

**Bridging the Gap Between Transportation and Stationary Power:
Hydrogen Energy Stations and their Implications for the Transportation Sector**

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Bridging the Gap Between Transportation and Stationary Power: Hydrogen Energy Stations and their Implications for the Transportation Sector

Jonathan Weinert, Timothy Lipman, and Stefan Unnasch

ABSTRACT

In the past two years, the Federal and California State governments have announced initiatives to invest in the development of hydrogen fueling infrastructure for hydrogen vehicles (1,2). Industry and government are now working together to determine cost-effective strategies for accomplishing this task. Key concerns are 1) high hydrogen cost, 2) equipment under-utilization while vehicle demand is low, and 3) high fuel cell costs when production volumes are low. A new infrastructure option is emerging (in the RD&D phase) that addresses these concerns by combining stationary power production with vehicle fueling. This new option of “energy stations” (E-Stations) could have significant implications for traditional fueling paradigms since these stations link vehicle-fueling facilities to stationary power production sites.

This paper explores the potential use of E-Stations for hydrogen infrastructure development and potential implications for the transportation sector. It characterizes the range of E-Station design configurations and identifies promising applications for each configuration. The applications are matched with E-Station attributes to assess the market potential of the stations. Estimated hydrogen costs for these stations are presented and compared to fueling-only hydrogen stations. The paper explores the implications that this new fueling paradigm may have on key stakeholders in the transportation sector. It concludes by identifying issues and areas of uncertainty critical to E-Station success. Though further analysis is needed to assess the economics of various station designs and settings, we find that the emerging trend in small-scale distributed power generation may increase hydrogen’s probability of success as a transportation fuel.

INTRODUCTION

There is a growing trend in the stationary power sector that could have important implications for the use of alternative fuels in the transportation sector. This trend is the concept of distributed generation (DG): electricity production (and often heat co-production) near the point of use. This is a compelling concept for both utilities and customers due to increasing grid congestion in urban areas, difficulty in siting new large-scale power plants and transmission lines, and commercial user requirements for high-reliability “premium” power. Fuel cell-powered DG systems are one solution to this problem since they have ultra-low emissions (important for siting plants in urban locations) and like other DG technologies would help to mitigate the need to expand transmission and distribution capacity.

E-Stations have received attention as a promising near-term hydrogen infrastructure option since they combine DG with vehicle fueling (see Table 3 for list of demonstration projects). An E-Station is a system that generates hydrogen for vehicles and power for buildings by converting a feedstock (e.g. natural gas) into hydrogen, electricity and heat. The four main systems are 1) the hydrogen production unit 2) the compression and storage system 3) the dispenser and 4) the electricity generator. Sometimes 1 and 4 are integrated into one unit. An additional option for

the E-Station is a cogeneration system that uses the waste heat from the electricity generator to help meet the building's heat and/or cooling loads. Figure 1 shows the main components of an E-Station.

By providing three value streams (vehicle fuel, building electricity, and building heating/cooling) they potentially offer a faster return on the initial capital investment cost (3). The additional value streams also helps combat the “cobweb dilemma”: underutilization of hydrogen stations in the early years when hydrogen vehicle demand is low.

APPLICATIONS

One goal of this paper is to characterize promising E-Station applications in order to identify opportunities for station placement. Previous cost analyses on E-Stations (3,4,5) point to the importance of the following factors for economic success:

1. Adequate anticipated hydrogen demand (for some combination of vehicle refueling, power production, and/ or industrial hydrogen uses)
2. Relatively high hydrogen selling prices (perhaps on the order of \$20/GJ or about \$2.80/kg)
3. Medium to large fuel cell sizes (>150kW) due to scale economies of the fuel cell system
4. High on-peak electricity price
5. Large spark spread (i.e. ratio of electricity price to gas price)
6. Large heating and/or cooling requirement (for combined heat and power (CHP))
7. Steady demand throughout day and year (to reduce storage requirements)

Characteristics of Ideal Applications

In order to determine ideal applications for E-Stations, the above factors are transformed into real-world characteristics of potential station sites, listed below:

1. Presence of dedicated vehicle fleets (buses, cars, or other ground transportation)

Fleets will ensure initial demand for hydrogen. Fleets that can refuel at night (such as buses) are even more ideal since they levelize the typical daytime-heavy hydrogen demand.

2. Industrial hydrogen applications

Companies that use hydrogen for industrial processes currently have hydrogen trucked to their facility. Some facilities are exploring on-site production with electrolyzers and steam reformers. Industrial uses of hydrogen can justify a higher price than vehicle fueling or fuel cell power.

3. Large electricity loads (>150kW) during peak hours

Economies of scale improve with larger fuel cell sizes. The principal benefit with the PEMFC systems lies in the fixed cost of power electronics and utility interconnection. For systems over 50 kW over 80 percent of the stack cost is in the membrane and precious metals. Peak shaving strategies, where there is adequate electricity demand or possibility of sell back to the grid, allow for higher revenues since electricity prices are typically highest during the daytime (3).

4. Located in urban environment

1) Hydrogen demand will be higher in urban areas since initial hydrogen vehicle and bus fleets will be placed primarily in cities. 2) Urban areas typically experience higher grid congestion making utility companies in these areas more likely to encourage distributed generation, possibly even net-metering (6). 3) Urban areas typically have more stringent permitting restrictions for fossil-fueled DG/cogeneration plants (e.g. reciprocating engines, combined-cycle plants) making low-emission alternative technologies more attractive. However, hydrogen station siting in urban areas is potentially problematic due to hydrogen-specific set-back distance requirements and “NIMBY”-ism (“not in my backyard”) caused by public unfamiliarity with the fuel.

