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Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles

Preprint

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ANALYSIS OF THE HYDROGEN INFRASTRUCTURE NEEDED TO ENABLE COMMERCIAL INTRODUCTION OF HYDROGEN-FUELED VEHICLES

M. Melendez[1], A. Milbrandt[1]

1. Introduction

In 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, policy analysis, and technology validation expertise. Using these capabilities, NREL has contributed to identifying and addressing barriers to the hydrogen economy. One specific barrier discussed in DOE's Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan is the development of a hydrogen fueling infrastructure [1]. The goal of this study was to investigate the barriers to developing a hydrogen fueling infrastructure and identify and quantify potential solutions for overcoming the barriers.

As hydrogen-fueled vehicles are first introduced, they will be few in number. This makes building a large number of hydrogen fueling stations difficult, because stations likely will not be economically viable without an adequate number of vehicles to create demand for fuel. Conversely, without adequate fueling options, consumers will be reluctant to purchase hydrogen-fueled vehicles. This is commonly known as the "chicken and egg" problem: which comes first? More importantly, how do you bring both into existence simultaneously?

2. Objective

This project was designed to address the "chicken and egg" problem by identifying a minimum infrastructure that could support the introduction of hydrogen-fueled vehicles. The objective was to determine the location and number of hydrogen stations nationwide that would make hydrogen fueling available at regular intervals along the most commonly traveled interstate roads, thus making interstate and cross-country travel possible. This approach to fueling

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station distribution is intended to lay the foundation for widespread commercial introduction of hydrogen-fueled vehicles and to provide a broad look at the scope of infrastructure necessary to bring this new technology to the marketplace.

3. Project Organization and Assumptions

The project was organized as follows:

Phase I: Develop an Initial Hydrogen Fueling Station Network

1) Identify existing hydrogen production facilities and alternative fuel stations
2) Identify highway traffic volumes throughout the U.S. interstate system
3) Select specific north-south and east-west routes as a focus for the project
4) Incorporate existing hydrogen production facilities, hydrogen and natural gas fueling stations, traffic volume, and county population data
5) Place stations on the interstate network

Phase II: Analyze Infrastructure Design and Cost

6) Categorize stations by predicted vehicle and hydrogen throughput
7) Estimate total costs for construction of the network
8) Identify federal government partners to improve economics and facilitate construction of infrastructure
9) Identify longer-term hydrogen distribution potential

Numerous assumptions were made during the analysis. Following is a list of these basic assumptions, which are described in further detail in each task description:

- The analysis focused on a transition period, the 2020/2030 timeframe, during which the purpose is to provide a "backbone" of hydrogen fueling stations to facilitate interstate travel for early adopters of hydrogen fuel cell technology.
- Hydrogen-fueled vehicles were assumed to have a range of 300 miles (DOE 2008 technical objective).
- Traffic volumes were assumed to be consistent from today through the 2020/2030 timeframe.
- The focus was on light-duty vehicles driven by the general public.
- Cost assumptions were for station construction and did not include hydrogen fuel costs or acquisition costs for property.
- Infrastructure was designed to tie into existing infrastructure where possible. If natural gas stations were nearby, the station design would include onsite reforming. Where a central production facility was nearby, a pipeline from that facility would supply the hydrogen.
- Drivers were assumed to be willing to travel up to 3 miles from the interstate exit to use a hydrogen fueling station.

4. Phase I: Develop an Initial Hydrogen Fueling Station Network

Phase I (tasks 1–5) focused on identifying station locations that support interstate travel while taking advantage of local resources and being accessible to the largest number of people. Key resources, population densities, and traffic volumes were identified and spatially categorized using a geographic information system (GIS).

A 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 a 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. This combination of geographic and tabular forms enables analysis and characterization of different phenomena that occupy the same geographic space. Many government and planning organizations use GIS for transportation-related projects, such as determining existing and projected traffic and managing road maintenance.

4.1. Identify existing hydrogen production facilities and alternative fuel stations

Data on existing hydrogen production facilities were obtained from the Chemical Economics Handbook [2]. Facilities were divided into four categories:

- Producers of liquid hydrogen
- Producers of gaseous hydrogen: hydrogen produced for resale to external customers
- Producers of captive hydrogen: hydrogen produced for internal use
- Producers of byproduct hydrogen: hydrogen recovered from a manufacturing process and sold to gaseous hydrogen producers, purified, and sold to external customers, or vented as waste.

The facilities were entered into the GIS at a city/state level. In some cases, exact street addresses could be identified, and those were used to make the locations more precise. A map of existing facilities nationwide was generated (Figure 1).

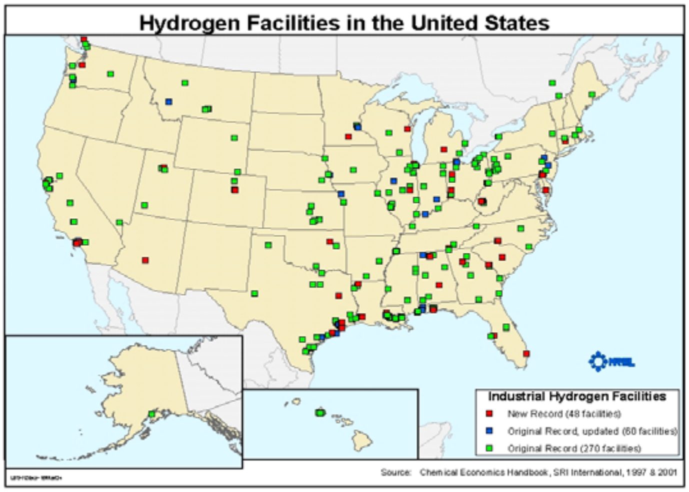

Figure 1. Hydrogen Facilities in the United States (Original Record 1997 contains 1997 data; Original Record, updated adds 1999 data; New Record adds 2001 data)

Data on compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen fueling stations were gathered from the Alternative Fuels Data Center [3], the California Hydrogen Highway Network Initiative [4], and the Online Fuel Cell Information Resource [5]. These datasets were processed using the GIS, and a map of existing alternative fuel stations was generated (Figure 2).

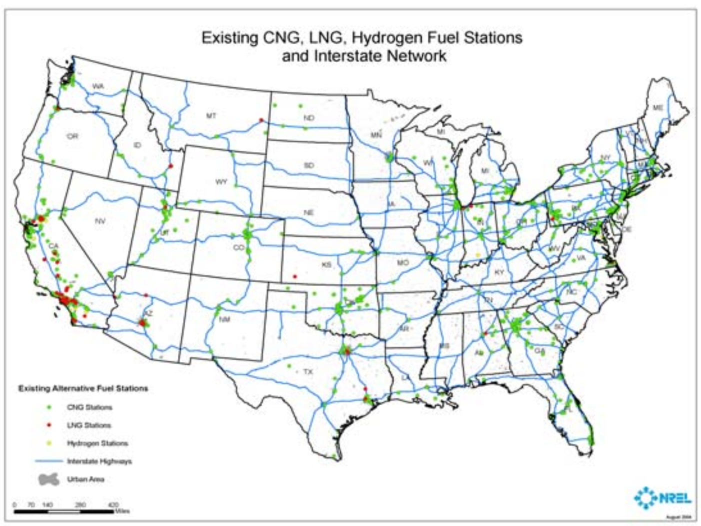

Figure 2. Existing Alternative Fuel Stations

4.2. Identify highway traffic volumes throughout the U.S. interstate system

Several sources of data were evaluated, including individual state traffic data, Bureau of Transportation Statistics data, and U.S. Department of Transportation (DOT) Federal Highway Administration (FHWA) data. After careful review of the data for various interstate segments, it was determined that the most reliable data were from the FHWA [6]. In addition, these data are frequently used for

FHWA and DOT planning purposes and are the accepted source for such data nationwide.

