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Hydrogen Infrastructure Transition Analysis

Milestone Report
NREL/TP-540-38351
January 2006

M. Melendez and A. Milbrandt

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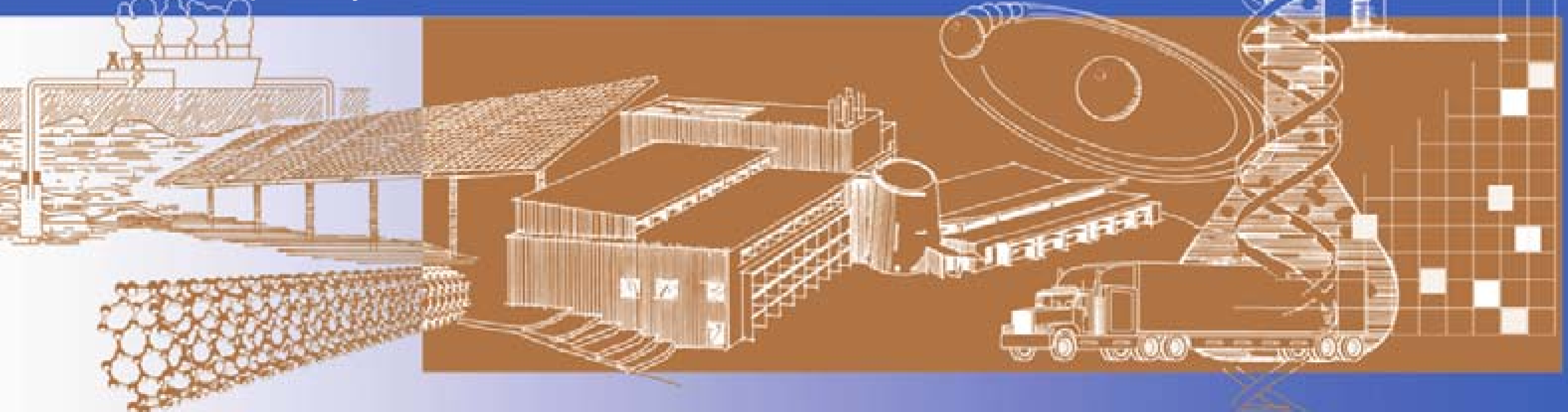

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Introduction

During 2002, President George W. Bush launched the Hydrogen Fuel Initiative, which envisions a future hydrogen economy for the United States. A hydrogen economy would increase U.S. energy security, environmental quality, energy efficiency, and economic competitiveness. Transitioning to a hydrogen economy, however, presents numerous technological, institutional, and economic barriers. These barriers apply not only to the development of fuel cell vehicles and stationary fuel cells, but also to the development of a hydrogen fueling infrastructure. The President asked the U.S. Department of Energy (DOE) to lead the efforts to overcome these barriers.

The National Renewable Energy Laboratory (NREL) works closely with DOE to evaluate the current status and future potential of hydrogen and fuel cell technologies. NREL's capabilities include fuel cell and vehicle modeling and analysis of fuel cells, vehicles, production technologies, and delivery options, as well as policy analysis and technology validation expertise. Using these capabilities, NREL has contributed to identifying and addressing barriers to the hydrogen economy. One barrier discussed in DOE's *Multi-Year Research, Development and Demonstration Plan* (2003) is the development of a hydrogen fueling infrastructure. The goal of this study is to investigate the barriers to developing a hydrogen fueling infrastructure and identify and quantify potential solutions for overcoming them.

As hydrogen vehicles are first introduced, they will be few in number. This makes it difficult to build a large number of viable hydrogen fueling stations. Conversely, without adequate fueling options, consumers will be reluctant to purchase hydrogen vehicles. This project addresses this "chicken-and-egg" situation by identifying a minimum infrastructure that could support the introduction of hydrogen vehicles. It also develops and evaluates transition scenarios supported by this infrastructure. The focus of this analysis is infrastructure located along major U.S. interstates to facilitate interstate travel.

Background

ArcGIS, a geographic information system (GIS), and Microsoft Excel were the primary analysis tools used in this project. GIS is a computer-based information system used to create, manipulate, and analyze geographic information. A GIS dataset consists of two elements: a graphic representation (map) and associated tabular information (data tables) for each graphic element. All information in GIS is linked to a spatial reference used to store and access data (i.e., each point on a map can be queried to view its associated information). The combination of geographic information and tabular forms enables analysis and characterization of different phenomena that occupy the same geographic space. Because GIS data and analysis are easily entered into tabular form, they can be converted for further analysis using a spreadsheet. In the case of this analysis, Excel was used.

The analysis done in fiscal year (FY) 2005 built upon the FY 2004 work described in the March 2005 report, "Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles"[1]. The FY 2005 project:

- Identified existing hydrogen production facilities and alternative fuel stations.
- Identified highway traffic volumes throughout the U.S. interstate system.
- Selected specific north/south and east/west routes as a focus for the project.
- Incorporated existing hydrogen production facilities, hydrogen and natural gas fueling stations, railroads, traffic volume, and county population data.
- Placed stations on the U.S. interstate network according to population density and station distances.
- Identified a significant potential to co-locate refueling with federal government partners.