5. Large heat requirement:

Since heat is a bi-product of the fuel cell and other station equipment, making use of this waste heat stream (50 to 80C for PEMFC and up to 800 C for solid oxide fuel cells (SOFC)) improves the economics of the system by displacing natural gas or other fuels for heating.

6. Need for reliable electricity:

Customers with critical operations are well suited for E-Stations since they offer a back-up source of electricity and heat.

7. Continuous Operation

Facilities that operate 24 hours (or part of the night) are well suited for the continuous operation of fuel reformers and high-temperature fuel cells. Continuous operation also reduces the hydrogen storage system size since hydrogen produced at night can be consumed by the fuel cell.

Potential E-Station Applications

The following section lists the applications that exhibit the above characteristics. Table 1 ranks each application according to these characteristics to show their suitability for E-Stations.

1. Specialty Manufacturing Plants

These sites may be attractive because they have hydrogen requirements aside from (or potentially in addition to) electricity production. Candidate users of industrial hydrogen are semiconductor manufacturing, food processing, chemical industries, and glass manufacturers to name a few. Small-scale vehicle applications at these facilities, such as liquid petroleum gas (LPG) forklifts, could also operate on hydrogen while achieving significant refueling emission reductions.

2. Airports

Airports have large energy loads, typically operate large fleets of ground crew vehicles, ground support equipment, and indoor vehicles, and require a reliable electricity supply.

3. Government Buildings

The main advantage to siting E-Stations here is that they are the most likely early adopters of hydrogen vehicles for their fleets. Government office buildings also have daytime-peak energy loads (heating or cooling), and varied heat requirements. Thermal loads typically correspond to space heating and hot water requirements.

4. Bus Transit Operators

This group exhibits a strong fleet presence of heavy-duty vehicles (HDV) that typically refuel at night (when electricity demands are often low).

5. Industrial Factories

Factories typically use indoor operated vehicles (i.e. forklifts), operate continuously, and have large electrical and process heat loads.

6. Hospitals

Hospitals are an ideal site for distributed generation and CHP because their critical operations require back-up power, and they have large hot water and steam requirements (for cleaning and sanitizing equipment). Health care buildings are the fourth highest consumer of energy for all building types, of which 38% is for electricity, 46% natural gas, 13% district heat, and 4% fuel oil (7).

7. Commercial Office Buildings

These buildings exhibit large daytime energy peaks, have consistent vehicle presence, and typically require back-up power. Commercial office buildings consume the most energy of all building types, of which 66% is for electricity, 23% natural gas, 7% district heat, and 3% fuel. (7)

8. Grocery stores

These facilities typically have high electricity loads due to refrigeration needs. E-Station waste heat could be used to drive absorption refrigeration. Absorption chilling systems shift cooling from an electric load to a thermal load by absorbing heat from a driving source to create chilled water (7). Furthermore, grocery stores are usually conveniently located for private vehicle owners, who visit them on a regular basis.

9. Residential Complexes: High-density housing developments could make use of waste heat for water and space heating. A shared E-Station would benefit from economies of scale and potential spread-out loads. Vehicle parking spaces would enable direct slow fill fueling, which would substantially reduce the cost of hydrogen storage. Less costly auto-thermal reformers (ATR) may be well suited for residential applications where waste process gas can be used as fuel for water heaters.

10. Truck Stops

Air quality planners are supporting the increasing electrification of truck stops in order to reduce idling emissions. Furthermore, stations along rural interstates could serve as connecting infrastructure for hydrogen vehicle users.

11. Light-Rail Transit Operators

These customers require large quantities of DC power. Using direct DC power (from e.g. fuel cells) would eliminate the efficiency loss in the DC to AC conversion.

12. Commercial Maritime Ports

E-stations could serve large electricity needs if ports switch to schemes whereby ships plug-in to onshore power sources when docked. The fuel could serve port fleet vehicles or maritime applications in the long term.

13. Home owners

Recent blackouts and summer brownouts have made home-owners more aware of electricity reliability. The prospect of being in control of one's electricity supply may be enticing to some consumers. Developers may also be interested in selling an E-Station system to customers buying pre-fabricated homes for grid-independent locations. Currently, there are more than one million U.S. homes that are not connected to the power grid (8). An integrated energy solution (electricity, heat, & vehicle fuel) could be attractive to this market (pending a supply of NG or the use of renewable energy).

14. Energy Service Companies

Another group of potential E-Station users are the companies that traditionally sell electricity and provide energy services. These companies include Generation Companies (GenCos), Retail Energy Service Providers (RESPs), and Utility Distribution Companies (UDCs) (9).

Of these electricity industry companies, RESPs are the most likely early adopters of the E-Station concept. These companies offer "energy services" to their customers and solutions such as uninterruptible power, CHP, premium power, and energy bill management. They are purchasing fuel cell units to demonstrate and understand the technology (8).

Utility distribution companies (UDCs) manage interconnections and are ultimately responsible for the safe delivery of power to the end-user. Thus, they are potential stakeholders of DG technologies. Peaking capability provided by the station is of great value to the UDC since grid congestion is one of the big issues they face.

