

Modeling the Market Potential of Hydrogen from Wind and Competing Sources

Preprint

W. Short, N. Blair, and D. Heimiller

*To be presented at WINDPOWER 2005
Denver, Colorado
May 15–18, 2005*

Conference Paper
NREL/CP-620-38138
May 2005

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

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/ordering.htm>



Modeling the Market Potential of Hydrogen from Wind and Competing Sources

WINDPOWER 2005 CONFERENCE POSTER SESSION

Walter Short, Nate Blair, Donna Heimiller
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
walter_short@nrel.gov

1. ABSTRACT

The Wind Deployment Systems (WinDS) model is a multiregional, multitime-period, Geographic Information System (GIS), and linear programming model, designed to address the principal market issues related to the penetration of wind energy into the electric sector over the next 50 years. These issues include transmission cost/access and the intermittency of wind power. WinDS examines these issues via a highly discrete regional structure, with explicit accounting for the transient variability in wind output, and consideration of ancillary services requirements and costs.

The modified WinDS model, HyDS (Hydrogen Deployment Systems model), is expanded to include the production of hydrogen from three competing technologies—wind, steam methane reforming (SMR), and distributed electrolysis powered by electricity from the grid—along with storage and transportation of hydrogen. Electrolyzers at the wind site can be powered either by wind power or by power from the electric grid. Hydrogen from wind or distributed electrolyzers can be used as either transportation fuel or as input energy to a fuel cell. The fuel cell is assumed to generate power during peak electric-load periods. In HyDS, a market for hydrogen as a transportation fuel exists in each city. The market clearing price is set exogenously. The three competing sources supply hydrogen up to the total transportation demand for fuel, but only if they can do so at the market clearing price or less. This paper presents initial results from this new model.

2. BACKGROUND and MODEL OVERVIEW

Developed from the WinDS model, HyDS is a computer model of U.S. market expansion of hydrogen production from wind and other sources over the next 50 years. The WinDS model was developed in 2003¹ to model the expansion of generation and transmission capacity in the U.S.

¹ Short, Walter; et al., May 2003, “Modeling the Long-Term Market Penetration of Wind in the United States,” WindPower 2003 Proceedings, Austin, Texas

electric sector spanning the next 50 years. It minimizes system-wide costs of meeting loads, reserve requirements, and emission constraints by building and operating new generators and transmission in 26 two-year periods from 2000 to 2050. While it includes all major types of conventional generators, the WinDS model focuses on addressing the market issues of greatest significance to wind—specifically issues of electricity transmission and intermittency. WinDS includes class 3-7 wind for both onshore and offshore wind resources. More details on the WinDS model can be found in the companion paper prepared for the AWEA 2005 Conference, “Reduced Form of Detailed Modeling of Wind Transmission and Intermittency for Use in Other Models.”

HyDS incorporates all the wind details of the WinDS model, but expands the focus to include hydrogen production and transportation. As shown in **Figure 1**, it includes not only the production of hydrogen from wind electrolysis, but also the transport of that hydrogen to load centers—and competition at those load centers with hydrogen from distributed electrolysis and steam methane reforming. The model also provides for fuel cells at the wind sites and at distributed electrolyzers to firm-up the wind power and to provide general energy storage for the electric grid.

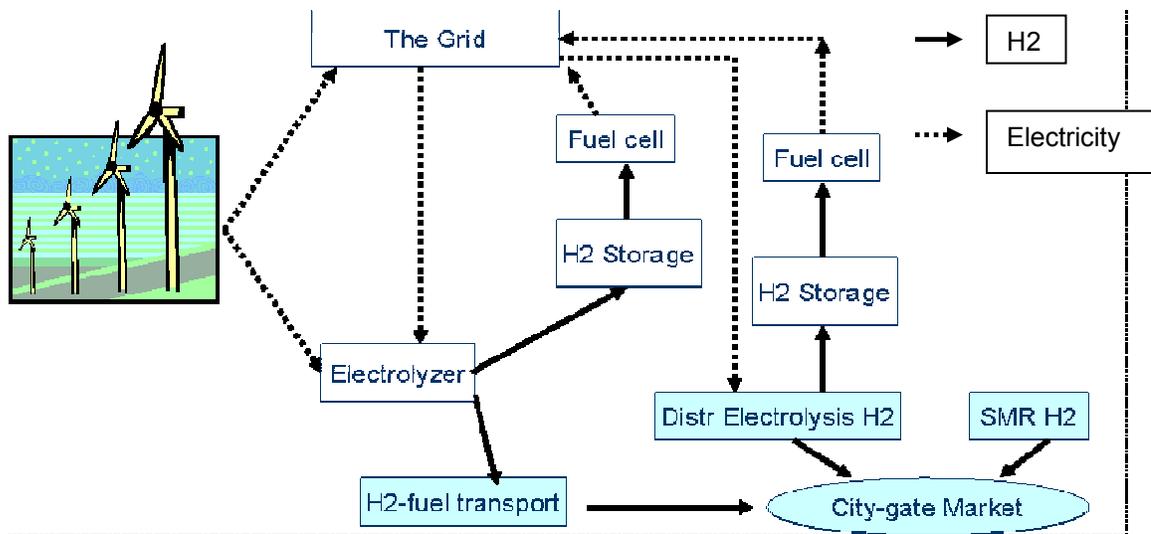


Figure 1. Hydrogen and Electricity Production and Transport from Wind

HyDS is designed to address the issues of greatest importance to the production of hydrogen from wind. These include the seasonal and diurnal timing of hydrogen production from wind, the cost of that production, use of the hydrogen as a form of storage within the electric grid, and the transport of the hydrogen to load centers for use as a transportation fuel.