In FY 2005, analysis focused on using the basic refueling station network proposed in FY 2004 to evaluate various scenarios for transition. These strategies and analyses are described in this report.

[1] "Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles," March 2005, NREL/CP-540-37903, www.nrel.gov/docs/fy05osti/37903.pdf

Demographics and Network Details

The proposed network includes 284 hydrogen refueling stations (see Figure 1). These stations, spaced approximately 50 miles apart east of the Mississippi River and 100 miles apart west of the Mississippi River, facilitate travel along 65% of the U.S. interstate highway system.

Using average daily traffic statistics from the Federal Highway Administration (FHWA), more than 13 million vehicles pass the proposed stations each day[2]. This data represents the count of vehicles driving past each station on the interstate, no matter how many times the same vehicles pass the station. While this information is helpful, it does not break out the number of unique vehicles that pass each station.

According to 2000 census data, almost 233 million people live in the 362 Metropolitan Statistical Areas (MSAs) in the United States. This represents nearly 83% of the overall U.S. population (281.4 million). The proposed network of hydrogen stations consists of at least one station in 87 of the total 362 MSAs. Approximately 91 million people, or 32% of the total U.S. population, live in these MSAs. Although the proposed hydrogen stations are technically within these MSAs, the stations may not be available to every person within that MSA. Many of the MSAs are situated in large land areas, and the station locations are optimized for interstate travel, not local city traffic. Therefore, a better way to evaluate the impact of the stations is population within a given radius. Total population living within a five-mile radius of the proposed hydrogen stations is 22.3 million; the population within 10 miles of the stations is 58.2 million.

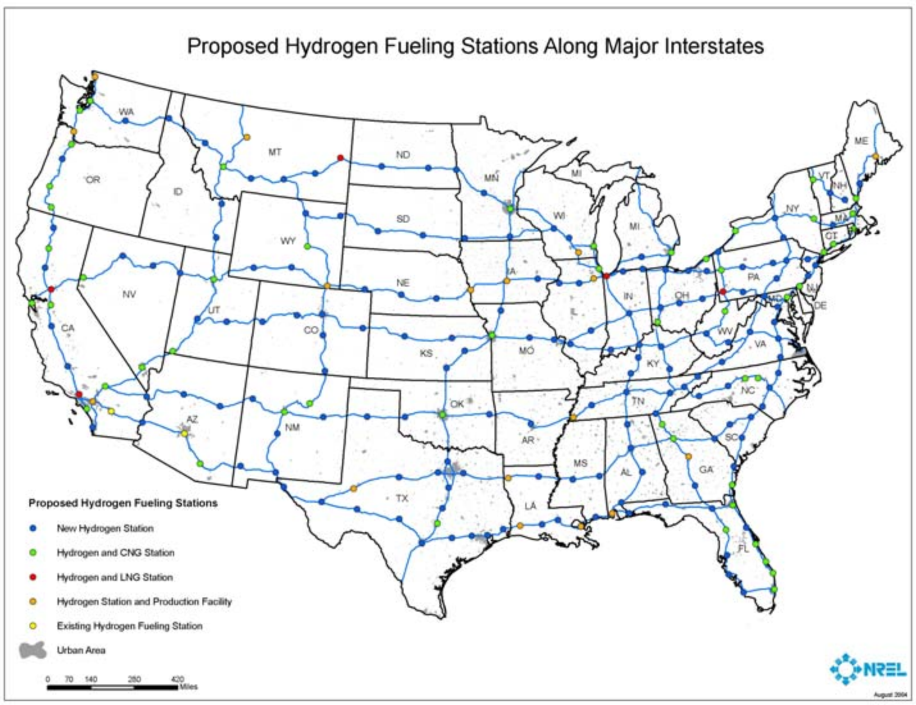

Figure 1. Proposed Hydrogen Fueling Stations

Forecourt Infrastructure Scenario

Assuming network-wide forecourt production and hydrogen analysis (H2A[3]) assumptions for capital equipment costs, a basic cost estimate for the proposed refueling network was completed for a baseline

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[2] Reference 6, page 4: "Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles," March 2005, NREL/CP-540-37903, www.nrel.gov/docs/fy05osti/37903.pdf

[3] Hydrogen, Fuel Cells & Infrastructure Technologies Program website: H2A Model section, www.eere.energy.gov/hydrogenandfuelcells/analysis/model.html

scenario and several variations on that scenario. Table 1 summarizes the H2A capital cost assumptions and shows the seven types of stations used in this analysis. As the H2A costs are updated, the values used in this model will be updated.

Using assumptions (described below) for hydrogen demand, station configuration (size and type of production) was fit to meet that demand. Resources and infrastructure at the station location were also considered. Table 2 shows the production and capital equipment assigned to each station.

