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ScienceDirect

Solar Energy 81 (2007) 773–780

SOLAR ENERGY

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An analysis of hydrogen production from renewable electricity sources ☆

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Received 22 November 2005; received in revised form 28 August 2006; accepted 4 October 2006
Available online 13 November 2006

Communicated by: Associate Editor S.A. Sherif

Abstract

Three aspects of producing hydrogen via renewable electricity sources are analyzed to determine the potential for solar and wind hydrogen production pathways: 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 kg^{-1}, using electrolyzers available in 2004, electricity prices would have to be less than \$0.01 kWh^{-1}. Additionally, energy requirements for hydrogen refueling stations are in excess of 20 GWh/year. It may be challenging for dedicated renewable systems at the filling station to meet such requirements. 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 configurations to provide renewable energy to distributed hydrogen refueling stations.

Keywords: Renewable hydrogen; Distributed refueling; Solar hydrogen; Wind hydrogen; Hydrogen production; Electrolysis; Hydrogen resource analysis

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: $2H_2O \rightarrow 2H_2 + O_2$ (Cox and Wiliamson, 1977). In this study, we assumed that the electricity used to split the water molecule comes from wind and solar energy. The authors considered three aspects of the renewable electrolysis system: 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

The authors, 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

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☆ This work has been authored by an employee of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the US Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

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doi:10.1016/j.solener.2006.10.005

determination, analysts identified the potential for hydrogen generation from photovoltaic (PV) and wind energy in the United States, and compared that to the country's motor gasoline consumption in 2000 (Conner, 2005). Geographical information system (GIS) data on actual 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.

PV combined with low temperature electrolysis was used for the solar electricity generation technology in this assessment because such a system provides a boundary for the greatest energy requirement for solar conversion to hydrogen. If PV shows potential, then technologies that use heat with electrical energy or heat alone, such as high temperature electrolysis (Takahashi, 1979) and thermochemical (Sato, 1979) cycles, will also show potential, as they need less electrical energy to split the water since some or all of the energy is provided as heat. Also, technologies that directly split water into hydrogen and oxygen photoelectrochemically will be more efficient as hydrogen is produced directly from sunlight and water (Turner, 2004). Finally, PV to hydrogen via low temperature electrolysis is a technology that exists today. High temperature electrolysis, thermochemical cycles, and photoelectrochemical conversion are longer term technologies, which may or may not be viable large scale technologies in the future.

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 specific designations (parks, wilderness, wilderness and study areas, wildlife refuges, wildlife areas, recreational areas, battlefields, monuments, conservation areas, recreational areas, and wild and scenic rivers), conservation areas, water, wetlands, and airports/airfields. All of these land and water areas are completely excluded; the land areas also exclude 3 km surrounding perimeters (NREL, 2006a). Furthermore, we assumed that solar energy can be converted to electricity at an average system efficiency of 10%. Current PV efficiencies range from 10% to 15%; and with cell/module and inverter efficiency improvements could reach 15–20% in the next decade (DOE, 2006c).

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 US wind resource data were used. The grid cell resolution of these data varies from 200 m to 1 km for the newer high-resolution data, and 25 km for the 1987 low-resolution wind data (NREL, 2006b). 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. Table 1 shows wind class capacity factors and was used to calculate the actual potential electricity generation from each grid cell. The wind capacity factor is defined as how much energy is actually produced from the wind turbine divided by how much energy the turbine would produce if it ran 100% of the time. So a wind Class 3 capacity factor of 0.2 means that a 1 MW turbine in that wind class would only produce 0.2 MW of power (Milbrandt and Mann, 2006).

As with the solar data, environmental and land use exclusions were defined to account for areas where wind energy development would be prohibited or severely restricted:

- 100% excluded are all National Park Service areas, Fish and Wildlife Service lands, all federal lands with special designations (parks, wilderness and study areas, wildlife refuges, wildlife areas, recreational areas, battlefields, monuments, conservation areas, recreational areas, and wild and scenic rivers), conservation areas, water, wetlands, urban areas, and airports/airfields. The land areas also exclude a 3 km surrounding perimeter.
- 50% exclusions were applied to the remaining Forest Service lands, Department of Defense lands, and non-ridge crest forest.

