Fuel Cell Backup Power System for Grid Service and Micro-Grid in Telecommunication Applications

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FUEL CELL BACKUP POWER SYSTEM FOR GRID-SERVICE AND MICRO-GRID IN TELECOMMUNICATION APPLICATIONS

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Abstract

This paper presents the feasibility and economics of using fuel cell backup power systems in telecommunication cell towers to provide grid services (e.g., ancillary services, demand response). The fuel cells are able to provide power for the cell tower during emergency conditions. This study evaluates the strategic integration of clean, efficient, and reliable fuel cell systems with the grid for improved economic benefits. The backup systems have potential as enhanced capability through information exchanges with the power grid to add value as grid services that depend on location and time. The economic analysis has been focused on the potential revenue for distributed telecommunications fuel cell backup units to provide value-added power supply. This paper shows case studies on current fuel cell backup power locations and regional grid service programs. The grid service benefits and system configurations for different operation modes provide opportunities for expanding backup fuel cell applications responsive to grid needs.

The objective of this work primarily focuses on how fuel cells can become a significant part of the telecom backup power to reduce system costs, environmental impact, and dependence on fossil fuels, while ensuring continuity of indispensable service for mobile users. The study identifies the approaches on the fuel cell application through nano/microgrids for an extensive network of fuel cells as distributed energy resources. The possibilities of various application scenarios extend the fuel cell technologies and microgrid for reliable power supply.

Keywords: Fuel cell; hydrogen; backup power; microgrid; grid service; cell tower

1. Introduction

Clean and efficient fuel cell power systems have shown great potentials as an alternative power supply technology for distributed energy resource (DER) needs. They are also attractive for telecommunications companies that want to avoid prolonged power outages and disruption of service to their customers. Backup power solutions using fuel cell system technologies offer improved network reliability, environmental benefit, and cost-effective operation over incumbent methods such as diesel backup power.

Between 2009 and 2012, the U.S. Department of Energy (DOE) supported the installation of more than 800 backup power fuel cell systems with American Recovery and Reinvestment Act (ARRA) funds [1, 2]. Since 2007, more than 3,000 fuel cell systems have been installed at cellular facilities owned by telecom companies—Sprint, T-Mobile, Verizon, AT&T, and others—to power their facilities. The sites include both remote and urban locations. The fuel cell systems are networked and monitored remotely, providing benefits that include:

- longer runtime (greater than 8 hours) to meet emergency power needs,
- quiet operation,
- rooftop installation capable,
- small foot print.

According to a 2013 cost of ownership analysis [2], fuel cell systems could be cost competitive with incumbent backup power technologies, especially with incentives. Current deployment is for emergency backup power only. The grid is fairly reliable if there are no natural disasters, so the backup systems are idle in most of time and under-utilized. Therefore, integrating under-utilized, efficient, and reliable fuel cell systems already installed in the U.S. for grid services can provide additional economic benefits for system owners and utilities.

The objective of this work is to develop an approach for increasing the utilization of installed fuel cell backup power systems. Furthermore, we studied the architecture of a microgrid using hydrogen fuel cells and a network of fuel cell backup power systems to implement information and energy flow for potential grid service, which could add a revenue stream for additional use of the backup power. We first investigated the regional cell tower locations and needs, including hydrogen availability. Then the conditions and the niche market of the fuel cell backup power usage were extended through demand response (DR) or suitable grid ancillary services.

Four types of fuel cells have been developed in the past few decades, including the proton-exchange membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), molten-carbonate fuel cell (MCFC), and solid-oxide fuel cell (SOFC). They are categorized as low-temperature or high-temperature fuel cells based on their operating temperatures. All fuel cells can achieve well-above 40% efficiency. High-temperature fuel cells such as MCFCs and SOFCs can use natural gas supplied through a pipeline and avoid the need of hydrogen delivery and storage. High-temperature fuel cells often work at temperatures ranging from 400°C to 600°C, need insulation to prevent heat loss, have a more complicated system for fuel processing, and have high thermal mass and materials considerations limit rapid power ramping. The cells are suitable for 100 kW or higher in continuous operation as distributed generation with minimum frequent startup/shutdown. Currently, the scale of hydrogen/fuel cells for grid integration is focused more on prime power (>100 kW) stationary fuel cells, but not for small-scale (< 20 kW) units. This study investigated the approach to extend the application of small-scale fuel cell backup systems with coordination to the grid condition to increase their utilization and economic return.

The PEMFC works at lower temperatures between 40°C to 120°C. They use industry-grade pure (99.95%) hydrogen to prevent catalyst poisoning by contaminants, and require hydrogen delivery and storage. PEMFCs can quickly ramp to the rated power; therefore, they represent an alternative emergency power source to batteries and internal combustion (IC) generators to provide power for portable electronics, stationary power, transportation, and, in this paper, a backup power system for a base station in a cell tower.