Table 1. H2A Capital Cost Assumptions (September 2004)

Station Type	Abbreviation	Installed Capital Costs				Cost per Station ($M)
		Production	Storage	Dispensing	Pipeline	
Forecourt, SMR, 100 kg/day	SMR100	$135,000	$73,000	$49,000	$0	$257,000
Forecourt, SMR, 1,500 kg/day	SMR1500	$906,000	$732,000	$103,000	$0	$1,741,000
Forecourt, SMR, 3,000 kg/day	SMR3000	$1,813,000	$1,464,000	$184,000	$0	$3,461,000
Forecourt, Electrolysis, 100 kg/day	EL100	$129,000	$73,000	$49,000	$0	$251,000
Forecourt, Electrolysis, 1,500 kg/day	EL1500	$905,000	$732,000	$103,000	$0	$1,740,000
Forecourt, Electrolysis, 3,000 kg/day	EL3000	$1,809,000	$1,464,000	$184,000	$0	$3,457,000
Pipeline, 3000 kg/day (three miles from plant)	P3000	$0	$0	$184,000	$3,000,000	$3,184,000

Table 2. Station Production and Volume Assignments

Conditions for Assigning Station Types		
Existing Infrastructure	**Volume of Hydrogen (kg/day)**	**Station Type**
CNG	<100	Forecourt, SMR, 100 kg/day
LNG	<100	Forecourt, SMR, 100 kg/day
Hydrogen Facility	<100	Forecourt, Electrolysis, 100 kg/day
Hydrogen	<100	NC
None	<100	Forecourt, Electrolysis, 100 kg/day
CNG	101-1,500	Forecourt, SMR, 1,500 kg/day
LNG	101-1,500	Forecourt, SMR, 1,500 kg/day
Hydrogen Facility	101-1,500	Forecourt, SMR, 1,500 kg/day
Hydrogen	101-1,500	NC
None	101-1,500	Forecourt, SMR, 1500 kg/day
CNG	>1,500	Forecourt, SMR, 3000 kg/day
LNG	>1,500	Forecourt, SMR, 3,000 kg/day
Hydrogen Facility	>1,500	Pipeline, 3,000 kg/day (three miles from plant)
Hydrogen	>1,500	NC
None	>1,500	Forecourt, SMR, 3,000 kg/day

Baseline Scenario: Vehicle penetration into the marketplace, average volume of a vehicle fill-up, and the percentage of vehicles that pass each station and stop to refuel were the primary factors affecting the overall hydrogen demand at each station.

Vehicle Penetration: Using the VISION 1.0 model vehicle penetration estimates under the "Go Your Own Way (GYOW)" scenario, vehicle penetration for the baseline scenario was selected to be 1.1% of the entire U.S. light-duty fleet in 2020. The GYOW scenario models the rate of penetration of fuel cell vehicles under conditions of a fast pace of innovation and a high level of environmental responsiveness in the market[4]. The model predicts that hydrogen fuel cell vehicles will be introduced in 2018 and the U.S. fleet will be composed of 50% hydrogen vehicles by 2050.

Average Fill-Up: Average fill-up was based on the DOE hydrogen program goal to achieve two times the efficiency of a conventionally fueled vehicle (25.1 mpg for light-duty fleet average in 2003) with a range of 300 mpg. With equal energy content for 1 kg of hydrogen and one gallon of gasoline, the usable tank capacity would need to be 6 kg. The average fill-up was selected to be two-thirds of the tank capacity, and therefore 4 kg was used in this analysis.

Vehicles Stopping at the Station: FHWA traffic data counts all the vehicles that drive past a particular point on the interstate. Vehicles traveling long distances or cross country will need to refuel at roughly every other or every third station (if the stations are 100 miles apart). Local vehicles, however, would refuel less frequently when passing the station, because they may take numerous short trips past a station. To determine the percentage of vehicles stopping at a station each day, we assumed that roughly 50% of the population is long-distance traffic stopping at every other station along the route. The remaining 50% of the traffic stops only once every 10 trips. Therefore, the overall percentage of vehicles stopping at a station is 30% (50%*1/2 + 50%*1/10).

Results for the baseline scenario and its various scenarios are shown in Table 3. The final row of the Table 3 represents a hybrid-like scenario.

Table 3. Cost Scenarios for Forecourt Hydrogen Production on Interstate Station Network

Vehicle Penetration in Fleet	Average Vehicle Fill-Up	Interstate Traffic Using Station	Total Capital Costs ($M)
1.10%	4 kg	30%	$472
1.10%	4 kg	50%	$556
2.50%	4 kg	30%	$619
2.50%	4 kg	50%	$747
5.00%	4 kg	30%	$770
5.00%	4 kg	50%	$847
0.08%	4 kg	30%	$156

Table 4. Total U.S. Hybrid Registrations

Category	Model Year (MY) 2000	MY 2001	MY 2002	MY 2003	MY 2004
New Hybrid Vehicles	6,479	19,033	34,521	43,435	83,153
U.S. Light-Duty Vehicle Sales	17,349,000	16,076,000	15,904,000	16,634,000	16,267,000
Hybrid Vehicle Penetration into Market	0.04%	0.12%	0.22%	0.26%	0.51%

Sources: R.L. Polk & Co. U.S. Registrations, VISION 1.0 Model

Hybrid-Like Scenario: This scenario assumes the same introduction rate into the marketplace as hybrid vehicles for the first five years of vehicle availability.

