A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

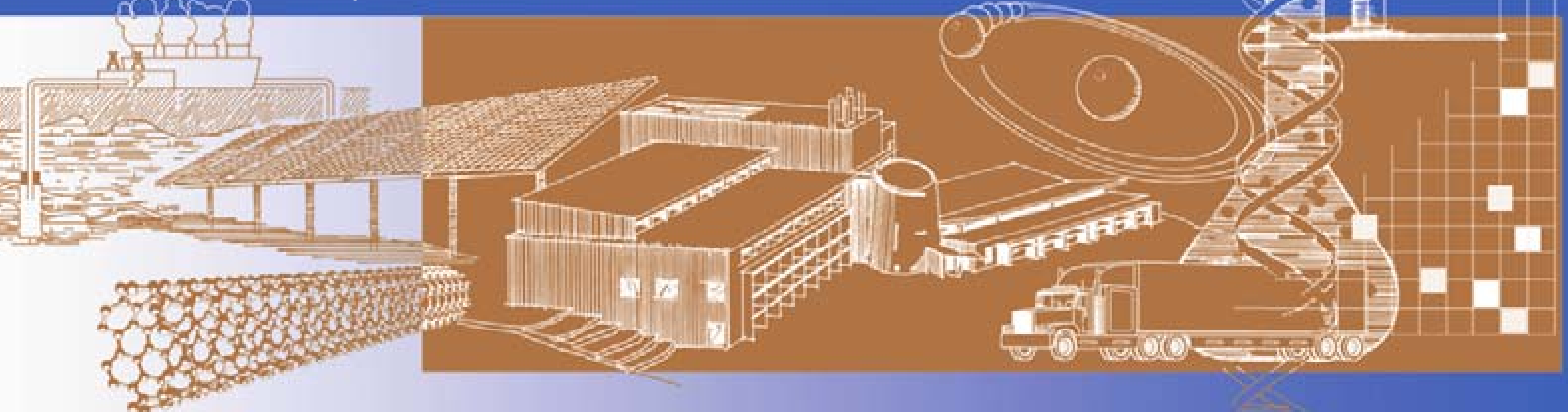
National Renewable Energy Laboratory
Innovation for Our Energy Future

Potential for Hydrogen Production from Key Renewable Resources in the United States

A. Milbrandt and M. Mann

Technical Report
NREL/TP-640-41134
February 2007

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



Potential for Hydrogen Production from Key Renewable Resources in the United States

Technical Report
NREL/TP-640-41134
February 2007

A. Milbrandt and M. Mann

Prepared under Task No. H278.2100

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

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

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Acknowledgments

The study was performed by analysts at the U.S. Department of Energy's National Renewable Energy Laboratory under contract number DE-AC36-99-GO10337. For their valuable contributions, the authors would like to acknowledge Donna Heimiller and Johanna Levene from the National Renewable Energy Laboratory. A special thanks to Fred Joseck from the U.S. Department of Energy's Hydrogen Program for his continued assistance, which made the completion of this study possible.

Executive Summary

This study was conducted to estimate the potential for producing hydrogen from key renewable resources (onshore wind, solar photovoltaic, and biomass) by county in the United States and to create maps that allow the reader to easily visualize the results. To accomplish this objective, the authors analyzed renewable resource data both statistically and graphically utilizing a state-of-the-art Geographic Information System (GIS), a computer-based information system used to create and visualize geographic information.

Land-use and environmental exclusions were applied to represent the most viable resources across the country. While wind, solar, and biomass are considered major renewable resources, other renewable energy resources could also be used for hydrogen production, thus contributing to hydrogen development locally and regionally. These additional resources include offshore wind, concentrating solar power, geothermal, hydropower, photoelectrochemical, and photobiological resources.

This study found that approximately 1 billion metric tons of hydrogen could be produced annually from wind, solar, and biomass resources in the United States. The greatest potential for producing hydrogen from these key renewable resources is in the Great Plains region. In addition, this research suggests that renewable hydrogen has the potential to displace gasoline consumption in most states if and when a number of technical and scientific barriers can be overcome.

Contents

List of Figures

List of Tables

Introduction

Hydrogen is the simplest element and most plentiful gas in the universe. Today, most hydrogen is produced from fossil fuels, but to most effectively impact the emissions and energy import balances associated with transportation fuels, hydrogen must be produced from domestically available renewable resources such as wind, solar, and biomass.

There are many options for producing hydrogen from renewable resources. This study considers hydrogen production using wind and solar electrolysis as well as gasification and steam methane reforming methods for converting biomass to hydrogen.

The electrolysis process involves the use of wind- or solar-generated electricity. In this study, a wind turbine is assumed to be used to produce electricity from the wind, and photovoltaic (solar electric) systems are assumed to be used to produce electricity from solar resources. This renewably produced electricity is then used in an electrolyzer, a device that uses electricity to split water into hydrogen and oxygen.

Biomass gasification is the conversion, by partial oxidation at high temperature, of a carbonaceous feedstock (agricultural and woody residues) into a gaseous fuel which is then reformed to produce hydrogen. In the steam methane reforming process, high-temperature steam and a nickel catalyst are used to produce hydrogen from a methane source (such as landfill gas, animal manure, and wastewater sludge).

The objective of this study was to estimate the potential for producing hydrogen from key renewable resources (onshore wind, solar photovoltaic, and biomass) by county for the United States, and to create maps for easy visualization of the results. To accomplish this objective, renewable resource data are analyzed both statistically and graphically utilizing a state-of-the-art Geographic Information System (GIS), a computer-based information system used to create, manipulate, analyze, and visualize geographic information.

Land-use and environmental exclusions were applied to this study to represent the most viable resources across the country. While wind, solar, and biomass are considered major renewable resources, other renewable energy resources could also be used for hydrogen production, thus contributing to hydrogen development locally and regionally. Future analyses could include studying the use of offshore wind, concentrating solar power, geothermal, hydropower, photoelectrochemical, and photobiological resources for hydrogen production.

Potential for Hydrogen Production from U.S. Wind Resources

Data Information

This analysis used updated wind resource data where available at the time the analysis was completed for California, Connecticut, Delaware, Idaho, Illinois, Maine, Maryland, Massachusetts, Montana, New Hampshire, New Jersey, New Mexico, North Carolina, North Dakota, Oregon, Pennsylvania, Rhode Island, South Dakota, Vermont, Virginia, Washington, West Virginia and Wyoming. These data were then combined with low-resolution 1987 U.S. wind resource data. The grid cell resolution of these data varies from 200 m^2–1 km^2 for the high-resolution data and is 25 km^2 for the low-resolution 1987 wind data (Figure 1).

The study considers areas with class 3 annual average wind speeds and greater, at 50 m above ground. These areas are suitable for most utility-scale wind turbine applications, whereas class 2 areas are marginal for utility-scale applications (some may be suitable for rural applications). Class 1 areas are generally not suitable for wind turbine installations. The degree of certainty with which the wind power class can be specified depends on three factors: the abundance and quality of wind data, the complexity of the terrain, and the geographical variability of the resource.[1]

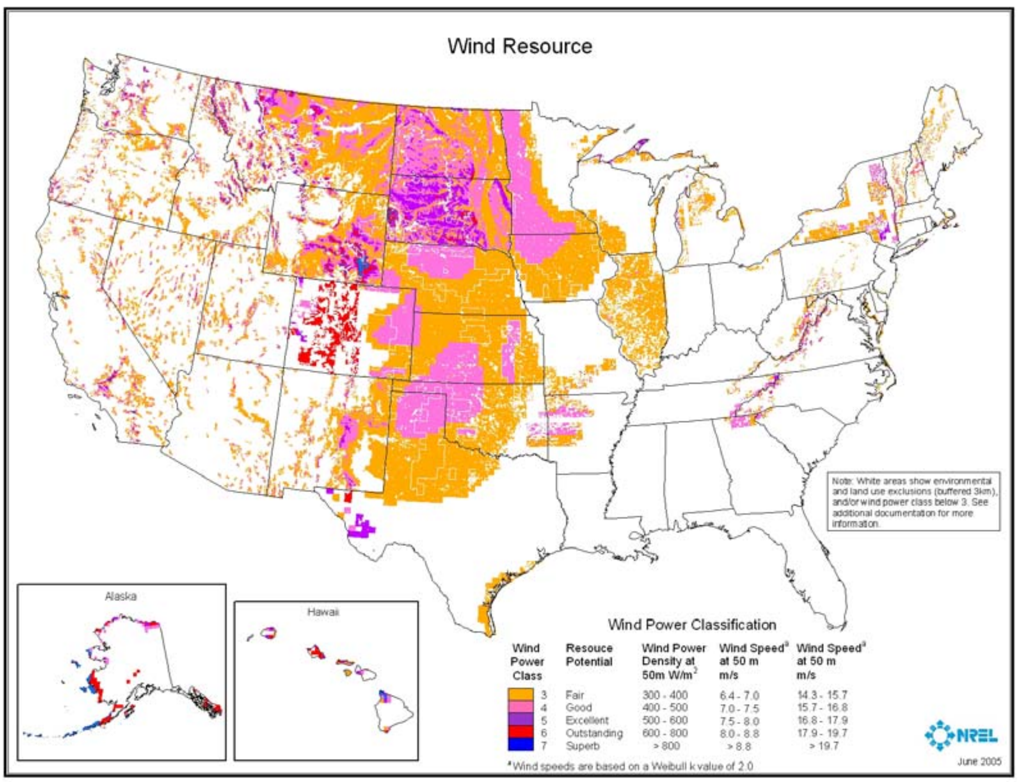


Figure 1. Available windy lands in the United States

[1] Wind data and maps, National Renewable Energy Laboratory, Golden, CO: http://www.nrel.gov/gis/wind.html, March 2005.