These entities may be more likely than others to pursue the E-Station concept. Commercial and industrial facility managers may be reluctant to implement the E-Station concept and DG more generally since they are particularly sensitive to costs and not as educated about power technologies. However, because these stations have the added benefit of on-site fuel, end-users may in fact become a primary market.

Demonstration Projects

There are E-Station demonstration projects under development throughout North America at several of these application sites. Electrolyzer and reformer stations are in the commercial testing phase with actual working demonstrations. Small-scale stations are in the prototype phase. None have yet been released to customers for demonstration. The high-temperature fuel cell E-Station is still in the design phase though the DOE is working with industry to construct a prototype system (10). Several fuel cell field trials include an E-Station feature, either in the form of combined heat and power or combined hydrogen and power. Table 3 shows some of the projects in North America arranged according to construction status. Many of these projects are funded by the DOE's \$1.34 million budget (2004) for power parks & energy stations. (10)

DESIGNS/CONFIGURATIONS

There are several types of E-Stations that incorporate different hydrogen technologies, different designs to connect the equipment, and different sizes of electrical generation and fuel storage

equipment. These station technologies can be configured for various uses and scaled appropriately -- such as primarily for vehicle refueling, primarily for DG/grid support, etc. This paper focuses on four major design types, summarized in Table 2.

1. Direct Hydrogen Steam Reformer PEMFC E-Station

Station Characteristics

In this type of energy station, a steam methane reformer (SMR) converts natural gas and water into reformat (a mixture of H₂, CO, and CO₂). Hydrogen is separated from the reformat, compressed, and stored. The unused reformat provides fuel for the reformer. The process of cooling the reformat provides a source of heat for cogeneration. The reformat is usually cooled to ambient temperature with a radiator. Heat recovery is also available from the purifier, which cools the reformat from 200C to 50 C. A fraction of the stored hydrogen is used in a fuel cell stack to produce electricity and heat for a nearby building; the rest is used to fuel vehicles. Figure 1 depicts the layout of this type of station.

A low-cost alternative to the fuel cell generator is to use a hydrogen internal combustion engine (H₂ICE) generator (gen-set) for heat and power. While these units have lower efficiency than fuel cells, and slightly higher emissions (NO_x), the cost of an engine power would be comparable to other internal combustion engines (\$50 to \$1000/kW) PEMFC costs (\$3,750-17,500/kW) depend on growth in other fuel cell applications to achieve cost reductions (8).

Operation Choices

This configuration typically uses a low-temperature PEMFC, which can load-follow the building and offer low-grade heat (80C). Ideally, a reformer would operate continuously to avoid energy losses associated with start-up. Reformers typically feature some turn down capability to accommodate variations in load. Since PEMFCs are capable of rapid start-up time (< 30 sec), without loss of performance, these systems can either operate as a load-follower, peak-shaver, emergency backup, or provide constant base-load power. Limitations on stack durability make base-load operation the most challenging operating mode.

2. Electrolyzer E-Station

System Description

In this type of station, water is split into hydrogen and oxygen using the electrolyzer and off-peak or excess electricity. The hydrogen is purified, compressed, and stored. A fraction of the stored hydrogen is used in a fuel cell stack to produce electricity and heat for a nearby building; the rest is used to fuel vehicles. The layout of this type of station is similar to the previous system.

Operation Choices

The operation choices for this type of station are similar to the previous design except that electrolyzers are able to load follow more than reformers, thus hydrogen production can be turned up or down depending on demand. This reduces the storage requirement.

3. High Temperature Fuel Cell E-Station

System Description

Molten Carbonate and Solid oxide fuel cell systems can be configured as energy stations.

Natural gas is reformed into “reformat” within the fuel cell. Product gas does not need to be separated into pure hydrogen for these fuel cells to operate. Figure 1 shows the layout for this type of system. A fraction of the reformer product gas is separated into a pure hydrogen stream, compressed, and stored for vehicles (20-40% of feed) (6). The reformat is used within the fuel cell stack to produce electricity and heat. For example, a 250 kW unit could produce 3.8 kg/hr (25 cars/day) and a 1000 kW unit could produce 15.1 kg/hr (100 cars/day). Stationary fuel cell manufacturers are exploring this configuration as a novel low-cost E-Station configuration (6). Additional equipment required for this system compared to a stand-alone DG unit include anode gas cooling and shift reactor and H₂ purifier (6).

This station type is best suited for users that have high electricity loads (250-1000 kW), large needs for process heat, steam, or cooling, and at least a moderate requirement for hydrogen for vehicles or industrial processes (4 kg/hr).

4. Community Residential-Scale E-Station:

This type of station uses a small-scale ATR in conjunction with a small (5 kW) PEMFC to provide power to a home (or homes) and hydrogen fuel for a small number of vehicles. The unit also requires a purifier, compressor, and storage tank. The configuration is similar to the first option, though smaller.

COSTS

The section provides cost estimates for the first type of E-Station. These estimates were derived from a model developed by Lipman et al. to analyze E-Station economics (3). For the remaining three stations, a more general indication of cost is presented based on a limited amount of industry data. Work is under way to refine the model to evaluate the costs of these alternative station types, and to more carefully and thoroughly analyze E-Station economics in general.

