The Role of V2G in the Smart Grid of the Future

by Richard A. Raustad

One of the world's first electricity generating plants was installed in 1882 on Pearl Street in New York City's financial district.[1] The transfer of electrical energy to the consumer originally occurred by means of direct current (DC). However, this form of energy transfer limited distribution to customers in close proximity to electric generators. Alternating current (AC) provided much longer transmission distances and soon took hold. Electric utility companies then began springing up in other U.S. cities, forming the beginnings of utilities and the grid as we now know it.

Fast-forward to the 21st century where utility companies now use, or have within their network, distributed generation, smart grid technology, and electric vehicles.

Con Edison defines distributed generation as a facility dedicated to the production of energy to support local loads.[2] The concept of distributed generation includes both AC and DC currents, renewable (photovoltaics, wind, hydroelectric) and non-renewable (conventional engines, turbines, fuel cells) generation. These energy sources must conform to the requirements of the grid-connected utility. The term "smart grid" describes the communication network between the user of energy and the utility company or between one utility and another.[3] Utility companies traditionally accomplished their communication using electric meters, which were manually read on a regular interval and then used to bill customers for energy consumed. This rudimentary form of energy monitoring did not provide the necessary detail to identify when energy was consumed or at what rate and duration. An initial step toward a solution was the installation of building electric meters, similar to the meter shown in Fig. 1, that could be automatically or remotely scanned to process the end use of energy. Automatic meter reading (AMR) originated in the 1970s and began a transformation where electric consumption information could be remotely collected or automatically communicated back to the utility company and to the consumer, if desired. Today's utility companies are installing AMR devices on residential, commercial, and industrial buildings throughout their territories. This effort creates a foundation for an advanced metering infrastructure (AMI) that relies on digital technology and allows for two-way communication between the utility company and the consumer.

In addition to smart meters, a true smart grid would include and monitor distributed generation and energy storage technologies. Active monitoring would provide real-time control over distributed generation, including any stored energy, and offer one more tool for balancing electricity supply and demand. For optimum grid control, energy storage must be a critical part. The fortuitous revitalization of electric vehicles (EVs) and the battery technologies being developed will provide the storage mechanisms for grid optimization and increased use of distributed generation.

Fig. 1. *PG&E smart meter. (Photo: EMS Safety Network.)*

The Department of Energy (DOE) *EV Everywhere* Grand Challenge, initiated in 2012, has identified technical targets in four areas of research: battery and electric drive system research and development, vehicle weight reduction, and advanced climate control technologies.

Reducing battery costs from their current $325/kWh to $125/kWh has the greatest potential to bring the perceived high cost of EVs in line with conventional vehicles.[4] Improvements in EV electric drive systems have led to lower cost inverters that meet or exceed DOE's 2015 EV challenge targets. Parallel research into vehicle light weighting and advanced climate control technologies has also led to reduced energy consumption and extended vehicle range.

EVs, given their projected penetration into the market, have the potential to provide (via their batteries) the most important component in the evolution of the smart grid—energy storage. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) store energy in a battery and later use that energy as the motive force for transportation. The battery is replenished through grid-connected electric vehicle supply equipment (EVSE), better known as charging stations.

The EVSE is the connection between the vehicle and the utility grid and manages the charging session. To store energy in the battery, the utility delivered AC must be converted to DC, which can occur in the vehicle itself (on-board charger) or the EVSE (off-board charger). On-board vehicle chargers generally provide lower charging rates because the vehicle must include, and therefore transport, the AC-DC conversion electronics at the expense of both initial cost and vehicle weight. Off-board vehicle chargers offer higher charging rates through the use of larger (and heavier) charging stations. These stations, referred to as DC fast chargers (DCFC), charge the EV using DC current that connects directly to the vehicle battery.

EV and EVSE manufacturers currently offer chargers solely as a mechanism for replenishing the vehicle battery. Energy flows in one direction from the utility grid, through the EVSE, and into the vehicle battery (grid to vehicle). Although these unidirectional devices are not capable of injecting energy into the utility grid, in the future grid system these charging stations could be used to support the transmission system through active management of the charging session (V1G, a.k.a. V2G half).[5]

A more proactive method of balancing utility supply and demand would be to access the EVs' stored energy and, when needed, feed that energy directly to the grid. In this case the energy transfers from the vehicle to the grid (V2G) and requires a bi-directional charger to accommodate both the charging and discharging of the traction battery.[6] Most vehicles are in actual operation for about one hour per day and EVs could therefore be connected to the utility grid for the majority of the day.[7] Thus, the energy stored in the vehicle's battery could be used for other purposes as long as the vehicle battery is sufficiently charged for the EV owners commute.