Exclusions

The following topographic, land use and environmental exclusions were applied to the analysis of the potential for hydrogen production from wind in this study:

- Completely excluded were areas with slopes greater than 20% for the high-resolution data. These areas maybe too steep for siting wind turbines.
- Environmental and land-use exclusions (Figure 2) were defined to account for lands where wind energy development would be prohibited or severely restricted.
  - 100% excluded: All National Park Service areas; Fish and Wildlife Service lands; all federal lands with a special designation (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; urban areas; and airports/airfields.
  - 50% excluded: The remaining Forest Service and Department of Defense lands and non-ridge-crest forests.
- Entirely excluded: The 3-km area surrounding 100% environmental and land-use exclusions, except for water bodies.

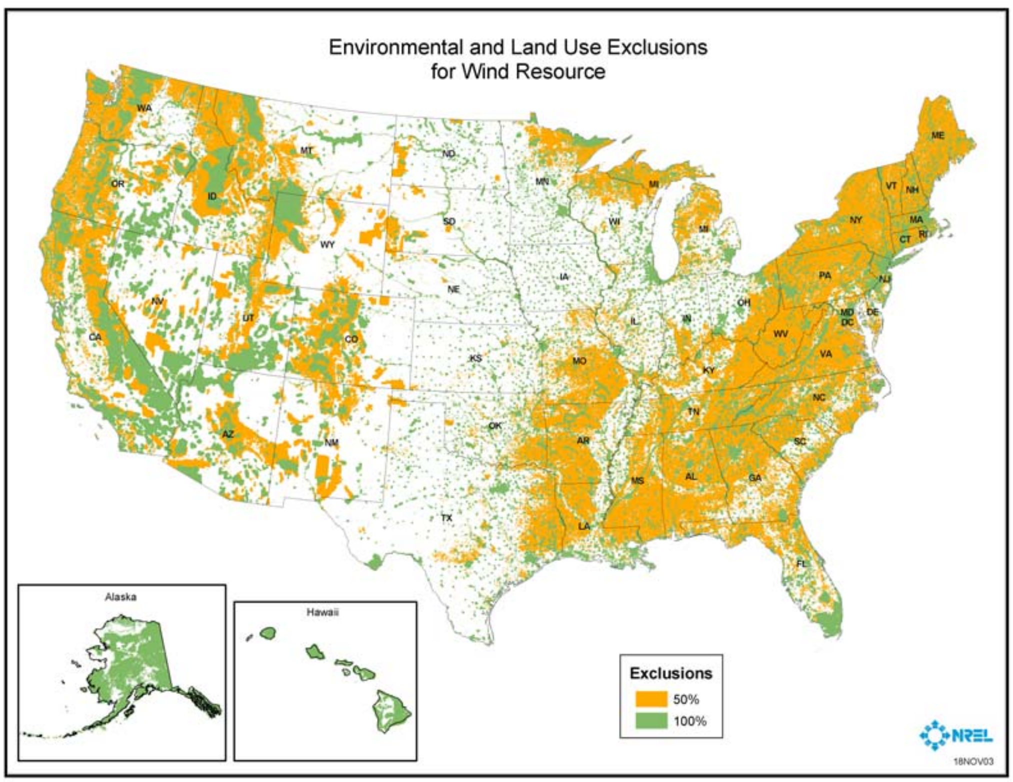


Figure 2. Environmental and land-use exclusions for U.S. wind resources

Additional analysis was performed for the high- and low-resolution data sets:

- Terrain (low-resolution data set only): The low-resolution 1987 wind resource data have assigned to each 25 km^2 grid cell a terrain exposure factor that represents the type of wind climate for exposed features in that grid cell. The terrain factors are 5% exposed for ridge-crest wind, 35% or 65% for hilly areas, and 90% for generally flat terrain.

- Minimum density (high-resolution data set only): Minimum density criteria of 5 km^2 per 100 km^2 of class 3 or better wind resources were applied to the high-resolution data. The purpose of this density analysis is to eliminate small, isolated wind resource areas with a low likelihood of development.

Analysis Methodology

After the exclusions were applied to the wind resource information, the low- and high-resolution data were merged together to create the final wind resource file used to summarize the data by county (Figure 1). Installed nameplate capacity was subsequently calculated, assuming 5 MW/km^2 conversion, and applied to the class 3 or better lands. Table 1 below shows the capacity factor[2] used for this study.

Table 1. Wind Resource Capacity Factor Used in This Study

Class	Year	Capacity Factor
3	2000	0.2
4	2000	0.251
5	2000	0.3225
6	2000	0.394
7	2000	0.394

Source: Power Technologies Energy Data Book[3]

An average hydrogen production rate of 58.8 kWh/kg hydrogen was applied to the final wind dataset, and the total kilograms of hydrogen per county per year were calculated. This hydrogen production rate assumes a 66.3% efficient electrolysis system (higher heating value basis). Typical energy requirements for electrolysis systems range from 53–70 kWh/kg (Ivy 2004), and larger systems have higher efficiencies. The average of the efficiencies of today's electrolyzers from Proton, Avalence, Teledyne, Stuart, and Norsk-Hydro is 58.8 kWh/kg.

Figure 3 illustrates the potential to produce hydrogen from wind in the United States, normalized by county area. Normalization is dividing one numeric value by another to minimize differences in values based on the size of areas. In this study, normalizing the hydrogen from renewable resources (wind, solar or biomass) by county areas, yields hydrogen from these resources per unit area (km^2). This allows transforming the data's measurements so that they can be compared regardless of the size of the counties. For example, a map of the raw hydrogen potential from all renewable resources by county would reveal that many large counties in the West have more resources than most of the counties east of the Mississippi River. A normalized map (Figure 12) reveals that, once the size of the county is factored out, some small counties in the East have similar values as some large counties west of the Mississippi River.

---

[2] Capacity factor is defined as the wind turbine's actual energy output divided by the rated maximum turbine output for the year. When the wind turbine's capacity factor at a given average annual wind speed is known, it allows a reliable calculation of the expected energy output per year. A reasonable capacity factor is 0.25 to 0.30. A very good capacity factor is 0.40.

[3] Power Technologies Energy Data Book, National Renewable Energy Laboratory, Golden, CO: http://www.nrel.gov/analysis/power_databook/, March 2005

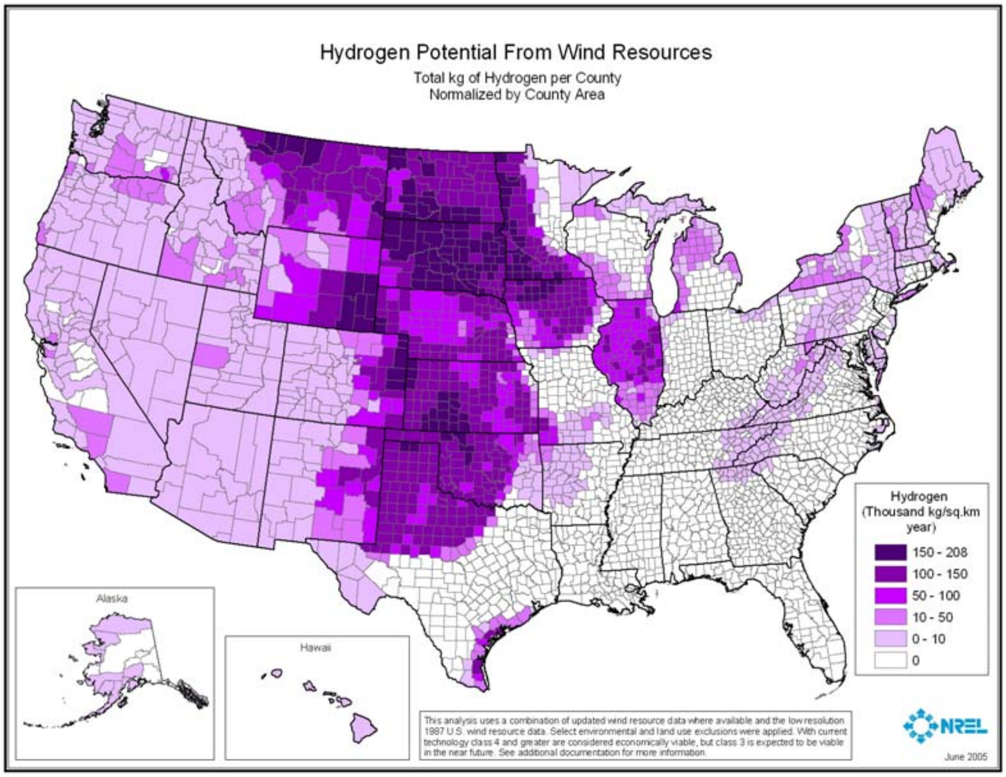


Figure 3. Hydrogen production potential from wind resources, by county

Figure 4 shows the amount of hydrogen that could be produced from wind per person in each county. Less populated counties in the Great Plains combined with very good wind resources define the high hydrogen potential from wind resources per person in this region.