This study also excludes areas with slopes greater than 20% for the high-resolution data. These areas are considered too steep for siting wind turbines (Milbrandt and Mann, 2006).

2.2. Hydrogen potential from renewable electricity

Once the potential electricity production from wind and solar was determined, the hydrogen production potential could be calculated. The potential energy generation from PV and wind was combined with an electrolyzer system

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

energy requirement to calculate the amount of hydrogen that could be produced from renewable resources across the United States. For this study, we assumed that an electrolyzer requires 53 kWh to produce a kilogram of hydrogen. A system using 53 kWh/kg is a 75% efficient system if the basis is the higher heating value (HHV) of hydrogen, 39 kWh/kg (Ivy, 2004). Typical energy requirements for electrolysis systems range from 53 to 70 kWh/kg (Ivy, 2004), with larger systems having higher efficiencies. This requirement represents the entire energy requirement of the system, including the electrolysis cell stack, any energy requirements from system auxiliaries, and system losses.

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 PV, wind, and combined PV and wind energy for each county can be seen in Figs. 1–3 (Wipke et al., 2004).

2.3. Resource analysis results

The results verified that there are abundant solar and wind energy resources to produce enough hydrogen to meet transportation fuel demand for the entire country using hydrogen. The gasoline consumption of the United States as a whole was 128 billion gallons (3,063,390 thousand barrels (Conner, 2005)) of gasoline in 2000. According to this study, the potential for hydrogen production from PV and wind for the entire country is 1110 billion kg of hydrogen. As a kilogram of hydrogen is roughly equivalent to a gallon of gasoline in energy content, 8.7 times the year 2000 gasoline consumption in the United States can be met using hydrogen produced from PV and wind. This result does not include any energy needed for compression, storage, or delivery.

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. Because hydrogen is costly to deliver, ideally the hydrogen use point should be located as close to the production point as possible. States were used as a way to break the nation into logical smaller areas. See Fig. 4 for a graphical representation of these results.

The state with the highest hydrogen production potential from PV and wind is Texas with 106 billion kg of hydrogen. The state with the lowest potential production of hydrogen from PV and wind is Rhode Island with 0.2 billion kg of hydrogen. Washington DC is even lower with the production potential of 0.005 billion kg of hydrogen from PV and wind. All but five states and Washington DC have enough renewable resources to meet transportation needs at the state level. New Jersey, Rhode Island, Massachusetts, Connecticut, Maryland, and Washington DC 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. So, ample resources are available in the small New England and mid-Atlantic regions.