The FHWA data were entered into the GIS, and a map of the annual average daily traffic (AADT) was generated (Figure 3). The traffic volume (vehicles per day) is measured for the highway segment, in both directions, representing an average 24-hour day in a year.

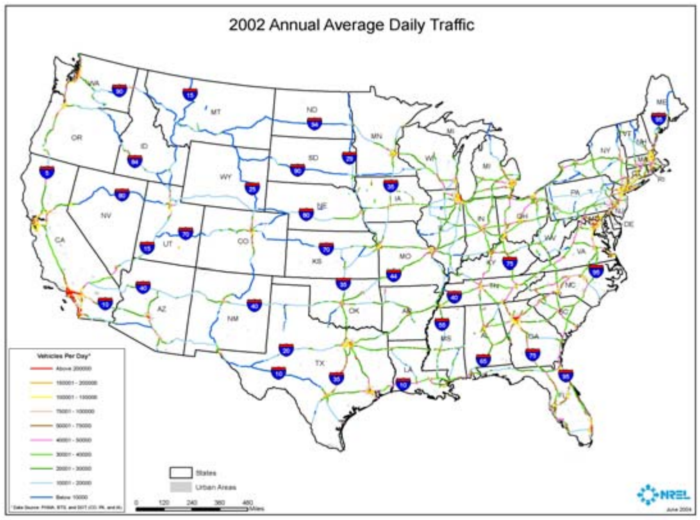

Figure 3. Annual Average Daily Traffic, 2002

4.3. Select specific north-south and east-west routes as a focus for the project

Once the traffic volume data were entered and validated, the data were analyzed to determine where traffic flow was greatest along highways. A flow of 20,000 vehicles per day appeared suitable as a base for this analysis (Figure 4). A flow above 25,000-30,000 vehicles only selected a small number of discontinuous interstate sections, and a flow of 10,000-15,000 vehicles did not adequately narrow the number of main traffic corridors selected.

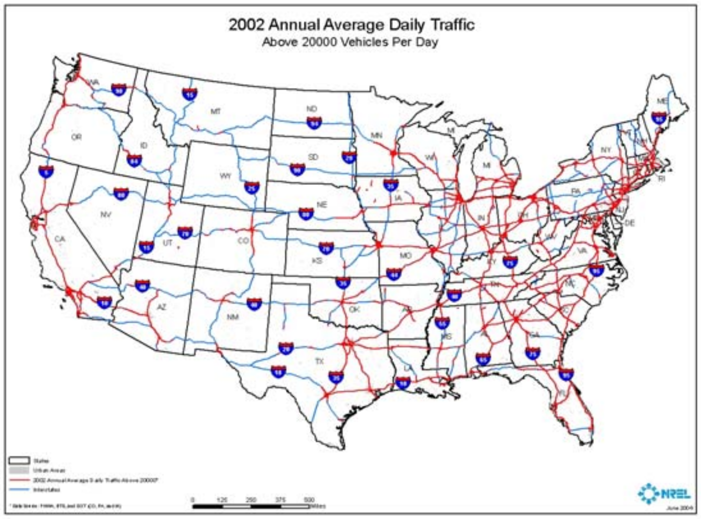

Figure 4. Interstate Traffic of More Than 20,000 Vehicles per Day

Figure 4 defines Interstates 5, 95, 75, and 65 as very well traveled throughout. This figure also defines three major regions based on AADT: east (heavy, mostly urban traffic), central west of the Mississippi River (light, mostly rural traffic), and Pacific west (heavy, urban traffic).

The need for infrastructure is based on a number of factors, including driving patterns or traffic flow (east-west and north-south), geographic coverage of all regions of the country, and continuity. Considering these factors, a proposed interstate network for the hydrogen infrastructure analysis was developed (Figure 5). The network is meant to ensure a convenient route and fueling stations between major population centers (e.g., from Chicago to San Francisco). The routes in the central region were chosen for connectivity between the east and Pacific west regions and locally heavy interstate traffic.

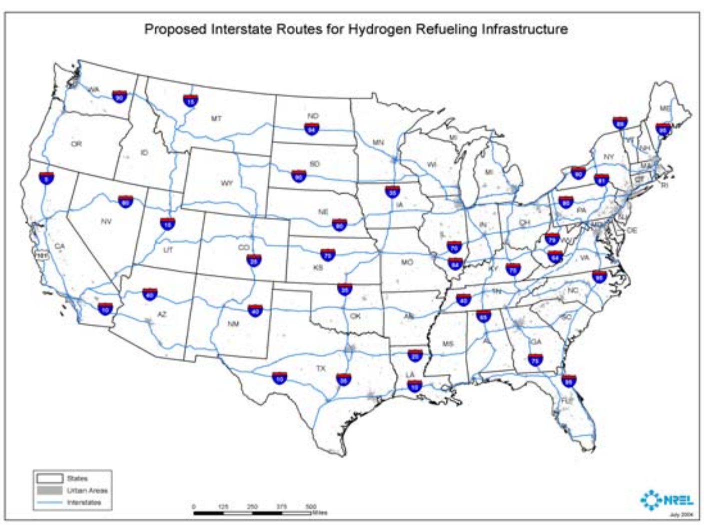

Figure 5. Proposed Interstate Routes for Hydrogen Infrastructure Analysis

4.4. Incorporate existing hydrogen production facilities, hydrogen and natural gas fueling stations, traffic volume, and county population data

Coordinating the hydrogen infrastructure with existing natural gas fueling sites is important because these locations have significant experience dealing with the permitting and logistic issues related to gaseous fuels. Additionally, these locations are likely to have several local fleets and customers accustomed to using gaseous fuels and may be likely early adopters of hydrogen fuel cell vehicles. For the purpose of this analysis, only existing alternative fueling stations within 3 miles of interstates in the proposed network (Figure 5) were included. Other interstate and U.S. highways intersecting the proposed interstates are important to this analysis because of the additional traffic they bring to the intersecting point. This assumes that a fueling station located at an intersection would provide service to more people than a station not at an intersection.

Population data from the U.S. Census Bureau were incorporated. An assumption was made that the greater the population, the more potential customers for a hydrogen station, leading to greater hydrogen demand and a higher likelihood that the station could be economically self sustaining. Figure 6 shows a map with the selected interstates, existing alternative fueling stations within 3 miles of these interstates, hydrogen production facilities, and counties with population over 50,000 people highlighted in brown. This provides a national overview of the proposed infrastructure and the number of major metropolitan areas and resources it overlaps.