For more than a decade, V2G has been the focus of research and development/demonstration, with the goal of proving conceptual viability. It is gradually finding application as a benefit for utility grid regulation and as a demand limiting technology. V2G could provide the distributed resource the utility grid and infrastructure needs to supplement generating capacity and alleviate transmission grid bottlenecks today and into the future.

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The Electric Power Research Institute (EPRI) has been collaborating with automotive and EVSE manufacturers, utility companies, government agencies, and other stakeholders to develop a two-way communication platform where utilities are able to send commands directly to the vehicle.[8,9] A utility-generated command could request that the vehicle begin charging, suspend charging when the grid is nearing its maximum capacity, resume charging when grid loads subside, or request energy from the on-board battery to supplement the electric grid. The two-way communication would allow the EV to become part of a larger network of resources participating in utility regulation.

The United States Air Force recently replaced some general purpose vehicles with V2G capable EVs. The vehicles are charged using Princeton Power Systems' bi-directional EV charging stations (Fig. 2) installed at Los Angeles Air Force Base in El Segundo, California. The EVs will be charged directly from the utility grid and, when called on, the bi-directional charger will reverse power flow from the vehicle's battery back to the grid.[10] This is reportedly the largest V2G installation in the world and consists of 42 plug-in electric vehicles, 36 of which are V2G-capable.

The United States Navy is collaborating with Imergy Power Systems to combine solar energy production with battery energy storage using vanadium flow batteries.[11] The system can store and discharge up to 200 kWhs of energy at a 50 kW rate. The containerized battery storage module currently delivers a cost of less than \$300/kWh and targets costs of \$220/kWh within the next two years. The California Energy Commission (CEC) and South Coast Air Quality Management District are providing funding to support research into electric school buses.[12] This is one of the first V2G demonstration projects targeting school transportation vehicles.

William Kempton at the University of Delaware and EV pioneer Tom Gage have been proactive in V2G for some time. The current program at the University of Delaware is offering to lease a small number of BMW Mini-E EVs. This program will allow research into driving patterns as part of an on-going V2G demonstration project where a utility grid operator signal can use the EV battery as part of grid regulation programs.[13]

Nissan has been field testing their new vehicle-to-home (V2H) energy storage system in Japan as shown in Fig. 3.[14] This is in response to the recent earthquake disaster, which left many without power. The average daily household consumption in Japan is about 10-12 kWh. So the Nissan Leaf's 24 kWh battery can supply emergency power for approximately 2 days. Field tests are being conducted by ENERES Corporation. Similar tests are underway in the U.S. where average daily household electricity consumption is approximately 32 kWh.[15]

Burns and McDowell together with Coritech Services developed a system of five 60 kW bi-directional, DC fast-charging stations for a fleet of electric trucks. This project is part of the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) microgrid project at Fort Carson which includes diesel generators and a 2 MW PV array. The project is managed by the U.S. Army Corps of Engineers (USACE), Omaha District, and includes technical guidance from the Construction Engineering Research Laboratory (CERL), and Tank Automotive Research, Development and Engineering Center (TARDEC).[16] Total charging and discharging power is 300 kW using SAE J1772 compliant bi-directional charging cables.

These demonstration projects are but a sampling of those performed today and in recent years. Grid regulation using EVs is becoming more prominent and can generate revenue for vehicle owners, making the economics of vehicle ownership more attractive. More importantly, grid regulation using V2G can provide stability at the local level in response to intermittent renewable energy generation (PV and wind) and highly variable end use loads (DCFC, water heaters, HVAC, etc.). V2G can also be applied on a larger scale where many energy storage devices act in unison as a utility grid resource.