Similar to WinDS, HyDS addresses the critical issues of hydrogen transport by using a much higher level of geographic disaggregation than other models. As **Figure 2** represents, HyDS includes 358 different regions in the United States. Much of the data inputs to HyDS are tied to these regions and derived from a detailed GIS model/database of fuel demands, the wind

resource, transmission grid, and existing plant data. This relatively fine regional disaggregation in HyDS allows the model to calculate transportation distances for hydrogen, as well as transmission distances for electric power.

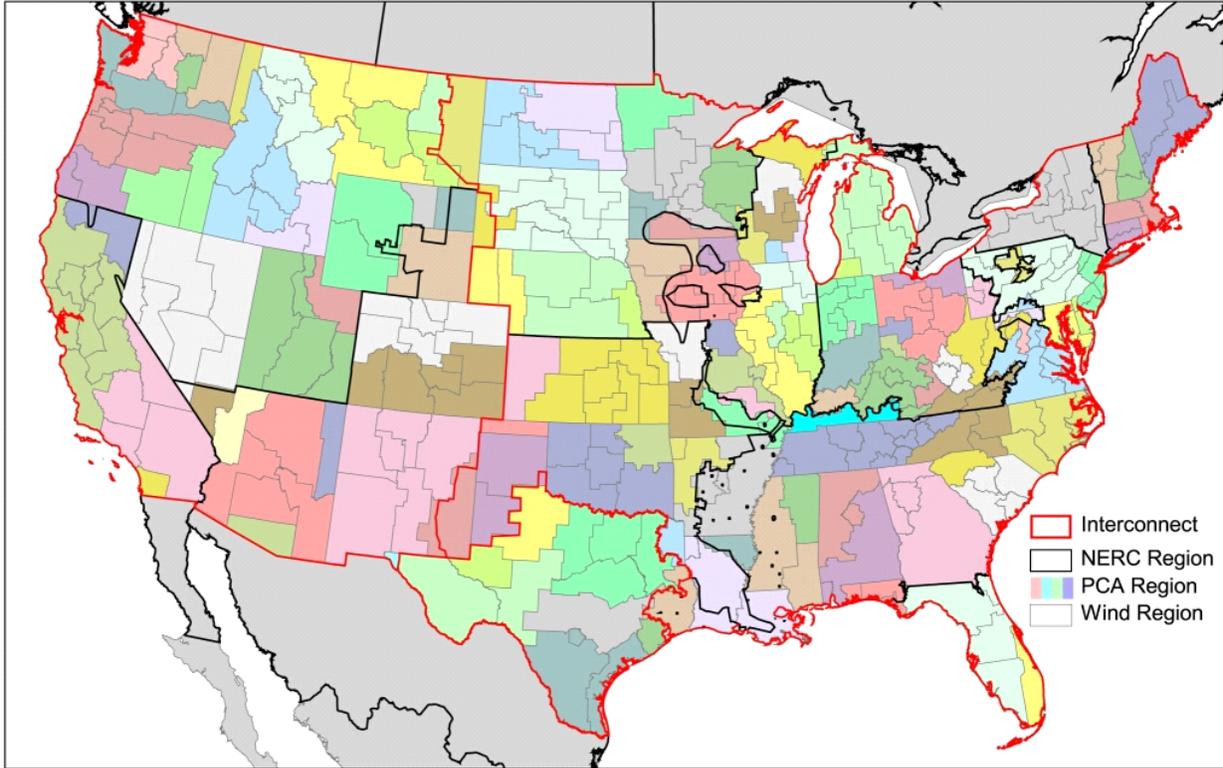


Figure 2. Regions within HyDS

Linear programs, such as HyDS, work by minimizing an objective function. The HyDS objective function is a minimization of all the costs associated with:

- Producing hydrogen to meet transportation fuel demands
- Transporting that hydrogen to load centers as needed
- Electric generation and transmission capacity installed in each period
- Operating costs for the electric system—fixed and variable operation and maintenance (O&M), fuel costs, and ancillary services.

By minimizing these costs while meeting the system constraints (discussed below), the linear program determines which types of new hydrogen and electric capacity are the most economical to add in each period and for each region in the country. It also determines when to operate that capacity.

