovoltaics (McConnell, et al. 2004).

3.2 Discounted Cash Flow Analysis

In addition to the electricity cost boundary analysis, a discounted cash flow (DCF) analysis was used to determine the cost of hydrogen production via electrolysis. The analysis was done using the U.S. Department of Energy Hydrogen Analysis (H2A) Central Modeling Tool, designed for cost analyses of central hydrogen production. Key parameters used in the analysis are presented in Table 2.

TABLE 2: KEY PARAMETERS USED IN THE DISCOUNTED CASH FLOW ANALYSIS FOR HYDROGEN PRODUCTION VIA ELECTROLYSIS

Parameter	Assumption
Process Parameters	
Primary Feedstock	Electricity and Water
Electricity Used	Industrial Electricity
Conversion Technology	Electrolysis
Hydrogen Purity (%)	99.8
Process Electricity Consumption (kWh/kg)	53.5
Financial Parameters	
Start-up Year	2005
Plant Design Capacity (kg/day)	1050
After-Tax Real IRR (%)	10
Depreciation Type	MACRS
Depreciation Schedule Length (No. of Years)	7
Analysis Period (years)	40
Plant Life (years)	40
Effective Tax Rate (%)	38.9
Operating Capacity Factor (%) (represents equipment availability)	97
% Equity Financing	100
Replacement Capital Parameters	
Electrolyzer cell stack lifetime (years)	10
Indirect Depreciable Capital Parameters	
Buildings (% of fixed capital investment)	14
Yard Improvements (% of fixed capital investment)	3.5
Construction (% of fixed capital investment)	9
Engineering and design (% of fixed capital investment)	8
Contingency (% of fixed capital investment)	25
Non Depreciable Capital Parameters	
Land (\$/acre)	5,000
Operation & Maintenance (O&M) Parameters	
Burdened Labor (\$/hour)	50

Parameter	Assumption
Overhead and G&A (% of labor cost)	20
Property Tax and Insurance Rate (% of depreciable capital costs)	2

The standard H2A assumptions for electricity prices were used, which project electricity prices through 2070. The projections from 2001 through 2025 come from the 2004 Annual Energy Outlook published by Energy Information Administration (EIA). The projections between 2025 and 2035 are extrapolations of the EIA projections. The projections past 2035 are derived from growth rates from a Pacific Northwest National Laboratory long-term energy model called Climate Assessment Model (M-CAM). The H2A industrial electricity price ranges from $0.044/kWh to $0.050/kWh, and is $0.045/kWh in 2005. The H2A commercial electricity price ranges from $0.067kWh - $0.077/kWh, and is $0.069/kWh in 2005. All electricity prices are in terms of year 2000 dollars.

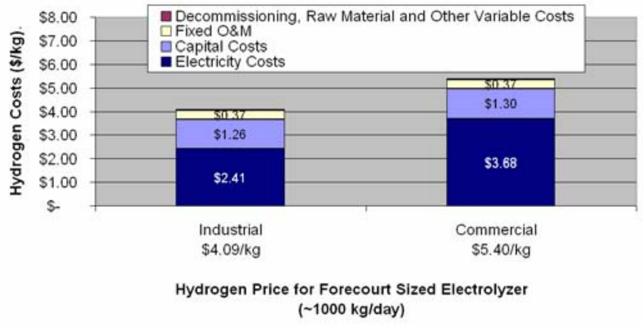

Fig. 4: Effects of electricity price on hydrogen costs on filling station sized electrolyzers (year 2000 dollars). The cost of producing 1000 kilograms of hydrogen per day via electrolysis using industrial and commercial electricity prices.

Figure 4 displays the results of the DCF analysis. For electrolysis units available in 2004, which produce 1000 kilograms of hydrogen per day, the cost driver for hydrogen is the electricity cost. With industrial electricity, 60% of the $4.09/kg hydrogen cost is from electricity. If more expensive commercial priced electricity is used, the cost of electricity makes up approximately 68% of the $5.40/kg cost of hydrogen. The increase electricity costs leads to an increase in hydrogen costs of 32%. The second most important factor is capital cost. The slight variation between the two systems' capital cost is because of the working capital being a function of the operating costs, which includes the higher electricity price. In both cases, the cost of fixed O&M is $0.37/kg of hydrogen. Decommissioning, raw materials and other variable costs are negligible in the cost of hydrogen produced via electrolysis.

This analysis is useful if standard grid electricity is used, and if that electricity available at average U.S. industrial or commercial electricity prices. However, the cost of electricity from renewable sources can vary widely from these average values. The graph in Figure 5 shows how the DCF calculated price of hydrogen varies according to electricity price. In contrast to the boundary analysis shown in Figure 3, Figure 5 figure illustrates how the cost of producing hydrogen from an electrolysis system varies with the cost of electricity, including capital, operating and maintenance costs. Three scenarios are shown. The first, solid line, displays how the cost of hydrogen changes with electricity prices using technology and prices available in 2004. The second, longer dashed, line shows the effect a 15% reduction in capital costs would have on hydrogen cost. Such improvements could come from mass production of these systems, or a simplification of the auxiliaries. The third, shorter-dashed, line shows the effect of a 10% increased system efficiency, which could come from electrolysis improvements, or a decrease in system losses. Note that decreasing the capital costs changes the intercept of the line, while increasing the efficiency changes the slope of the line.