Fuel cell backup power systems have many advantages relative to incumbent technologies. IC generators have been widely used for portable and backup power, and they are commercially available at low cost and have standard product series to serve the backup power market. However, they have several installation and operating issues that prevent wider adoption for cell tower backup power applications. Local government agencies may limit IC generator installations because of emissions and noise concerns. Many cell antennas are located on top of buildings, where IC generators often cannot obtain a permit for rooftop installation. Another option, battery backup power, is quiet and easy to install. However, battery capacity depends on mass; so high-capacity batteries are large and heavy, which could incur weight/space limitations in confined spaces and on rooftops. The fuel cell option offers longer continuous runtimes than a battery power system with adequate hydrogen supply.

Compared with IC generators and batteries, PEMFCs are clean, efficient, and light if they are separated from hydrogen storage facility. Although the nominal cost of PEMFCs is still higher than IC generators and batteries at a certain capacity, a 2012 NREL technology validation indicates that under certain implementation conditions, the PEMFC system can be cost effective and has 99.5% reliability for successful starts [1]. PEMFCs can also take advantage of clean-energy incentives, which could further reduce the installation cost and make them more cost competitive needed for deploying innovative energy technologies. In long-term broad deployment of fuel cell electric vehicles, PEMFCs will be benefit from the cost reduction with the mass production of automotive fuel cells. PEMFCs can be promising for broad usage as cell tower power backup or other critical power supply needs.

2. Fuel Cell Systems for Telecommunication Backup Power

Implementing a backup power system for a cell tower will add costs for telecom companies; however, the benefits of reliable cell service may outweigh the increased cost. Figure 1 shows a fuel cell backup power system integrated with a cell tower. The system consists of a power generator (e.g., fuel cell stack, typically within a protective enclosure), hydrogen from renewable sources, grid power supply, electric connection to the base station, and the integration with a cell tower. According to the fuel cell system providers and telecom users, the fuel cell power system is often installed in accordance with safety and operation rules, and in compliance with local code requirements.

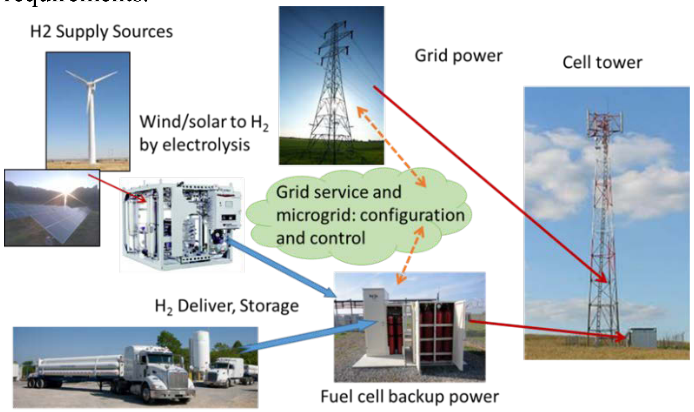


Figure 1. Fuel cell backup power system integrated with a cell tower with renewable (biomass, wind, and solar energy) hydrogen supply.

In a typical cell tower, the transceiver load in the base station requires about 2 to 3 kW. The baseload electricity consumption of a cell tower may be relatively stable over the service time, but starting air-conditioning units can create peak power events [3]. The fuel cell backup power is rated between 4 and 6 kW to cover the baseload with 40% excess capacity. The product line from fuel cell manufacturers can supply power packages from 2 to 30 kW. Fuel cell stack can be fabricated in a modular unit that is flexible to scale within a wide range. Fuel cells generate DC electricity, and their electric output can connect directly to telecom equipment from 12 V to 48 V without using a DC/AC inverter, thus reducing the system cost. The fuel cell modules are enclosed in power cabinets with formed and welded metal construction that can withstand all weather conditions (-40°C to +50°C). The system used for emergency power supply could work reliably for 15 years. The emergency power supply for cell towers often requires a minimum of 8 hours of runtime, so the hydrogen fuel storage cabinets hold steel tank enclosures for 8–48 hours of H2 storage. Higher pressure composite tank enclosures can have 8–120 hours of H2 storage.

Other than the added cost of the fuel cell backup power system, no obvious hurdles—considering technique, installation, and operation—exist in deploying such a system for telecom applications. The hydrogen level may be monitored remotely to allow the user to maintain the fuel supply. The backup system requires a regular check of operability and maintenance including a hydration run every month to have the system ready for emergency operation.