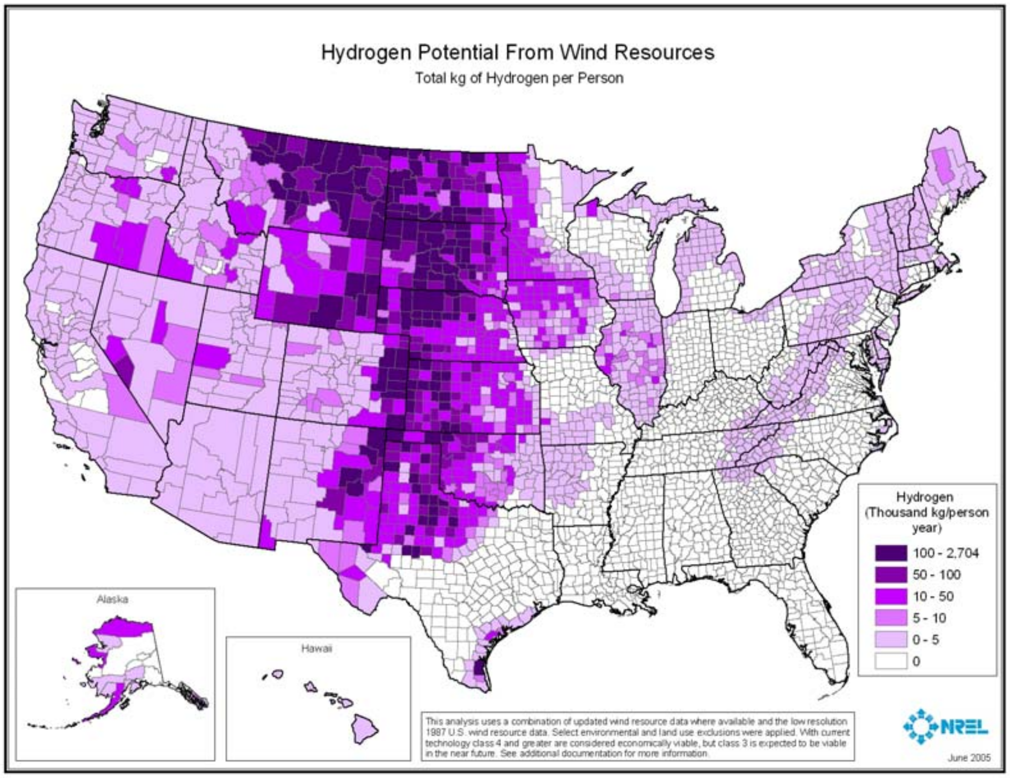


Figure 4. Hydrogen production potential from wind resources, per person

Potential for Hydrogen Production from U.S. Solar Resources

Data Information

This analysis uses solar resources available for nontracking flat-plate collectors oriented toward the south at latitude tilt. Estimates of annual average daily total global radiation falling on these collectors are modeled using inputs derived from satellite and surface cloud cover observations as well as other key meteorological variables. The cloud cover observations are on a 40-km^2 resolution grid representing the period 1985–1991. Values range from about 2.2 $kWh/m^2/day$ in portions of Alaska to about 7.0 $kWh/m^2/day$ in portions of the Southwestern United States (Figure 5).[4]

Exclusions

These environmental and land use exclusions were applied to the solar resources (Figure 6):

- 100% excluded: All National Park Service areas; Fish and Wildlife Service lands; all federal lands with a specific designation (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.
- Also 100% excluded: A 3-km area surrounding environmental and land-use exclusions, except for water bodies.

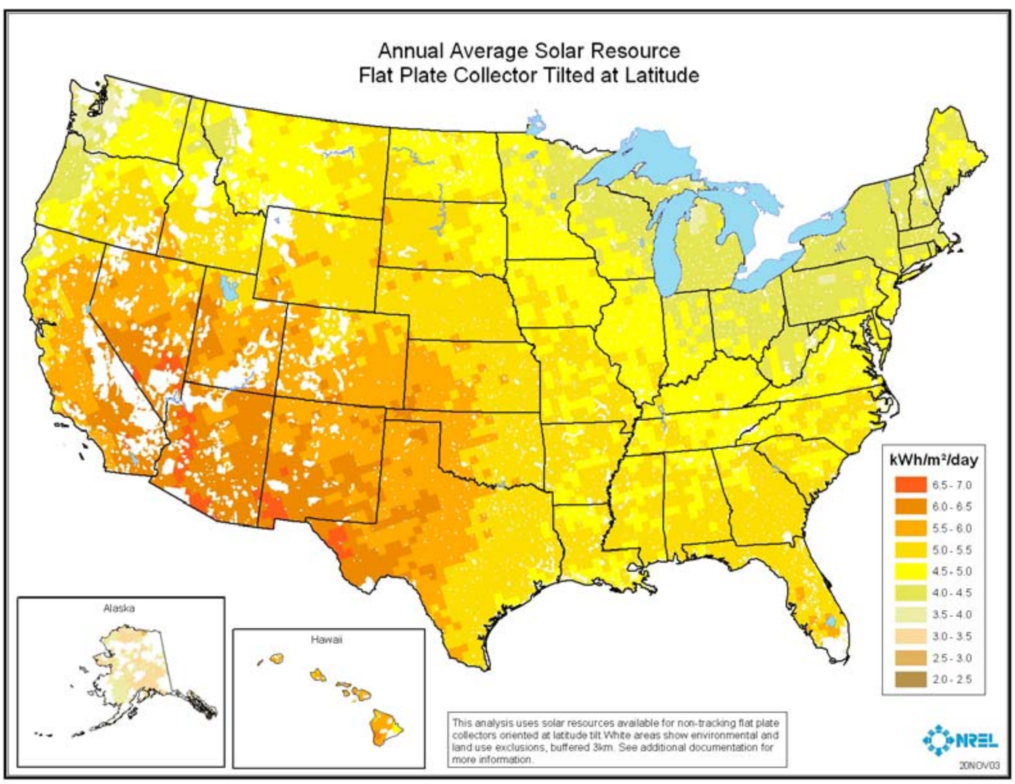


Figure 5. U.S. solar resource: flat-plate collector tilted at latitude

[4] Solar data and maps, National Renewable Energy Laboratory, Golden, CO: http://www.nrel.gov/gis/solar.html, March 2006

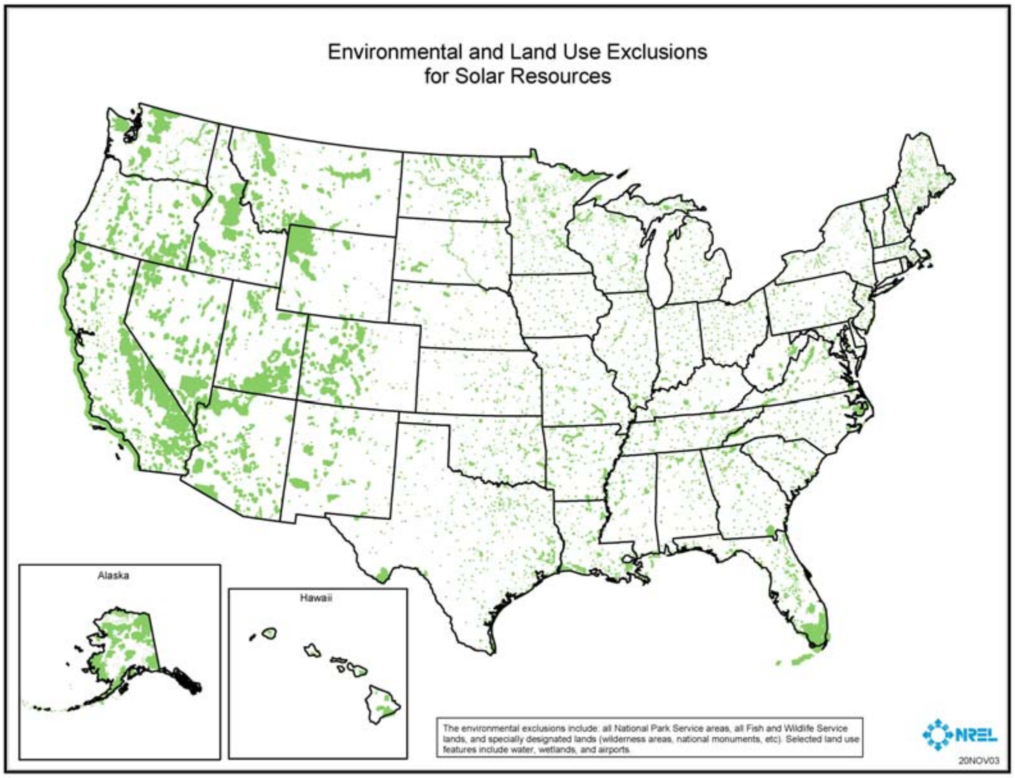


Figure 6. Environmental and land-use exclusions for solar resources

Analysis Methodology

It was assumed that any given 40-km by 40-km cell will have no more than 10% of its land area dedicated to photovoltaic development, and only 30% of this area will be covered with solar panels. The photovoltaic solar panels are assumed to have a solar-to-electricity conversion efficiency of 10%. As with the analysis of the hydrogen production potential via wind electrolysis, the electricity requirement of the electrolysis system was assumed to be 58.8 kWh/kg hydrogen, or approximately 66.3% on a higher heating value basis.

Figure 7 depicts the hydrogen production potential from solar-driven electrolysis normalized by county; the Southwest is shown to have the highest potential. Similar to the wind analysis results, counties with very good solar resources and low population count (such as the Rocky Mountain-Great Plains region) clearly show high potential for producing hydrogen from solar resources, per person (Figure 8).