The cost minimization that occurs within HyDS is subject to 73 types of constraints, which result in thousands of equations in the model (due primarily to the large number of regions). These constraints fall into several main categories, including:

- *Hydrogen demand limits:* Preclude the hydrogen production from exceeding the demand for transportation fuels in any individual region. HyDS will produce hydrogen for each region only if the cost of production is less than the exogenously specified market price. Transportation fuel demand not met by hydrogen is assumed to be met by other fuels.
- *Hydrogen production limits:* The hydrogen produced in a region in a time period must be less than the production capacity available. In addition, for wind, it must be less than the wind generation available from the wind capacity.
- *Fuel cell generation transmission limits:* Prevent fuel cell and direct wind turbine output at a wind site from exceeding the transmission capacity available to the site.
- *Wind resources:* The total amount of wind installed in each region must be less than the wind resource potentially available.
- *Wind access to existing transmission lines:* The amount of new wind-power capacity that can be transmitted on existing lines is limited by the transmission capacity available on nearby lines. The GIS portion of HyDS determines which wind resources would be most cost-effective in using existing transmission capacity.
- *Load constraints:* The primary load constraint is that the electric load in each power control area (there are 136 power control areas in HyDS) must be met in each time-slice (of which there are 16) throughout a year. The load and its rate of growth in each North American Electric Reliability Council (NERC) region are derived from the Reference Case of U.S. Energy Information Agency's (EIA) Annual Energy Outlook.
- *Reserve margin constraint:* There are two types of reserves constraints—planning reserve margin and operating reserve. For the reserve margin constraint, HyDS updates its estimate (for each period) of the marginal capacity value of the next wind farm built in each region, using a detailed statistical approach. The capacity value is set equal to the amount of load that could be added—along with the wind—without changing the risk of a shortage in generation capacity at peak load times. The approach accounts for the dispersion of the wind sites contributing to the load and the correlation in the output of those sites.
- *Operating reserve constraint:* The operating reserve requirement induced by each new wind farm is also modified each period for each region. The additional operating reserve requirements due to wind are not proportional to the amount of wind, but rather to the variance in the sum of the normal operating reserve and the wind generation. This means that the operating reserves induced by wind are generally low per unit of wind capacity initially, but can grow quickly if the wind capacity becomes a significant part of system capacity—especially if the output of the new wind capacity is highly correlated with that of existing capacity.
- *Wind Surplus:* HyDS also accounts for surplus wind-generated electricity that is lost at the interconnection region level. When demand is low and the wind is blowing, there can be instances where the wind generation cannot all be used. HyDS uses the variance of the sum of all wind generation—together with a load duration curve and the forced outage rates of conventional technologies—to stochastically compute the expected amount of wind that cannot be used.
- *Emissions constraints:* At the national level, HyDS caps the air emissions from fossil-fueled generators for sulfur dioxide, nitrogen oxides, mercury, and carbon. The annual national emission caps and the emissions per MWH are input by the user.

3. BASE CASE COST ASSUMPTIONS

In this analysis, the Base Case is a business-as-usual case that relies heavily on the Reference Case scenario of the U.S. Energy Information Agency Annual Energy Outlook for 2004² to determine inputs that fall outside the scope of HyDS. These include electricity demand, fossil fuel prices, existing federal energy policies, and the cost and performance of non-wind electric-generating technologies.

Table 1 shows the hydrogen technology cost inputs over time, which are derived from the DOE Program goals for hydrogen as published in the spring of 2004. A key assumption in this base case analysis is that hydrogen will be produced by these technologies for use as a transportation fuel, only if it is competitive with other transportation fuels. Based on the DOE Program goals, the breakeven cost of hydrogen with these alternative fuels is assumed to be \$2/kg in 2003 dollars in the base case.

Table 1. Base Case Hydrogen Technology Cost Inputs

Technology	Capital Cost	Efficiency %
Electrolyzer	\$150/kWe	80
Fuel Cell	\$400/kWe	50
Steam Methane Reformer	\$4/kg per year	70

Onshore wind-power cost and performance data are derived from projections made in 2002 by Princeton Energy Resources International³ (PERI) for the DOE Wind Program. In addition to the R&D driven improvements over time shown in **Table 2**, HyDS also allows for “learning” improvements in both the hydrogen and wind technologies’ costs and efficiencies.

² United States Department of Energy (DOE), Energy Information Administration (EIA), “Annual Energy Outlook 2004,” January 2004, DOE/EIA-0383(2004)

³ Personal communication with Joe Cohen of Princeton Energy Resources International (PERI), April 29, 2003

Table 2. Base Case R&D-Driven Onshore Wind Costs and Performance

Capital Cost \$/kW	Class	2005	2010	> 2020
	3	929	923	916
	4	916	914	899
	5	898	898	881
	6	880	880	864
	7	880	880	864
Capacity Factor				
	3	0.25	0.275	0.30
	4	0.29	0.35	0.36
	5	0.35	0.40	0.41
	6	0.42	0.45	0.47
	7	0.44	0.47	0.49

There are two possible cost synergisms between the wind turbines and the co-located electrolyzers and hydrogen storage. First, the electronic controls for the wind turbines and electrolyzers can be combined into one. This was assumed to reduce the wind-sited electrolyzer capital cost by 12.5%. Second, the wind turbine towers could provide a storage vessel for the on-site storage of hydrogen. This was assumed to reduce the capital cost of on-site storage by 40%

Fuel prices are probably as important as the above technology costs in determining the potential for hydrogen from wind. **Figure 3** shows the average national base case fuel prices (prices vary by NERC region within HyDS). Through 2025, the price of natural gas and coal are derived from the DOE’s Annual Energy Outlook 2004, with post-2025 prices extrapolated at the same rate as between 2005 and 2025. These prices are obviously subject to considerable uncertainty, especially given that through 2025 the natural gas prices are lower than today’s prices.