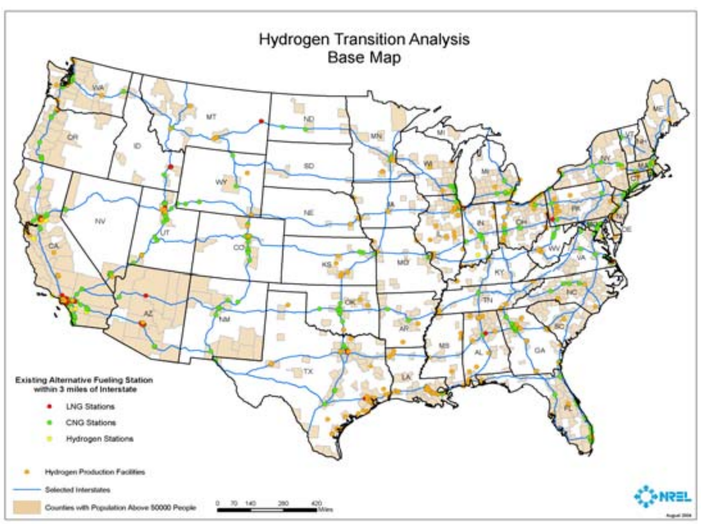

Figure 6. Hydrogen Transition Analysis Base Map

4.5. Place stations on the interstate network

Because of an assumed vehicle range of about 300 miles, station placement was set to a maximum of 100 miles between stations. This allows drivers on a cross-country trip a level of comfort in the event that one of the stations on their route is closed. After a network was selected and traffic volumes and routes were examined, several key north-south/east-west routes west of the Mississippi River were identified. In the east, the network was not as clearly defined. Overall there is a greater interstate volume in the east, and these routes do not display clear north-south/east-west patterns. This could indicate that the interstates are used extensively for short trips, such as daily commuting, rather than more linear cross-country travel. For this reason, the station placement in the east, and in urban areas with traffic volumes greater than 20,000 vehicles per day, was selected to be approximately 50 miles to accommodate more drivers on these short trips.

Considering all the factors collected, stations were placed along the selected interstate routes. This was done somewhat subjectively: each station site was manually selected based on proximity to existing infrastructure (hydrogen infrastructure, natural gas fueling stations, and intersection with other roads), daily traffic, and local population. Therefore, stations are not exactly 50 miles apart in the east region or 100 miles apart in the rural central and Pacific west regions. Rather, stations were placed to ensure that they were not further than 50 or 100 miles apart, respectively, and to attempt to minimize cost and maximize potential use and coverage. Table 1 summarizes the proposed stations by interstate. Figure 7 shows proposed station locations.

Table 1. Summary of Proposed Hydrogen Stations Along Major Interstates

Interstate	Mileage	Number of Stations*	Existing Natural Gas Stations*	Existing Hydrogen Stations*	Sites Near Hydrogen Production Facilities*	New Stations Needed*
5	1,381	20	10	0	2	8
10	2,460	29	1	2	5	21
15	1,434	17	5	0	3	9
20	1,539	18	1	0	2	15
25	1,063	13	3	0	1	9
35	1,568	18	4	0	2	12
40	2,555	28	5	0	0	23
64	938	7	0	0	2	5
65	887	11	1	0	1	9
70	2,153	23	3	0	0	20
75	1,786	19	6	0	1	12
79	343	5	3	0	1	1
80	2,900	33	6	0	4	23
81	855	9	0	0	0	9
89	191	3	1	0	0	2
90	3,021	35	7	0	2	26
94	1,585	16	6	0	0	10
95	1,920	30	13	0	1	16
Total Mileage	28,580					
Total Stations		**284**	**58**	**2**	**22**	**202**

*Stations intersected by multiple interstates are counted multiple times; e.g., a station intersected by two interstates is counted twice. Therefore, totaling the number of stations shown in the rows for each interstate gives a larger number than the number of stations in the total stations row. The total stations row shows the correct number of total stations.

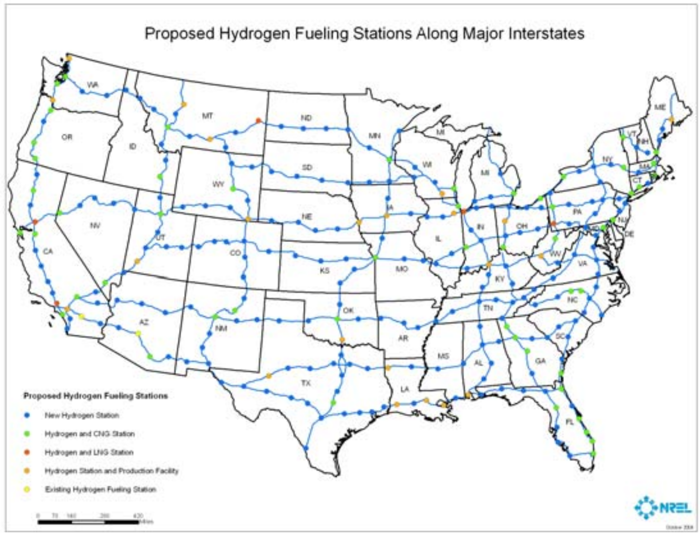

Figure 7. Proposed Hydrogen Fueling Stations Along Major Interstates

5. Phase II: Analyze Infrastructure Design and Cost

Phase II (tasks 6–9) focused on assigning design specifications to the proposed initial hydrogen stations and identifying costs associated with the stations. Strategies that may facilitate the transition to hydrogen-based transportation were also identified.

5.1. Categorize stations by predicted vehicle and hydrogen throughput

Once a reasonable set of backbone station locations was identified, potential future use could be estimated. The vehicle penetration rates for the scenario used in this analysis, called the "Go Your Own Way (GYOW)" scenario, are shown in Table 2. The GYOW scenario was created to support the *Joint DOE/NRCan Study of North American Transportation Energy Futures* [7]. This 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. The model predicts that hydrogen fuel cell vehicles would be introduced in 2018 and represent 50% of the vehicles on the road by 2050.

Table 2. Estimates of Vehicle Penetration (Go Your Own Way Scenario)

Year	Light-Duty Fuel Cell Vehicle Stock (Millions)	Total Light-Duty Vehicle Stock (Millions)	Fuel Cell Vehicles as Percent of Stock
2020	3	274	1.1%
2030	59	306	19.4%
2040	140	328	42.8%
2050	175	353	49.5%

Once the number of hydrogen vehicles on the road was estimated it could be used to predict the total hydrogen demand for each station. The following assumptions were made with regard to estimating hydrogen demand:

1. Ninety-one percent of all vehicle-miles traveled are done so in passenger vehicles. The figures for AADT represent all vehicle types passing through a certain stretch of interstate. To determine the number of fuel cell vehicles passing through the same stretch, the percentage of AADT that are vehicles that potentially could be fuel cell vehicles (passenger vehicles) must first be estimated [8].

2. Fifty percent of all passenger vehicles in 2020 and 35% of all passenger vehicles in 2030 that pass a hydrogen station will use that station. Because there are fewer stations in 2020, drivers have fewer station options and therefore use the stations they pass at a higher rate than in 2030 or further into the future, as the number of stations begins to increase.

3. Each vehicle fill-up is 5 kg of hydrogen.

5.2. Estimate total costs for construction of the network

Once the hydrogen demand at each station was established based on predicted 2020 vehicle penetration, station configurations were selected for each station. The station configurations and costs were taken from a University of California-Davis (UC-Davis) study [9]. Table 3 shows these station types. Table 4 shows the decision matrix for each station configuration based on its predicted use or hydrogen demand. When stations required more hydrogen production than the station design selected, a whole number multiplier was put on the UC-Davis cost estimate, e.g., when a mobile refueler capable of 10 kg/day was selected at a site that needed 25 kg/day, the cost of three 10-kg/day stations was used as long as this cost was less than the cost of the next larger station that would satisfy the 25 kg/day need. To improve these cost estimates, future work could include more detailed cost estimates for stations. Using this methodology, the overall infrastructure cost is approximately $837 million, based on 2020 demand for hydrogen.