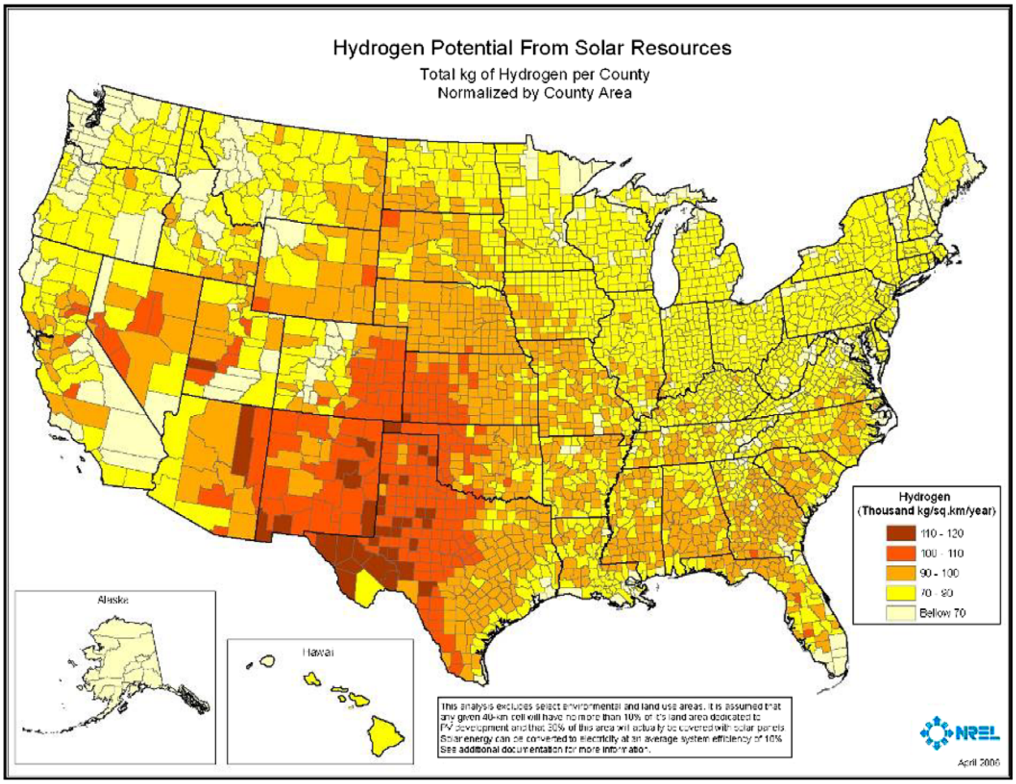
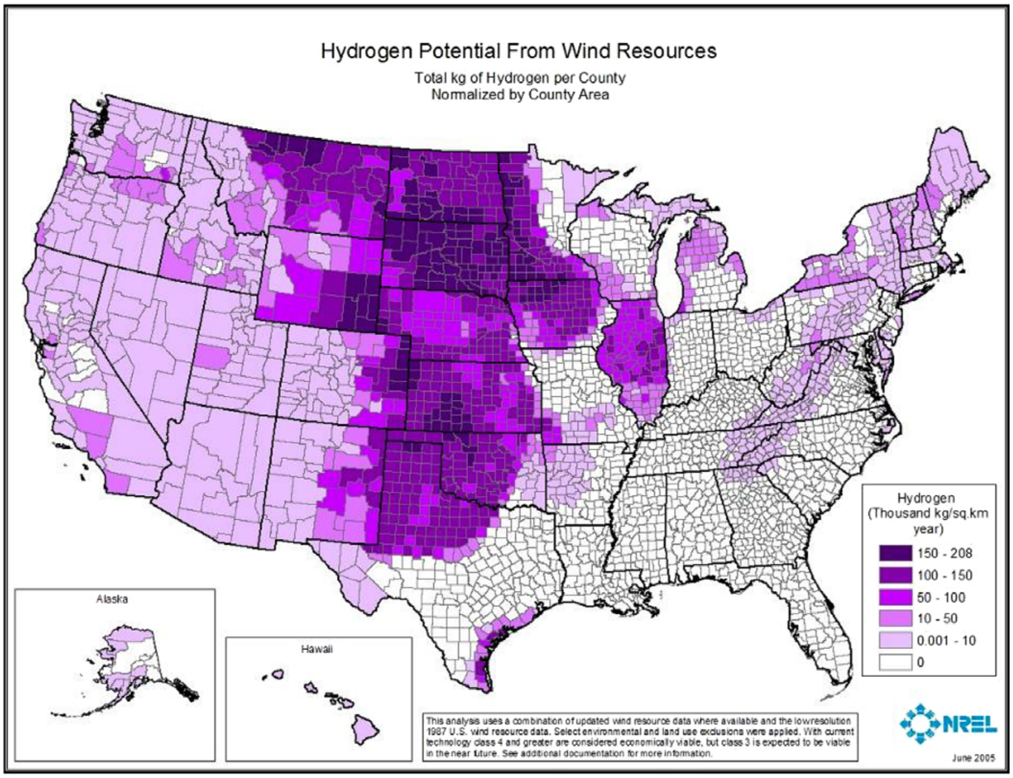


Fig. 1. Total kilogram of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from solar.