2.1 Cell tower regions with high concentration of fuel cell backup power units

More than 3,000 fuel cell backup systems totaling 16.3 MW have been installed through 2013. The installations were mainly to telecommunications towers in locations shown in Figure 2. Other deployment examples include a greater than 1 MW installation in California by Plug Power (formerly ReliOn), and more than 8.3 MW deployed by Altergy for telecom usage. The start reliability of those systems was 99.5% [1]. Most of the systems were in the 4–6 kW range. Modules of smaller fuel cell units could be combined to adjust the system size to an individual site's needs. Figure 2 shows the U.S. cell tower installed with fuel cell backup power systems. The map shows that a large portion of the fuel-cell backup power systems are in the Northeast and Southwest. The East coast of the United States is often affected by strong storms and hurricanes, and prefers reliable communications by backup power systems.

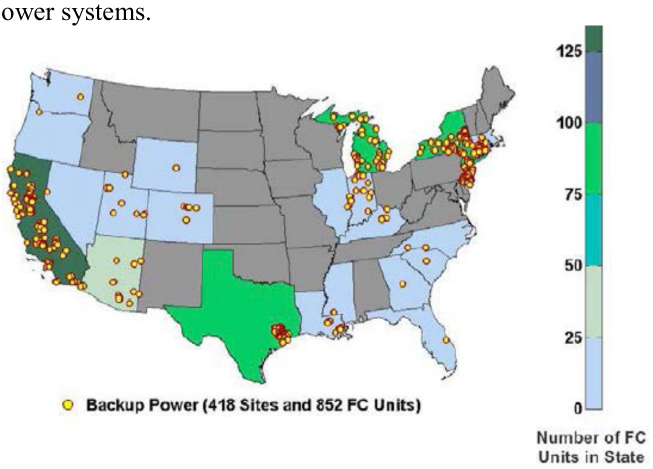


Figure 2. ARRA-installed fuel cell backup power location.

Figure 3 shows that during the 2012 Hurricane Sandy, the cell towers in New Jersey could continue operation after grid blackout. Some 122 ARRA-funded backup power systems were installed in the Federal Emergency Management Agency Modeling Task Force (FEMA MOTF) Hurricane Sandy impact area. Between 10/29/2012 and 11/12/2012, five of the ARRA sites that reported data operated during Sandy for 112 total hours of operation. Cell sites located near the disaster areas would benefit from fuel cell backup power systems for providing non-interruptible service during grid blackouts and emergency power needs.

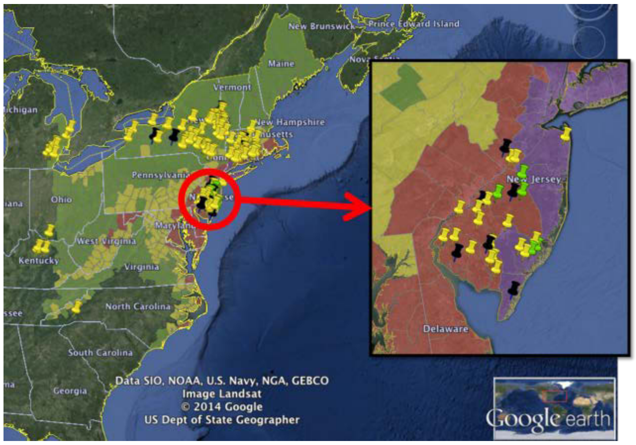


Figure 3. Location of working cell towers (green and yellow) in New Jersey during the 2012 Hurricane Sandy (NREL).

A concern often raised in deploying fuel-cell power generation systems is the availability of pure hydrogen for fueling the PEMFC system. Two refueling methods are used in the backup power system: bottle swapping or filling on-site fixed bottles. Typically, bottle swapping is applied for systems with a short runtime of 8-hour emergency power. The on-site fixed bottles can store a hydrogen supply for longer hours (typically 72 hours), although the initial cost of fixed bottles is higher than the bottle-swapping method.

The installed fuel cell backup power for emergency power purposes may under-utilize the fuel cell power generation capability and can benefit from the expanded usage of the systems for grid needs. With the increasing amount of solar and wind power added to the grid, grid service by backup power can help firm up the grid and provide ancillary services. Small backup fuel cells can be aggregated in concert to react to grid demand, and may reduce grid congestion in some densely populated areas where demand could fluctuate significantly at times. The quick response of PEMFC to power demand can provide reliable power supply for telecommunications and other critical facilities.

2.2. Regional grid services and electric pricing

The regional grid and pricing policies identify the potential niche markets where fuel cell backup power can play a role in ancillary service markets. The utility regional information indicates geographically-sensitive regions with high electric cost, low grid reliability, more frequent natural disasters, utility rate structures that reward grid service, remote areas that need high electricity availability, and densely populated areas sensitive to pollutant emission, noise, and leakage of contaminating materials. This information can help determine strategic locations that need the fuel cell backup power system most.