Table 3. Standard Station Configurations and their Construction Costs

Station Type	Cost per Station	Abbreviation
Steam Methane Reformer, 100 kg/day	$1,052,921	SMR100
Steam Methane Reformer, 1,000 kg/day	$5,078,145	SMR1000
Electrolyzer, grid, 30 kg/day	$555,863	EL30G
Electrolyzer, grid, 100 kg/day	$945,703	EL100G
Electrolyzer, renewable, 30 kg/day	$667,402	ER30R
Mobile Refueler, 10 kg/day	$248,897	MR10
Delivered Liquid Hydrogen, 1,000 kg/day	$2,617,395	DLH21000
Pipeline Station, 100 kg/day	$578,678	PIPE

Table 4. Assumptions for Assigning Station Configuration Based on Existing Infrastructure and Hydrogen Demand

Existing Infrastructure	Hydrogen Volume (kg/day)	Station Type
CNG	<30	MR10
LNG	<30	MR10
Hydrogen Facility	<30	PIPE
Hydrogen	<30	No Change
None	<30	EL30G
CNG	30-100	SMR100
LNG	30-100	SMR100
Hydrogen Facility	30-100	PIPE
Hydrogen	30-100	No Change
None	30-100	EL100G
CNG	100-1,000	SMR1000
LNG	100-1,000	SMR1000
Hydrogen Facility	100-1,000	PIPE
Hydrogen	100-1,000	No Change
None	100-1,000	DLH21000
CNG	>1,000	SMR1000
LNG	>1,000	SMR1000
Hydrogen Facility	>1,000	PIPE
Hydrogen	>1,000	No Change
None	>1,000	DLH21000

5.3. Identify federal government partners to improve economics and facilitate construction of infrastructure

Because of high costs of infrastructure, especially during the transition period during which technologies are new and volumes are low, there is incentive to look for innovative ways to reduce costs and increase infrastructure use. One possible way is to focus on locating infrastructure at existing federal facilities. An Executive Order could encourage the concept of co-generation at federal facilities; i.e., these facilities could generate hydrogen onsite and use it in stationary fuel cells as a power source. Facilities also could be designed to permit vehicle fueling for local federal fleets and the general public.

Data on federal property were obtained from the Federal Energy Management Program and mapped in relation to the proposed network of stations. About 80% of the proposed hydrogen fueling stations have at least one civilian federal facility within 10 miles (Figure 8).

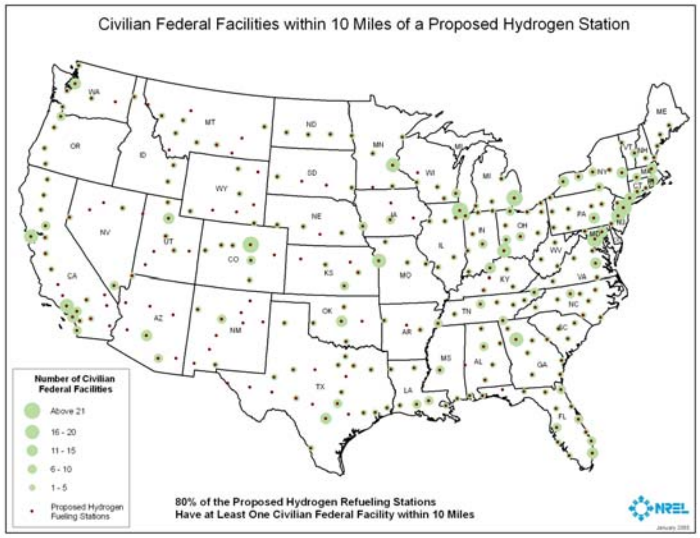

Figure 8. Civilian Federal Facilities within 10 Miles of a Proposed Hydrogen Fueling Station

This shows that, given the right incentives, federal facilities could provide a good starting point for a transitional hydrogen infrastructure because they offer broad geographic coverage. In particular, federal agencies that have been proactive with the introduction of other alternative fuels into their fleets may have an interest in pursuing hydrogen for not only their fleet, but also for co-generation and public fueling. Figure 9 shows U.S. Postal Service (USPS) facilities. The USPS is a good candidate for the co-generation option in the near term because it operates its own fleet, which could use hydrogen, and is dispersed widely across the country.

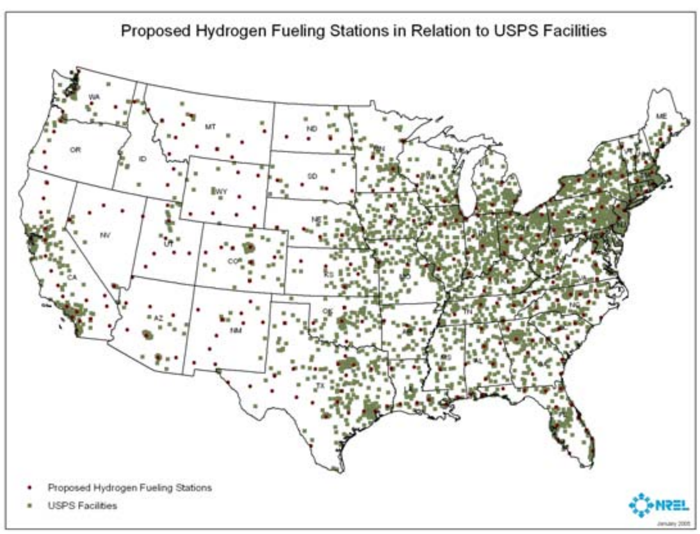

Figure 9. Proposed Hydrogen Fueling Stations in Relation to U.S. Postal Service Facilities

5.4. Identify longer-term hydrogen distribution potential

Although the analysis shown in this report is primarily a transition analysis, using GIS to show multiple characteristics graphically also is applicable to evaluating longer-term, full-scale hydrogen infrastructure. One possible way to support a broader infrastructure, after the technology is mature and upwards of 75% of the vehicle stock is hydrogen fueled, is to use existing gasoline and diesel depots for centralized hydrogen production, storage, and distribution. These would be excellent candidates because, as the transition from petroleum to hydrogen occurs, the petroleum facilities will become underutilized, making them available for the construction of hydrogen facilities. The locations of individual petroleum depots were acquired from MAPSearch, a PennWell Company. A gasoline terminal stores and transfers petroleum products (gasoline and distillate) received from the pipeline or rail cars and distributes them to regional markets via tank truck.

Assuming these depots could distribute hydrogen to stations up to 30 miles away, fairly broad coverage could be attained from this strategy. Figure 10 shows a map of the U.S. coverage within 30 miles of existing gasoline/diesel depots, with the proposed infrastructure superimposed. This shows that about 60% of the proposed facilities could be supplied with hydrogen from a centralized facility in the long term.

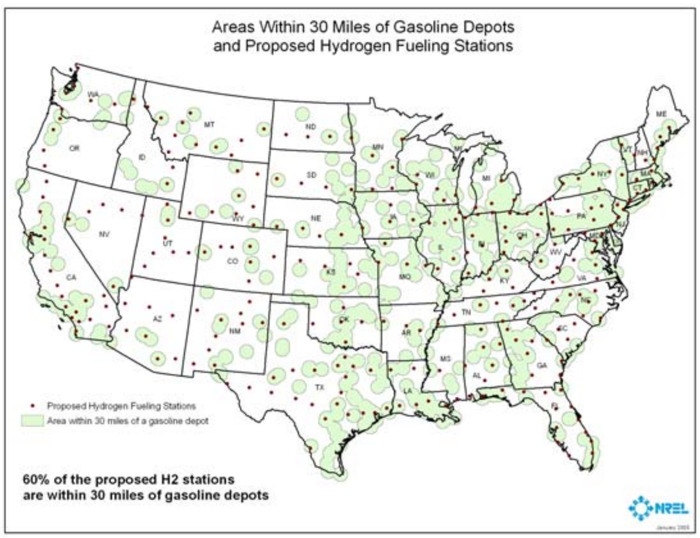

Figure 10. Areas Within 30 Miles of a Petroleum Depot and Proposed Hydrogen Fueling Stations

6. Results and Conclusions

Overall, 284 stations were identified that could make up a potential transitional national hydrogen fueling infrastructure backbone, with a total construction cost of $837 million if constructed to meet the needs of 2020. This is based on the aggressive assumptions of a 50% fuel cell vehicle stock by 2050, and approximately 1% in 2020 and 20% in 2030. Section 9 shows the complete list of station locations selected.