Vehicle Penetration: Vehicle penetration into the marketplace was determined based on the introduction of the hybrid electric vehicle. Table 4 shows total U.S. hybrid sales beginning with

[4] "Joint DOE/NRCan Study of North American Transportation Energy Futures," U.S. Department of Energy, May 2003, www.nrel.gov/analysis/seminar/docs/2003/es_3-13-03.ppt

the 2000 introduction of the technology. Assuming hydrogen vehicles are introduced in 2017—and that after five years no vehicles have been taken out of service—the vehicle penetration into the marketplace after five years (2022) would be roughly 0.08% (sum of all vehicles sold for 2000 through 2005 divided by the total U.S. fleet of roughly 222 million).

Average Fill-Up: 4 kg (See baseline scenario.)

Vehicles Stopping at the Station: 30% (See baseline scenario.)

These costs represent the price of purchasing and installing the equipment at each site using the H2A reference year of 2005 dollars. This does not take into account any operational costs or costs required to subsidize these stations until they are economically self-sustaining.

Under the baseline scenario, the network consists of 58 reforming stations, 223 electrolysis stations, and one station with delivery via pipeline from a nearby production facility. Two stations currently have the ability to fuel hydrogen, and no change is necessary (we assumed these can adequately meet demand in their current configuration). These stations are in Phoenix, Arizona, and Rancho Mirage, California.

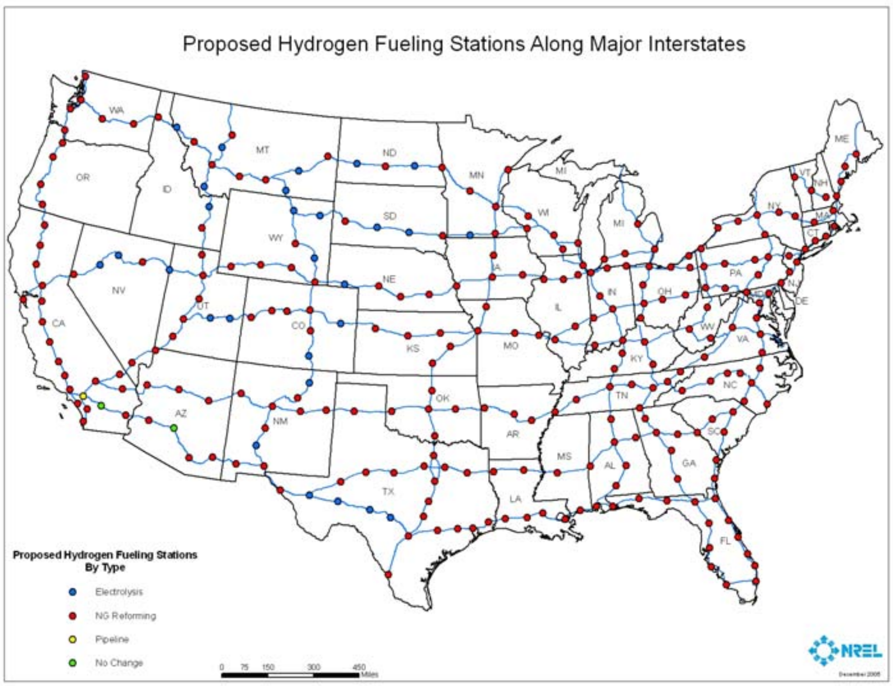

Figure 2. Forecourt Infrastructure—Baseline Scenario

Because stations were limited to a maximum of 3,000 kg/day (as shown in Table 1), under the baseline scenario, nine stations do not have sufficient capacity to support demand. Of the stations operating below their capacity, the average utilization is about 44% of capacity. Table 5 shows how hydrogen demand grows with increasing vehicle sales.

The stations with excess high demand for hydrogen are located in urban areas and should ultimately be supported by central production facilities. Therefore, this analysis under predicts capital costs for forecourt production at these stations. Because of this limitation, this analysis is best used for early transition scenarios with low rates for vehicle penetration into the marketplace. Future work will focus on a mix of forecourt and centrally produced hydrogen to address this issue, incorporating other models to evaluate delivery to high volume stations.

Table 5: Hydrogen Demand at Stations—Baseline Scenario

Vehicle Penetration in Fleet	Average Vehicle Fill-Up	Interstate Traffic Using Station	Annual Demand (Mil. kg H2)	Stations with Excess Demand	Average Utilization of Stations with Sufficient Capacity
1.10%	4 kg	30%	58	1	39%
1.10%	4 kg	50%	97	11	46%
2.50%	4 kg	30%	132	25	49%
2.50%	4 kg	50%	220	55	52%
5.00%	4 kg	30%	264	71	55%
5.00%	4 kg	50%	441	137	56%
0.08%	4 kg	30%	4	0	29%

Using the baseline scenario, hydrogen demand is 159,000 kg/day or 58 million kg/year (more than 14 million fill-ups per year). Assuming that each kilogram of hydrogen used displaces two gallons of gasoline (because of 2X vehicle efficiency), the capital infrastructure costs represent roughly $4.06 per gallon of gasoline displaced in the first year. Considering that the population within five miles has relatively convenient access to the infrastructure, capital costs are $21 per person served by the infrastructure.