Providing grid services may increase the value of the fuel cell backup system and decrease the installation payback time. The minimum capacity requirements for bidding DR devices into electricity markets is high compared to the size of an individual backup power fuel cell unit. The bidding capacity thresholds for ISOs are as low as 100 kW, but can be as high as

50 MW [4]. The threshold may continue to fall in the future and provide greater opportunities for aggregation. In many cases, multiple units, even at different locations, can be aggregated to achieve the required size. A network of fuel cell backup power with aggregated coordination may provide grid service capability. Implementing real-time response may favor aggregation of the networked fuel cell backup power to create a virtual power plant that serves regional needs.

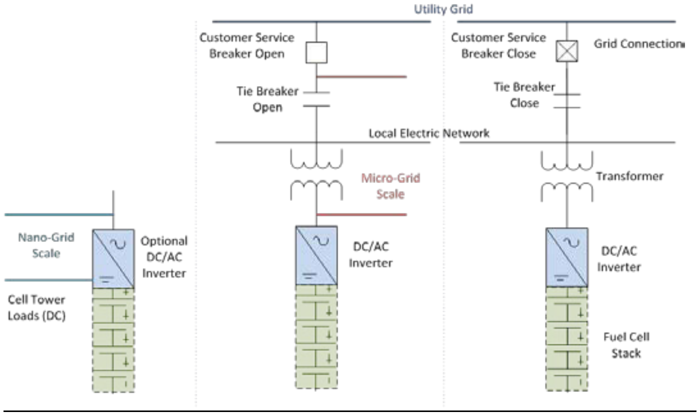
Bidding into electricity markets or participation in DR programs requires verifiable increase in generation—or equivalently, reduction in system load [5]. The cell tower power demand is a fraction of the available power from the fuel cell, so without additional electrical infrastructure (i.e., DC/AC invertor and export capability), the fuel cell can only provide generation/load reduction equal to the cell tower power demand at that time [6]. The backup system is not designed to export power. A basic backup system reduces the potential revenue from providing grid services unless grid connection is configured. This trade-off is a consideration when determining the value of a specific system.

3. System Integration Methods

When a grid blackout occurs for a cell tower, current backup power systems provide electricity in a standalone grid mode. When the backup system provides grid services, power generated may be limited to on-site load which is load that is connected to the electricity meter (behind-the-meter). Expanding the fuel cell fleet may increase the opportunity for generating power in parallel with other generation sources in microgrid or grid-tied operations [7]. Additional hardware and logic control for the grid connection will be needed, and examples of such connections are shown in Figure 4, which shows a schematic of the electric connections of nanogrid, microgrid, and grid-connected modes.

In the event of power disruption, the power connection to the backup equipment automatically isolates from the grid. The local backup power supply delivers its own power to the site without interruption or loss in power quality. The circuit diagram in Figure 4, which shows that electric circuits from standalone nanogrid mode to microgrid or grid-connected mode needs additional equipment of DC/AC inverter, circuit breakers, and transformer over the current basic fuel cell system. The cost of additional equipment may not be justified for a small fuel cell backup system (4–6 kW) that provides grid services. In case that the system capacity increases and meets the condition for direct grid connection, the diagram illustrates electric circuit and components for different configurations, including those that allow bidirectional power flow.

Some telecom cell antennas are located on top of the buildings that may be integrated with the building backup power systems by using quiet, zero-emission fuel cell systems. In such applications, the fuel cell may also supply critical load for the building, and provide hot water to reduce burning of other fuels. The integration can benefit cell tower owners as well as building owners.



a. Standalone nanogrid mode
b. Microgrid mode
c. Grid-connected mode

Figure 4. Load-connection options of fuel cell power system in standalone nanogrid, microgrid, and grid-connected modes [8].

The current standalone backup system for cell towers does not have the necessary equipment to provide grid services. However, small aggregated generation equipment has an existing pathway for providing grid services. The services that can be provided and the size of the aggregated system, along with the generation interconnection process, vary for each region. We first estimated the behind-the-meter generation by the current backup system and then considered hardware and software needs as shown in Figure 5.

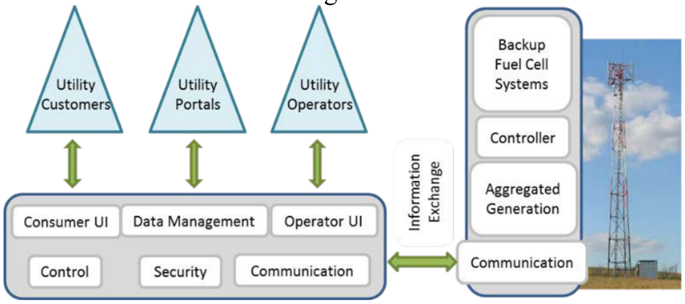


Figure 5. Transactive energy and nano/microgrid functions for market participation and potential ancillary services [6].

