



Electric Vehicle Transportation Center

Fuel Cell Vehicle Technologies, Infrastructure and Requirements

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The objective of the Fuel Cell Vehicle Technologies, Infrastructure and Requirements project was to evaluate state-of-the-art of fuel cell (FC) vehicles technologies and current and future fuel station infrastructure roll-out for the deployment of large scale fuel cell electric vehicles (FCEVs). The work was conducted by Dr. Nan Qin, Principle Investigator, Dr. R. Paul Brooker, and Dr. Ali Raissi of the Florida Solar Energy Center.

Final Research Project Report

Fuel Cell Vehicle Technologies, Infrastructure and Requirement

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1.0 Abstract

Fuel cell electric vehicles (FCEVs) use hydrogen as fuel and exhaust only water and heat. They provide driving ranges and fueling times comparable to gasoline vehicles. Despite the advantages, FCEVs have been in and out of the spot light of the auto industry for the past several decades. As FCEVs finally moved from concept demonstration to commercialization in 2015, it is critical to analyze the opportunities and challenges this technology brings. This project placed emphasis on four areas: (1) Analysis of the development of FCEVs from a historic and technology point of view; (2) analysis of hydrogen fueling station infrastructure costs, technical and operational challenges, as well as safety codes and standards; (3) exploration of using fuel cell as vehicle range extenders through modelling; and (4) investigation of FCEVs as backup power options. The results of each research area are published as technical reports and a journal article. This final project report will provide an overview of these research areas and reiterate some key findings.

2.0 Research Results

The research results for this project are presented in three research reports and one article that can be found on the EVTC website. These are:

1. N. Qin, A. Raissi, and P. Brooker (2014), “*Analysis of Fuel Cell Vehicle Developments.*” Electric Vehicle Transportation Center, [FSEC-CR-1987-14](#).
2. N. Qin, P. Brooker, and S. Srinivasan (2014), “*Hydrogen Fueling Stations Infrastructure.*” Electric Vehicle Transportation Center, [EVTC-RR-02-14](#).
3. P. Brooker (2015), “*Fuel Cells as Electric Vehicle Range Extenders*”, Electric Vehicle Transportation Center, [FSEC-CR-1995-14](#).
4. P. Brooker, N. Qin, N. Mohajeri (2015), “*Fuel Cell Vehicles as Back-Up Power Options*”, [DOI: 10.1149/2.F05151if](#).

A summary of the findings from each of these reports follow.

2.1 Analysis of Fuel Cell Vehicle Developments (Report 1)

A FCEV uses a fuel cell and an electric motor as its propulsion system. The onboard fuel cell directly converts chemical energy to electric energy. A hydrogen fuel cell is the most popular type used in FCEVs. It consumes hydrogen and oxygen as fuels and produces water vapor and heat as the only exhaust products. Therefore, a hydrogen fuel cell vehicle produces zero tailpipe greenhouse gas (GHG) emissions.

2.1.1 The History of FCEV Development

FCEVs have been in and out of the spotlight of the auto industry a number of times. The landmarks in the history of FCEV development are summarized in a timeline in shown Figure 1.



Figure 1. Timeline of major events in fuel cell vehicle developments.

The first fuel cell powered vehicle was produced by General Motors (GM) in 1966, named GMC Electrovan.¹ It utilized 32 fuel cell modules with a continuous output of 32 kW and a peak power of 160 kW. The Electrovan achieved a top speed of 70 MPH and had a range of 120 miles. However, the whole fuel cell system turned the 6-seat van into a 2-seat vehicle due to the two large hydrogen and oxygen tanks along with the required piping. The project was discontinued due to the prohibitive cost and lack of hydrogen infrastructure at that time.

The next historic landmark was the NECAR series introduced by Daimler-Benz in 1994. The NECAR-1 utilized a 50 kW fuel cell powered by a compressed hydrogen tank at 300 bar. It achieved a top speed of 56 mph and range of 81 miles. Similar to the GM Electrovan, the fuel cell system took up the entire cargo space and left only two-seat space in the van. NECAR-2, introduced two years later featured a fuel cell system one third of the weight of its predecessor.

It was at this point in time during 1996-1999 that the automakers of Toyota, GM, Mazda, Ford, Honda, Nissan, and Volkswagen began producing and testing their own version of FCEVs. The fuel cells on these vehicles ranged from 10 to 75 kW and the ranges were up to 310 miles. Many of these auto companies had then set goals to commercialize fuel cell vehicles in 2003-2004

timeframe. However, none of these goals were realized. In 2002, Toyota launched the world's first limited leasing of its fuel cell hybrid vehicle (called FCHV) in the USA and Japan. Its powertrain was comprised of a 90 kW fuel cell and a nickel-metal hybrid battery. The combined range of the fuel cell and battery was 155 miles. Since then, eight major automakers have put in significant efforts to test the real-world performance of the fuel cell vehicles. GM, Honda, and Toyota all had FCEV fleets in excess of 100 vehicles.