Forecourt production seems to be a relatively inexpensive way to produce hydrogen during the transition. This is because it has relatively low capital costs and allows for tailoring stations to meet localized hydrogen demands. This can translate into a high utilization rate and, in turn, easier payback. Future work will evaluate growth of hydrogen demand and key parameters for avoiding stranded assets. For example, in areas where hydrogen demand is anticipated to grow significantly, it may be more economical to install a larger-capacity station or use central production with truck or pipeline delivery to support future demand, instead of installing infrastructure that will be outgrown in a short period of time. FY 2006 work will include an analysis on demand growth over time and the best way to address infrastructure issues to meet this growing demand.

Renewable Infrastructure Scenario

One of the advantages of using hydrogen as a transportation energy source is the ability to generate it in many ways from many resources. This diversity allows each region to utilize its best resources to produce hydrogen. If transition infrastructure is installed at each station using a forecourt technology, such as electrolysis, renewable energy could be incorporated at each station. Because of the relatively low volumes at more rural stations, forecourt technologies could present an opportunity to utilize renewables.

Using NREL analysis[5] as a basis, the availability of renewables was evaluated at each station to determine whether there were sufficient resources to meet the hydrogen demand at each site (at a 1.1% vehicle penetration). Each of the stations had sufficient renewable capacity. All 284 stations had enough usable solar resources to satisfy the hydrogen demand for vehicle refueling. Wind and biomass resources were sufficient at 163 and 281 stations, respectively.

Solar has the ability to meet the demands at nearly every station during the transition phase where demand is relative low. The most abundant and accessible in more rural areas, wind can meet demands at a little more than half of the stations with lower volume, and biomass can meet demands at more than 90% of the stations.

[5] "Hydrogen Potential from Wind and Solar," Anelia Milbrandt, FY 2004 DOE Milestone Report; "Hydrogen from Renewable Resources," Anelia Milbrandt, FY 2005 DOE Milestone Report

Table 6. Ability of Renewable Resources to meet Hydrogen Demand at Refueling Stations

Vehicle Penetration Rate	Average Vehicle Fill-Up	Interstate Traffic Using Station	Stations with Sufficient Renewable Resources: Solar	Wind	Biomass
1.10%	4 kg	30%	284	164	282
1.10%	4 kg	50%	284	163	280
2.50%	4 kg	30%	284	162	278
2.50%	4 kg	50%	284	159	274
5.00%	4 kg	30%	284	156	270
5.00%	4 kg	50%	284	150	264
0.08%	4 kg	30%	284	169	284

Using the most prevalent renewable resource at each station, for the baseline case, 248 stations would incorporate solar and 36 would incorporate wind. Although biomass has sufficient potential to satisfy demand at 282 stations, it is not the resource with the most hydrogen production potential and was therefore not selected for any of the stations. In practice, other issues (besides the greatest hydrogen production capacity) would factor into the renewable decision, such as incentives and local initiatives. Figure 3 shows the network and the types of locally available renewable energy sources for each station.

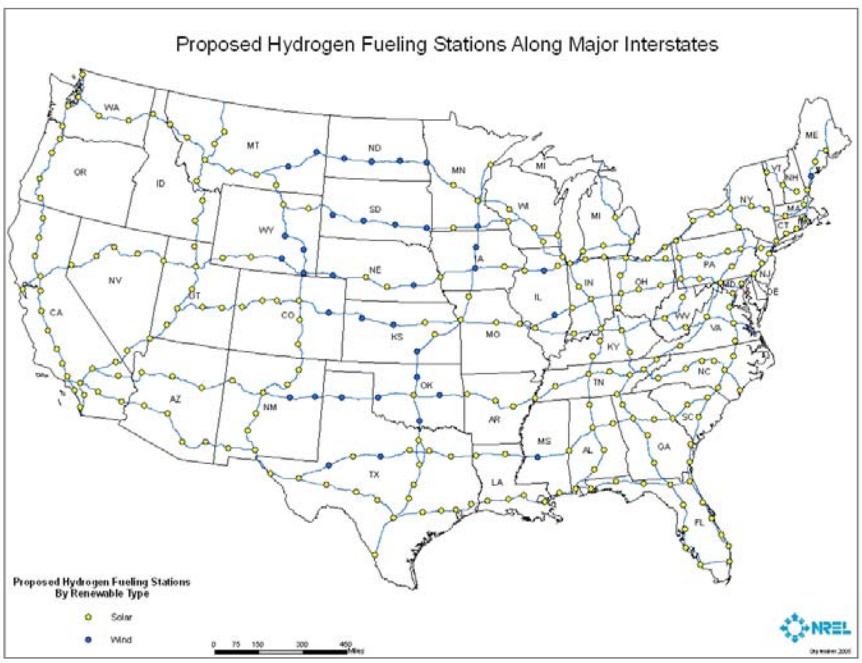

Figure 3. Scenario of Renewably Produced Hydrogen Network

Transition Strategies

Successful transition from conventional vehicles to hydrogen vehicles takes more than just technology. The coordination of simultaneous and strategic infrastructure and vehicle deployment are critical components. Roughly 17 million new vehicles are sold per year[6]. In comparison to the overall vehicle stock in the U.S. (222 million[7]), if all the new vehicles sold were hydrogen vehicles, hydrogen vehicles would penetrate vehicle stock around 7.5% each year. Perhaps a more realistic scenario could be