The construction cost of $837 million is an initial cost for the early hydrogen network. Because the infrastructure is based on anticipated station use, many of the stations could be economically self sustaining in the near term (2020–2030). This depends on how evenly the fuel cell vehicles are distributed geographically. Most likely, they would be concentrated in key urban areas, making those stations economically viable, whereas rural stations that do not serve as many vehicles may need additional financial support until sufficient vehicles are operating in their region.

One way to help the economic viability of stations is to incorporate co-generation. In particular, using co-generation (hydrogen for fuel cell vehicles and power-producing stationary fuel cells) at federal facilities could reduce the federal government's overall fossil fuel consumption and environmental impacts while helping facilitate interstate travel in fuel cell vehicles for the driving public.

7. Future Work

Below are suggestions for potential future work that would build on this project:

Incorporate DOE analysis: Incorporate DOE's H2A forecourt and delivery cost analysis to improve infrastructure analysis and design and ensure consistency with DOE hydrogen program assumptions.

Expand current station network: Identify key metropolitan areas based on a series of factors (e.g., Clean Cities participation and success, population demographics, locally available energy resources, and completed and ongoing metropolitan area infrastructure analysis) that will expand the network beyond the limited interstate focus to have a broader reach of consumers.

Identify co-generation options for federal facilities: Identify which specific federal facilities would be good candidates for the installation of co-generation so that hydrogen can be used in stationary fuel cells while providing a vehicle fueling location. Specify the co-generation equipment, costs, and potential impacts on the transition. Focus on key federal facilities/agencies that have been proactive with the use of alternative fuels or energy efficiency in the past.

Improve estimates for utilization rates at each station: Identify the number of vehicles visiting each station and their hydrogen demand based on vehicle penetration estimates (using the VISION model), population demographics, traffic data, and experience from conventional fuel stations. Predict hydrogen demand at each station for hydrogen fuel cell vehicles and for hydrogen-natural gas blends in natural gas vehicles.

Tailor stations based on location and available local resources: Tailor several types of stations to the needs and resources of specific station locations. These stations could be designed based on factors including predicted use and available resources (e.g., renewable energy sources, natural gas pipelines, and centralized hydrogen production facilities).

Estimate station costs and perform break-even analysis: For each station, identify the construction and operating costs. Use estimates of use and hydrogen fuel costs from DOE's H2A effort to predict when stations will become self sustaining and to evaluate the impacts of hydrogen-natural gas blends as a transition strategy to reduce break-even time.

Evaluate situations for which government financial assistance would be most beneficial: Analyze various scenarios and identify key partners and projects that would make the best use of funding for aiding in the transition to hydrogen, such as funding key refueling stations in partnership with the USPS, or selecting primary and secondary metropolitan areas and/or routes that have the greatest impacts on transition.

8. References

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9. Station Details

Location	State	Interstate	Existing Infrastructure	AADT	Utilization 2020	Demand 2020	Station Type	Cost
Buffalo	WY	90, 25	None	4,884	24	119	DLH21000	$2,677,362
Moorcroft	WY	90	None	5,317	26	129	DLH21000	$2,677,362
Cassa	WY	25	None	6,340	31	154	DLH21000	$2,677,362
Lyman	WY	80	None	11,427	56	278	DLH21000	$2,677,362
Elk Mountain	WY	80	None	11,520	56	280	DLH21000	$2,677,362
Table Rock	WY	80	None	11,838	58	288	DLH21000	$2,677,362
Casper	WY	25	Natural Gas	10,849	53	264	SMR1000	$5,137,202
Cheyenne	WY	80, 25	Hydrogen Facility	13,918	68	338	PIPE	$583,141
Lewisburg	WV	64	None	13,455	65	327	DLH21000	$2,677,362
Clarksburg	WV	79	Natural Gas	29,789	145	724	SMR1000	$5,137,202
Charleston	WV	64, 79	Hydrogen Facility	54,101	263	1,315	PIPE	$583,141
French Island	WI	90	None	22,313	108	542	DLH21000	$2,677,362
Northfield	WI	94	None	23,044	112	560	DLH21000	$2,677,362
Portage	WI	90, 94	None	31,641	154	769	DLH21000	$2,677,362

Milwaukee	WI	94	Natural Gas	116,131	564	2,822	SMR1000	$5,137,202
Milton	WI	90	Hydrogen Facility	48,695	237	1,184	PIPE	$583,141
Ritzville	WA	90	None	13,821	67	336	DLH21000	$2,677,362
Ellensburg	WA	90	None	18,971	92	461	DLH21000	$2,677,362
Olympia	WA	5	Natural Gas	96,347	468	2,342	SMR1000	$5,137,202
Seattle	WA	5, 90	Natural Gas	186,593	907	4,535	SMR1000	$5,137,202
Bellingham	WA	5	Hydrogen Facility	43,333	211	1,053	PIPE	$583,141
Kalama	WA	5	Hydrogen Facility	54,977	267	1,336	PIPE	$583,141
South Burlington	VT	89	Natural Gas	34,050	166	828	SMR1000	$5,137,202
Emporia	VA	95	None	31,248	152	759	DLH21000	$2,677,362
Kent	VA	81	None	34,770	169	845	DLH21000	$2,677,362
Staunton	VA	64, 81	None	42,873	208	1,042	DLH21000	$2,677,362
Richmond	VA	64, 95	None	84,164	409	2,046	DLH21000	$2,677,362
Fredericksburg	VA	95	None	118,314	575	2,876	DLH21000	$2,677,362
Emery	UT	70	None	5,027	24	122	DLH21000	$2,677,362
Wendover	UT	80	None	6,802	33	165	DLH21000	$2,677,362
Thompson Springs	UT	70	None	6,829	33	166	DLH21000	$2,677,362
Cove Fort	UT	15	None	9,934	48	241	DLH21000	$2,677,362
Levan	UT	15	None	14,918	73	363	DLH21000	$2,677,362
Tremonton	UT	15	None	15,280	74	371	DLH21000	$2,677,362
Salt Lake City	UT	15, 80	Natural Gas	93,521	455	2,273	SMR1000	$5,137,202
Cedar City	UT	15	Hydrogen Facility	19,967	97	485	PIPE	$583,141
Bakersfield	TX	10	None	4,689	23	114	DLH21000	$2,677,362
Sonora	TX	10	None	5,903	29	143	DLH21000	$2,677,362
Kent	TX	10, 20	None	7,565	37	184	DLH21000	$2,677,362
Mountain Home	TX	10	None	8,249	40	200	DLH21000	$2,677,362
Finlay	TX	10	None	9,535	46	232	DLH21000	$2,677,362
Westbrook	TX	20	None	12,345	60	300	DLH21000	$2,677,362
Baird	TX	20	None	17,606	86	428	DLH21000	$2,677,362
Schulenburg	TX	10	None	20,703	101	503	DLH21000	$2,677,362
Owentown	TX	20	None	25,802	125	627	DLH21000	$2,677,362
Laredo	TX	35	None	33,660	164	818	DLH21000	$2,677,362
Amarillo	TX	40	None	42,700	208	1,038	DLH21000	$2,677,362
Hudson Oaks	TX	20	None	42,917	209	1,043	DLH21000	$2,677,362
Hillsboro	TX	35	None	43,425	211	1,055	DLH21000	$2,677,362
Denton	TX	35	None	49,227	239	1,196	DLH21000	$2,677,362
Temple	TX	35	None	54,508	265	1,325	DLH21000	$2,677,362
Baytown	TX	10	None	57,627	280	1,401	DLH21000	$2,677,362
Beaumont	TX	10	None	69,980	340	1,701	DLH21000	$2,677,362
Katy	TX	10	None	71,663	348	1,742	DLH21000	$2,677,362
Lawson	TX	20	None	94,438	459	2,295	DLH21000	$2,677,362
San Antonio	TX	10, 35	None	101,158	492	2,459	DLH21000	$2,677,362
Austin	TX	35	Natural Gas	164,744	801	4,004	SMR1000	$5,137,202
Odessa	TX	20	Hydrogen Facility	17,784	86	432	PIPE	$583,141
Kingsport	TN	81	None	33,117	161	805	DLH21000	$2,677,362
Jackson	TN	40	None	35,088	171	853	DLH21000	$2,677,362
Cookeville	TN	40	None	36,172	176	879	DLH21000	$2,677,362
Baneberry	TN	81, 40	None	40,713	198	990	DLH21000	$2,677,362
Memphis	TN	40	None	65,608	319	1,595	DLH21000	$2,677,362
Oak Ridge	TN	40, 75	None	69,752	339	1,695	DLH21000	$2,677,362
Chattanooga	TN	75	None	86,470	420	2,102	DLH21000	$2,677,362
Berry Hill	TN	40, 65	None	101,543	494	2,468	DLH21000	$2,677,362
Stamford	SD	90	None	6,175	30	150	DLH21000	$2,677,362
Kimball	SD	90	None	6,918	34	168	DLH21000	$2,677,362
Rapid City	SD	90	None	21,281	103	517	DLH21000	$2,677,362
Crooks	SD	90	None	22,453	109	546	DLH21000	$2,677,362
Santee	SC	95	None	31,493	153	765	DLH21000	$2,677,362
Florence	SC	95, 20	None	37,634	183	915	DLH21000	$2,677,362
North Augusta	SC	20	None	47,306	230	1,150	DLH21000	$2,677,362
West Columbia	SC	20	None	63,404	308	1,541	DLH21000	$2,677,362
Cranston	RI	95	Natural Gas	119,178	579	2,897	SMR1000	$5,137,202
Milton	PA	80	None	11,395	55	277	DLH21000	$2,677,362
DuBois	PA	80	None	11,974	58	291	DLH21000	$2,677,362
Erie	PA	90, 79	None	15,378	75	374	DLH21000	$2,677,362
Hazleton	PA	80, 81	None	15,724	76	382	DLH21000	$2,677,362