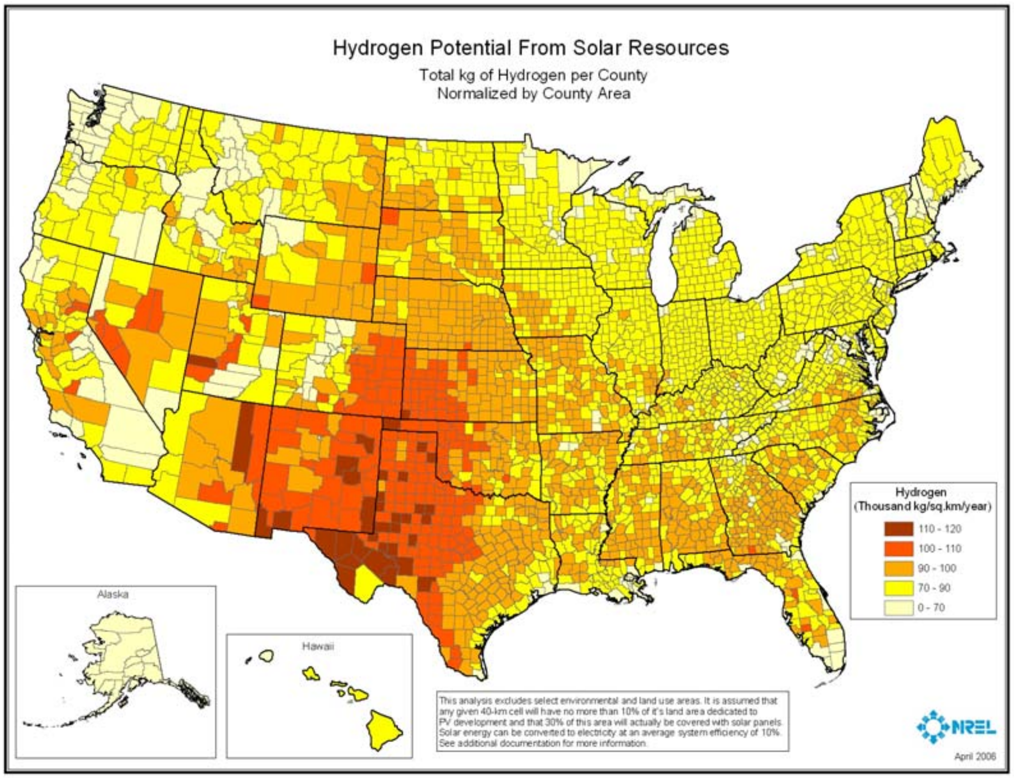


Figure 7. Hydrogen production potential from solar resources, by county

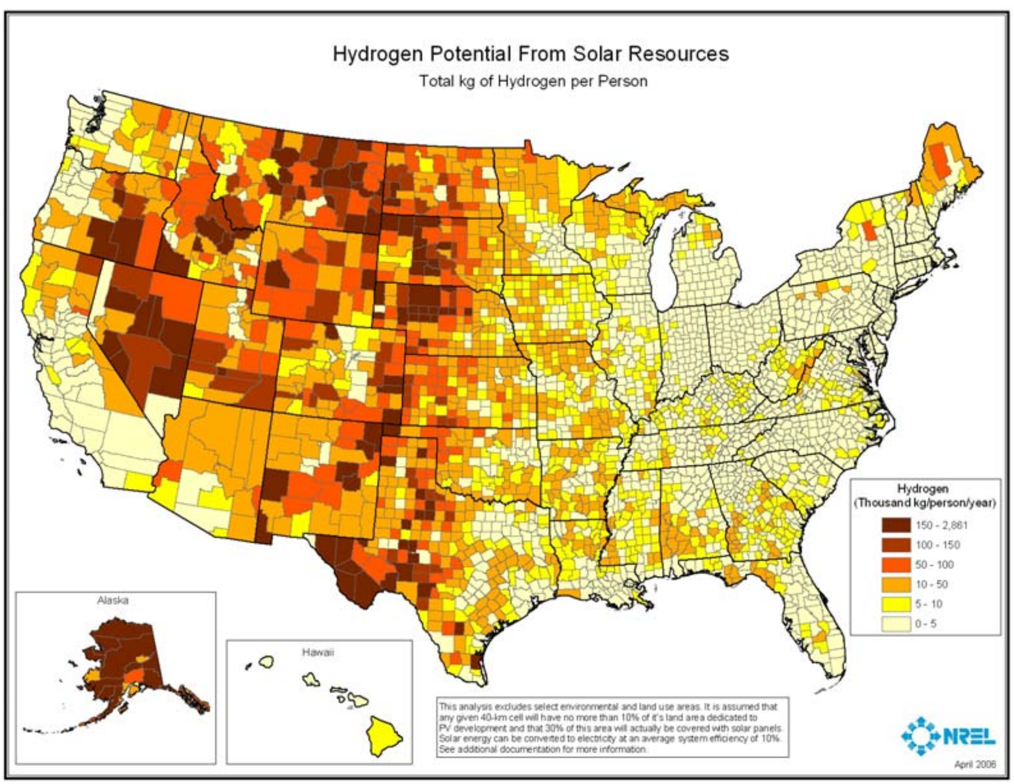


Figure 8. Hydrogen production potential from solar resources, per person

Potential for Hydrogen Production from U.S. Biomass Resources

Data Information

The assessment of the hydrogen production potential from biomass is based on a recently published study by the National Renewable Energy Laboratory (NREL) of biomass resource availability in the United States by county. It includes the following feedstock categories: agricultural residues (crop residues and animal manure); wood residues (forest residues, primary and secondary mill residues, urban wood waste); municipal discards (methane emissions from landfills and domestic wastewater treatment); and dedicated energy crops (switchgrass on Conservation Reserve Program lands). Each feedstock category was processed using the appropriate methodology, as described in the milestone report (Milbrandt 2005), to estimate the biomass potential by county depicted in Figure 9.[5]

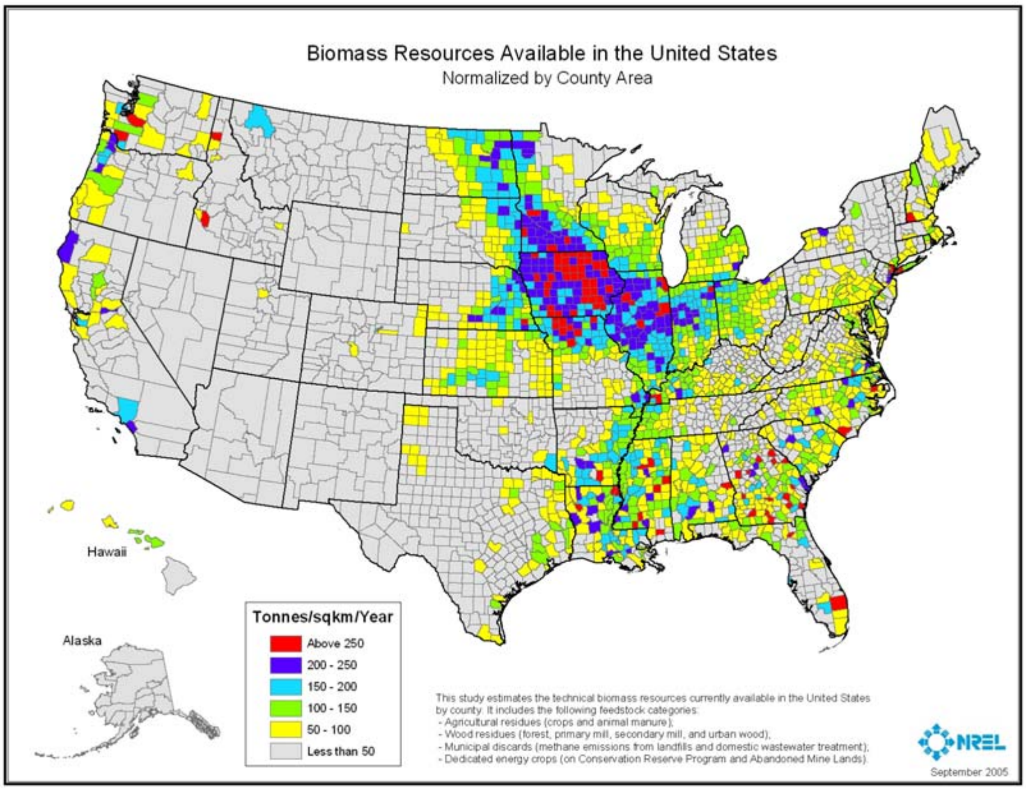


Figure 9. Available biomass resources in the United States

Exclusions

Because of the wide range of feedstock types, biomass is available from many sources and has a broad geographic distribution. Therefore, it is difficult to define land use and environmental exclusions that would be applicable to all categories. Additional study is needed to improve the spatial distribution of biomass resources to define excluded areas appropriately.

[5] Biomass data and maps, National Renewable Energy Laboratory, Golden, CO: http://www.nrel.gov/gis/biomass.html, March 2006

Analysis Methodology

Different conversion rates of biomass to hydrogen were used, depending on the feedstock. For crops and woody residues, a relationship formula of 13.8 kg bone dry weight (BDW)/kg hydrogen was applied. This rate is based on the conversion of lignocellulosic plant material to hydrogen via gasification analyzed by the U.S. Department of Energy's Hydrogen Analysis (H2A) Group.[6] For gaseous feedstock (methane emissions from manure management, landfills, and domestic wastewater treatment), a conversion of 2.34 kg methane/kg hydrogen was used. This value represents 85% conversion efficiency from the stoichiometric maximum possible from steam reforming of methane. Figure 10 illustrates the results of this analysis. Counties in the Midwest, along the Mississippi River, and in the Southeast show the highest potential for hydrogen production from biomass as a result of the large quantities of crop, forest, and primary mill residues. High amounts of secondary mill and urban wood residues, as well as methane emission from landfills and domestic wastewater treatment, contribute to the high potential for hydrogen production from biomass in the New York metropolitan area. The counties in the Midwest and Great Plains with their low population counts and good biomass resources contribute to the high amount of hydrogen from biomass per person (Figure 11).