To expand the role of distributed generation including the backup system in the power generation market, energy/information flow architecture as shown in Figure 5 and control strategy can enable the platform for power utilities to accommodate flexible generation from small, distributed generators such as backup systems for cell towers. Key challenges and opportunities related to developing such strategies include adoption and implementation of new technologies, changes in utility pricing and markets, and integrated forecast modeling for on-demand generation. Figure 6 shows an example of the analytic model including demand forecast, together with weather and energy data, to predict the ideal operation of the fuel cell backup power system. The grid-integration model illustrates the primary components in coordinating power supply and forecasted demand.

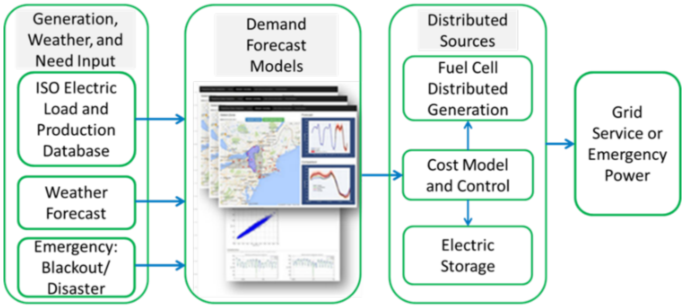


Figure 6. A model architecture for load prediction based on weather and utility data to coordinate backup-power operation.

The program for demand forecasting in the left-hand box of the flowchart takes utility production data, weather condition, and emergency events such as grid black-out or natural disaster to predict the load. The demand forecast model in the middle box can use a statistical method or time-series analysis, which are methods that already exist in a variety of software packages. Then, using the modeling method, the backup power generation cost is computed and compared to the utility price. If economic benefits can be realized from providing grid services, then the control logic allows the backup power unit to provide those services. The operation may depend on improving hydrogen fueling, storage, and delivery economics for better hydrogen availability while ensuring that sufficient backup operation is maintained.

The grid-service modeling concept can be based on utility data analysis and dynamic pricing. Dynamic pricing involves an electricity price that varies based on time of day, system demand, and other factors. The concept of small generation devices participating in dynamic pricing in a utility is fairly new, whereas time-of-use rates are more commonly used for changing the operation of loads. The dispatch of backup power systems can complement grid dynamics with a control algorithm as shown in Figure 7.

The fuel cell operation hierarchy in Figure 7 follows a top-down sequence wherein the top operation could supersede the lower operation. The program communicates with the grid to obtain the grid conditions for necessary operation of the backup fuel cells. Meanwhile, the fuel cell condition, such as hydrogen level and maintenance need, are also monitored and reported to the operator. Figure 7 shows the sequence of operation with emergency backup power generation as a basic function with high priority. When the hydrogen level checks out and the emergency condition is satisfied, the control algorithm will optimize the running condition by comparing retail electricity rate, energy market price, and ancillary service need to determine if the fuel cell system should be turned on to provide some service in lieu of a system check. If operating the system is preferred, then the fuel cell can run for both power generation and maintenance hydration. This is a preferred operating mode such that the operation of fuel cell systems could be synchronized with the fuel cell maintenance timing and hydration need while meeting the grid demand by generating power in the peak pricing period.

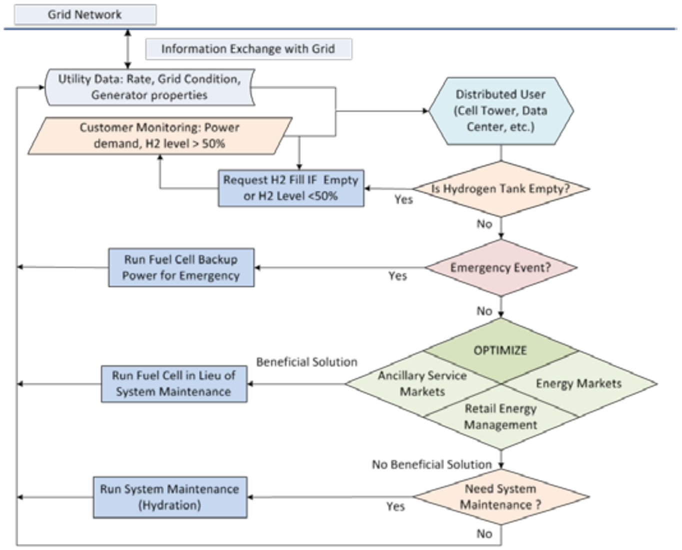


Figure 7. Control logic for fuel cell backup power operation.

The control algorithm as shown in Figure 7 can be embedded in a device, which can communicate with the grid/microgrid, as shown in Figure 5. The device may coordinate with other renewable generation devices such as solar panels or wind turbines to determine the optimum generation for maximizing the reliability. The collected information of grid electricity price will be compared with the backup power generation cost to decide if the backup power generation should start and supply the power.

As the grid evolves toward an interconnected bidirectional network with central and distributed resources, grid operators will need to be informed in their planning to anticipate the complex interdependencies that exist in the network. The integration of the grid and the information network will create new types of power systems. One example is called the "energy cloud" by Navigant Research [8]. The energy cloud is the result of both a fundamental shift in how electricity is generated and distributed as well as an evolution of the traditional relationship among stakeholders across the electrical grid, particularly between utilities and their customers [8].