Somerset	PA	70	None	33,196	161	807	DLH21000	$2,677,362
Harrisburg	PA	81	None	35,705	174	868	DLH21000	$2,677,362
Newportville Terrace	PA	95	None	45,625	222	1,109	DLH21000	$2,677,362
Grove City	PA	80, 79	Natural Gas	11,463	56	279	SMR1000	$5,137,202
Washington	PA	70, 79	Natural Gas	19,204	93	467	SMR1000	$5,137,202
Albany	OR	5	None	55,966	272	1,360	DLH21000	$2,677,362
Roseburg	OR	5	Natural Gas	36,681	178	892	SMR1000	$5,137,202
Medford	OR	5	Natural Gas	38,611	188	938	SMR1000	$5,137,202
Tualatin	OR	5	Natural Gas	114,034	554	2,772	SMR1000	$5,137,202
Perry	OK	35	None	15,792	77	384	DLH21000	$2,677,362
Henryetta	OK	40	None	16,709	81	406	DLH21000	$2,677,362
Sayre	OK	40	None	18,854	92	458	DLH21000	$2,677,362
Oklahoma City	OK	40, 35	Natural Gas	83,221	405	2,023	SMR1000	$5,137,202
Ardmore	OK	35	Hydrogen Facility	28,736	140	698	PIPE	$583,141
Cambridge	OH	70	None	27,396	133	666	DLH21000	$2,677,362
Windham	OH	80	None	33,814	164	822	DLH21000	$2,677,362
Elyria	OH	90, 80	None	39,010	190	948	DLH21000	$2,677,362
Rossford	OH	90, 80, 75	None	65,908	320	1,602	DLH21000	$2,677,362
Vandalia	OH	70, 75	None	69,135	336	1,680	DLH21000	$2,677,362
Columbus	OH	70	None	98,070	477	2,384	DLH21000	$2,677,362
Geneva	OH	90	Natural Gas	31,771	154	772	SMR1000	$5,137,202
Cincinnati	OH	75	Natural Gas	112,366	546	2,731	SMR1000	$5,137,202
Lima	OH	75	Hydrogen Facility	43,055	209	1,046	PIPE	$583,141
Saint Johnsville	NY	90	None	23,765	116	578	DLH21000	$2,677,362
Binghamton	NY	81	None	32,179	156	782	DLH21000	$2,677,362
Victor	NY	90	None	43,441	211	1,056	DLH21000	$2,677,362
Syracuse	NY	90, 81	None	48,590	236	1,181	DLH21000	$2,677,362
Buffalo	NY	90	Natural Gas	70,968	345	1,725	SMR1000	$5,137,202
Albany	NY	90	Natural Gas	71,753	349	1,744	SMR1000	$5,137,202
Golconda	NV	80	None	6,695	33	163	DLH21000	$2,677,362
Woolsey	NV	80	None	7,557	37	184	DLH21000	$2,677,362
Elko	NV	80	None	9,010	44	219	DLH21000	$2,677,362
Reno	NV	80	Natural Gas	68,568	333	1,667	SMR1000	$5,137,202
Las Vegas	NV	15	Natural Gas	135,290	658	3,288	SMR1000	$5,137,202
Springer	NM	25	None	5,514	27	134	DLH21000	$2,677,362
Williamsburg	NM	25	None	5,961	29	145	DLH21000	$2,677,362
Socorro	NM	25	None	10,782	52	262	DLH21000	$2,677,362
San Jon	NM	40	None	12,211	59	297	DLH21000	$2,677,362
Wilna	NM	10	None	13,356	65	325	DLH21000	$2,677,362
Santa Rosa	NM	40	None	14,794	72	360	DLH21000	$2,677,362
Gallup	NM	40	None	19,005	92	462	DLH21000	$2,677,362
Las Cruces	NM	10, 25	None	21,452	104	521	DLH21000	$2,677,362
Las Vegas	NM	25	Natural Gas	6,626	32	161	SMR1000	$5,137,202
Albuquerque	NM	25, 40	Natural Gas	98,316	478	2,390	SMR1000	$5,137,202
Netcong	NJ	80	None	65,451	318	1,591	DLH21000	$2,677,362
Fords	NJ	95	None	119,002	578	2,892	DLH21000	$2,677,362
Lebanon	NH	89	None	23,742	115	577	DLH21000	$2,677,362
Concord	NH	89	None	43,888	213	1,067	DLH21000	$2,677,362
Portsmouth	NH	95	Natural Gas	66,774	325	1,623	SMR1000	$5,137,202
Sidney	NE	80	None	7,776	38	189	DLH21000	$2,677,362
North Platte	NE	80	None	16,855	82	410	DLH21000	$2,677,362
Elm Creek	NE	80	None	17,623	86	428	DLH21000	$2,677,362
York	NE	80	None	23,479	114	571	DLH21000	$2,677,362
Dickinson	ND	94	None	5,316	26	129	DLH21000	$2,677,362
Jamestown	ND	94	None	6,970	34	169	DLH21000	$2,677,362
Bismarck	ND	94	None	15,318	74	372	DLH21000	$2,677,362
Fargo	ND	94	None	26,448	129	643	DLH21000	$2,677,362
Smith Creek	NC	40	None	24,200	118	588	DLH21000	$2,677,362
Rocky Mount	NC	95	None	32,667	159	794	DLH21000	$2,677,362
Benson	NC	95, 40	None	38,655	188	939	DLH21000	$2,677,362
Lumberton	NC	95	None	39,933	194	971	DLH21000	$2,677,362
Statesville	NC	40	None	46,536	226	1,131	DLH21000	$2,677,362
Ashville	NC	40	None	54,426	265	1,323	DLH21000	$2,677,362
Durham	NC	40	Natural Gas	62,571	304	1,521	SMR1000	$5,137,202
Greensboro	NC	40	Natural Gas	86,902	422	2,112	SMR1000	$5,137,202