In 2003, the U.S. Department of Energy invested \$1.2 billion with targets to mature hydrogen and fuel cell technologies for transportation. One of the most notable projects was the \$170 million "Controlled Hydrogen Fleet and Infrastructure Validation and Demonstration Project". The objective of this project was to test small fleets of FCEVs as well as hydrogen fueling infrastructures in five regions in the United States covering a range of temperature and humidity conditions. These sites were Northern California, Southern California, Southeastern Michigan, the Mid-Atlantic, and Central Florida. The four automobile manufacturer/energy company teams were—Hyundai-Kia/Chevron, DaimlerChrysler/BP, Ford/BP, and GM/Shell who collectively demonstrated more than 500,000 individual trips and 3.6 million miles travelled by 183 FCEVs.² The DOE's 2009 targets of 250 mile range, fuel cell durability of 2000 hours, and fuel cell efficiency of 60% were met during the demonstration.

Finally, in 2015, Toyota and Hyundai introduced their first commercially available FCEVs (limited lease program started in 2014) in California market where public hydrogen fueling stations are currently available. This program continues.

2.1.2 FCEV Fuel Choices and Powertrain Configurations

The next part of the project effort was analysis of the 117 FCEV models in terms of fuel types, manufacturers, and powertrain configurations from the 31 automakers producing vehicles since 1994. The major findings were:

- 91% of the models used compressed gas, liquid, or metal hydride as the form of stored hydrogen fuel, while 9% of the models use liquid methanol.
- Fuel cell hybrid vehicles are vehicles that use both a fuel cell and an energy storage system (ESS) to provide propulsion power. A fuel cell usually suffers from poor response time and low traction power during start up and acceleration. Therefore, fuel cells are usually paired with an ESS to provide propulsion power for these events. The ESS can be batteries or super capacitors.
- For FCEVs without ESS propulsion systems, the fuel cell sizes are mostly 80-100 kW; whereas for fuel cell hybrid vehicles, the fuel cell ranges from 20-100 kW.
- A fuel cell range extender has been shown to be an option for a battery electric vehicle and is gaining interest in recent research efforts.

The report shows that after half century of research and development from the collective effort of both auto industry and government, FCEVs have reached commercialization. However, the early market is limited to California which is the only place that provides public hydrogen fueling infrastructure. The lack of hydrogen infrastructure is presently one of the biggest obstacles in the widespread deployment of FCEV technology. Report 2 examines the hydrogen fueling infrastructure technology and rollout strategies.

2.2 Hydrogen Fueling Stations Infrastructure (Report 2)

This report is based on a survey of recent literature on several key aspects of a hydrogen infrastructure that include types of hydrogen fueling stations, station costs, station rollout strategies, and applicable codes and standards.

2.2.1 Hydrogen Fueling Stations

Hydrogen fueling stations are one of the most important building blocks of the FCEV transportation infrastructure. In contrast to conventional gas stations where gasoline is delivered by tanker trucks, hydrogen fuel can be delivered by trucks, by hydrogen pipelines, or by being produced onsite at the fueling station. Most stations require the following hardware: hydrogen production equipment (for on-site hydrogen production stations), purification system, storage vessels, compressor, mechanical equipment, electrical equipment, and safety equipment. The hydrogen fueling stations are usually equipped with dispensers operating at either 35 or 70 MPa (350 or 700 bar), to accommodate FCEVs onboard compressed hydrogen storage tanks. The 70 MPa dispenser is more technically challenging than the 35 MPa dispenser, as multi-stage compression needs to take place as well as extra cooling systems. The details can be found in the full report.

Hydrogen fueling stations can take various forms. They mainly differ in hydrogen production methods or the hydrogen delivery methods. The processes used include onsite steam reforming stations (SMR), onsite water electrolyzing stations, stations relying on liquid hydrogen (LH₂) or gaseous hydrogen (GH₂) delivery, stations relying on pipeline hydrogen delivery, and mobile refueling stations. The production used and the approximate capacities of each type are listed in Table 1.

Table 1. Types of hydrogen fueling stations and their capacities.

Station Type	Onsite Production	Approx. Capacity (kg/day)
Steam methane reformer-based production	Yes	100-1000
Electrolyzer-based production	Yes	30-100
Mobile refueler	No	10-60
Pipeline gas delivery	No	100-1000
Delivered liquid or gaseous hydrogen	No	20-1000

The cost, location and amount of hydrogen used dictate the technical solution selected for the station. According to HyWays, a European hydrogen energy roadmap,³ the suitability requirements of different fueling station types are described as:

- Stations in remote areas with a constant and small demand are best suited for onsite production.
- Stations in rural areas with higher demand, e.g. along highways, may be suitable for liquid hydrogen delivery.
- Stations with large demands at city borders may be suitable for liquid hydrogen delivery or pipeline gaseous hydrogen delivery.