Fig. 2. *Princeton Power System bi-directional charger. (Photo: Tech Sgt Sarah Corrice, AFSC.)*

Participants in the electricity services market respond to demand requests by utilities and grid operators in a variety of ways to improve reliability, increase economic efficiency, and to integrate renewable generation capacity. Of the three major categories of demand response products, experts agree that the ancillary services market holds the greatest potential for EVs and V2G technology.[17]

Ancillary services provide the short-term electrical capacity needed to adjust for temporary changes in overall grid capacity. As the reliance on renewable generation capacity (wind and solar) increases, the intermittent nature of these resources requires additional generation to balance the inconsistencies in energy production (changes in wind speed or cloud coverage). Ancillary services are required to dispatch resources within seconds or minutes to help balance the system on a short-term basis. This market provides an opportunity for EV and energy storage owners, and the aggregators that manage these resources, to create an additional revenue stream.

A single EV would have minimal impact on the electric grid, but the combination of many vehicles would provide the capacity needed to significantly impact grid operation. V2G participation in the ancillary services market in the current and future transmission system would require a large number of EVs to be grouped or aggregated to create a single block of electrical capacity. Ancillary market services typically requires that 1 MW of capacity be available for dispatch and control on an hourly basis. The number of EVs required for a 1 MW block of capacity is estimated at 100-200 vehicles operating at or below 10 kW of available output capacity. Those EVs not connected to the grid could not participate while others could only participate during the charging process (V1G). Those that opted to actively participate while their vehicles were parked, for example those that connected to the grid via bi-directional V2G chargers, could reduce electricity loads on the transmission system, alleviate bottlenecks, and regulate grid frequency.

There are several aspects of utility grid regulation where V2G and energy storage can play an important role. V2G capable EVs could provide peak power or serve as a demand response resource in the ancillary services market. While V2G capable vehicles could provide these services, the economic returns do not generally justify the expense.[18] Two ancillary service areas where V2G shows promise are frequency regulation and operating reserve.

Frequency regulation, where electricity supply and demand (generation vs load) are imbalanced and utility generators must adjust to maintain a tight operating frequency (60 Hz in the U.S.), can benefit from V2G technology given the fast response time inherently available from batteries and the limited energy required to stabilize that imbalance. Participation occurs as either regulation up or down events where the battery either provides energy to or accepts energy from the utility grid. Over time, these events balance to where the amount of energy in the storage device does not change dramatically. These events are also limited in time duration and are believed to have very little impact on battery life. Letendra, *et al.,* estimate frequency regulation revenue per V2G capable EV as $578 and $2,891 per year for 2 kW (AC Level 1) and 10 kW (AC Level 2) capacity, respectively. These are the average costs for PJM Interconnection LLC, a regional transmission organization in the eastern United States and the Electric Reliability Council of Texas (ERCOT), an independent transmission system operator representing 85% of the state's electric load.

Operating reserve is spare generating capacity. Spinning reserve refers to the generating equipment that is online and synchronized with the utility grid and available for dispatch within 10 minutes. Non-spinning reserve refers to off-line generating capacity that can be started and synchronized with the grid within 10 minutes. Mechanical equipment cannot adjust quickly enough to respond to rapidly changing demand while battery energy storage offers a resource that can quickly adjust to the changing needs of the utility grid. Letendra, *et al.,* estimate spinning reserve revenue per V2G capable EV as $204 and $1,019 per year for 2 kW and 10 kW capacity, respectively.[18]

The regulations for the ancillary services market may also need adjustment to maximize the available potential of V2G capable vehicles. The Northeast Power Coordination Council requires a minimum runtime of one hour for resources providing synchronized, 10- or 30-minute reserves.[19] Actual participation in this market requires dispatch in much less than one hour and this requirement limits the accessible capacity each vehicle could offer. Under this regulation, a 24 kWh battery could reasonably provide no more than 20 kW of capacity when, for shorter durations, this battery could easily supply 40 kW or more. Limiting the available capacity of EVs in the ancillary services market would limit the potential of V2G in the future.

Transmission system components used to ensure reliability and quality of service were engineered assuming the flow of energy in one direction. As more distributed resources come online, thereby feeding energy back into the grid, these components would need to be redesigned to ensure the same high quality of service. If energy storage, including V2G technology, were connected to the utility grid, and that energy were used locally and efficiently, the necessity for two-way energy flow through the transmission system might be minimized or eliminated.