4. Case Study of Fuel Cell Power for Market Participation

The case study with market participation considers the energy and ancillary service market value for a few selected regions. Participation in energy markets involves increasing generation based on the amount of energy that is bid into energy markets. These markets are settled at different intervals including day-ahead and real-time. Ancillary services considered for this analysis are regulation reserve, spinning reserve, and non-spinning reserve. Regulation reserve ensures that grid frequency is maintained by providing adjustments to compensate for day-ahead and real-time energy imbalances. Regulation is separated into regulation up (increase in generation / reduction in load demand) and regulation down (reduction in generation / increase in load demand). Spinning and non-spinning are contingency reserves that are called sequentially in the event of a grid outage. Spinning reserve can respond very rapidly to accommodate energy imbalances that regulation cannot handle. Generators providing non-spinning reserve are often turned off at the time of the event and must turn on rapidly to provide service when needed.

There are several requirements for participating in energy or ancillary service markets within the territory of an Independent System Operator (ISO) or Regional Transmission Operator (RTO), which are responsible for balancing the generation and demand in their territory. First, the devices typically must be greater than 100 kW or a number of devices can be aggregated to meet this threshold [4]. Additionally, customers need to verify their participation with the ISO/RTO, which, for non-aggregated systems, requires communication and involves installing a meter to monitor energy flows. This meter is an additional expense and should be considered when customers are determining their value proposition.

4.1. Region-Specific Energy Market Prices

The first step to determining the value for market participation of backup fuel cell systems is to understand the conditions that will result in positive revenue. We examine the price profiles for different regions in the U.S. Figure 8 shows the price distributions for three different ISOs—the California Independent System Operator (CAISO), PJM Interconnection, and the New York Independent System Operator (NYISO).

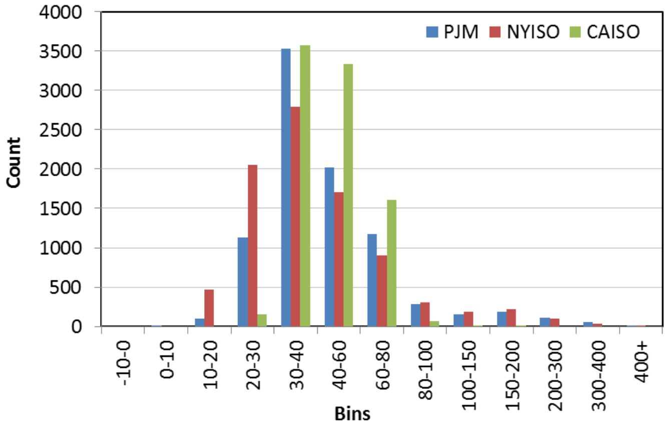


Figure 8. Distribution of day-ahead hourly energy prices ($/MWh) for different regions in 2015.

To generate positive revenues for fuel cell participation in the energy markets, the market prices must be higher than the cost of purchasing and delivering hydrogen. The prices in all regions are around $30–40/MWh. The tails of the distribution are smaller for CAISO, which does not experience any hours greater than $200/MWh, whereas PJM has an average of 10 hours that are above $400/MWh per region and NYISO has an average of 1 hour above $400/MWh for each region.

4.2. Potential Value of Market Participation

In addition to providing energy to the grid, fuel cell backup units could provide ancillary services.

4.2.1. Energy market value

The cost of hydrogen delivery and storage affects the frequency that the fuel cell can provide generation and participate in additional markets. A high hydrogen price discourages participation unless the electricity price is very high, whereas a low hydrogen price encourages greater participation in providing load reduction and grid services. In the 2014 NREL study, 8-hour and 72-hour runtime scenarios of the fuel cell backup power were examined [2]. The 8-hour scenario assumes that the hydrogen storage unit is a pack of rented hydrogen gas bottles that are swapped out when the gas is low; the 72-hour runtime scenario assumes a fuel cell system with a hydrogen storage module (HSM) that is purchased and refilled in place, instead of using bottle swapping. There is a fixed cost to receive a delivery truck of hydrogen and a cost for the hydrogen molecules. From the 2014 NREL study, the base cost for 8 hours of hydrogen using delivered bottles was $100 fixed and $10/kg. By installing a fill-in-place system, the costs dropped to $50 fixed and $8/kg.

For this study, we assume that having only 8 hours of storage means that all hydrogen must be conserved for emergency purposes, so we focus on systems with greater than 8 hours of storage that are willing to consume some hydrogen to bid into electricity markets. As a result, the default price considered is $50 fixed and $8/kg. Several sensitivities are performed to understand the impact of reducing the cost of each component. One sensitivity explores the impact of reducing the fixed price by 50% to $25 per delivery; another sensitivity reduces the hydrogen cost by 50%, and the final sensitivity combines both reductions. By comparing the hydrogen cost of the fuel cell against the potential range of energy price, we can assess the required electricity price to offset fuel costs. Figure 9 presents that comparison.