2.2.2 Hydrogen Fueling Station Codes and Standards

Hydrogen fueling stations represent a series of emerging technologies and applicable standards and codes are required and are still under development or revision. Some pioneer hydrogen fueling stations in California followed the Society of Automotive Engineers (SAE) standard J2601: “Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles”.⁴ This standard applies to light duty vehicles fueling for vehicles with storage capacity from 1 to 10 kg H₂ for 70 MPa and 1 to 7.5 kg for 35 MPa. The criteria include maximum fuel temperature at the dispenser nozzle, the maximum fuel flow rate, the maximum rate of pressure increase and other criteria based on the cooling capability of the station’s dispenser.

Other standards include the National Renewable Energy Laboratory (NREL) who published a list of codes and standards applicable for U.S. hydrogen infrastructure projects. In addition, the California Fuel Cell Partnership (CaFCP) and California Department of Food and Agriculture are developing test methods for evaluating metering equipment and dispensers for the purpose of selling hydrogen as a vehicle fuel in California. This standard will very likely to be adopted by more states as hydrogen fueling stations roll out.⁵

2.2.3 Fueling Stations Cost Estimates

The cost of hydrogen fueling stations is a complex issue due to the fact that hydrogen can be either produced at a centralized location and transported or generated on-site. In addition, there are multiple hydrogen generation methods, as mentioned above. Factors such as government incentives, increased scale of FCEV fleets, increased utilization efficiencies, and economies of scale associated with high capacity stations can play important roles in the final cost of the fueling stations. The report presents four notable cost analysis models for hydrogen stations. These models are:

(1) Hydrogen Analysis (H2A) model developed by the US Department of Energy’s Fuel Cell Technologies Office – The H2A model includes both onsite production types and delivery types of hydrogen fueling stations. The model was developed with inputs and deliberation from industrial stakeholders such as American Electric Power, BOC Gases, British Petroleum, Chevron, ExxonMobil, etc.⁶

(2) Models Developed by University of California, Davis (UCD) -- UCD studies took inputs from California Fuel Cell Partnership (CaFCP), Chevron, DOE, General Motors, Honda Motor Company, Shell Hydrogen, Toyota Motor Company, etc. for their model.⁷ The model takes into consideration the different types of fueling stations in their cost estimates. Both the H2A model and UCD model indicates a reduction of cost per capacity (\$/kg/day) as the total capacity increases. This result is shown in Figure 2.

(3) Hydrogen Station Cost Calculation (HSCC) – The HSCC model was developed by the National Renewable Energy Laboratory (NREL). The results from the HSCC model do not distinguish between stations of different production or delivery types. Their cost estimates apply to various types of hydrogen stations that are likely to be installed over the next 5 to 10 years.⁸

(4) Hydrogen Station Installation Estimates from California Stations -- Table 3 shows the cost estimates of early demonstration and recently funded hydrogen stations in California. The station capacities range from 60-350 kg/day, and total capital cost of stations range from \$2-6 million.