Cost of Reformer Based E-Station

As mentioned in the ‘Applications’ section, station economics depend heavily on hydrogen price (\$/kg), hydrogen demand (kg/day), and fuel cell size (kW). Figures 2 and 3 show how the annual revenue of an E-Station is affected by these factors. To summarize, Figure 2 shows that stations achieve a 10% return on investment (ROI) when hydrogen price exceeded \$20/GJ (\$2.80/kg) and the number of hydrogen vehicles fueled each day exceeded 40. Figure 3 shows that stations require fuel cell size greater than 150 kW to generate revenue.

Cost for Alternative E-Stations

One manufacturer has determined that hydrogen generated from high-temperature fuel cell E-Station will cost \$5/kg when built in small volumes and has a projected cost of \$2.2-3.0/kg hydrogen (6). This compares to \$6.39/kg for hydrogen derived from an on-site natural gas reformer-type fueling-only station, and \$12.42/kg for hydrogen from an on-site electrolyzer-type fueling-only station (11).

TRANSPORTATION SECTOR IMPLICATIONS

The development of E-Stations will have implications on many groups within the transportation sector. The following section explores the impacts on each group and the challenges facing E-Station commercialization.

Impacts On Stakeholders

E-Station stakeholders are defined as groups that will be affected by station deployment. Some of these stakeholders will be affected in both positive and negative ways. Table 4 presents a summary of the speculated effects E-Stations will have on the various stakeholders.

Hydrogen Vehicle Users

This group's biggest concerns are fuel availability and fuel price. As discussed in the cost section, hydrogen price is likely to be lower since greater utilization of the station equipment is achieved. In term of hydrogen availability for fleet vehicles at commercial or industrial E-Stations, on-site fueling would clearly be convenient. To private vehicle owners who work elsewhere, the convenience will depend on the location of the station (proximity to highways and other commuter routes) and access to the site during off-hours.

A home-scale E-Station will be very useful to private vehicle owners, but typically off-limits for fleet customers and other hydrogen vehicle groups. In either case, travel behavior studies show that the majority of people's refueling takes place within a few miles from home or work which fits well with the projected hydrogen availability using E-Stations (12).

Vehicle user safety is also a concern. Station location could exacerbate or help this issue. Refueling at a remote industrial plant late at night may be more intimidating to some users than visiting a well-populated gas station. On the other hand, an apartment-based E-Station or station outside one's office building would be ideal to some users.

To the extent that E-Stations put fueling more into the vehicle users control, users will most likely embrace the concept. Studies of battery electric vehicle owners indicate that their ability to fuel at home was one of the things they liked most about the vehicle.

Hydrogen Vehicle Manufacturers:

Hydrogen vehicle manufacturers share the same concerns as vehicle users (since users' concerns impact purchase behavior). They are also concerned, however, with hydrogen purity and station reliability. Station reliability may be a concern in the near term since small-scale reformer technology has not been field tested extensively (there are only a handful of units in the US today making hydrogen).

Electric Utilities:

The impact on this group varies. Some utilities are reluctant to encourage distributed generation on the customer side of the meter because it eats into their profits. Others like the idea (at least for certain locations within the grid) since it saves them the cost of adding transmission and distribution capacity.

Gas Utilities:

This group will benefit in all cases since they control natural gas distribution. Their sales will increase since they will be gaining a share of the vehicle fueling market segment.

Fuel Providers:

Traditional fuel providers (major oil companies) could see a drop in market share if vehicle fuel is made from natural gas. Oil companies involved in the sale of natural gas will benefit, however.

Fuel Cell Manufacturers:

This group stands to gain on two fronts if E-Stations succeed. Sales of both automotive and stationary fuel cell will increase. This will affect production volumes and the accumulation of manufacturing experience and eventually lead to lower cost fuel cells.

Transportation Policy Makers:

Since policy makers are most concerned with pleasing their constituents, they will be especially concerned with the public perception of the project. They will also be concerned with the financial and safety risk associated with the station. They will also be attentive to NIMBY concerns, project cost, and air quality benefits.

Issues and Challenges

There are several barriers to E-Station market penetration, each of which share a large amount of uncertainty. This uncertainty is contained not only in the reliability of the equipment, but also in the capital cost of stations, the complex incentive, rebate, and tax credit programs, and in the future cost of electricity or natural gas (8). The following section presents some of these issues.

Fuel Cell Cost and Durability: Modeling analysis by Lipman et al. (3) and others have shown that California office-building E-Station systems under 150kW and fueling less than 50 cars/day exhibit a poor return on investment, even with considerably lower fuel cell system costs than are observed today. Small-scale E-Stations may not make financial sense until fuel cells and other hydrogen equipment reach sufficient production volumes. It is likely to take several years for stationary fuel cell systems to mature, and for costs to be driven down.

Distributed Generation Interconnection Standards: standards for connecting DG equipment have only recently been developed and are still being adopted by many utility companies. This makes E-Station siting more difficult in some areas. Additionally, utility companies often assign charges or penalties for leaving the grid (exit charges) or for taking power from the grid when the DG unit cannot meet supply (stand-by charges). These charges can make operating costs prohibitive.

Fuel Cell Vehicle Commercialization: FCV demand is very low and could be for some time. Hydrogen ICE cars, industrial uses of hydrogen, and niche FCV markets (forklifts, APU, etc.), may provide an opportunity for the co-production of hydrogen.

Lack of Working Hardware or Demonstrations: Although the high-temp fuel cell E-station is being funded through the DOE, no prototype system has yet been assembled. Few home-scale E-Station prototypes have been built, although stationary fuel cell manufacturers have similar systems in without the vehicle fueling capability.