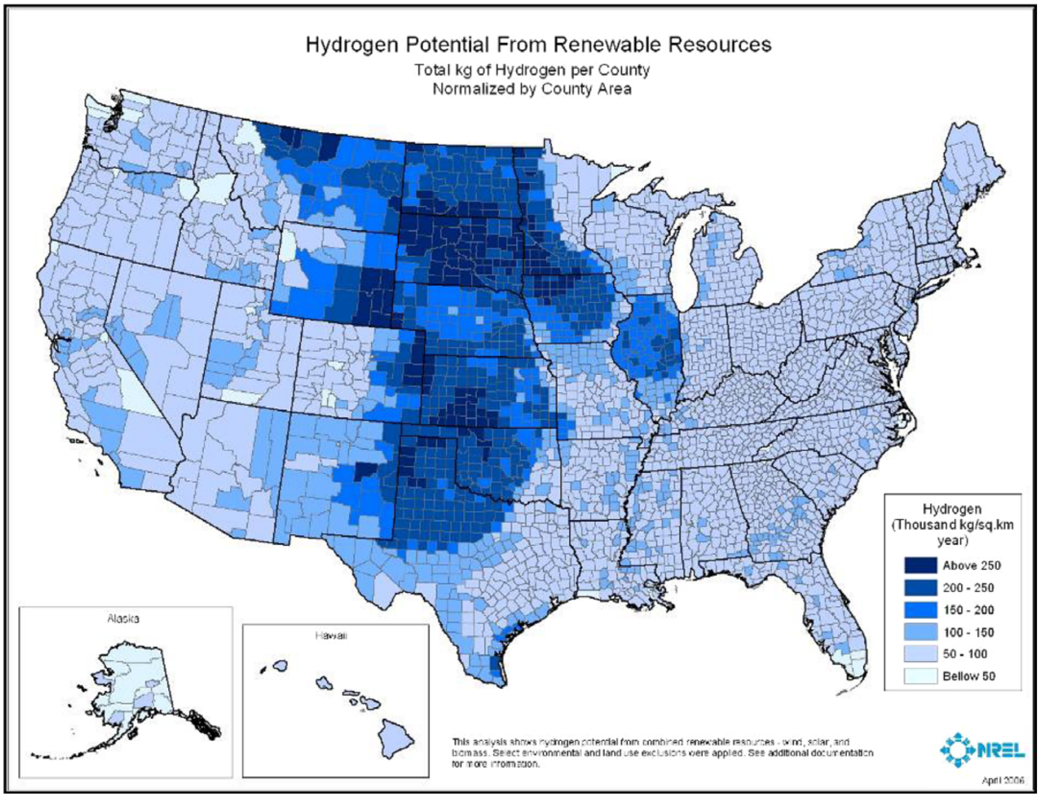
Hydrogen Potential From Wind Resources

Total kg of Hydrogen per County
Normalized by County Area

This analysis uses a combination of updated wind resource data where available and the lowresolution 1987 U.S. wind resource data. Select environmental and land use exclusions were applied. With current technology class 4 and greater are considered economically viable, but class 3 is expected to be viable in the near future. See additional documentation for more information.

June 2005

Fig. 2. Total kilogram of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from wind.



Hydrogen Potential From Renewable Resources

Total kg of Hydrogen per County
Normalized by County Area

This analysis shows hydrogen potential from combined renewable resources - wind, solar, and biomass. Select environmental and land use exclusions were applied. See additional documentation for more information.

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Fig. 3. Total kilogram of hydrogen per county, normalized by county area. This analysis shows the hydrogen potential from combined wind and solar resources.