Energy storage used as a local electricity source or grid resource will play a key role in the future. For example, the unpredictable and intermittent operation of photovoltaic and wind generating equipment is one characteristic of renewable generation that is difficult to resolve. If renewables are to provide an increasingly higher percentage of available grid capacity, the variation in generation must be addressed. Storage of renewable energy and the subsequent dispatch of that energy on an as needed basis will be key to the future of energy storage and its interaction with the utility grid.[18]

Batteries are capable of responding to a request for a change in output very quickly. As end use loads and renewable generation vary, on the order of seconds (air conditioners turning on or clouds covering a PV system), battery storage technology can respond to these variations much faster than other available technology.

As Harris and Myers so aptly described only four years ago, "The modern grid, however, is still largely based on the original design that Westinghouse and Edison debated in the late 1800s, and isn't designed for modern electrical loads, distributed energy sources, or optimal efficiency. Power is generated and distributed by utility companies, without local competition to speak of, and with fairly little communication between utilities and end users in terms of how to get more out of the system. To date, the revolutions that we have seen in communications have very few analogs in the electric grid."[20]

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Fig. 3. *Nissan LEAF to home. (Photo: Nissan.)*

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Although there has been some progress, the future of V2G and smart grid technology, renewable energy, and energy storage, as they relate to the electric grid, is unclear to a certain degree. It is hard to believe that any of these individual technologies would not be part of the future electricity system. The uncertainty lies in the role each will play. A well placed bet would be to spread an investment over each of these technologies and reap the rewards well into the future.

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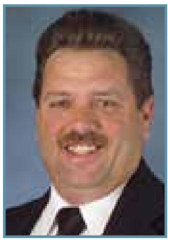
About the Author



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Fuel Cell Vehicles as Back-Up Power Options

by Paul Brooker, Nan Qin, and Nahid Mohajeri

Over the past few years, the United States has seen a significant impact of major storms on the lives of its citizens. Hurricane Katrina left several hundred thousand individuals without power for several days. Hurricane Irene and Superstorm Sandy similarly affected millions. The ability of the government to effectively mitigate the impact on each and every individual can only go so far. To this end, the following statement is posted on the DOE's website:

> "While these government and industry groups initially focus on critical facilities, homeowners, business owners, and local leaders may have to take an active role in dealing with energy disruptions on their own."[1]

With this in mind, a few comments on power security may be in order. Figure 1 illustrates the fraction of power outages over the past three years, as a function of the number of days without power. The majority of outages (57%) lasted less than a day, but a significant portion (31%) lasted 1-3 days. There were a variety of causes for these electricity interruptions, but most were weather-related. The number of customers affected from these outages also varied, from a few hundred to a few million, in extreme cases. For example, after Hurricane Sandy hit the eastern U.S. on October 29, 2012, over 8 million people lost power.[2] For many of these individuals, power was not restored until November 19, 2012.

Electricity was not the only commodity shortage that resulted from Sandy. Gasoline supply was also significantly impacted. Figure 2 plots the response of gas stations to a telephone survey conducted by the U.S. Energy Information Administration (EIA) after Hurricane Sandy.[3] Four days after Sandy hit, only 33% of gas stations were operating, and 10% reported they had no gasoline. The remaining gas stations either could not be reached (53%) or were without power (3%). As time progressed and more gas stations re-opened, New York City and New Jersey experienced a fuel shortage, and gasoline rationing was implemented on the eleventh day after Sandy.

With all this, the New York City government did its best to provide energy to as many people as possible, by distributing gasoline-powered generators to those areas where it would make the greatest difference, *e.g.*, hospitals, care facilities, and multi-family units. However, families living in individual residences were lower in priority, since it was easier to service a larger population in more densely populated areas. So, the question arises: what is an individual homeowner to do in the event of a power outage?

One approach is for homeowners to purchase their own generators. These generators vary in size from a few kW (powering a few small appliances) to large, whole-home generators. The small, portable generators are cheaper, but are unable to provide a significant contribution to the home's energy consumption. Additionally, they cannot operate indoors, and they consume gasoline or diesel, which may be in short supply during extended outages. Whole-home emergency generators are costly (>$20,000), require upkeep, and are used infrequently. In this article, fuel cell-powered cars are discussed as an alternative to the whole-home generator. In this case, the generator would not need upkeep, is used frequently, and could provide heat, water, and electricity in the event of an emergency, all without noise or air pollution.