[6] 2003 Transportation Energy Data Book, 2002 data, tables 4.7 and 4.8
[7] 2003 Transportation Energy Data Book, 2002 data, tables 4.7 and 4.8

penetration approaching that of hybrid vehicles. If hydrogen vehicles penetrated the marketplace as effectively as hybrid vehicles (88,000 hybrid electric vehicles were sold in 2004 or about 0.51% of new vehicle sales in the United States, according to the J.D. Power-LMC "Automotive Forecasting Services Hybrid Electric Vehicle Outlook," February 3, 2005), after five years of vehicle sales, hydrogen vehicles would only represent 0.08% of the U.S. fleet of vehicles. There are many different scenarios and strategies, but, overall, the challenge to transform the marketplace to hydrogen vehicles is daunting and will not happen overnight. Therefore, transition strategies are critical. In FY 2005, two specific strategies to aid in the transition were evaluated.

Coordination with the USPS and Other Federal Agencies

Because the U.S. Postal Service (USPS) operates roughly 170,000 vehicles—nearly 37,000 of them capable of being powered by alternative fuel—across the country, it could be a valuable partner in infrastructure and vehicle deployment. In particular, remote post offices may have potential for co-generation options. A rural facility can meet its energy demands using a stationary fuel cell for power, while allowing local postal or public vehicles to refuel. This could stimulate demand for hydrogen (by building energy demand), while introducing the vehicles into the community. Figure 4 shows that postal facilities are widespread across the country. Many stations from the FY 2005 analysis are within the proximity of post offices and could be designed to coordinate with a post office co-generation project.

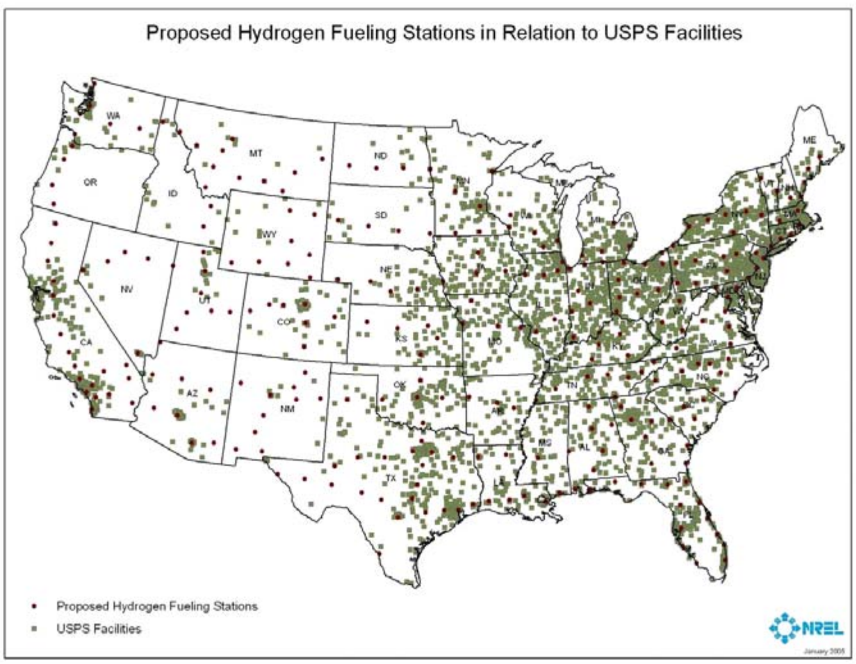

Figure 4. USPS Facilities Nationwide

Non-postal federal facilities are also prevalent nationwide. Coordination with non-postal federal entities is important because federal agencies are subject to Executive Order 13149, which requires certain federal fleets to utilize alternative fuels. They are also covered under Executive Order 13123, which requires renewable energy use in federal facilities. The combination of these requirements makes federal entities an important factor in the transition to hydrogen. For example, Figure 5 shows the federal facilities in the Denver metropolitan area. Federal facilities are located widely across the country and could be key to transition from a geographic, as well as logistic, standpoint.