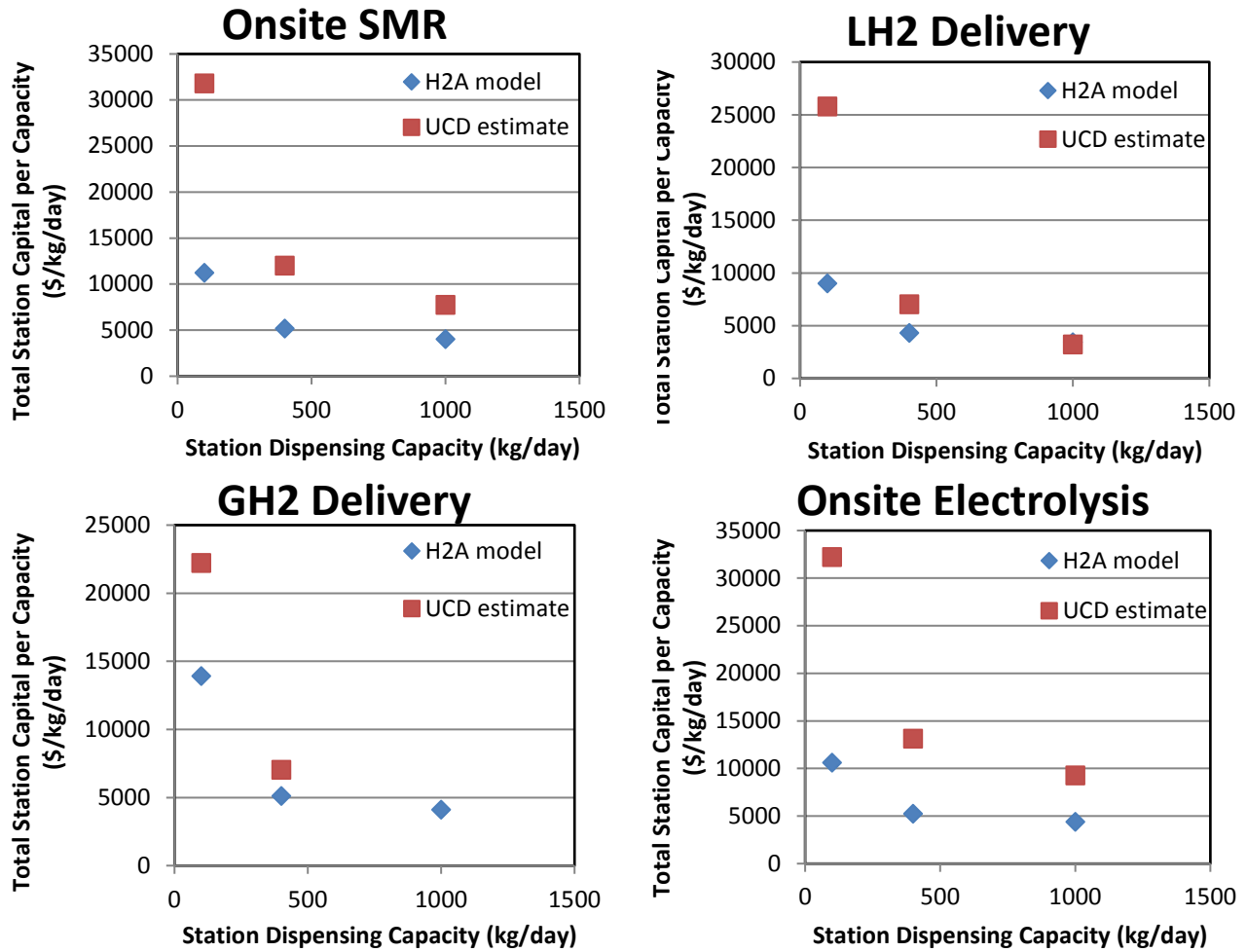


Figure 2. The cost for four types of stations predicted by H2A and UCD

Table-3. Cost estimates of hydrogen fueling stations in California.

Hydrogen Stations	Station Capacity (kg/day)	Cost per Capacity (\$/kg/day)	Total Capital (\$M)
Hydrogen stations 2009			
Onsite electrolysis (Emeryville)	60	93,000	5.56
Electrolysis (CSULA)	60	73,000	4.40
Onsite SMR	100	40,000	4.03
LH2 Delivery (Oakland)	180	33,000	5.96
Onsite SMR (UCLA)	140	31,000	4.32
GH2 Truck (Harbor city)	100	25,000	2.47
LH2 Delivery (SFO)	120	20,000	2.41
Hydrogen stations planned in 2014			
GH2 truck (APCI, 2 Stations)	180	13,000	2.29
LH2 truck (Linde, 3 Stations.)	350	7,200	2.52
LH2 truck (Air Liquide, 1 Station.)	200	12,000	2.43
Onsite Electrolysis (H2 Frontier, 1 Station.)	105	44,000	4.62

2.2.4 Fueling Stations Rollout Strategies

A number of hydrogen fueling station rollout strategies have evolved over time. One of the earliest policy initiatives was aimed at creating a “hydrogen highway” with hydrogen stations every 20 miles along highways in California. This plan would have created many underutilized stations as many would be located in rural areas and would not benefit the early FCEV adopters. A second policy proposed placements of hydrogen stations according to population density within major metropolitan areas in the state. It failed to consider that different cities or areas may adopt the technology at different rates. Currently, “clustering” strategies are considered a more realistic approach for early stations siting with efficient use of stations at lower cost. Clustering focuses on introduction of both hydrogen vehicles and refueling stations in a limited number of geographic areas such as smaller cities (e.g. Santa Monica, Irvine) within a larger region (e.g. the Los Angeles Basin). By concentrating early stations in a cluster area, a certain level of consumer convenience can be achieved with minimum number of strategically planned stations. Connector stations can be added to facilitate travel between clusters to create a hydrogen transportation network. For details and examples of the cluster methodology, please refer to the full report.

Report 2 concludes that hydrogen fueling stations relying on delivery methods are generally lower in cost per capacity (\$/kg/day) than stations with equivalent capacities that rely on onsite hydrogen production. The onsite production eliminates transportation and delivery costs, and are most suitable for remote areas with smaller consumer concentration while stations relying on hydrogen delivery are more suited for urban areas with high demand. Stations should be equipped with both 35 MPa and 70 MPa dispensers to cover both types of FCEVs. Smaller scale fueling stations (100-350kg/day) are likely to be installed to accommodate early markets. Larger stations with 1000+ kg/day capacity will be economically favored as more consumers adopt FCEV transportation.

The costs of fueling stations will drop due to the lowering cost of components, standardization of station design, and economies of scale. Government incentives and funding are critical in the early stages of building and operating fueling stations in selected geographic “clusters.” The clusters with strategically placed fueling stations will serve as seeding elements to spur FCEV market growth.

When planning to build a hydrogen fueling station, there are currently sixteen categories of codes and standards to follow. New codes and standards are still under development to accommodate the development of fuel cell and fueling station technologies. California is a leading state in implementing hydrogen fueling infrastructures. The lessons learned during the station planning, building, and operation will be valuable for other states or regions planning on constructing or expanding their hydrogen infrastructures.