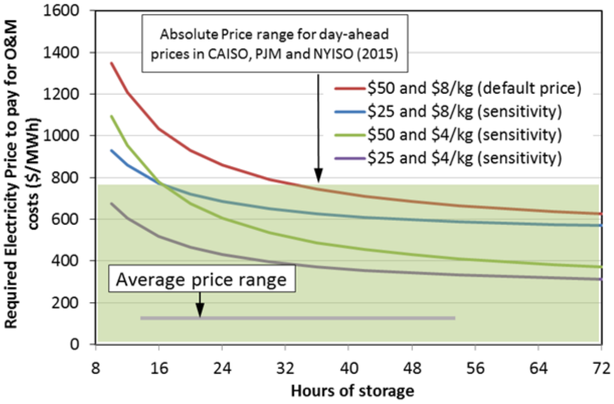


Figure 9. Electricity price by the fuel cell backup power.

Figure 9 indicates that the price range for day-ahead markets is sufficient to offset the cost of fuel. From Figure 8 and Figure 9, we recognize that there are limited high-price hours where the opportunity cost of providing energy can offset the cost of hydrogen delivery. Figure 9 also shows how lowering the cost of hydrogen fueling, storage, and delivery with easy access to hydrogen supply is important for the economic return from energy markets.

4.2.2. Ancillary service market value

Using the energy prices in Figure 8, we can estimate the value for ancillary service participation. Figure 8 contains the anticipated value from capacity reservations for the North and South ancillary service regions of CAISO in 2015. The revenue represents the value for bidding into every hour of the year for the given service. If the fuel cell wins a contingency reserve bid (spinning or non-spinning), then the device can be called several dozen times per year, resulting in energy production and requiring additional hydrogen to refill the storage system [9].

Typically, when spinning or non-spinning reserves are called, it is as a result of an emergency (e.g., generator outage). During these events, the energy price is likely to be elevated, which increases the revenue; however, hydrogen will need to be consumed during that period and resupplied. Reserve events typically last around 10 minutes, but reserves must be available to provide several hours of energy if requested by the system operator [9]. Regulation is called even more often than spinning and non-spinning reserves; and since dispatch of regulation occurs both during normal grid operation and during emergencies, the energy price is less likely to be sufficiently high to offset hydrogen fuel costs. Thus, the most viable markets to provide for fuel cell backup units are spinning and non-spinning reserves. One caveat is that, spinning reserve requires that generation be provided very rapidly, which means that if the fuel cell is not operating, then the backup system may need a battery to provide generation until the fuel cell can start and begin providing power. Backup units can provide non-spinning reserve from a cold start and would not require additional equipment, but would also receive substantially less revenue.

4.2.3. Lifetime impacts on backup fuel cells

Backup power systems are typically designed to be low cost with low utilization. A specific concern that arises when considering a greater number of hours of backup operation is the impact on system lifetime. However, the fuel cell systems must perform a system check every several weeks. At present, this operation reduces the consumption of electricity from the utility for the time that the fuel cell is checking its operation and hydrating the membrane. Participation in electricity markets can be made to align with the fuel cell system check and can increase revenue in the process of a periodic event.

To assess the economic impact of operating fuel cells more often, we leverage the basic technical and economic information (e.g., equipment cost, delivery cost, efficiency) necessary to conduct a benefit/cost analysis [2]. The assumed lifetime for the fuel cell backup units is 15 years, and according to publicly available data from Ballard Power Systems, the installed cost for the 2-kW ElectraGen-H2 system is about $20,000 and the installed cost for the 4-kW ElectraGen-ME system is $36,000. We calculate the fuel cell, hydrogen delivery and storage cost from following expressions:

(1) Fuel Cell Cost [$/year] = (Capital Cost [$] + Permitting and Installation Cost [$]) * (r + (r / (((1 + r)^L) - 1))) + Annual maintenance cost [$/year];

(2) Delivery Cost [$/year] = Fuel Cost [$/kg] * Usage [kg/year] + Fixed Delivery Charge [$/fill] * Number of fills per year;

(3) Storage Cost [$/year] = Tank Cost [$/hour at rated capacity] * Storage Capacity [hours at rated capacity] * (r + (r / (((1+r)^L) - 1))),
Tank Cost [$/hour at rated capacity] = 2625;
where r = interest rate, and L = lifetime [years].