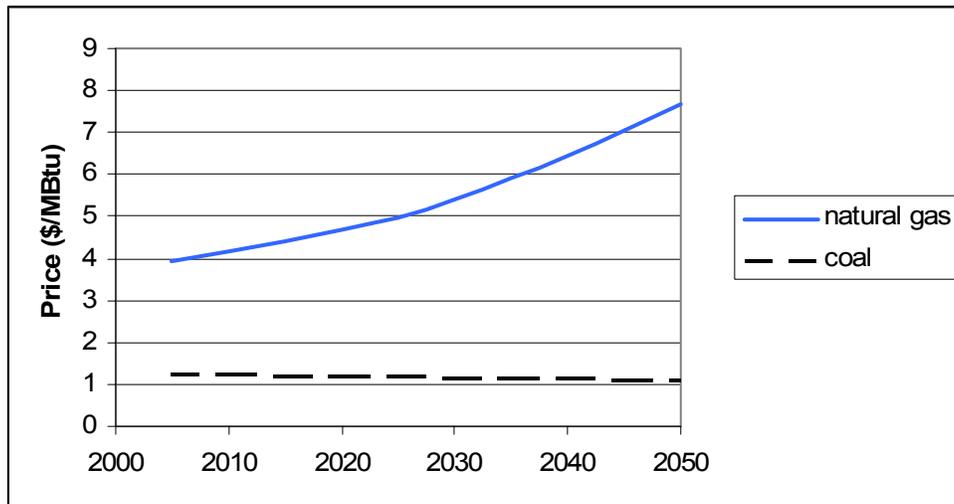


Figure 3. Base Case Fuel Prices

4. BASE CASE RESULTS

Wind: With these Base Case inputs, HyDS projects that wind will provide about 210 GW of electricity capacity to the grid in 2050, far larger than today’s 6 GW (see top slice of graph in **Figure 4**). This growth is largely attributable to improvements in the cost and performance of wind turbines—however, there are other drivers. By about 2014, the increase in natural gas prices (as forecast by the AEO2004) stalls the recent growth in new installations of combined-cycle, natural gas-fired power plants (third slice from the bottom in Figure 4). At about the same time, installations of advanced pulverized coal plants with stringent emission controls begin to penetrate the new-build market (second slice from the top in Figure 4). To accommodate these new coal plants under the Phase 2 provisions of Title IV XXX of the Clean Air Act, existing coal plants switch to low-sulfur coal and install scrubbers (third and fourth slice from the top in Figure 4).