2.3 Fuel Cells as Electric Vehicle Range Extenders (Report 3)

The rollout of both battery electric vehicles (BEVs) and FCEVs are hindered by different factors: the limited range and long charging time present difficulties for BEVs’, while the initial high capital investment and lack of hydrogen fueling infrastructure network limits the adoption of FCEVs. In this report, a new powertrain configuration was investigated. This configuration is the fuel cell-plug in hybrid electric vehicle (FC-PHEV) which uses a battery to supply the main propulsion power while utilizing a fuel cell to extend the vehicle range by recharging the battery.

For the analysis, the powertrain model was constructed using FASTSim, a simulation tool developed by the National Renewable Energy Laboratory (NREL).⁹ This modelling tool allows

simulation of a variety of vehicles and predicts the component costs and fuel economy using simulated drive cycles. The two driving cycles used were the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET). To simulate a FC-PHEV, a Chevy Volt was used as the basic model. The Volt's modified parameters were the inclusion of a fuel cell and hydrogen tank using published data from the US Department of Energy. Simulations were conducted using fuel cells with a variety of different power ratings, while other parameters (e.g. vehicle size, batteries, electric motor size and weight) were kept unchanged. During simulation, the program subjects the simulated vehicle to a driving cycle based on the UDDS (city) and HWFET (highway) driving tests, and calculates the power required to meet the driving demands. This propulsion power is initially obtained from the battery, until the state of charge (SOC) reaches 20%, at which point the generator turns on. The fuel economy was determined by calculating the energy from the battery and generator used during the drive cycle, and dividing it by the distance traveled. Following the EPA gas mileage calculation procedures, the combined fuel economy (weighted for city and highway travel) was calculated as 0.55 city fuel economy and 0.45 highway fuel economy. Two fuel cell parameters were investigated: fuel cell power from 10 to 50 kW, and hydrogen tank that ranged from 2.5 to 5 kg of storage.

The most notable results are briefly discussed here. The fuel economies of the Volt-FC and Volt-ICE were compared based on their battery-only and generator-only operation. This comparison is important since the range-extending vehicles will operate part-time on the battery, and part-time on the generator. For trips of shorter duration, the battery operation will dominate, while longer trips operate more on the generator. Figure 3 compares Volt-FCs with 10, 30, and 50kW fuel cell stacks (indicated as Volt-FC10, Volt-FC30, and Volt-FC50, respectively) to the Volt-ICE. The results show that the fuel cell and ICE options exhibit similar battery-only fuel economies. When the vehicle operates on the generator-only mode, however, the Volt-FCs demonstrate significantly higher fuel economies than the Volt-ICE. This is due to the significantly higher efficiency of the fuel cell over the gasoline engine. The Volt-FC30L represents a 30kW fuel cell range extender with a larger hydrogen tank, which will provide longer driving ranges, without a significant decrease in fuel economy.