Red Rock	MT	15	None	3,121	15	76	EL100G	$923,039
Wolf Creek	MT	15	None	3,640	18	88	EL100G	$923,039
Forsyth	MT	94	None	3,717	18	90	EL100G	$923,039
Lodge Grass	MT	90	None	3,820	19	93	EL100G	$923,039
Haugan	MT	90	None	7,015	34	170	DLH21000	$2,677,362
Livingston	MT	90	None	15,040	73	366	DLH21000	$2,677,362
Missoula	MT	90	None	15,584	76	379	DLH21000	$2,677,362
Glendive	MT	94	Natural Gas	3,698	18	90	SMR100	$1,047,927
Butte	MT	90, 15	Natural Gas	8,808	43	214	SMR1000	$5,137,202
Great Falls	MT	15	Hydrogen Facility	12,345	60	300	PIPE	$583,141
Laurel	MT	90	Hydrogen Facility	14,053	68	342	PIPE	$583,141
Gulfport	MS	10	None	43,286	210	1,052	DLH21000	$2,677,362
Jackson	MS	20	None	66,802	325	1,624	DLH21000	$2,677,362
Bethany	MO	35	None	12,660	62	308	DLH21000	$2,677,362
Columbia	MO	70	None	44,821	218	1,089	DLH21000	$2,677,362
Wentzville	MO	70	None	73,956	359	1,797	DLH21000	$2,677,362
Kansas City	MO	35, 70	Natural Gas	86,550	421	2,104	SMR1000	$5,137,202
Jackson	MN	90	None	7,467	36	181	DLH21000	$2,677,362
Albert Lee	MN	90, 35	None	14,757	72	359	DLH21000	$2,677,362
Sauk Centre	MN	94	None	19,529	95	475	DLH21000	$2,677,362
Duluth	MN	35	None	35,437	172	861	DLH21000	$2,677,362
Minneapolis	MN	94, 35	Natural Gas	124,322	604	3,022	SMR1000	$5,137,202
Marshall	MI	94	None	31,923	155	776	DLH21000	$2,677,362
Benton Heights	MI	94	None	37,272	181	906	DLH21000	$2,677,362
Kawkawlin	MI	75	None	38,146	185	927	DLH21000	$2,677,362
Detroit	MI	94, 75	Natural Gas	126,456	615	3,073	SMR1000	$5,137,202
Augusta	ME	95	None	23,787	116	578	DLH21000	$2,677,362
Westbrook	ME	95	None	47,935	233	1,165	DLH21000	$2,677,362
Hampden Highlands	ME	95	Hydrogen Facility	25,723	125	625	PIPE	$583,141
Hagerstown	MD	70, 81	None	49,596	241	1,205	DLH21000	$2,677,362
North Bethesda	MD	95	None	169,820	825	4,127	DLH21000	$2,677,362
White Marsh	MD	95	Natural Gas	129,302	629	3,143	SMR1000	$5,137,202
Holyoke	MA	90	None	58,529	285	1,423	DLH21000	$2,677,362
Bedford	MA	95	Natural Gas	166,699	810	4,052	SMR1000	$5,137,202
Lafayette	LA	10	None	43,169	210	1,049	DLH21000	$2,677,362
Monroe	LA	20	None	53,738	261	1,306	DLH21000	$2,677,362
Lake Charles	LA	10	Hydrogen Facility	43,455	211	1,056	PIPE	$583,141
Shreveport	LA	20	Hydrogen Facility	43,792	213	1,064	PIPE	$583,141
New Orleans	LA	10	Hydrogen Facility	69,854	340	1,698	PIPE	$583,141
Baton Rouge	LA	10	Hydrogen Facility	69,933	340	1,700	PIPE	$583,141
Corbin	KY	75	None	36,533	178	888	DLH21000	$2,677,362
Elizabethtown	KY	65	None	39,409	192	958	DLH21000	$2,677,362
Bowling Green	KY	65	None	46,589	226	1,132	DLH21000	$2,677,362
Lexington-Fayette	KY	75, 64	None	46,676	227	1,134	DLH21000	$2,677,362
Louisville	KY	64, 65	Hydrogen Facility	76,242	371	1,853	PIPE	$583,141
Oakley	KS	70	None	9,302	45	226	DLH21000	$2,677,362
Russel	KS	70	None	11,170	54	271	DLH21000	$2,677,362
Emporia	KS	35	None	13,248	64	322	DLH21000	$2,677,362
Junction City	KS	70	None	19,636	95	477	DLH21000	$2,677,362
Wichita	KS	35	None	33,102	161	805	DLH21000	$2,677,362
Elberfeld	IN	64	None	18,131	88	441	DLH21000	$2,677,362
Fremont	IN	90, 80	None	22,046	107	536	DLH21000	$2,677,362
South Bend	IN	90, 80	None	24,854	121	604	DLH21000	$2,677,362
Battle Ground	IN	65	None	42,311	206	1,028	DLH21000	$2,677,362
Indianapolis	IN	70, 65	None	95,107	462	2,312	DLH21000	$2,677,362
Terre Haute	IN	70	Natural Gas	31,931	155	776	SMR1000	$5,137,202
Gary	IN	90,80,65,94	Natural Gas	74,199	361	1,803	SMR1000	$5,137,202
Colona	IL	80	None	19,760	96	480	DLH21000	$2,677,362
La Salle	IL	80	None	22,168	108	539	DLH21000	$2,677,362
Effingham	IL	70	None	24,664	120	599	DLH21000	$2,677,362
O'Fallon	IL	70	None	33,194	161	807	DLH21000	$2,677,362
Chicago	IL	90, 94	Natural Gas	202,647	985	4,925	SMR1000	$5,137,202
Joliet	IL	80	Hydrogen Facility	55,195	268	1,341	PIPE	$583,141
Camas	ID	15	None	3,082	15	75	EL100G	$923,039
Coeur d'Alene	ID	90	None	33,251	162	808	DLH21000	$2,677,362