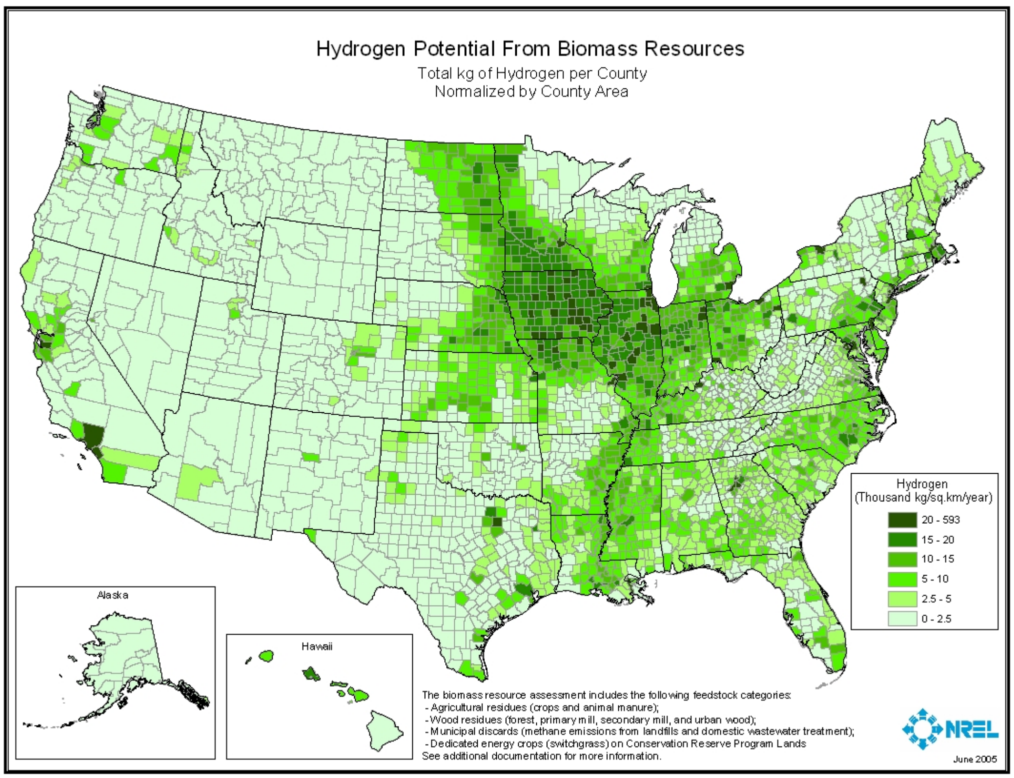


Figure 10. Hydrogen production potential from biomass resources, by county

[6] The Hydrogen Analysis (H2A) Project: http://www.hydrogen.energy.gov/h2a_analysis.html

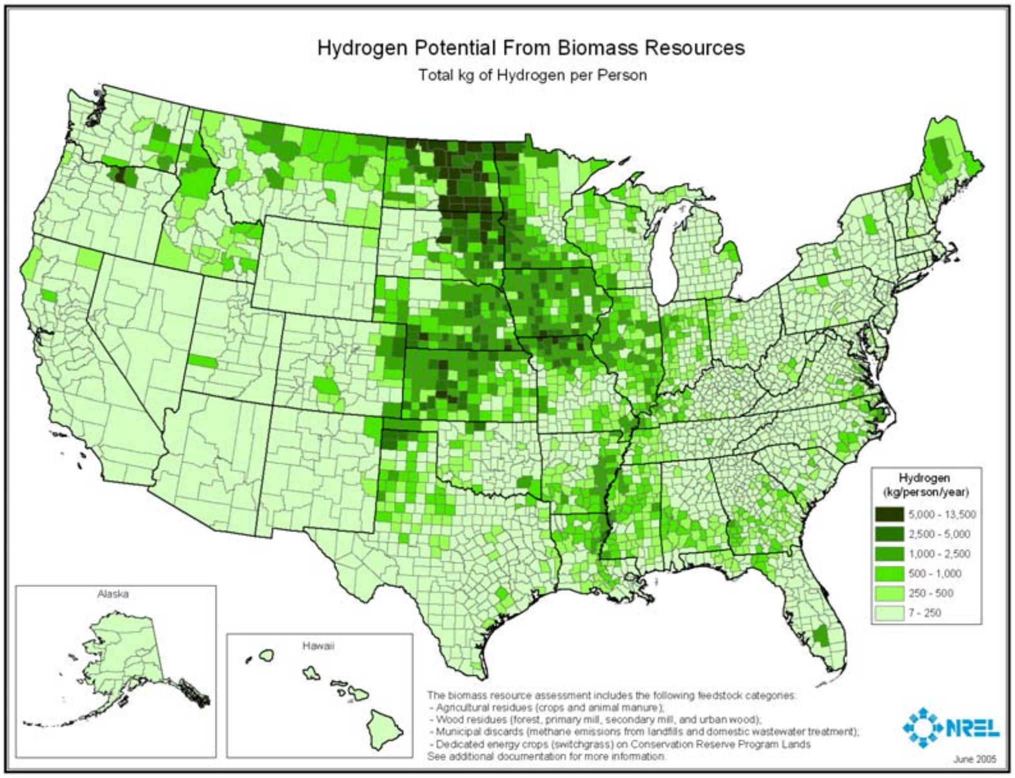


Figure 11. Hydrogen production potential from biomass resources, per person

Hydrogen Production Potential from Combined Renewable Resources: Wind, Solar, and Biomass

The results from the previous three analyses were combined to illustrate the total amount of hydrogen that could be produced from renewable resources by county (Figure 12). The large quantities of wind, solar, and biomass resources in the Great Plains are the reason for the high potential for hydrogen production from renewable resources in this region. Figure 13 gives further details on whether the highest amount of hydrogen in each county comes from wind, solar, or biomass—in other words, which one is the dominant renewable resource.

Wind is the leading resource for hydrogen production in many counties in the central states and solar is a dominant resource in the rest of the country; the highest values are in the Southwest. Hydrogen from biomass has higher values than hydrogen from wind and solar in only a few counties—New York and Miami metropolitan areas—because of activities related to high concentrations of people, such as the generation of waste. The results by state are presented in Table 2 and Figure 16. The amount of hydrogen from combined renewable resources per person is shown in Figure 14, and Figure 15 illustrates the geographic distribution of the population. The Rocky Mountain-Great Plains region shows the highest potential quantity of renewable hydrogen per person because of its low population count and large amount of renewable resources.