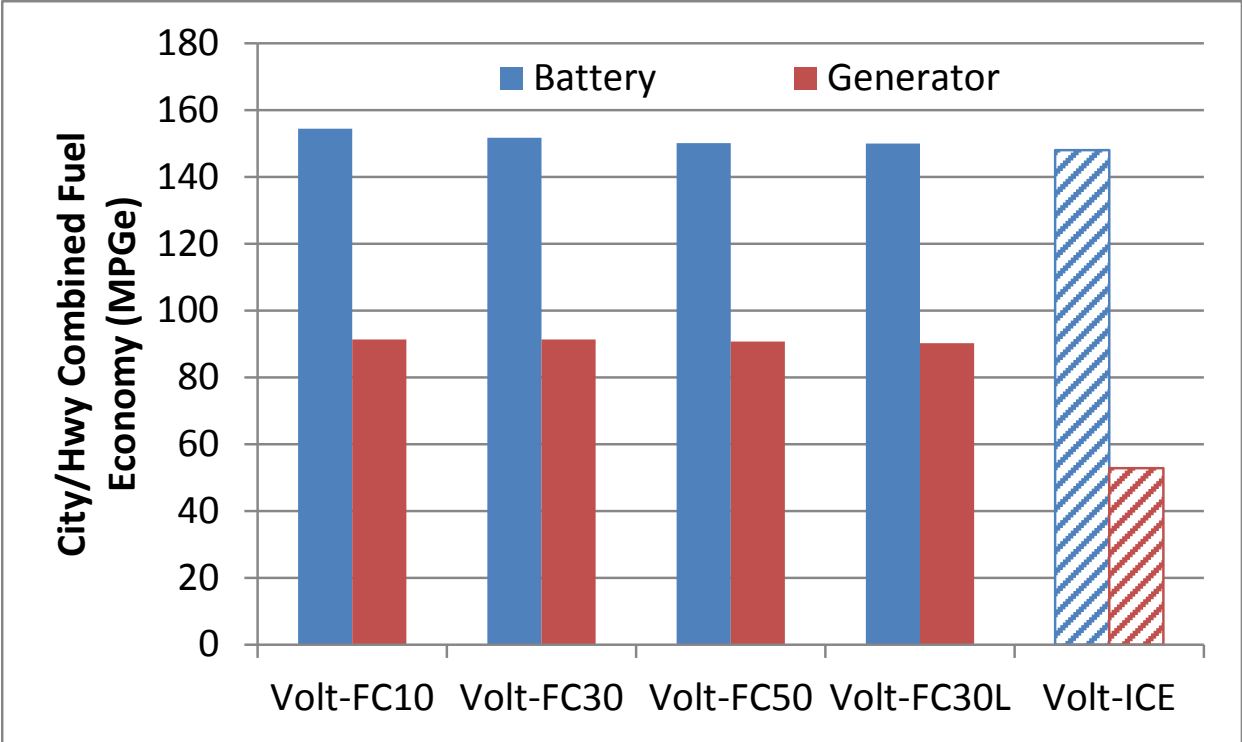


Figure 3. Fuel economy for Volt-FCs, as a function of fuel cell stack sizes.

In the next analysis, the fuel economy for the Volt-FC30L was compared to that of the BEV, conventional vehicle (CV), hybrid, and PHEV as a function of trip distance. The results are presented in Figure 4. These results show that the Volt-FC30L outperforms the PHEV in fuel economy especially at longer trip distance, and has a much larger range than BEVs. The cost per mile was also compared and shown in Figure 5. Gasoline costs of \$2.19 /gallon were used for the results. The cost of hydrogen is highly dependent on production and delivery method and was assumed to be \$4/kg. The cost of electricity used a residential rate of \$0.12 /kWh. For short distances, the BEV is the cheapest vehicle to operate but its range does not permit long trips without recharging. The Volt-FC30L shows a cost per mile that is roughly equivalent to that of the PHEV, assuming \$4/kg H₂. However, it should be noted that based on DOE cost projections for fuel cell stacks, the FC-PHEV initial cost would be about \$3000 more than the ICE PHEV, and using these gasoline costs, the fuel savings would not be sufficient incentive to purchase an FC-PHEV.