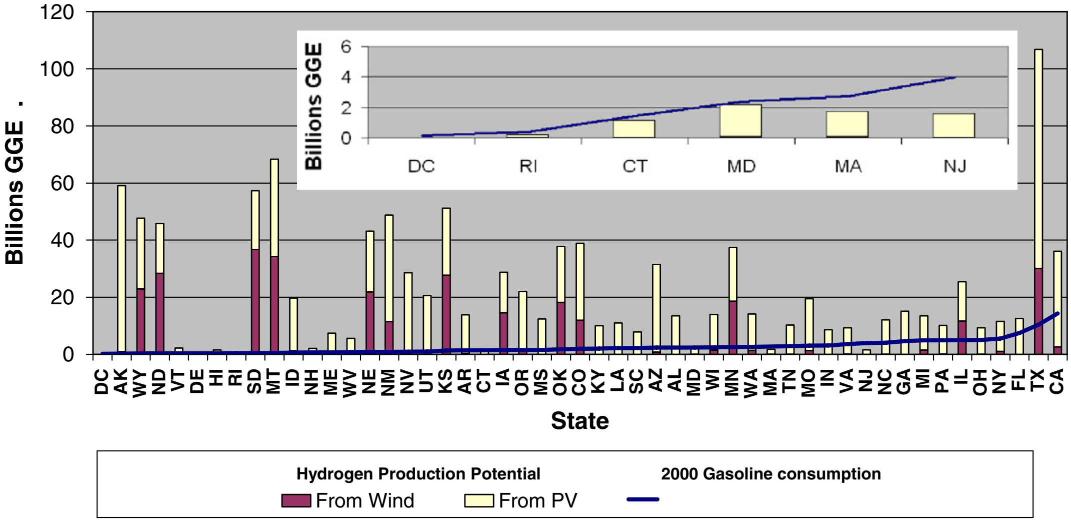

Fig. 4. Gasoline usage vs. renewable hydrogen potential. Gasoline consumption is plotted on the solid line in terms of gallons of gasoline consumed in the year 2000. The potential for hydrogen production is plotted in the dark bars (wind potential) and the light bars (PV potential). The inset shows a 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 the cost of hydrogen from renewable electricity sources. In order to determine the cost of hydrogen, other analysis methodologies need to be employed.

3.1. Boundary analysis

The authors' 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, all available in 2004: Stuart IMET; Teledyne HM and EC; Proton HOGEN; Norsk Hydro HPE and Atmospheric; and Avalence Hydrofiller (Ivy, 2004). For each electrolyzer, the system energy requirement was used to determine how much electricity is needed to produce hydrogen. Fig. 5 shows the results of this study.

This analysis demonstrated that at electrolyzer energy requirements from 54 to 67 kWh/kg (72–58% efficient on a HHV basis of hydrogen respectively), electricity costs must be between \$0.04 and \$0.055 kWh^{-1} to produce hydrogen at lower than \$3.00 kg^{-1}. For an ideal system operating at 100% efficiency (39 kWh/kg), electricity costs must be less than \$0.075 kWh^{-1} to produce hydrogen at lower than \$3.00 kg^{-1}. 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 increasing the efficiency of the electrolyzer can provide limited improvement to the cost of hydrogen. Thermodynamically, low-temperature electrolyzers cannot be more efficient than the ideal line shown in Fig. 5. Thus, the only way to decrease the amount of electricity needed 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 and 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 US Department of Energy's (DOE) Hydrogen Analysis (H2A) Central Modeling Tool, designed for cost analyses of central hydrogen production (DOE, 2006b). Key parameters used in the analysis are presented in Table 2.

The standard H2A assumptions for electricity prices were used, with projected electricity prices through 2070. The projections from 2001 through 2025 come from the 2004 Annual Energy Outlook published by the Energy Information Administration (EIA) (Aniti, 2004). 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 Mini Climate Assessment Model (MiniCAM) (Geffen, 2003). The H2A industrial electricity price ranges from \$0.044 to \$0.050 kWh^{-1}, and was \$0.045 kWh^{-1} in 2005. The H2A commercial electricity price ranges from \$0.067 to \$0.077 kWh^{-1}, and was \$0.069 kWh^{-1} in 2005 (DOE, 2006b). All electricity prices are in terms of year 2000 dollars.