Energy Price Trends: Prices for natural gas, the most common feedstock for E-Stations, have been on the rise. However, several trends in energy prices are positive factors for E-Station

systems. Constraints on transmission and distribution systems have also led to interruptions in power supplies and demands for costly system upgrades. E-Station systems with either a high overall efficiency through combined heat and power production or the capability to address distribution constraints through peak shaving may become attractive options.

CONCLUSIONS

The emerging trend of distributed power generation in the stationary power sector has important implications on the transportation sector. This paper introduces the concept of the E-station and characterizes a range of station design configurations. It identifies promising applications for these configurations and matches the applications with station attributes to assess their market potential. Projected E-Station revenue has been estimated based on varying important station parameters. Hydrogen costs for E-Stations have also been projected and compared against stand-alone hydrogen fueling stations. The paper explores the implications that E-Stations may have on key stakeholders in the transportation sector and identifies areas of uncertainty critical to E-Station success. Though further analysis is needed to assess the economics of various E-Station designs and settings, we find that the emerging trend in small-scale distributed power generation may increase hydrogen's probability of success as a transportation fuel.

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REFERENCES

1. Bush, G.W., State of the Union Address, 2003
2. Schwarzenegger, A., State of California Executive Order S-7-04, 2004
3. Lipman, T., J. Edwards, and D. Kammen. Economic Analysis of Hydrogen Energy Station Concepts, *Energy Development and Technology Working Paper Series*, EDT-003, University of California Energy Institute (UCEI), 2002, p.5,
4. Kreutz, T.G., J.M. Ogden. Assessment of Hydrogen Fueled Proton Exchange Membrane Fuel Cells for Generation and Cogeneration, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, 2001
5. Thomas, C.E., J.P. Reardon, F.D. Lomax, J. Pinyan & I.F. Kuhn. Distributed Hydrogen Fueling Systems Analysis, DTI, Arlington, VA, 2001
6. Jahnke, F., S. Torres, P. Patel. Distributed Generation of Hydrogen Using High Temperature Fuel Cells, Proceedings of the National Hydrogen Association 15th Annual U. S. Hydrogen Conference, Fuel Cell Energy, Inc., 2004, p.6,8,12,
7. Samuelsen, S. (CaSFCC) Draft Fuel Cells Economics Analysis Report, 2004, p.16, 21
8. California Stationary Fuel Cell Collaborative, White Paper: Summary of Interviews with Stationary Fuel Cell Manufacturers, 2003, p.6,8,
9. Rastler, D. Challenges for Fuel Cells as Stationary Power Resource in the Evolving Energy Enterprise", *Journal of Power Sources*, v.86, 2000, pp.34-39
10. Gronich, S. DOE Program-Technology Validation Sub-program Summary, Presentation to Technology Validation Subteam at the 2004 DOE Hydrogen Program Review,

http://www.eere.energy.gov/hydrogenandfuelcells/2004_annual_review.html#valid. Accessed July 28, 2004, p.3,5

11. Seeking permission to use this source. p.5

12. Nicholas, M., "Hydrogen Station Siting in Sacramento County", TRB, 2003

13. Boehm, R. (University of Nevada Las Vegas), Renewable Hydrogen Fueling Station System, Presentation to Technology Validation Subteam at the 2004 DOE Hydrogen Program Review, http://www.eere.energy.gov/hydrogenandfuelcells/2004_annual_review.html#valid. Accessed July 28, 2004

14. Lipman, T, G. Nemet, D. Kammen. A Review of Advanced Power Technology Programs in the United States and Abroad Including Linked Transportation and Stationary Sector Developments. Energy and Resources Group, University of California – Berkeley, Prepared for the California Air Resources Board (ARB) and the California Stationary Fuel Cell Collaborative (CaSFCC), 2004, pp.60-61, 70-72

15. Kaya, M., (University of Hawaii). Hawaii Hydrogen Power Park, Presentation to Technology Validation Subteam at the 2004 DOE Hydrogen Program Review, http://www.eere.energy.gov/hydrogenandfuelcells/2004_annual_review.html#valid. Accessed July 28, 2004

16. Regan, R., DTE Energy Hydrogen Technology Park, Presentation to Technology Validation Subteam at the 2004 DOE Hydrogen Program Review.

http://www.eere.energy.gov/hydrogenandfuelcells/2004_annual_review.html#valid. DTE Energy Co., Accessed July 28, 2004

17. Honda Motor, Honda Begins Experiments with Hydrogen Home Energy Station and Improves Solar-Cell Technology for Production of Hydrogen, Press Release, 2003

18. Chevron Texaco Press Release, <http://www.actransit.org/onthehorizon/fuelcell.wu>. Accessed July 29, 2004

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FIGURE 3 Estimated Profit/(Loss) from Office Building H₂E-Stations with 50 to 250-kW Fuel Cell and 10 Hydrogen Vehicles per Day Refueled