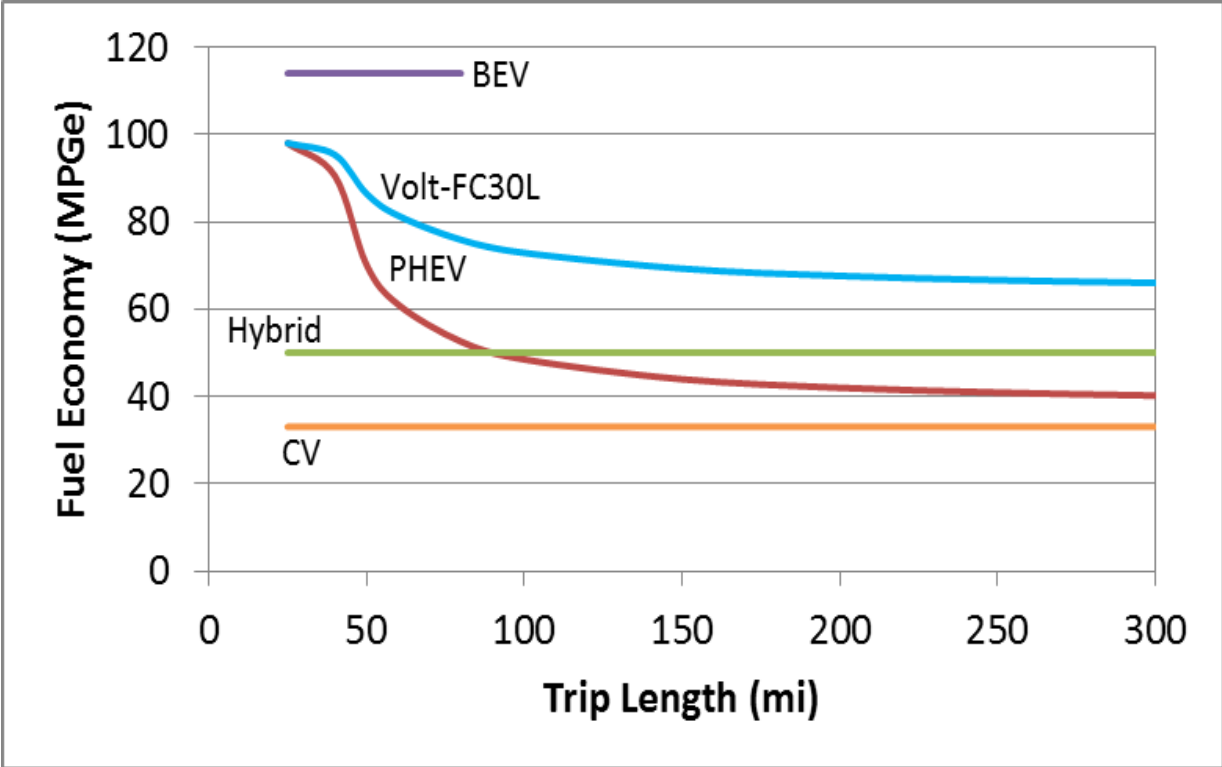


Figure 4. Fuel economy for various vehicles as a function of trip distance

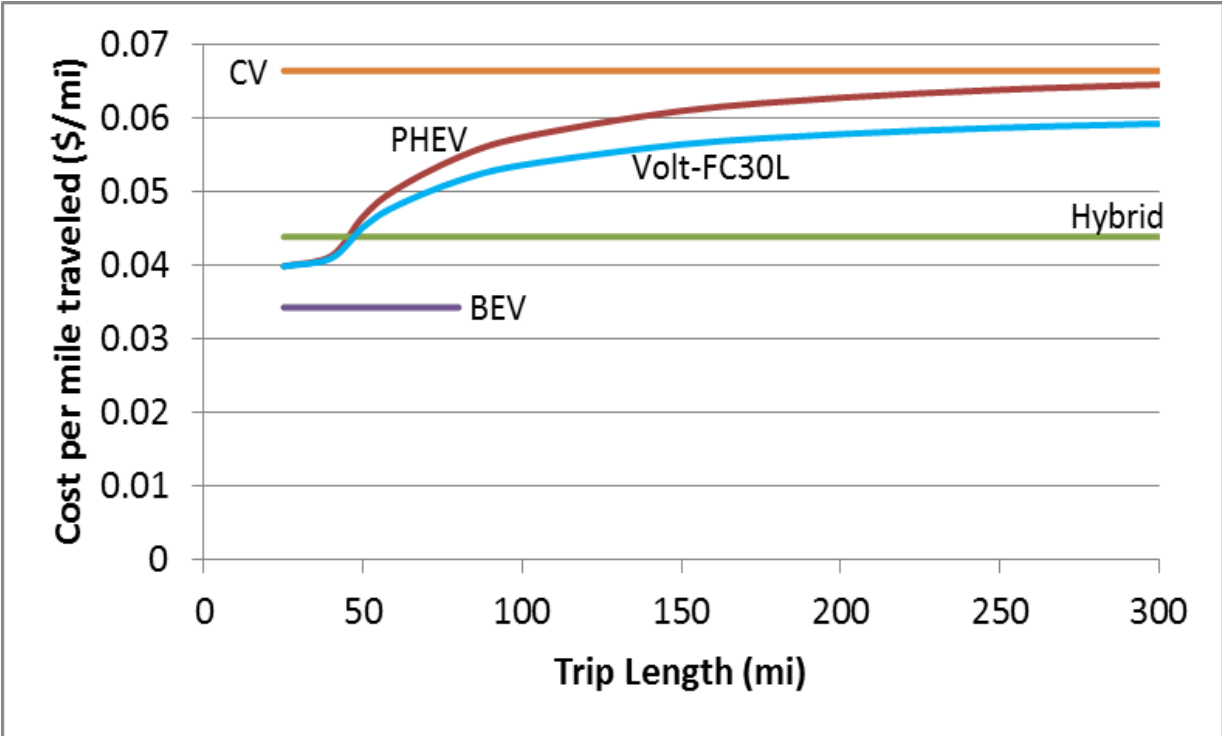


Figure 5. Cost per mile traveled for different vehicles.

In conclusion, modelling showed that the combination of a fuel cell with a battery would operate very well as a plug-in hybrid electric vehicle. The results showed that the fuel cell's increased efficiency would enable much greater fuel economy (~40%) than the equivalent internal combustion engine, and provide a significantly higher range than a battery electric vehicle (>200 miles). The FC-PHEV would also result in improved performance over BEVs in cold weather applications. Assuming hydrogen costs of \$4/kg H₂, the FC-PHEV could travel at costs 30% lower than a conventional vehicle and 25% lower than an ICE-based PHEV. Availability of charging stations is currently a roadblock for both BEVs and FCEVs, although BEVs benefit from at-home charging. FC-PHEVs would still require hydrogen fueling stations, however, due to the ability to charge at home, and majority of travel within residential areas would utilize only battery power, meaning there would be less need for hydrogen fueling stations near residential areas. Instead, hydrogen fueling stations could be located along major highways, as most long trips involve highway travel. Thus the successful rollout of FC-PHEVs could be achieved with far less hydrogen fueling infrastructure than the FCEV scenario.

2.4 Fuel Cell Vehicles as Back-Up Power Options (Report 4)

In the event of natural disasters and other emergencies, power outage and gasoline shortage may significantly impact people's living conditions. Whole-home residential emergency generators are costly (>\$20,000), require regular upkeep, and are used infrequently, a FCEV could be used to provide back-up power for a house during such an outage. As an example, Toyota states that their Mirai FCEV can power the essentials of a home for a week on a single tank of H₂. This report investigated the scenario of using FCEVs, particularly FC-PHEVs described in Report 3 as emergency generators.