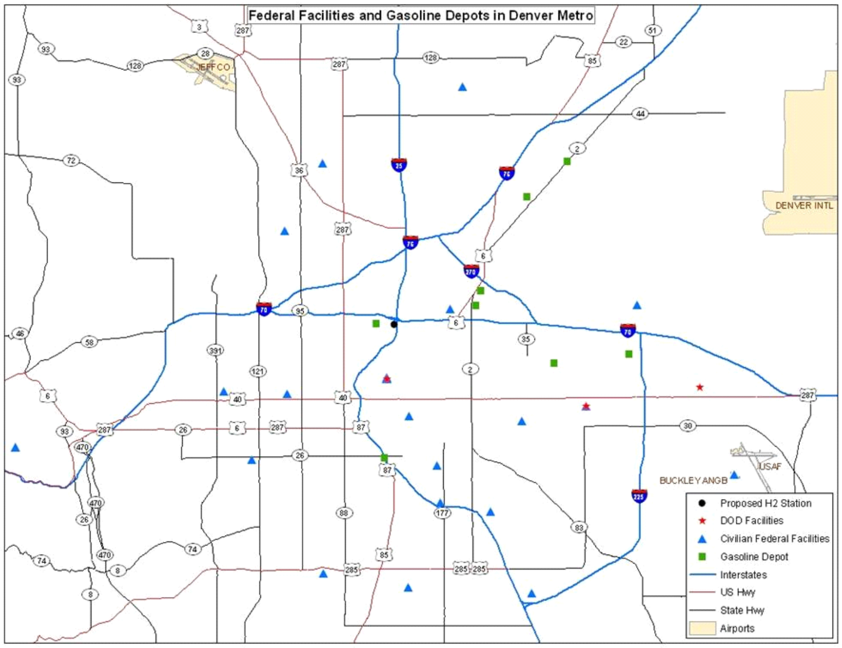

Figure 5. Federal Facilities in the Denver Metropolitan Area

Petroleum Depots

As the United States transitions from a petroleum-driven transportation system to one that is hydrogen based, existing petroleum-related assets may become underutilized (as we transition to the 20% or 30% penetration level). One such type of asset is the petroleum depot for short-term storage and the distribution of transportation fuel. It would be advantageous to use these existing facilities for hydrogen production and distribution. To evaluate the potential for this type of transition, the existing petroleum depots in the United States were examined. Figure 6 shows these depots throughout the United States.

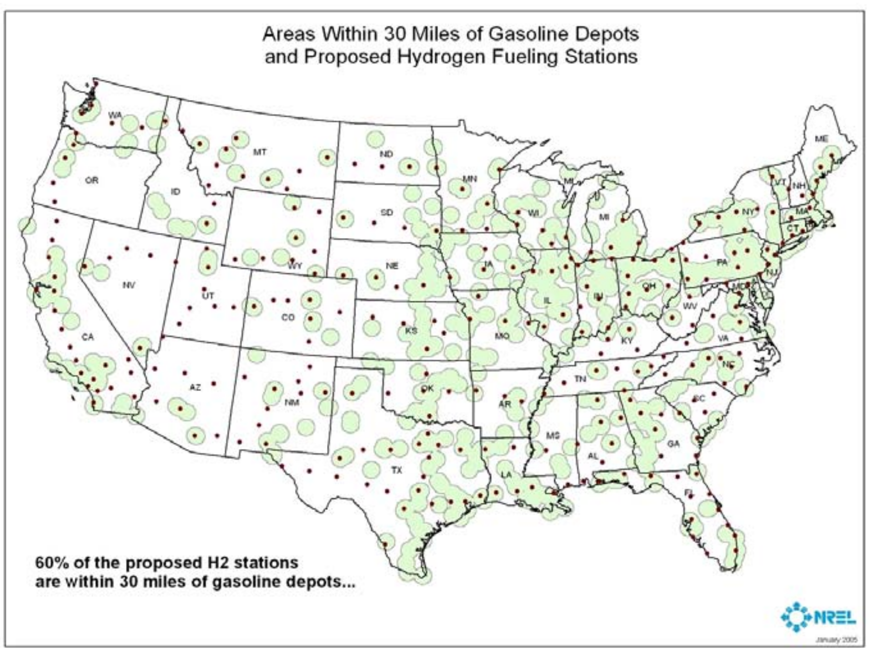

Figure 6. Areas within 30-Mile Radius of Gasoline Depots and Proposed Hydrogen Stations

It would be relatively easy to transport hydrogen via truck to support refueling stations within a 30-mile radius of these depots. Because 60% of the proposed interstate stations fall within this range, the depots could be good candidates for centralized production with distribution to the proposed stations. Furthermore, because these depots were designed to distribute transportation fuel they should also be suited to support hydrogen distribution. Analysis for trucking delivery costs from depots to the proposed stations will be incorporated in FY 2006 and will harmonize with the H2A delivery analysis.

Hydrogen Production Facilities

More than 370 U.S. facilities (such as petroleum refineries and ammonia and chemical plants) produce hydrogen as a primary product or have hydrogen as a by-product. During the transition phase when hydrogen demand is relatively low, these existing facilities may be able to increase production to satisfy emerging needs for transportation hydrogen. Figure 7 shows the existing hydrogen facilities and the proposed interstate stations within a 30-mile radius of these facilities.