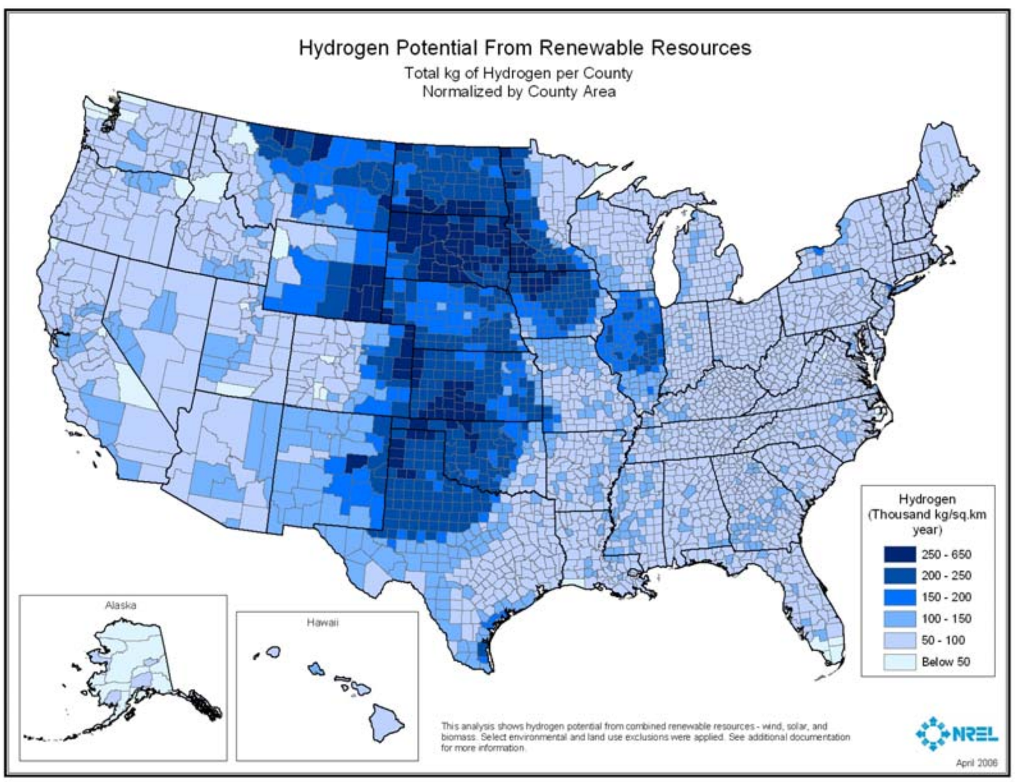


Figure 12. Hydrogen production potential from renewable resources, by county

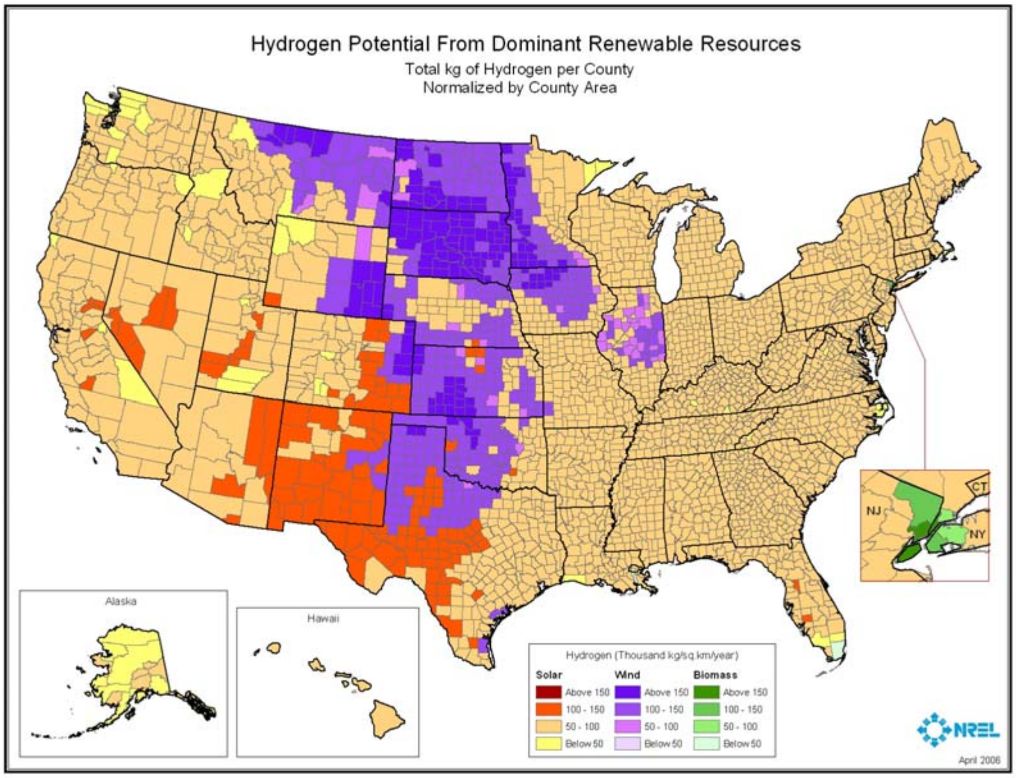


Figure 13. Hydrogen production potential from dominant renewable resources

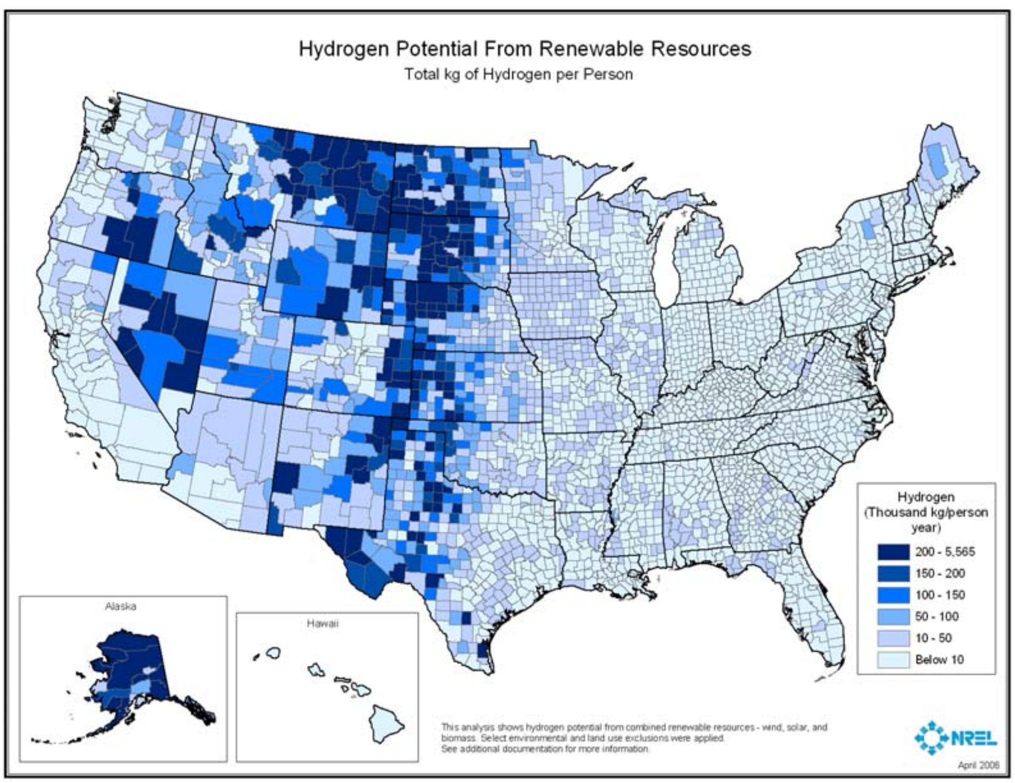


Figure 14. Hydrogen production potential from renewable resources, per person

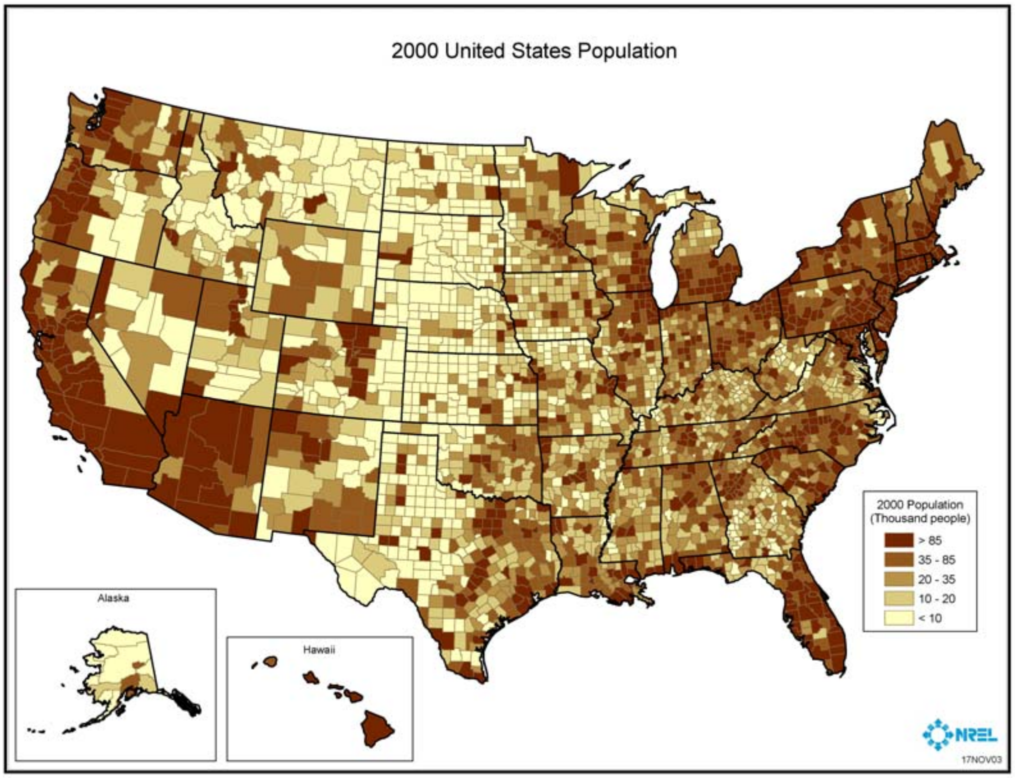


Figure 15. Population of the United States, by county

Table 2. Hydrogen Production Potential from Renewable Resources, by State

State	Hydrogen from Biomass per km^2 (thousand kg)	Hydrogen from Biomass (million kg)	Hydrogen from Solar per km^2 (thousand kg)	Hydrogen from Solar (million kg)	Hydrogen from Wind per km^2 (thousand kg)	Hydrogen from Wind (million kg)	Total Hydrogen per km^2 (thousand kg)	Total Hydrogen (million kg)
Alabama	293	588	6,003	12,014	0	0	6,296	12,602
Alaska	5	73	901	51,887	19	868	926	52,828
Arizona	7	142	1,413	27,433	28	727	1,448	28,302
Arkansas	394	729	6,618	12,102	145	308	7,156	13,139
California	314	1,165	4,536	29,926	215	2,309	5,066	33,401
Colorado	93	289	5,422	24,036	2,244	10,669	7,759	34,994
Connecticut	37	64	621	1,004	1	1	659	1,069
Delaware	36	55	228	399	1	2	264	457
District of Columbia	24	4	27	5	0	0	51	9
Florida	254	557	5,475	11,319	0	0	5,728	11,876
Georgia	712	675	14,070	13,475	31	25	14,812	14,175
Hawaii	30	65	323	1,365	34	17	387	1,447
Idaho	73	225	3,605	16,462	207	1,160	3,886	17,847
Illinois	1,590	2,408	8,544	12,281	6,763	10,414	16,897	25,103
Indiana	1,086	1,148	7,489	7,600	22	24	8,596	8,772
Iowa	1,782	2,624	8,626	12,691	8,745	12,996	19,153	28,311
Kansas	582	1,112	10,256	20,962	11,642	24,738	22,481	46,812
Kentucky	605	570	10,200	8,914	11	11	10,816	9,496
Louisiana	476	749	5,231	9,827	0	0	5,707	10,576
Maine	51	235	1,143	6,271	52	355	1,246	6,860
Maryland	258	219	1,823	1,935	32	42	2,113	2,196
Massachusetts	131	150	932	1,499	172	66	1,234	1,714
Michigan	449	759	5,988	10,855	857	1,328	7,295	12,942
Minnesota	975	1,902	6,918	16,800	8,055	16,605	15,948	35,307
Mississippi	586	891	7,356	11,048	0	0	7,942	11,939
Missouri	962	1,411	10,314	16,162	722	1,199	11,998	18,772
Montana	29	187	4,527	30,357	4,535	30,603	9,091	61,147
Nebraska	716	1,120	8,785	18,925	9,211	19,551	18,712	39,595
Nevada	13	52	1,541	24,684	51	796	1,605	25,532
New Hampshire	50	101	710	1,686	39	142	799	1,929
New Jersey	654	293	1,518	1,424	2	2	2,174	1,719
New Mexico	14	71	3,438	33,237	1,192	10,248	4,644	43,557
New York	1,364	682	4,469	9,368	431	938	6,263	10,988
North Carolina	581	779	8,379	10,786	47	47	9,007	11,612
North Dakota	387	1,249	4,513	15,505	7,364	25,340	12,264	42,094
Ohio	786	934	6,776	8,257	51	44	7,613	9,236
Oklahoma	130	311	7,351	17,425	6,762	16,256	14,243	33,993
Oregon	60	212	2,560	17,997	260	1,624	2,880	19,833
Pennsylvania	407	625	5,102	8,926	68	132	5,577	9,683
Rhode Island	36	21	336	198	5	1	376	220
South Carolina	209	355	4,051	7,013	5	8	4,265	7,376
South Dakota	360	756	6,006	18,368	10,689	32,756	17,055	51,880
Tennessee	395	492	7,957	9,141	41	42	8,392	9,675
Texas	507	1,201	24,935	68,564	10,938	26,869	36,381	96,633
Utah	21	65	2,377	17,723	75	635	2,473	18,423
Vermont	29	52	971	1,771	94	177	1,094	1,999
Virginia	993	430	10,383	8,250	80	81	11,455	8,761
Washington	94	378	2,514	11,393	296	1,260	2,903	13,030
West Virginia	145	144	4,239	4,811	94	150	4,478	5,105
Wisconsin	502	866	5,478	11,080	717	1,351	6,697	13,297
Wyoming	3	24	2,051	22,089	1,890	20,442	3,944	42,555
U.S. Total	**20,292**	**30,209**	**265,028**	**717,249**	**94,933**	**273,361**	**380,253**	**1,020,819**