Most of the FCEVs being offered are powered by large fuel cells (80-100 kW), and a small battery (<2 kWh). The fuel cell provides primary power at all times, while the battery is able to recapture energy during regenerative braking. In the case of a FC-PHEV, a medium-sized battery (16-20 kWh) is paired with a medium-sized fuel cell (30 kW) and a tank containing up to 5 kg H₂. As mentioned above, the battery would be large enough to provide the energy needed for short trips, while the fuel cell would provide the range required for longer trips (up to 300 mi). For most urban type of trips, a majority of trips could be completed on the battery alone, as our research indicated that 80% trips are 40 miles or shorter.¹⁰

Substantial benefits to the home during power outages could be envisioned when a FC-PHEV is in place. Charging of the FC-PHEV battery could happen at home, which would require the installation of a level 2 charging station (3.3-10 kW) to handle household power loads, and integration of the station with the home's power circuits. Since typical home loads are near this range, if the charging station were to include the necessary hardware, it could double as the automatic transfer switch (ATS) that is found in a whole-home emergency generator. The ATS isolates the home from the grid and allows the back-up generator to provide power to the home. With some modifications in the circuits during charging station installation, one should be able to create a system where the FC-PHEV with the modified charging station is able to provide power for entire house. Since the charging station and installation are required for the operation of the vehicle, the majority of the hardware are readily available to utilize the back-up power functionality of a FC-PHEV. In the event of an emergency, the FC-PHEV could provide power to a home over an extended period. The advantage of this approach is that no separate equipment would be needed, and all equipment would be in constant upkeep. This way, when an emergency does occur, there would be a high degree of confidence that all components would be operational,

and that there would be minimal impact on the homeowner. Figure 6 shows the approximate setup using a FCEV and a FC-PHEV, and the required additional components for whole-home power backup.

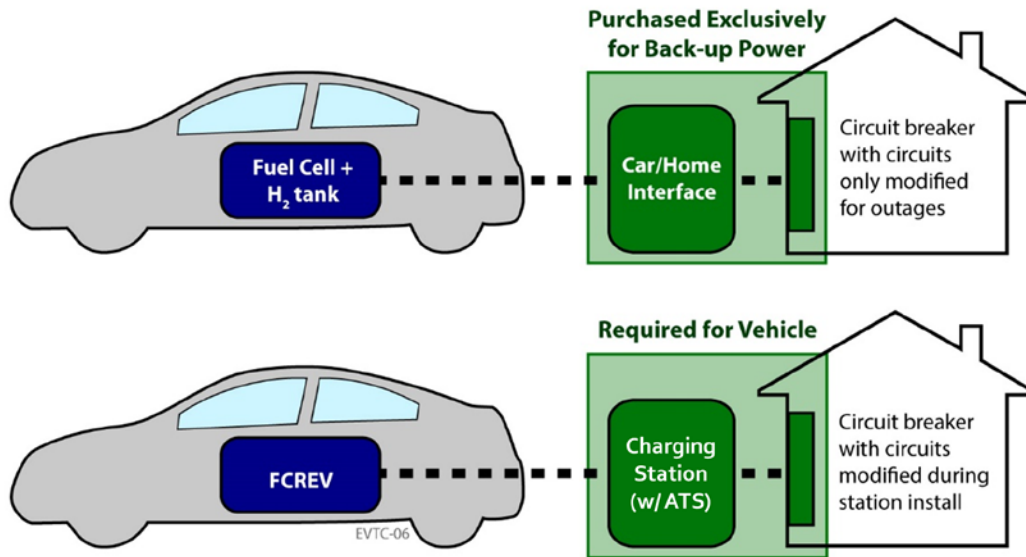


Figure 6. Schematic demonstration of the possible use of FCEV and FC-PHEV as whole-home

In conclusion, a FC-PHEV can be used as a backup power option that is potentially more cost-effective than a FCEV and can serve a large community. This approach can be incorporated at the consumer level, or at the municipal level, as part of their emergency response and green-fleet initiatives.

3.0 Impacts/Benefits

- (1) The FCEV development overview provides the stakeholders a historical and technical perspective of the technology. FCEV technology, after nearly half century of development from almost all the major auto makers, is no longer a technology in the future, but a realistic competitor that challenges conventional gas vehicles. The transportation planners and policy makers should envision and plan for the changes such as new transportation infrastructure requirements, incentives, amended tax structures, and policies.
- (2) The lack of hydrogen fueling infrastructure poses a major barrier for FCEV market penetration. Effective public policy to address the high capital cost of stations include subsidy to build hydrogen stations, environmental mandates, license regulations, and tax benefits.
- (3) The FC-PHEV model points to benefits of combining a battery electric vehicle and fuel cell electric vehicle. It provides insights into a new field of study for many vehicle and fuel cell engineers and system integrators.
- (4) The analysis of FC-PHEV as a back-up power option provides an insight to other positive assets of FC-PHEVs beyond transportation. It showcased added values of fuel cell vehicles, therefore may increase the attractiveness of this technology and to help facilitate market penetration.

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