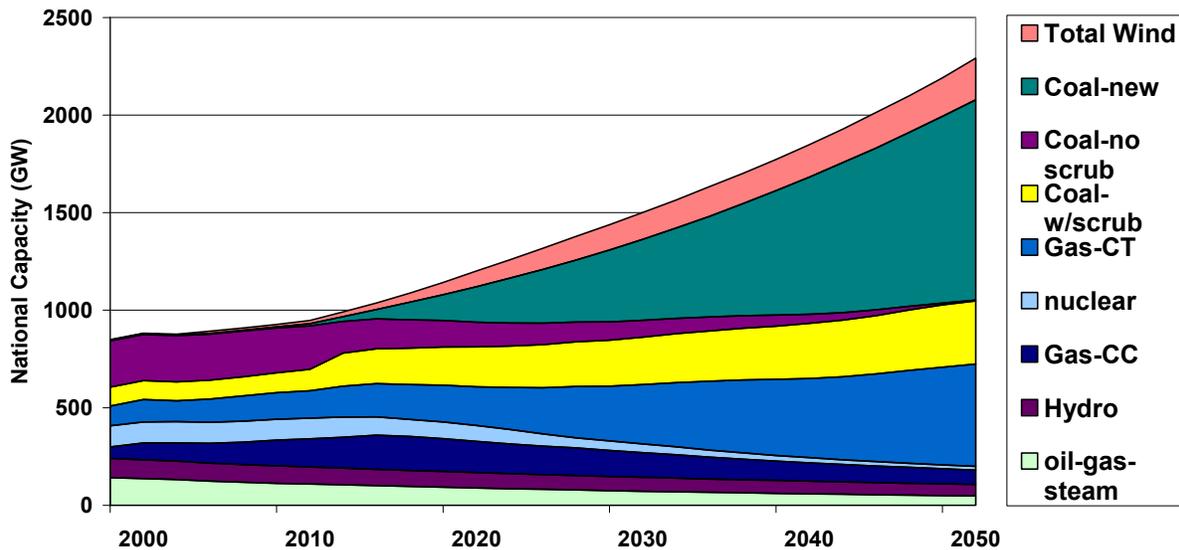


Figure 4. National Capacity Projections for the HyDS Base Case

Realistically, the role of future coal plants in the base case may be somewhat mitigated by the fact that the increase in demand for coal will put upward pressure on coal prices—HyDS currently does not capture such feedback. Because it is not a general equilibrium model, but only a model of capacity expansion in the electric sector, HyDS does not include price elasticity for coal or other fossil fuels. In addition, our base case does not include any penalty for carbon emissions.

Hydrogen: Additional wind capacity is constructed in this base case to generate a limited amount of hydrogen at the wind sites. As the map in **Figure 5** shows, hydrogen production in 2050 from this base case is greatest where there is a reasonable wind resource near a significant population center. For example, southeastern California near the Los Angeles region, western

Iowa near Chicago, and southwestern New York state near New York City all have areas with annual hydrogen production greater than 195 kilotons in 2050. Additionally, wind hydrogen production is seen in areas with significant wind resources such as the north-central United States and the Midwest.

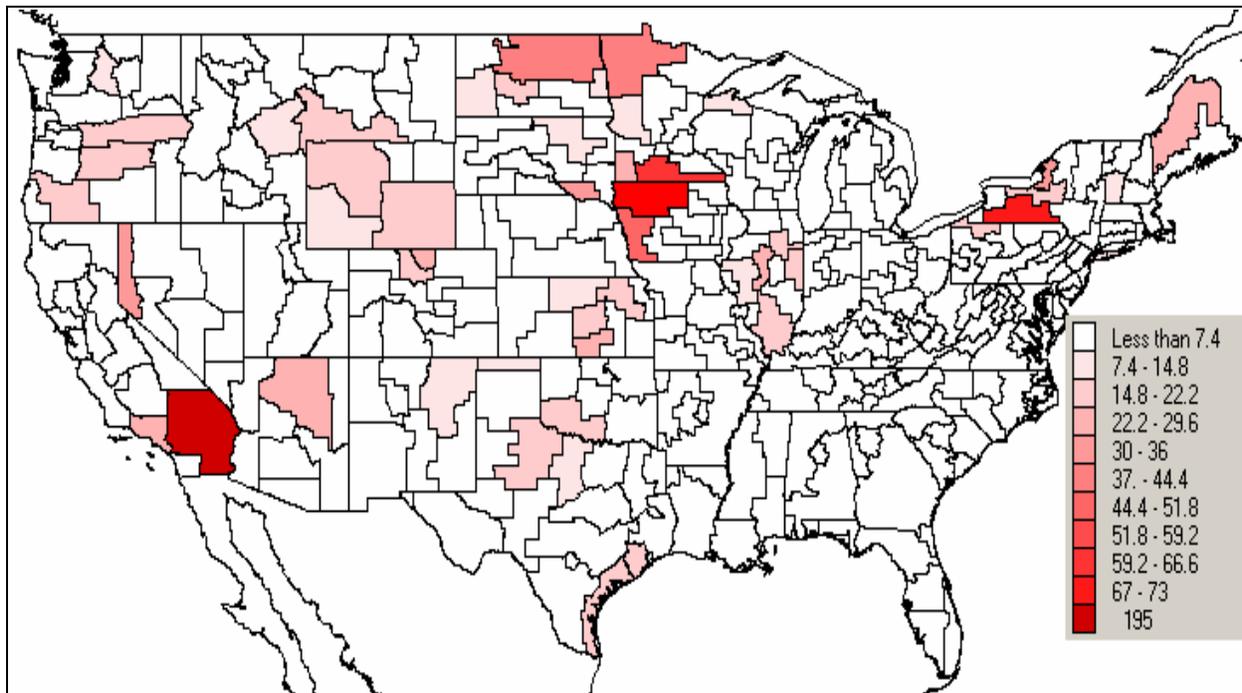


Figure 5. Annual H2 Production from Wind in 2050 (kilo tons)

From the base case, we can also examine the viability of various hydrogen production pathways. For example, **Figure 6** shows that, by 2050, approximately 28 GWe of distributed electrolyzers are deployed to produce hydrogen. To help meet the additional electricity demand of these distributed electrolyzers, approximately 25 GWe of additional wind energy are deployed by 2050, as shown in Figure 6. Much of the electricity from these new wind turbines is transported to the distributed electrolyzers, as the transport of electricity across regions is generally more economical than the transport of hydrogen.

While the distributed electrolyzers provide more hydrogen, hydrogen is also produced at wind sites for use as a transportation fuel and to shore up wind power in 2030 and beyond. Also shown in Figure 6, co-located wind turbine/electrolyzer systems are deployed with approximately 9 GWe of capacity in 2050. In addition, fuel cells are deployed at wind sites with approximately 8 GWe of capacity by 2050.