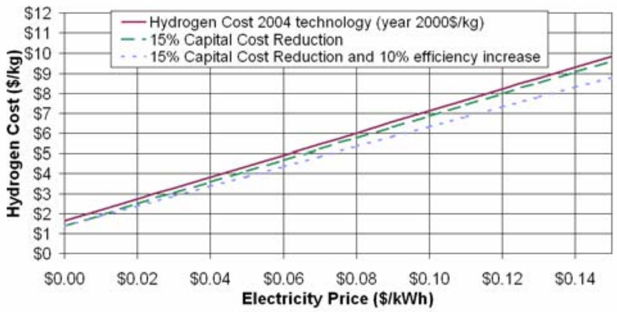

Fig. 5: How Hydrogen Cost varies with Electricity Price. The linear relationship between electricity price in $/kWh and hydrogen cost in $/kg.

This graph can be used to determine the cost of hydrogen from electrolysis for electricity prices up to $0.15/kWh. For example, using 2004 technology, $0.02/kWh electricity yields a hydrogen price of $2.70/kg and $0.14 /kWh electricity yields $9.30/kg of hydrogen. If electricity is free, the lowest price hydrogen the 2004 electrolysis units can produce is $1.60/kg of hydrogen. To produce $2.00/kg hydrogen, electricity prices will need to be available for $0.007/kWh, $0.011/kWh, and $0.012/kWh with 2004 technologies, a 15% capital cost reduction, and a capital cost reduction plus an efficiency improvement, respectively. Thus, to be competitive with $2/gallon gasoline prices, electrolyzers need to not only obtain inexpensive electricity, but also likely need to reduce capital costs and/or improve the efficiency of the systems.

3.3 Implications of the Cost Analyses

The implication of these two analyses is that for renewables to be able to produce hydrogen at $2/gallon gasoline prices using 2004 technology, electricity will have to be produced at rates lower than today's industrial electricity prices, or an optimized hybrid system of renewable and grid electricity will have to be deployed where electricity is purchased from the grid when prices are low, and produced from renewable sources when grid prices are high.

4. ENERGY REQUIREMENTS FOR ELECTROLYSIS

A final area of analysis involves the amount of electricity necessary to produce hydrogen for refueling stations. Current electrolysis units that could be used for transportation fuel have production rates that range from 1 kilogram of hydrogen per day to 1000 kilograms of hydrogen per day. The 1 kg/day unit would fuel 1 car per week, assuming a 6 kg/fill average, and would be considered a home refueling unit. The 1000 kg/day unit would fill approximately 170 cars per day, and would be considered a small filling station sized unit. Two such units operating at 75% capacity factor would provide 1500 kg/day of hydrogen and fuel 250 cars per day. This is one of the system sizes analyzed by the H2A forecourt production team. Forecourt in this context means filling station. The power requirements for electrolysis systems are not insignificant. The 1 kg/day unit would require 3 kW of power, or 26 MWh annually. The 1000 kg/day unit, which is the largest system available in 2004 and more efficient than the 1 kg/day system, would require 2.3 MW of power, or 20 GWh annually.

A boundary analysis determines whether or not a distributed renewable energy system could independently provide the electricity needed for producing 1500 kg of hydrogen per day at the forecourt. Such a station would require 3.5 MW of power, or 31 GWh of electricity annually. Assuming a PV system can provide 100 W per square meter of PV array, and the PV array has a capacity factor of 20%, a fueling station of this size would require at least 175,000 square meters (43.2 acres) of PV cells. A distributed wind system would require 11 MW of installed turbine capacity assuming a class 5 wind source with a 32% capacity factor (see Table 1) to meet the entire energy needs of this hydrogen fueling station. Assuming 5 MW of wind turbines could be installed on each square kilometer, a station providing 1,500 kg of hydrogen would require a wind farm of approximately 2.2 km^2 (540 acres). Both these boundary analyses assume energy storage is available in some form. Such large renewable systems at the forecourt seem unlikely in a populated region. However, several other scenarios deserve a more detailed feasibility analysis including: fueling stations fed from renewable electricity generation decoupled from the forecourt; renewable on-site electricity generation and grid electricity blend; remote renewable energy generation blended with on-site renewable energy supplies; or using solar energy in conjunction with high temperature electrolysis. These scenarios are of interest because certainly enough renewable energy resources exist to provide the electricity needs for renewable hydrogen generation, but the most economic configuration has yet to be identified.

5. CONCLUSIONS

The renewable electrolysis analysis work at NREL focused on three different aspects of the electrolysis system: solar and wind resource availability, cost analysis, and annual energy requirements. Each analysis has helped to define the challenges and opportunities for hydrogen produced from renewable electricity to participate in the future hydrogen economy. Ample solar and wind resources exist to meet the transportation fuel needs of the United States, but renewable energy systems face challenges to reduce the cost of electricity and to independently meet the energy requirements of distributed fueling stations.

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