The fuel cell-powered vehicle has taken many forms over the years, with different configurations being explored. The first attempt to employ fuel cells as vehicle propulsion systems dates back to 1966, with General Motor's introduction of their fuel cell-powered Electrovan.[4] Over the last two decades, over 30 auto manufacturers have researched and developed more than 110 fuel cell concept vehicle models.[5] In 2003, the DOE funded a $170 million project that saw deployment of 183 fuel cell electric vehicles (FCEVs), with more than 500,000 vehicle trips covering 3.6 million miles.[6] 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. More recently, Toyota and Hyundai have announced their first commercially available fuel cell vehicles for 2015 (limited lease program started in 2014). The sales will be first opened in California where a hydrogen fueling station network is located. Ford/Nissan/Daimler and GM/Honda have teamed up to bring fuel cell vehicles to the market in the next five years.[7,8]

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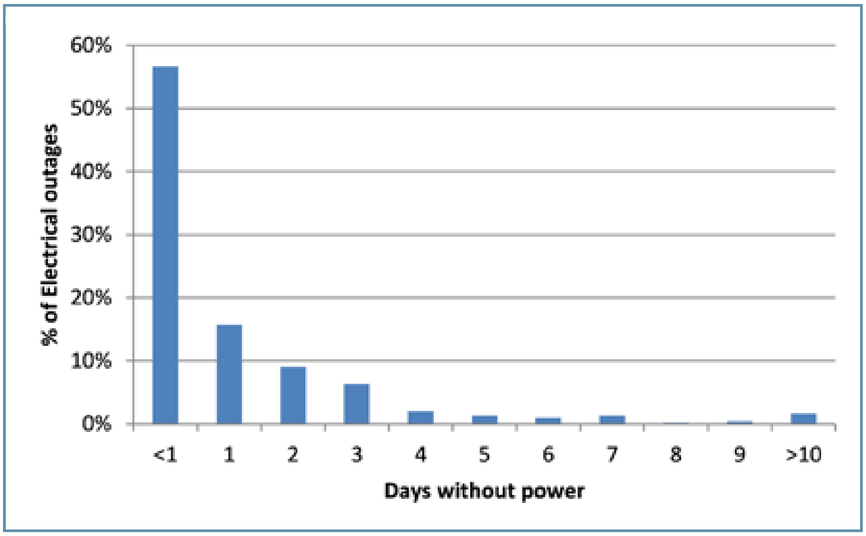

Fig. 1. *Power outages in the U.S. over the past three years, as a function of days without power.*

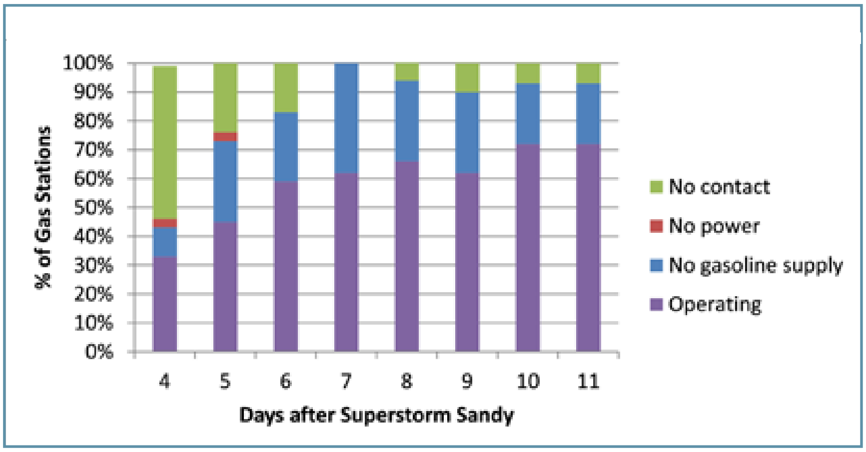

Fig. 2. *Gasoline stations' response to EIA survey after Superstorm Sandy.*

A FCEV can be used to provide back-up power for a home during 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 H_2. However, in the case of the Mirai, a separate unit would need to be purchased to interface the FCEV with the home, which may not be the most economical approach in terms of cost-per-use. A different paradigm may provide a more cost effective route to back-up power.