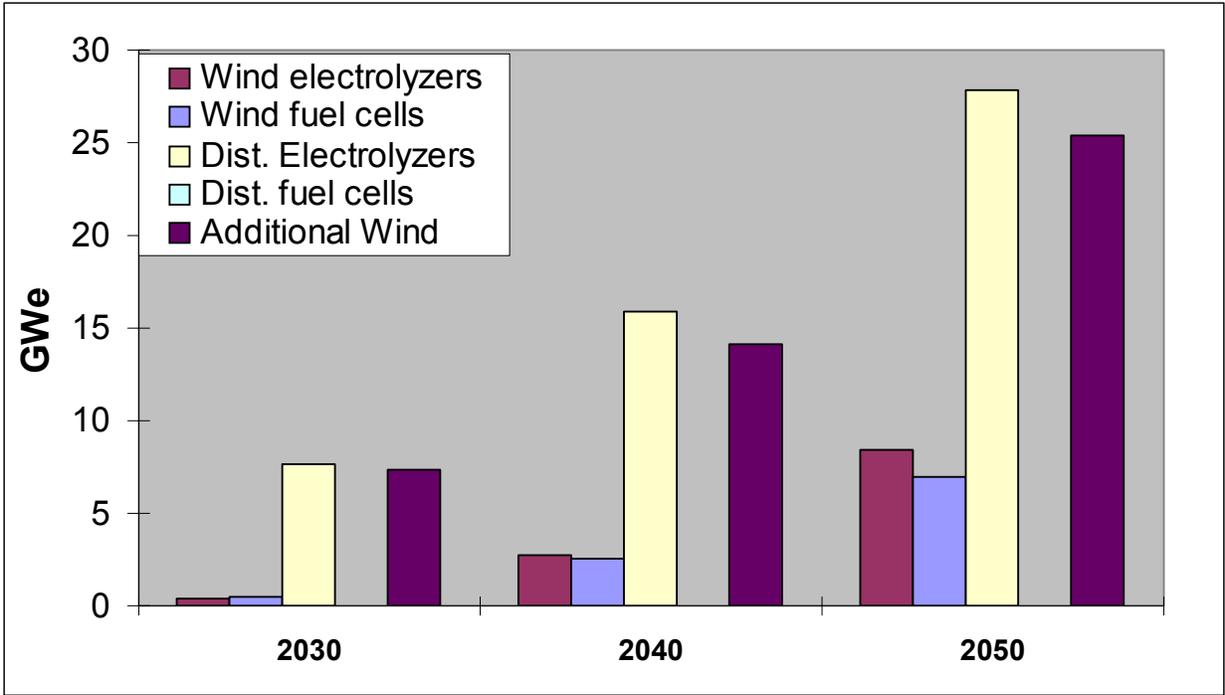


Figure 6. Base Case Hydrogen Technology Capacity

Figure 7 shows the amount of hydrogen produced by each technology, and reveals that a majority of the electricity fed to the wind-sited electrolyzers is drawn from the grid when the wind is not blowing. This grid power allows the amortization of the wind-sited electrolyzer costs over a substantially larger output. Figure 7 also shows that, in 2050, the bulk (1.3 Bkg) of the hydrogen produced by the wind-sited electrolyzers (1.4 Bkg) is used as a transportation fuel, with the remainder (0.1 Bkg) stored on-site for generation of power through a fuel cell at times of peak electric load. Because the base case produces hydrogen from wind only when it can be produced for less than or equal to \$2/kg, a higher market price for hydrogen would significantly increase the amount of fuel produced. Most of this wind-sited production of hydrogen transportation fuels occurs in regions where the wind resource is close to towns and cities, and therefore requires little or no transport by pipeline. Less than 2% of the hydrogen transportation fuel from wind is transported between regions within the model.

In the base case, the distributed electrolyzers are not accompanied by fuel cells. Although distributed fuel cells would have capacity value equal to their nameplate capacity, they do not allow the reduction of transmission-line size, as do their counterparts located at wind sites.