TABLE 4 Summary of E-Station Impacts on Transportation Stakeholders

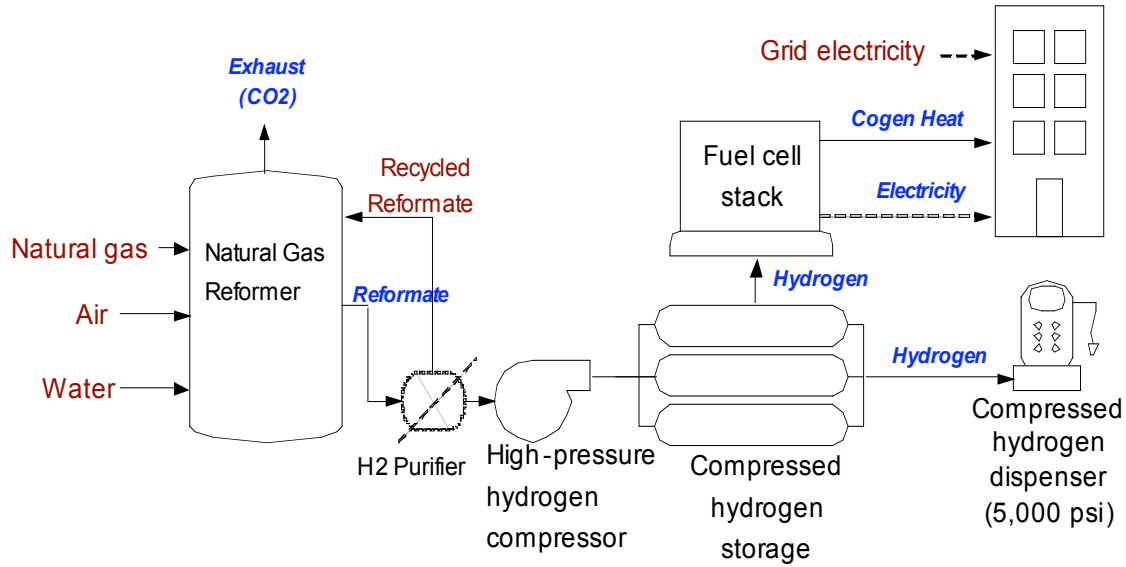
TABLE 1 Qualitative Evaluation of Candidate Energy Station Applications

Application	Fleet/ Vehicle Presence	Merchant H2 Use	Size	Daytime peaks	Urban Location	Process Heat	Back-up power	24-hour Operatio n
Specialty Manufacturing Plants	L	H	M	M	L	H	H	H
Airports	H	L	H	H	M	M	H	H
Government Building	H		M	H	H	M	M	L
Bus Transit Operators	H		M	H	H	L	L	L
Industrial Factories	M	M	H	M	L	H	H	H
Hospitals	M		H	M	H	H	H	H
Commercial Office Buildings	M		M	H	H	L	H	L
Grocery Stores	M		M	H	H	M	L	M
Residential Complexes	M		M	M	H	M	L	M
Truck Stops	L			L			L	H
Rail Transit Operators	L		H	H	H	M	H	L
Maritime Ports	M		H	L	H	M	M	H
Home Owners	L	L		H	H	L	M	L
<i>Energy Service Companies</i>	M	M	M	H	M	M	H	H

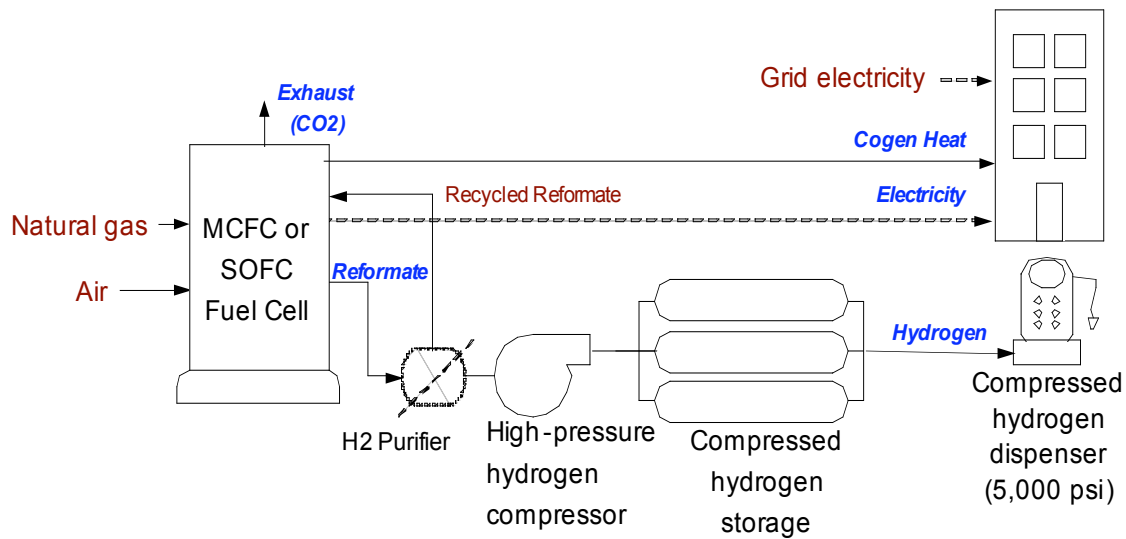
Code: H (high) = this application normally exhibits this characteristic, M (medium) = the application sometimes exhibits, L (low) = rarely exhibits, blank = never exhibits