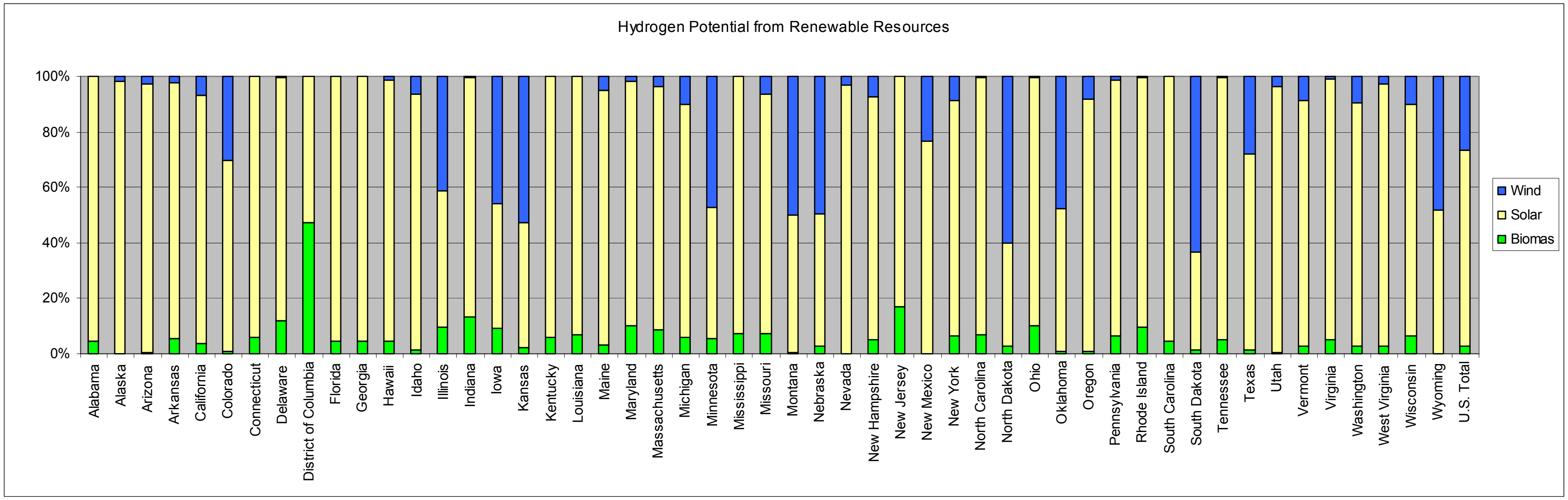


Figure 16. Hydrogen production potential from renewable resources

Renewable Hydrogen as a Transportation Fuel

A study was conducted to estimate the amount of gasoline consumption that could potentially be displaced by renewable hydrogen in each county. Gasoline consumption data for 2002 were obtained from the Federal Highway Administration[7] to generate the map of Figure 17. The results of this analysis show that the most populated counties cannot produce enough hydrogen from renewable resources to completely displace their high gasoline consumption. However, they could, in most cases, rely on hydrogen from surrounding counties (Figure 18). Renewable hydrogen in these counties (urban areas) could displace less than 50% of their gasoline consumption.

In contrast, counties in the Rocky Mountain-Great Plains region, because of their relatively low gasoline consumption and high amounts of renewable resources, have the potential to displace more than 40–50 times their current gasoline demand. At the state level, only Connecticut, the District of Columbia, Maryland, Massachusetts, New Jersey, and Rhode Island lack the resources to completely displace gasoline with renewably generated hydrogen (Figure 19). Table 3 presents the accompanying values.

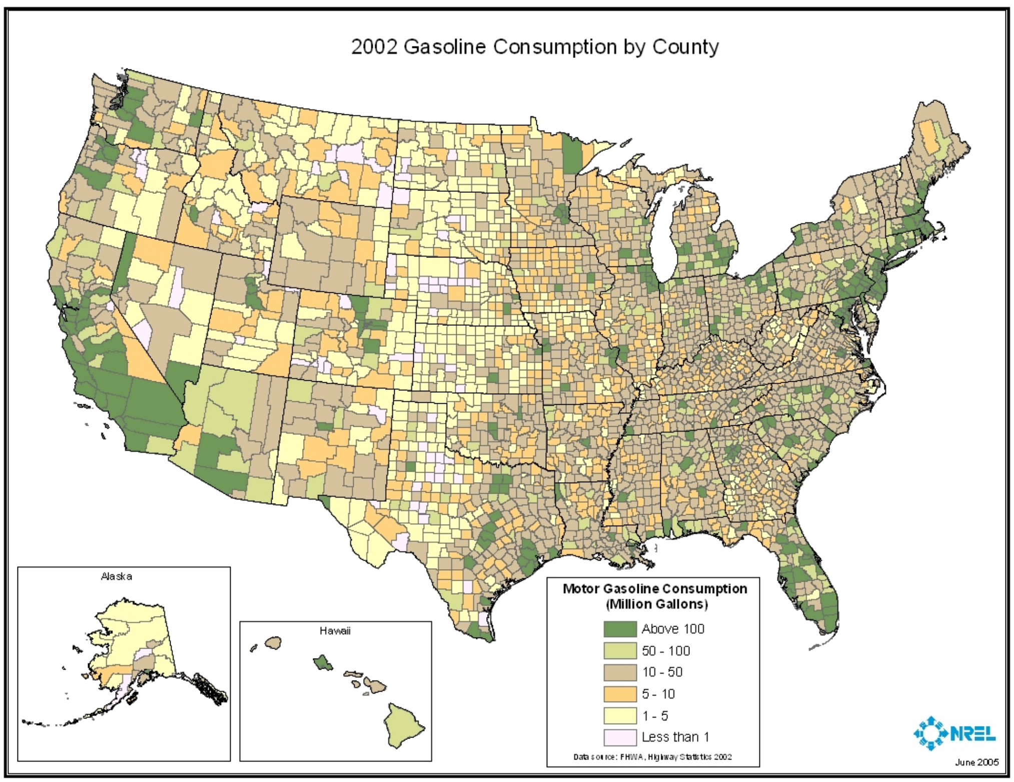


Figure 17. U.S. gasoline consumption by county, 2002

[7] U.S. Department of Transportation, Federal Highway Administration, Highway Statistics 2002, http://www.fhwa.dot.gov/policy/ohim/hs02/

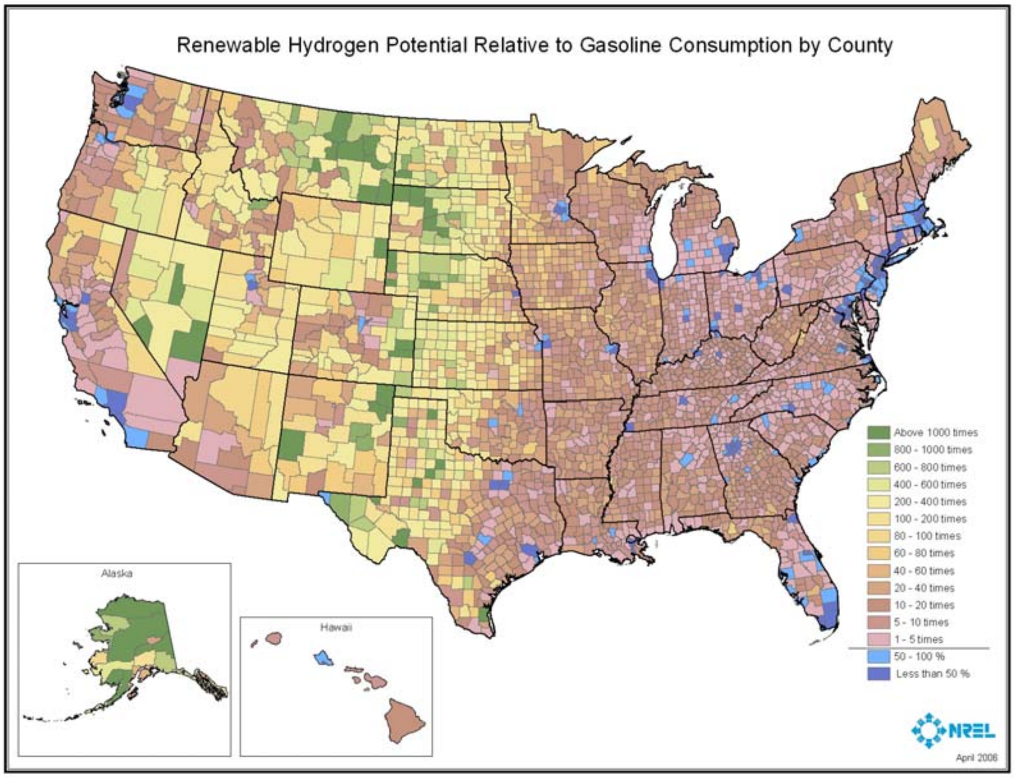


Figure 18. Renewable hydrogen production potential relative to gasoline consumption, by county