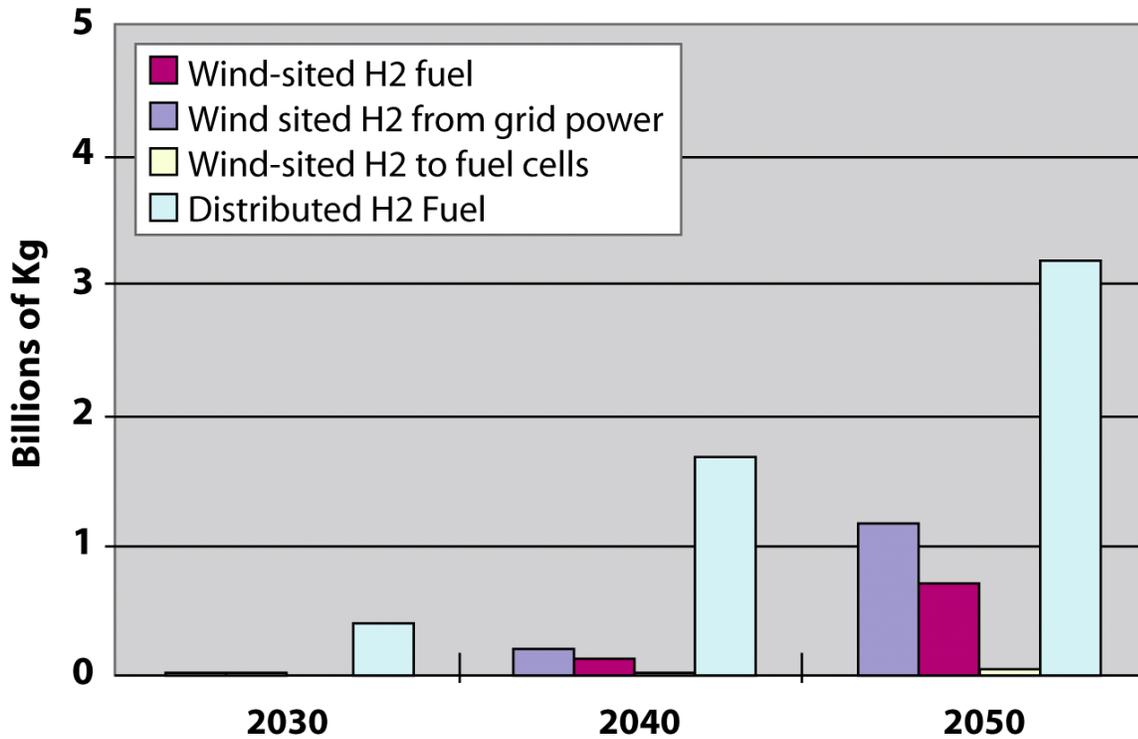


Figure 7. Base Case Hydrogen Fuel Production

Figure 8 shows that the 8 GW (see Figure 6) of fuel cells installed at the wind sites by 2050 are located in remote regions with substantial wind resources. These fuel cells provide two advantages. First, they allow a reduction in the size of any new transmission built, because they allow the wind generation at times of peak wind speeds to be stored as hydrogen and used to produce power at times of peak electric load. Second, they are sited in regions where significant wind generation capacity has already been installed. Without the storage provided by electrolysis/fuel cells, any additional wind capacity installed at these sites would have negligible capacity value, because the output from the new turbines would be completely correlated with the output of existing turbines in the region. Thus, fuel cells at these sites provide capacity value essentially equal to their nameplate capacity. Figure 7 shows that these fuel cells require very little of the hydrogen produced by the wind-sited electrolyzers, because they operate only during peak load periods.

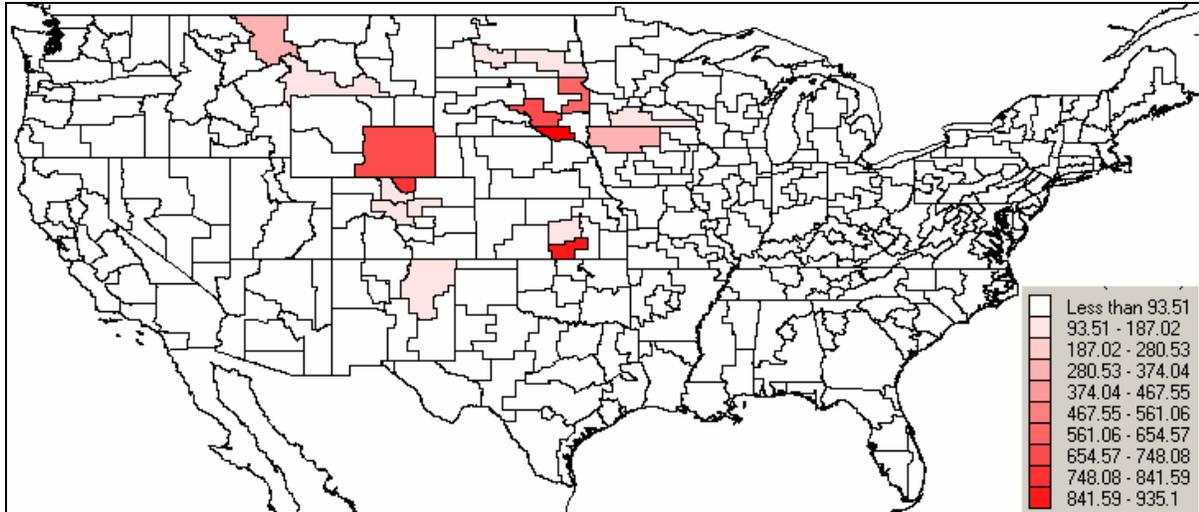


Figure 8. 2050 Wind-Sited Fuel Cells (MW) in the Base Case

Although Figure 6 shows considerable potential exists for electrolysis capacity, based on the fuel prices shown in Figure 3, the most economical method for producing hydrogen in the early years is steam methane reforming (SMR) of natural gas. In **Figure 9**, SMR production of hydrogen dominates electrolysis by several orders of magnitude in the first quarter century. In those early years, the HyDS results are constrained only by price increases due to rapid growth in SMR plants and the size of the transportation fuel market itself. In the real world, the production of such large amounts of hydrogen from natural gas would probably strain natural gas supplies and increase natural gas prices; in HyDS, such feedbacks on fuel prices are not modeled. In HyDS, SMR hydrogen production starts to decline by 2040, when the price of natural gas is too high to warrant the construction of new SMR plants to replace those built in the first quarter of the century.