TABLE 2 Four Potential Types of Hydrogen Energy Stations

	Vehicle Refueling E-Station	DG E-Station	Utility Support E-Station	Residential E-Station
Location	Service station	Commercial or industrial facility	Utility substation	Home or apartment building
Primary Purpose	Hydrogen refueling for vehicles	Electricity production	Local distribution grid support	Hydrogen refueling for vehicles
Hydrogen Production Technology	SMR, Electrolyzer	SMR, MCFC, SOFC	SMR, MCFC, SOFC	ATR
Vehicles Refueled	5-500 per day	5-50 per day	5-50 per day	1-10 per day
Fuel Cell Technology	PEM	MCFC or SOFC	MCFC or SOFC	PEM
Approximate Fuel Cell Size	25-50 kW	100-1000 kW	100-500 kW	1-50 kW
Key Issues	<ul style="list-style-type: none"> • DG/fuel cell economics with low electrical loads 	<ul style="list-style-type: none"> • Utility tariffs and interconnection rules • Public access for refueling? 	<ul style="list-style-type: none"> • Public access for refueling? 	<ul style="list-style-type: none"> • Natural gas costs • Economics with low electrical loads



a) Direct Hydrogen PEMFC E-Station



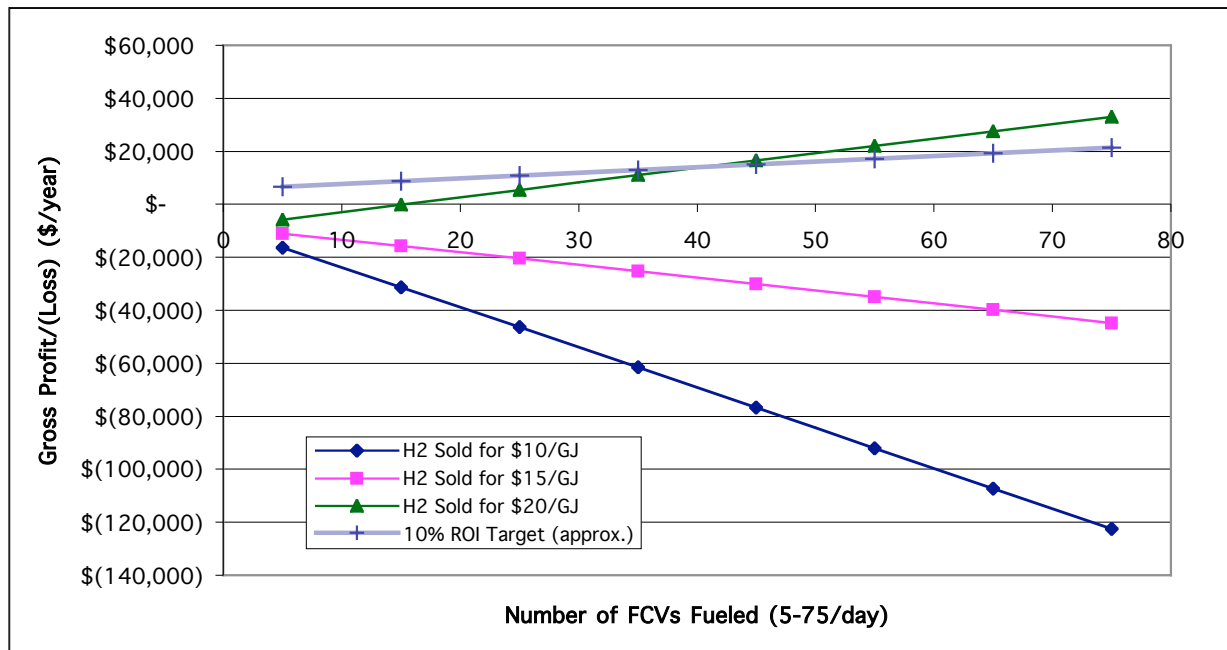
b) High-Temperature Fuel Cell E-Station

FIGURE 1 Energy station configurations.