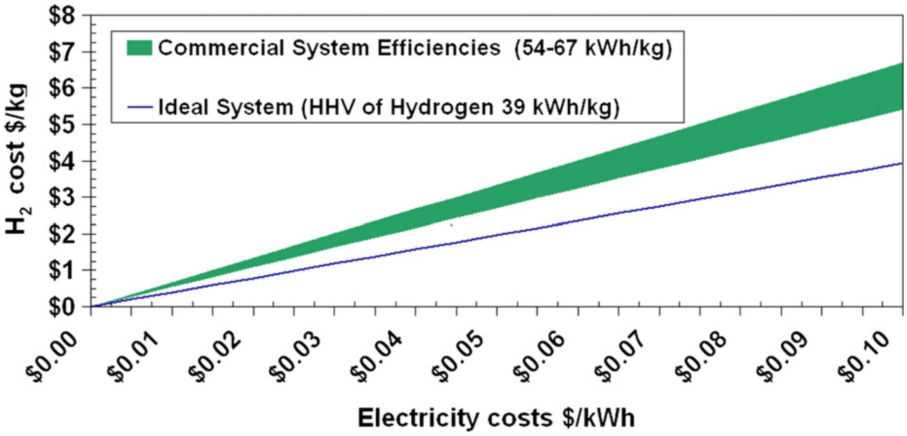

Fig. 5. The cost of hydrogen production via electrolysis considering only electricity contribution (no capital, operating, or maintenance costs are included). This analysis demonstrates that regardless of any additional cost elements, electricity costs will be a major price contributor to the price of hydrogen produced via electrolysis.

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 ($/acre)	5000
Operation and maintenance (O&M) parameters	
Burdened labor ($/h)	50
Overhead and G&A (% of labor cost)	20
Property tax and insurance rate (% of depreciable capital costs)	2

Fig. 6 displays the results of the DCF analysis. For electrolysis units available in 2004, which produce 1000 kg of hydrogen per day, the cost driver for hydrogen is the electricity cost. With industrial electricity, 59% of the $\$4.09\,\mathrm{kg}^{-1}$ hydrogen cost is from electricity. If more expensive commercial priced electricity is used, the cost of electricity makes up approximately 68% of the $\$5.40\,\mathrm{kg}^{-1}$ cost of hydrogen. The increased electricity costs led to a 32% increase in hydrogen costs. The second most important factor is capital cost. The slight variation between the two systems' capital cost is due to the working capital being a function of the operating costs, which include the higher electricity price. In both cases, the cost of fixed O&M is $\$0.37\,\mathrm{kg}^{-1}$ 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 is available at average US industrial or commercial electricity prices. However, the cost of electricity from renewable sources can vary widely from these average values. The graph in Fig. 7 shows how the DCF calculated price of hydrogen varies according to electricity price. In contrast to the boundary analysis shown in Fig. 5, Fig. 7 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 15% capital cost reduction plus 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. 7 can be used to determine the cost of hydrogen from electrolysis for electricity prices up to $\$0.15\,\mathrm{kWh}^{-1}$. For

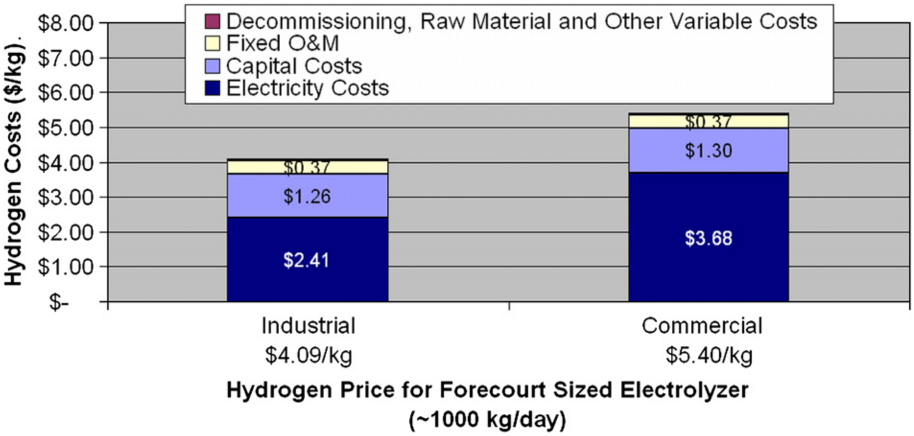

Fig. 6. Effects of electricity price on hydrogen costs on filling-station-sized electrolyzers (year 2000 dollars). The cost of producing 1000 kg of hydrogen per day via electrolysis using industrial and commercial electricity prices.