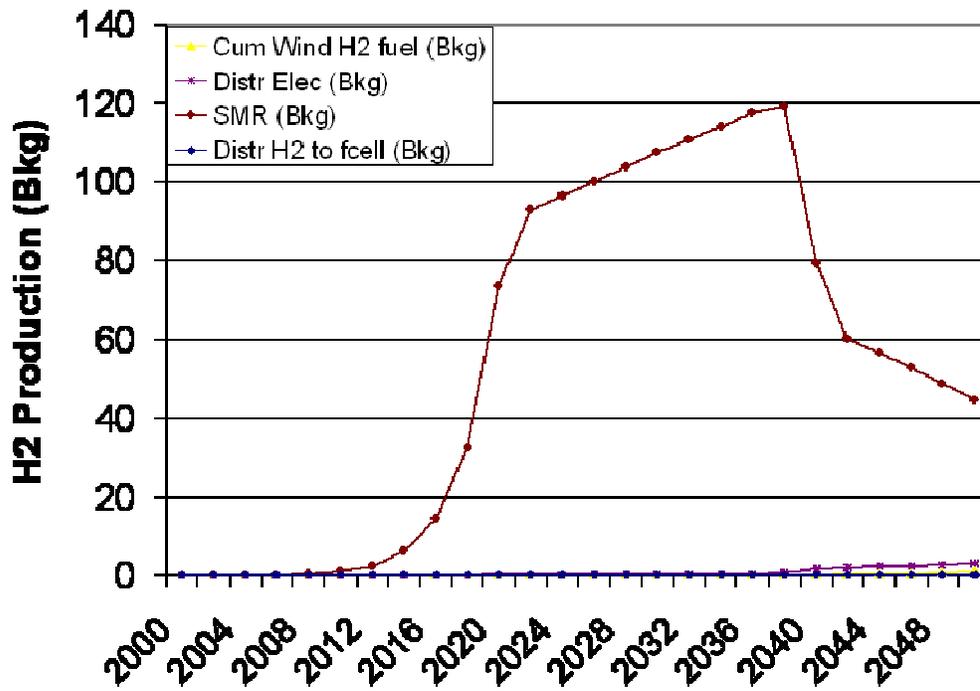


Figure 9. Hydrogen Production from Steam Methane Reforming and Electrolysis

CONCLUSIONS

- If the cost and performance of wind turbines continue to improve, wind energy will contribute a substantial share of future U.S. electric generation.
- Wind energy will also contribute to the production of hydrogen through electrolyzers located primarily at load centers, but also at wind sites.
- Hydrogen production at wind sites will probably be largely limited to wind sites that are coincident with hydrogen loads, minimizing hydrogen transport costs.
- Remote, well-developed wind sites with some remaining high-quality undeveloped wind resources may use electrolyzers and fuel cells to shift wind electricity production to peak periods and minimize the costs of transmission lines.
- The most economical source of hydrogen for the near term is steam methane reforming of natural gas.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE (DD-MM-YYYY) May 2005			2. REPORT TYPE Conference Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Modeling the Market Potential of Hydrogen from Wind and Competing Sources: Preprint				5a. CONTRACT NUMBER DE-AC36-99-GO10337		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) W. Short, N. Blair, and D. Heimiller				5d. PROJECT NUMBER NREL/CP-620-38138		
				5e. TASK NUMBER HY55.2300		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393				8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-620-38138		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT (Maximum 200 Words) Developed from the Wind Deployment Systems (WinDS) model, the Hydrogen Deployment Systems (HyDS) model is a computer model of U.S. market expansion of hydrogen production from wind and other sources over the next 50 years. The WinDS model was developed in 2003 to model the expansion of generation and transmission capacity in the U.S. electric sector spanning the next 50 years. It minimizes system-wide costs of meeting loads, reserve requirements, and emission constraints by building and operating new generators and transmission in 26 two-year periods from 2000 to 2050. While it includes all major types of conventional generators, the WinDS model focuses on addressing the market issues of greatest significance to wind—specifically issues of electricity transmission and intermittency.						
15. SUBJECT TERMS Wind Deployment Systems Model; WinDS; Hydrogen Deployment Systems Model; HyDS; GIS; wind; analysis models; wind power; production tax credit; PTC; renewable portfolio standard; RPS; wind resources; wind classes; wind markets; load constraints; offshore wind; PERI; Walter Short; Nate Blair; Donna Heimiller						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code)	