TABLE 3 Energy Station Development Projects

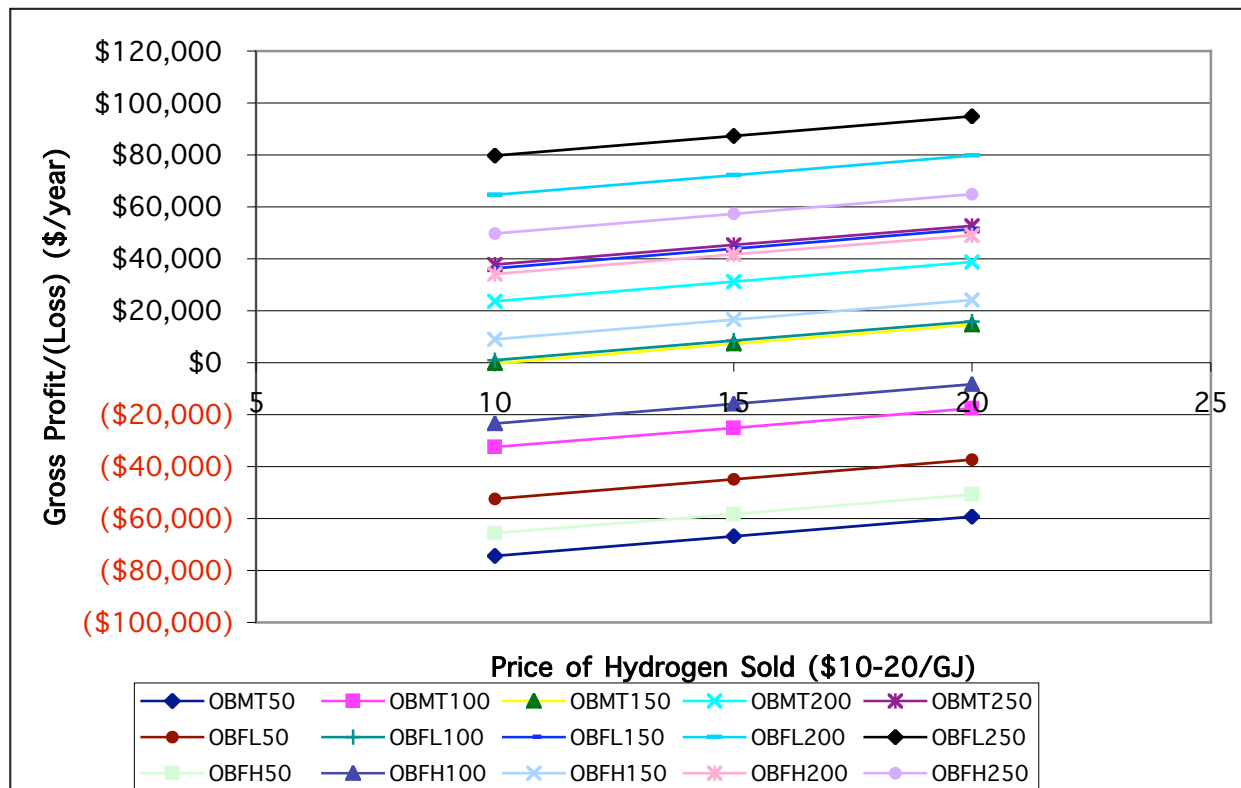
Project Description	Participants	Application	Fuel output (kg/hr)	Power output (kW)	Equipment	Status
PEMFC energy station (13)	Air Products, Plug Power, Collier Technologies, DOE	Transit Operator (Las Vegas Fleet & Transportation Service Center)	6.2	50	PEMFC, SMR	Operational
Electrolyzer Energy Station (14)	SCAQMD, Stuart	Government Office Building, (SCAQMD Headquarters, Diamond Bar, CA)	-	120	Electrolyzer, H2ICE genset	Operational
Toronto Hydrogen Energy Station (14)	Hydrogenics, John Deere, Quest Air	(Toronto, CAN)	-	50		Operational
Stationary PEMFC with heat recovery	PlugPower, DOD	Military Research Office (Watervliet Arsenal, NY)	-	50	PEMFC (10 x 5 kW), ATR	Operational
ATR hydrogen generator	HyRadix, SunLine Transit, DOE	Transit Operator (Sunline, Palm Desert, CA)	10		ATR, Electrolyzer Solar DG	Operational
Hawaii Hydrogen Power Park (15)	Hawaii Natural Energy Institute, Pinnacle West, DTE, DOE	Government Office Building (Kapolei Hale City Hall, HI)	-	5	Solar powered electrolyzer, PEMFC	Under Construction
Hydrogen Technology Park (16)	DTE, Ford	Energy Service Facility (DTE, Detroit, MI)	2.7	85-95	electrolyzer, (10 x 5 kW PEMFC + Stirling engine	Under Construction
Home Energy Station (17)	Honda Motor Company, PlugPower	Residential	0.18	-	PEMFC,	Testing
Energy Station (18)	Chevron Texaco, AC Transit	Transit Operator (Oakland, CA)	6.2	-	Reformer	Planning

Note: '-' indicates missing data.



Notes: FCV = fuel cell vehicle (or other hydrogen powered vehicles); GJ = gigajoule.
 Source: Lipman et al., 2002a

FIGURE 2 Estimated profit (or loss) from H₂E-service station with a 40 kW fuel cell and 5 to 75 hydrogen vehicles refueled per day (w/approx. 10% ROI target) (14).



Notes: FH = future high cost case; FL = future low cost case; MT = medium term; OB = office building; 50-250 = fuel cell peak power in kW.

Figure 3 Estimated Profit/(Loss) from Office Building H₂E-Stations with 50 to 250-kW Fuel Cell and 10 Hydrogen Vehicles per Day Refueled (14).

Table 4 Summary of E-Station Impacts on Transportation Stakeholders

Stakeholder	Positive Impacts	Negative Impacts
H2 Vehicle Customers	<ul style="list-style-type: none"> - Lower cost hydrogen - Fueling availability at work or home 	<ul style="list-style-type: none"> - Possibly less hydrogen at “corner” gas-stations, stations near freeways - hydrogen price volatility will mirror NG price volatility
Auto Makers	<ul style="list-style-type: none"> - Potential to market/sell home refueling equipment with car - more predictable supply of h2 infrastructure (stations arrive before vehicles) 	
Electric Utility Companies	<ul style="list-style-type: none"> - Reduced strain on grid with DG - Reduced need to install transmission, distribution, and generation capacity 	<ul style="list-style-type: none"> - Erosion of profits from electricity sales (use of other mechanisms to recoup costs?)
Gas Utility Companies	<ul style="list-style-type: none"> - Enter into vehicle fuel sales market 	
Fuel Providers		<ul style="list-style-type: none"> - Erosion of fuel sales market
Fuel Cell Manufacturers	<ul style="list-style-type: none"> - Increased sales, higher production volumes, lower costs 	
Policy Makers	<ul style="list-style-type: none"> - Perception of “win-win” situation despite high capital costs in early years. Avoids risk of “cob-webbed” stations. 	<ul style="list-style-type: none"> - Higher up front capital costs, danger of natural gas price spikes undermining economics