Figure 10 shows the relative capital cost increases per year from the reduction in fuel cell lifetime due to increased running hours. The curve includes the fuel cell cost and indicates that greater usage of the current fuel cell system will not compensate the fuel cell cost sufficiently to warrant very high usage from a fuel or capital cost perspective. Therefore, the use of backup power should be limited to providing reserve capacity with limited hours of dispatch or for energy markets with high prices. Additionally, it is valuable to synchronize the hydration and maintenance schedule with events and opportunities to provide grid services.

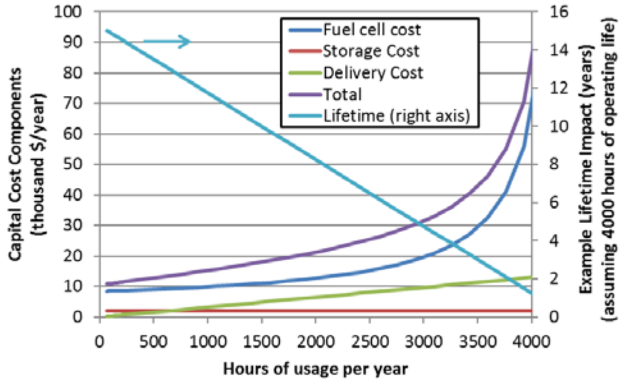


Figure 10. Relative capital cost increases for 72-hour systems from reductions in lifetime due to greater usage.

Although the usage of small-scale backup power system for grid services may not be favorable immediately, the technology advancement as indicated above can bring expanded application and economic returns to the backup power of the future. The technical recommendations from this project include:

- Aggregating the networked fuel cell backup power to create a larger dispatchable resource.
- Developing fuel cell backup power grid service hardware (such as a controller) and software (as in Figure 6).
- Implementing a real-time responsive web-based application to monitor the system.
- Considering future market trends, and investigating the potentials of the fuel cell backup power in providing grid service and DR for additional economic benefits.

- Studying long-term market potential in an increasingly renewable grid for more reliable and flexible power supply for the electric power needs—including data centers, hospitals, and military uses—in the form of grid-tied and microgrid configurations.

Hydrogen storage and delivery cost is a major limiting factor for the long-term operation of the fuel cell system as a grid resource. Future development and deployment of hydrogen demands (e.g., vehicle fueling infrastructure) can impact the delivery price for hydrogen and the cost of hydrogen equipment.

With increased fuel cell backup power installations and more renewable generation on the grid, providing grid services with the configuration and control strategy introduced in this paper can increase the value of the fuel cell backup system and improve the installation payback time. The large stationary-fuel cell systems designed as DER often run continuously. The algorithm to run for high-demanding peak shaving and demand response can help those systems to increase their economic return of those systems even more.

Conclusions

The primary purpose of backup systems is to provide power in the event of a grid outage. Integrating backup systems with electricity markets and demand response programs can provide equipment owners an early warning of potential grid outages—and, more importantly, enable a more seamless transmission to islanded mode during a grid outage. Grid outages as a result of contingencies including generator outage or transmission/distribution line failures cause fluctuations in the electricity and ancillary service prices. To be dispatched in the energy markets, the energy price must be very high, which can be coincident with stress on the system. Similarly, to be dispatched in ancillary service markets, namely spinning and non-spinning, there has likely been some contingency event. Dispatch in ancillary service markets or from high energy prices signals that there is a higher chance of a grid outage. If the fuel cell system is turned on and operating before an outage event, then it can more easily transition to an islanded configuration.

Providing grid services can bring additional benefit to installations of fuel cell systems for cell towers. The fuel cell can participate in energy markets if the energy price is sufficiently high (i.e., during price spikes). These price spikes must be large enough to cover the cost of hydrogen fuel and delivery, as well as the potential system degradation resulting from additional hours of dispatch. Participation in ancillary services provides a more predictable value and was determined to be the preferred market for fuel cells in backup-power configurations. There are challenges with aggregation of units, and monitoring and reporting the changes that must be addressed. Cell-tower communication networks are ideal for monitoring and can also be used to communicate information to a central server for analysis and management. The architecture of monitoring and data-transmission subsystems is designed for the systems to be connected and coordinated for operation. The connected systems make it possible to adapt to the grid situation for economic returns to the owner.

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List of Acronyms

ARRA	American Recovery and Reinvestment Act
CEC	California Energy Commission
DER	Distributed Energy Resources
DG	Distributed Generation
DOD	Department of Defense
DOE	Department of Energy
DR	Demand Response
FCC	Federal Communications Commission
FCEV	Fuel Cell Electric Vehicle
FEMA	Federal Emergency Management Agency
HSM	Hydrogen Storage Module
IC	Internal Combustion
ISO	Independent System Operator
MCFC	Molten-Carbonate Fuel Cell
NYISO	New York Independent System Operator
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PSA	Pressurize Swing Adsorption
R&D	Research and Development
RTO	Regional Transmission Organization
SOFC	Solid-Oxide Fuel Cell
VPP	Virtual Power Plant

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