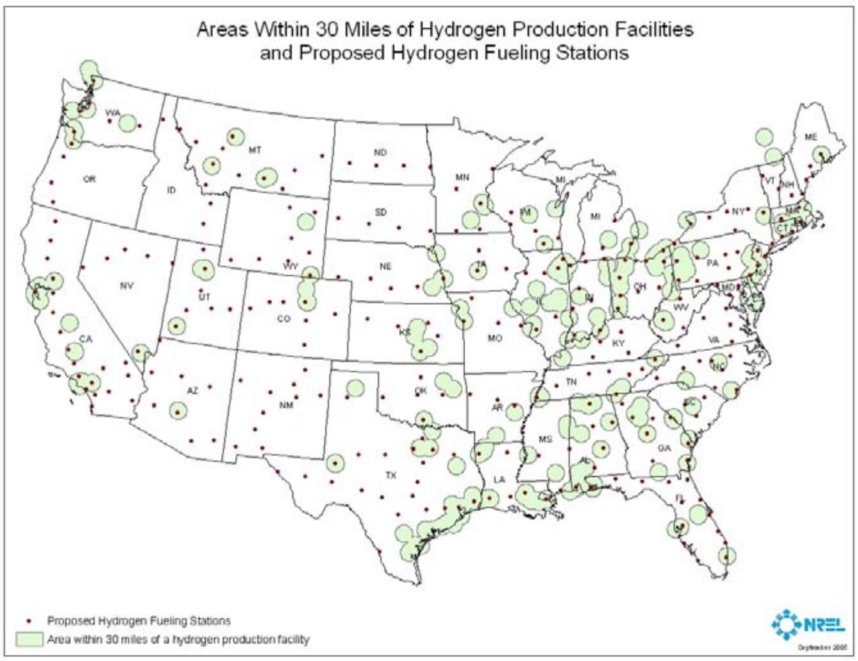

Figure 7. Areas within 30-Mile Radius of Hydrogen Production Facilities and Proposed Refueling Stations

Conclusions and Recommendations

Hydrogen infrastructure is a big challenge in the transition to hydrogen vehicles. This project suggests possible first steps. It identifies a minimum infrastructure that could support the introduction of hydrogen vehicles and evaluates transition scenarios supported by this infrastructure. It represents an infrastructure to facilitate interstate or longer-distance trips. For this type of travel the vehicle distribution is of secondary concern because the emphasis is connecting major urban centers.

The second aspect of infrastructure that needs analysis is local trips, where drivers refuel near their homes or work. This is especially challenging because during the transitional phase, vehicles will not be uniformly distributed. Understanding the spatial distribution of vehicles and corresponding hydrogen demand to accommodate local trips is critical for transitional infrastructure analysis.

To adequately address local infrastructure, the following issues must be better understood.

- Effects of changing demand throughout the transition to avoid stranded assets
- Consumer vehicle choices and if/how previous new product introduction can aid in this understanding (i.e. hybrid and/or alternative fuel vehicles, cellular telephones, etc.)

- Relationship between availability of fuel and vehicle choice
- Policy and economic implications of very early transition (<1%) versus later transition (5%-10%)

During FY 2006, this project will address some of these concerns. It will focus on hydrogen demand analysis, including:

Defining Key Demographics and Attributes, Rank Attributes, and Predict Vehicle Penetration and Hydrogen Demand Growth under Various Market Scenarios: Key attributes affecting consumer acceptance of a hydrogen fuel cell vehicle will be identified (with consultation from Oak Ridge National Laboratory) and spatially analyzed using GIS. Attributes will be assigned rankings and scores geographically to represent the likelihood to purchase/operate a fuel cell vehicle.

Conducting Sensitivity Analyses: Sensitivity analysis will ensure that the scores assigned for each demographic/characteristic are reasonable.

Defining Infrastructure Scenarios at Various Penetration Rates: The final infrastructure (100% vehicle penetration into the marketplace) will be the initial analysis with transitional demand scenarios (TDS) to follow (50%, 30%, and 10% vehicle penetration). At each penetration rate, the infrastructure will be spatially defined using GIS in terms of quantity of hydrogen required, station configuration, production and distribution, and percentage of population with access to hydrogen.

Identifying Costs and Stranded Assets: Evaluate the degree to which infrastructure installed during the transition phases (TDS10, TDS30, TDS50) will become stranded assets and minimize wherever possible. For each scenario, incremental and cumulative infrastructure investment costs will be calculated.

Evaluating Sustainability Levels: Determine the point when the stations become profitable and the private sector could be responsible for infrastructure development and operational costs without government funding.

Identifying and Evaluating Transitional Strategies: Identify specific postal facilities with transitional potential, renewable community partnerships, hydrogen distribution from MTBE and ammonia plants, and hydrogen plug-in hybrid potential.

Incorporating Centralized Production: Trucking and pipeline delivery costs from central to the proposed stations will be incorporated in FY 2006 and will harmonize with the H2A delivery analysis.

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This milestone report identifies a minimum infrastructure that could support the introduction of hydrogen vehicles and develops and evaluates transition scenarios supported by this infrastructure.

15. SUBJECT TERMS
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