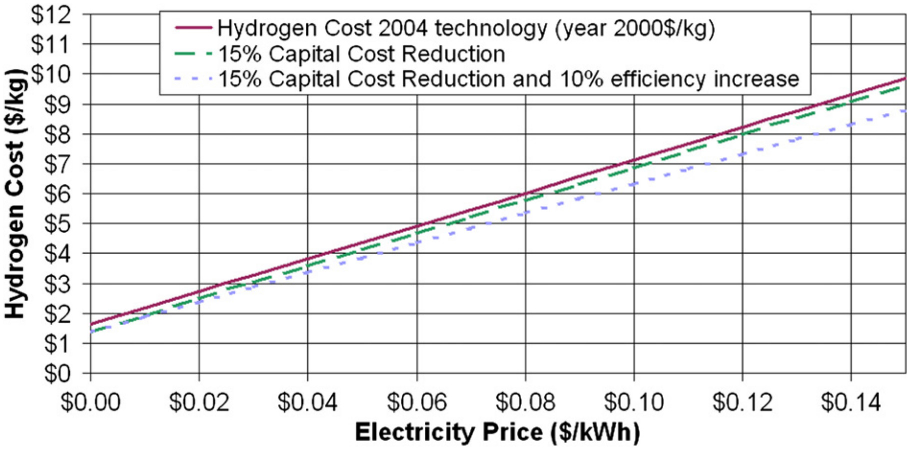

Fig. 7. How hydrogen cost varies with electricity price. The linear relationship between electricity price in $/kWh and hydrogen cost in $/kg.

example, using 2004 technology, \$0.02 kWh^{-1} electricity yields a hydrogen price of \$2.70 kg^{-1} and \$0.14 kWh^{-1} electricity yields \$9.30 kg^{-1} of hydrogen. If electricity is free, the lowest price hydrogen the 2004 electrolysis units can produce is \$1.60 kg^{-1} of hydrogen. To produce \$2.00 kg^{-1} hydrogen, electricity prices will need to be available for \$0.007 kWh^{-1}, \$0.011 kWh^{-1}, and \$0.012 kWh^{-1} with 2004 technologies, a 15% capital cost reduction, and a capital cost reduction plus an efficiency improvement, respectively. Thus, to be competitive with \$2 gal^{-1} 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 several system improvements need to be made for renewables to be able to produce hydrogen at prices that can compete with \$2–3 gal^{-1} gasoline (DOE, 2006a) prices using 2004 technology. Electricity will have to be produced at rates lower than today's industrial electricity prices. Another option is that an optimized hybrid system of renewable and grid electricity be deployed. This system will purchase electricity from the grid when prices are low, and use electricity from renewable sources when grid prices are high, potentially allowing for lower average electricity price and higher equipment utilization than when renewable electricity is used alone.

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 kg of hydrogen per day to 1000 kg of hydrogen per day (Ivy, 2004). The authors calculated that the 1 kg/day unit would fuel one car per week, assuming a 6 kg/fill average. An electrolyzer with this fill rate could be used for home refueling. The 1000 kg/day unit would fill approximately 170 cars per day, and would be considered a small filling station 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 standard system sizes analyzed by the H2A team (DOE, 2006b). 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 was 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. The energy needed for compression, storage, and dispensing at the fueling station is estimated to be 2.2 kWh/kg, and would add a power requirement of 92 kW, 800 MWh annually, to the 1000 kg/day fueling station.

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 filling station. 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% (PowerLight, 2003), 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 1500 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 filling station 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 filling station, 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 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 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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