Pocatello	ID	15	Natural Gas	18,173	88	442	SMR1000	$5,137,202
Dows	IA	35	None	14,691	71	357	DLH21000	$2,677,362
Iowa City	IA	80	None	37,917	184	922	DLH21000	$2,677,362
Council Bluffs	IA	80	Hydrogen Facility	27,551	134	670	PIPE	$583,141
Des Moines	IA	80, 35	Hydrogen Facility	66,597	324	1,619	PIPE	$583,141
Greensboro	GA	20	None	22,427	109	545	DLH21000	$2,677,362
Pooler	GA	95	None	40,503	197	984	DLH21000	$2,677,362
Tifton	GA	75	None	40,939	199	995	DLH21000	$2,677,362
Brunswick	GA	95	Natural Gas	41,623	202	1,012	SMR1000	$5,137,202
Macon	GA	75	Natural Gas	47,571	231	1,156	SMR1000	$5,137,202
Calhoun	GA	75	Natural Gas	59,733	290	1,452	SMR1000	$5,137,202
Atlanta	GA	75, 20	Natural Gas	183,185	890	4,452	SMR1000	$5,137,202
Caryville	FL	10	None	16,424	80	399	DLH21000	$2,677,362
Winfield	FL	10, 75	None	28,792	140	700	DLH21000	$2,677,362
Naples	FL	75	None	33,857	165	823	DLH21000	$2,677,362
Tallahassee	FL	10	None	34,886	170	848	DLH21000	$2,677,362
Ensley	FL	10	None	46,676	227	1,134	DLH21000	$2,677,362
Daytona Beach	FL	95	None	50,455	245	1,226	DLH21000	$2,677,362
Venice	FL	75	None	59,568	290	1,448	DLH21000	$2,677,362
Temple Terrace	FL	75	None	102,805	500	2,499	DLH21000	$2,677,362
Fort Pierce	FL	95	Natural Gas	44,333	215	1,077	SMR1000	$5,137,202
Rockledge	FL	95	Natural Gas	50,731	247	1,233	SMR1000	$5,137,202
Ocala	FL	75	Natural Gas	63,811	310	1,551	SMR1000	$5,137,202
Jacksonville	FL	95	Natural Gas	104,762	509	2,546	SMR1000	$5,137,202
Palm Beach Gardens	FL	95	Natural Gas	121,776	592	2,960	SMR1000	$5,137,202
Dania Beach	FL	95	Natural Gas	219,715	1,068	5,340	SMR1000	$5,137,202
Wilmington	DE	95	Natural Gas	60,845	296	1,479	SMR1000	$5,137,202
New London	CT	95	None	62,557	304	1,520	DLH21000	$2,677,362
New Haven	CT	95	Natural Gas	110,638	538	2,689	SMR1000	$5,137,202
Greenwich	CT	95	Natural Gas	120,918	588	2,939	SMR1000	$5,137,202
Flagler	CO	70	None	3,569	17	87	EL100G	$923,039
Walsenburg	CO	25	None	6,006	29	146	DLH21000	$2,677,362
Grand Junction	CO	70	None	14,858	72	361	DLH21000	$2,677,362
Vail	CO	70	None	16,286	79	396	DLH21000	$2,677,362
Glenwood Springs	CO	70	None	19,612	95	477	DLH21000	$2,677,362
Colorado Springs	CO	25	None	35,271	171	857	DLH21000	$2,677,362
Denver	CO	25, 70	None	60,084	292	1,460	DLH21000	$2,677,362
Fenner	CA	40	None	12,100	59	294	DLH21000	$2,677,362
Kingman	CA	40	None	17,477	85	425	DLH21000	$2,677,362
Weed	CA	5	None	18,200	88	442	DLH21000	$2,677,362
Blythe	CA	10	None	19,840	96	482	DLH21000	$2,677,362
WIllows	CA	5	None	22,250	108	541	DLH21000	$2,677,362
Huron	CA	5	None	32,000	156	778	DLH21000	$2,677,362
Buttonwillow	CA	5	None	32,667	159	794	DLH21000	$2,677,362
Los Banos	CA	5	None	33,750	164	820	DLH21000	$2,677,362
Cima	CA	15	None	36,175	176	879	DLH21000	$2,677,362
Gorman	CA	5	None	64,667	314	1,572	DLH21000	$2,677,362
Temecula	CA	15	None	77,250	376	1,878	DLH21000	$2,677,362
San Diego	CA	5	None	182,633	888	4,439	DLH21000	$2,677,362
Barstow	CA	15, 40	Natural Gas	34,422	167	837	SMR1000	$5,137,202
Anderson	CA	5	Natural Gas	45,083	219	1,096	SMR1000	$5,137,202
Stockton	CA	5	Natural Gas	91,250	444	2,218	SMR1000	$5,137,202
Sacramento	CA	5, 80	Natural Gas	122,685	596	2,982	SMR1000	$5,137,202
San Francisco	CA	80	Natural Gas	158,260	769	3,846	SMR1000	$5,137,202
Los Angeles	CA	5	Natural Gas	192,750	937	4,685	SMR1000	$5,137,202
Irvine	CA	5	Natural Gas	264,000	1,283	6,416	SMR1000	$5,137,202
Ontario	CA	15, 10	Hydrogen Facility	177,350	862	4,310	PIPE	$583,141
Rancho Mirage	CA	10	Hydrogen	68,167	331	1,657	NC	$0
Williams	AZ	40	None	13,981	68	340	DLH21000	$2,677,362
Bowie	AZ	10	None	15,350	75	373	DLH21000	$2,677,362
Joseph City	AZ	40	None	15,805	77	384	DLH21000	$2,677,362
Littlefield	AZ	15	None	19,909	97	484	DLH21000	$2,677,362
Brenda	AZ	10	None	23,189	113	564	DLH21000	$2,677,362
Tucson	AZ	10	Natural Gas	83,139	404	2,021	SMR1000	$5,137,202
Phoenix	AZ	10	Hydrogen	186,576	907	4,535	NC	$0

Alma	AR	40	None	24,655	120	599	DLH21000	$2,677,362
Menifee	AR	40	None	35,023	170	851	DLH21000	$2,677,362
de Valls Bluff	AR	40	None	42,274	205	1,027	DLH21000	$2,677,362
Cuba	AL	20	None	19,500	95	474	DLH21000	$2,677,362
Evergreen	AL	65	None	22,370	109	544	DLH21000	$2,677,362
Heflin	AL	20	None	33,479	163	814	DLH21000	$2,677,362
Huntsville	AL	65	None	34,160	166	830	DLH21000	$2,677,362
Montgomery	AL	65	None	62,512	304	1,519	DLH21000	$2,677,362
Birmingham	AL	20, 65	None	83,468	406	2,029	DLH21000	$2,677,362
Tillmans Corner	AL	10	Hydrogen Facility	69,232	337	1,683	PIPE	$583,141

10. Authors

Margo Melendez analyzes hydrogen transportation at NREL, with an emphasis on the transition from today's vehicle and infrastructure technologies to the hydrogen technologies of the future. Previously she led NREL projects promoting the transition to alternative fuel transportation. These efforts included government regulatory programs, consumer education, engine and infrastructure R&D, and transition analysis. Before joining NREL, she worked on environmental compliance and regulatory affairs at Ford Motor Company. She holds a B.S. in mechanical engineering from the University of Iowa and an M.S. in engineering management from the University of Michigan.

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14. ABSTRACT *(Maximum 200 Words)*
Paper for the 2005 National Hydrogen Association conference analyzes the hydrogen infrastructure needed to accommodate a transitional hydrogen fuel cell vehicle demand. Overall, 284 stations were identified, with an initial total construction cost of $837 million if constructed to meet the needs of 2020. This is based on the aggressive assumptions of a 50% fuel cell vehicle stock by 2050, and approximately 1% in 2020 and 20% in 2030. Because the infrastructure is based on anticipated station use, many of the stations could be economically self sustaining in the near term (2020–2030). This depends on how evenly the fuel cell vehicles are distributed geographically. Most likely, they would be concentrated in key urban areas, making those stations economically viable, whereas rural stations that do not serve as many vehicles may need financial support until sufficient vehicles are operating in their region. One way to help the viability of stations is to incorporate co-generation, in particular co-generation at federal facilities.

15. SUBJECT TERMS
fuel cell; hydrogen; national renewable energy laboratory; hydrogen economy; hydrogen transition; fuel cell vehicles; hydrogen infrastructure; hydrogen fueling

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