Most of the fuel cell cars 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. An alternative configuration that has yet to be seen is the fuel cell range-extending vehicle (FCREV). In this case, 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 H_2. The battery would then be large enough to provide the energy needed for short trips (less than 40 mi), while the fuel cell would provide the range required for longer trips (up to 300 mi). With a FCREV, the majority of trips (near 80%) could be completed on the battery alone, assuming charging takes place at the destinations (*e.g.*, home and work). Since the majority of travel within residential areas would utilize only battery power, there would be less need for hydrogen filling stations near homes. Instead, hydrogen filling stations could be located along interstates, assuming most long trips involve highway travel. While the need for an extensive distribution of hydrogen filling stations exists for both FCREV and FCEV, the FCREV could tolerate a fewer number of filling stations, provided there are sufficient numbers along major routes to support long trips.

Furthermore, substantial benefits to the home during power outages could be envisioned when a FCREV is in place. Charging of the FCREV battery could happen at home, which would entail the installation of a level 2 charging station (3.3-10 kW) 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 FCREV with the modified charging station is able to provide whole-home power. Since the charging station and installation are required for the purpose of powering the vehicle, only a small incremental cost is incurred for whole-home back-up power. Thus, in the event of an emergency, the FCREV 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 did 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 3 shows the approximate setup using a FCEV vs. FCREV, and the required additional components for whole-home power backup.

While the above concept suggests that the issue of powering the home during an outage can be addressed using an FCREV, a key question that remains is: what about H_2 supply? During past long-term outages, severe gasoline shortages have occurred. How would a fuel cell range extender vehicle be able to mitigate this issue (*i.e.*, unavailability of fuel)?

H_2 Generation

The lack of hydrogen fueling infrastructure has been identified as a major obstacle in FCEV commercialization.[9] Hydrogen fuel can be produced in centralized locations and distributed by trucks or by hydrogen pipelines. Alternatively, hydrogen can be produced on site at the fueling stations via methane steam reforming or water electrolysis methods. The decentralized nature of onsite hydrogen production renders these stations unique during emergencies in that they do not rely on deliveries for supplying fuel. The water electrolysis method is especially relevant as it does not depend on raw materials such as natural gas; only water is required. If each filling station were to store 3 m^3 of water, this could provide sufficient hydrogen for 100 cars over a three-day power outage.

In a water electrolyzer, electricity is used to split water into hydrogen and oxygen. The electricity can come from either the grid or from renewables such as photovoltaics and/or wind, or from a mixture of sources. Most commercial electrolyzers today are capable of electricity to hydrogen production efficiencies of 80% to 90% (based on the higher heating value, HHV).[10,11] The complete electrolyzer-based hydrogen generating station requires the following hardware:

- Water electrolyzer (for onsite hydrogen production)
- Purification system: to purify hydrogen to meet the purity standards for fuel cell vehicles
- Storage vessels: to store hydrogen in gaseous or liquid form
- Compressor: to minimize storage volume and prepare the gas for pumping into high pressure (35 MPa-70 MPa) vehicle storage tanks
- Safety equipment (*e.g.*, pressure relief valves, vent stack, hydrogen sensors, fencing)
- Mechanical equipment (*e.g.*, underground piping, valves)
- Electrical equipment (*e.g.*, control panels, high-voltage connections, meters)

During Sandy, several gas stations were unable to function due to the lack of power. Clearly, the utility of an H_2 generating station during an outage would be similarly impaired if there were no electricity. By building PV into the station's power supply, it will be able to function during a grid outage. By coupling the FCREV to power the home with a local H_2 filling station with PV backup, both transportation and residential power needs may be met, even for extended outages. A H_2 filling station will also be able to serve individuals who may not have purchased PV for their homes, but own a FCREV.

Another advantage of using a FCREV is its ability to be distributed to different locations. At low levels of penetration, it is not reasonable to expect a FCREV owner to provide power to the entire community. Therefore, one might consider a scenario in which the municipality owns a fleet of FCREVs. In this case, these cars could be dispatched to suitably retrofitted public emergency shelters to act as the generators. This approach may be able to serve a wider group of people than a typical residential application, since the emergency shelter would be able to accommodate a larger group, and the economies of scale would make this approach more energy efficient.