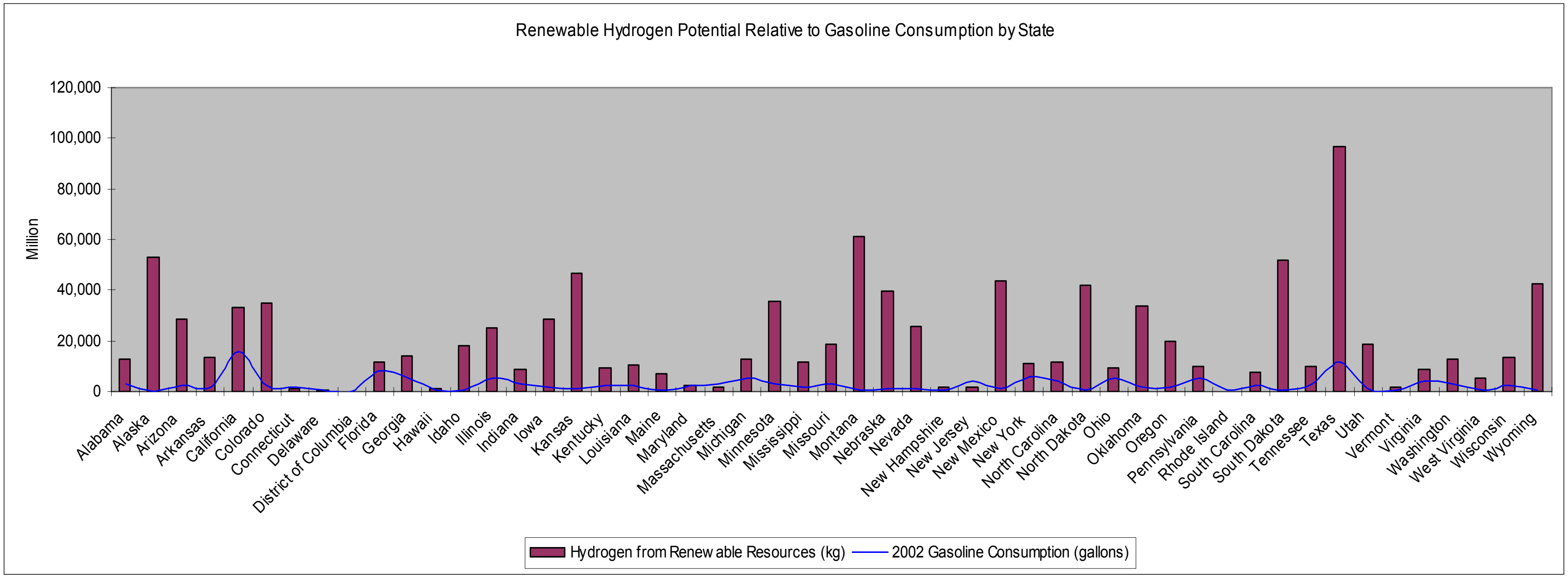


Figure 19. Renewable hydrogen production potential relative to gasoline consumption, by state

Table 3. Renewable Hydrogen Production Potential Relative to Gasoline Consumption and Population

State	Hydrogen from Renewable Resources (million kg)	2002 Gasoline Consumption (million gallons)	2000 Population (thousand people)
Alabama	12,602	2,624	4,447
Alaska	52,828	260	627
Arizona	28,302	2,605	5,131
Arkansas	13,139	1,467	2,673
California	33,401	15,699	33,872
Colorado	34,994	2,106	4,301
Connecticut	1,069	1,590	3,406
Delaware	457	426	784
District of Columbia	9	167	572
Florida	11,876	7,999	15,982
Georgia	14,175	4,961	8,186
Hawaii	1,447	446	1,212
Idaho	17,847	668	1,294
Illinois	25,103	5,212	12,419
Indiana	8,772	3,188	6,080
Iowa	28,311	1,617	2,926
Kansas	46,812	1,230	2,688
Kentucky	9,496	2,158	4,042
Louisiana	10,576	2,349	4,469
Maine	6,860	720	1,275
Maryland	2,196	2,568	5,296
Massachusetts	1,714	2,851	6,349
Michigan	12,942	5,170	9,938
Minnesota	35,307	2,727	4,919
Mississippi	11,939	1,632	2,845
Missouri	18,772	3,164	5,595
Montana	61,147	509	902
Nebraska	39,595	889	1,711
Nevada	25,532	1,004	1,998
New Hampshire	1,929	715	1,236
New Jersey	1,719	4,095	8,414
New Mexico	43,557	952	1,819
New York	10,988	5,808	18,976
North Carolina	11,612	4,315	8,049
North Dakota	42,094	366	642
Ohio	9,236	5,295	11,353
Oklahoma	33,993	1,796	3,451
Oregon	19,833	1,572	3,421
Pennsylvania	9,683	5,241	12,281
Rhode Island	220	404	1,048
South Carolina	7,376	2,346	4,012
South Dakota	51,880	456	755
Tennessee	9,675	3,090	5,689
Texas	96,633	11,410	20,852
Utah	18,423	1,038	2,233
Vermont	1,999	346	609
Virginia	8,761	3,888	7,079
Washington	13,030	2,760	5,894
West Virginia	5,105	820	1,808
Wisconsin	13,297	2,591	5,364
Wyoming	42,555	354	494
U.S. Total	**1,020,819**	**137,664**	**281,422**

Conclusions

About 1 billion metric tons of hydrogen could be produced from wind, solar, and biomass resources annually in the United States. The Great Plains emerge as the area with the highest potential for producing hydrogen from these key renewable resources. Each county in this region could produce more than 30 million kg of hydrogen per year (greater than 150,000 kg/km^2). Moreover, because they have fewer environmental and land-use exclusions and low populations, most counties in the Great Plains have the highest hydrogen production potential per capita, more than 100,000 kg of hydrogen per person. Results are shown in terms of kilograms of hydrogen, because 1 kg of hydrogen contains approximately the same energy as 1 gallon of gasoline, both on a lower heating value basis.

Finally, this research suggests that renewable hydrogen has the potential to displace gasoline consumption in most states. However, the infrastructure needed to enable the widespread use of hydrogen as a transportation fuel is not available, resources are located outside demand areas, and the methods of producing hydrogen from renewable resources face many technical and economic hurdles. All these barriers must be overcome if hydrogen is to fuel a sustainable transportation economy.

References

Elliott, D.L., Holliday, C.G., Barchet, W.R., Foote, H.P., Sandusky, W.F. 1987. *Wind Energy Resource Atlas of the United States*. DOE/CH100093-4. Produced by the National Renewable Energy Laboratory for the U.S. Department of Energy, Washington, DC.

George, R., Maxwell, E. 1999. “High-Resolution Maps of Solar Collector Performance Using A Climatological Solar Radiation Model.” *Proceedings of the 1999 Annual Conference*, American Solar Energy Society, Portland, ME.

Heimiller, D.M., Haymes, S.R. 2001. *Geographic Information Systems in Support of Wind Energy Activities at NREL*. National Renewable Energy Laboratory, Golden, CO.

Hydrogen Analysis (H2A) Project, December 2006: http://www.hydrogen.energy.gov/h2a_analysis.html

Ivy, J. April 2004. *Summary of Electrolytic Hydrogen Production*. National Renewable Energy Laboratory, Golden, CO.

Levene, J., Mann, M., Margolis, R., Milbrandt, A. 2005. *Analysis of Hydrogen Production from Renewable Electricity Sources*. National Renewable Energy Laboratory, Golden, CO.

Maxwell, E., George, R., Wilcox, S. “A Climatological Solar Radiation Model.” *Proceedings of the 1998 Annual Conference*, American Solar Energy Society, Albuquerque, NM.

Milbrandt, A., 2005. *A Geographic Perspective on the Current Biomass Resource Availability in the United States*. National Renewable Energy Laboratory, Golden, CO.

Milne, T., Elam, C., Evans, R. 2002. *Hydrogen from Biomass – State of the Art and Research Challenges*. National Renewable Energy Laboratory, Golden, CO.

National Renewable Energy Laboratory, March 2006. Solar data and maps: http://www.nrel.gov/gis/solar.html, Golden, CO.

National Renewable Energy Laboratory, March 2006. Wind data and maps: http://www.nrel.gov/gis/wind.html, Golden, CO.

National Renewable Energy Laboratory, March 2006. Biomass data and maps: http://www.nrel.gov/gis/biomass.html, Golden, CO.

Power Technologies Energy Data Book, December 2005: http://www.nrel.gov/analysis/power_databook/.

Short, W., Blair, N., Heimiller, D. 2005. *Modeling the Market Potential of Hydrogen from Wind and Competing Sources*, National Renewable Energy Laboratory, Golden, CO.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. **REPORT DATE** *(DD-MM-YYYY)*	2. **REPORT TYPE**	3. **DATES COVERED** *(From - To)*
February 2007	Technical report	

4. TITLE AND SUBTITLE
Potential for Hydrogen Production from Key Renewable Resources in the United States

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
A. Milbrandt and M. Mann

5d. PROJECT NUMBER
NREL/SR-640-41134

5e. TASK NUMBER
H278.2100

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/SR-640-41134

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES
NREL Technical Monitor:

14. ABSTRACT *(Maximum 200 Words)*
This study was conducted to estimate the potential for hydrogen production from key renewable resources (onshore wind, solar photovoltaic, and biomass) by county in the United States and to create maps that allow the reader to easily visualize the results. To accomplish this objective, the authors analyzed renewable resource data both statistically and graphically utilizing a state-of-the-art Geographic Information System (GIS), a computer-based information system used to create and visualize geographic information.

15. SUBJECT TERMS
hydrogen; potential; renewable resources; United States; resource map; GIS; National Renewable Energy Laboratory; NREL

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		19b. TELEPHONE NUMBER (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18