Another approach for distributing energy in an emergency would be to deliver hydrogen in a tube-trailer to the various shelters. It is quite possible that a few FCREVs at a single site would be sufficient to provide the power needed over a short time frame. However, for larger emergencies that extend for several days, it may be necessary to provide additional energy to those areas that are not co-located with a PV-powered electrolyzer. In this case, a tube-trailer of hydrogen may be dispatched to the shelters (or an appropriate location for residential customers to access), so that the FCREVs can be refilled. Tube-trailers provide >500 kg of hydrogen, and could be outfitted with the appropriate filling equipment for FCREVs. Tube-trailers have been used for fuel cell vehicle demonstrations and this approach is commonly used for fueling stations supporting short term events and demonstrations. In an event of emergency, these mobile refuelers can travel between hydrogen production plants and the fuel cell vehicle fleets to ensure a continuous supply of hydrogen.

Conclusions

A power outage is inconvenient if it lasts for a few hours, and could be dangerous if it lasts for several days, especially under adverse weather conditions. A FCREV offers a back up approach that is potentially cost-effective and that serves 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.

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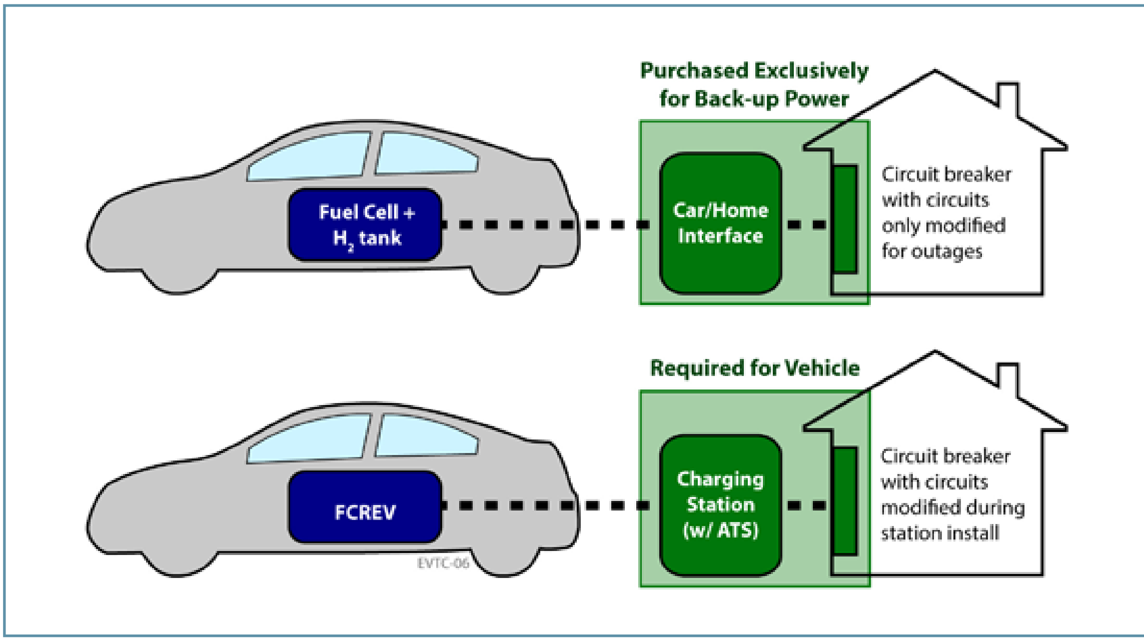

Fig. 3. *Schematic demonstrating the possible use of FCEVs as whole-home generators.*

About the Authors

Paul Brooker received his BS in Chemical Engineering from Brigham Young University Provo, Utah in 2004 and his PhD from the University of Connecticut in 2009. His graduate and post-doctoral studies investigated the performance of fuel cells, as a function of electrode structure and membrane/electrode interfaces. In addition to fuel cell membrane and electrode characterization, Dr. Brooker has extensive experience electrochemical devices, such as fuel cells and flow batteries, in identifying failure mechanisms and developing electrodes for enhanced performance and durability. Additionally, Dr. Brooker provides support for the Photovoltaic Manufacturing Consortium (PVMC), where he has assisted in identifying failure modes and wear mechanisms for diamond wires used in silicon wafer slicing. He is currently an Assistant Research Professor at the Florida Solar Energy Center. He may be reached at pbrooker@fsec.ucf.edu.

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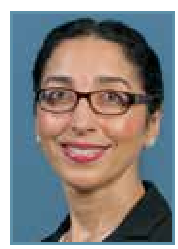

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