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# Development of an Optimal Operating Strategy for a Combined Heat, Power and Hydrogen System

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## Abstract

The operation of a combined heat, power and hydrogen (HPH) system is analyzed. In this system, hydrogen from a natural gas fuel processor is compressed, stored and used to fuel fleet vehicles. The hydrogen is also supplied to a building fuel cell system that provides both electricity and hot water for space heating and water heating. An approach is developed to optimize the operation of an HPH system. The approach is illustrated by application to a laboratory/office building that is part of a large industrial facility which also operates a fleet of vehicles. Results show that, for the assumed first cost values of the fuel processor and fuel cell, coupling a stationary fuel cell system to a vehicle refueling system provides economical refueling for smaller vehicle fleets and increases the economic value of the refueling station at all fleet sizes. For larger fleet sizes, the combined HPH system offers higher economic value than a stationary fuel cell system alone. A sensitivity study shows that for a natural gas cost of $0.0065/MJ and an electrical demand cost that exceeds $7.50/kW, the HPH system yields a greater net present value than an independent vehicle refueling system.

*Key words: Fuel cell, hydrogen, reformer, transportation, building, heat, power*

## 1. Introduction

The widespread application of polymer electrolyte membrane (PEM) fuel cells for transportation applications is likely to be possible only after the development of a hydrogen refueling infrastructure. However, the development of a significant hydrogen refueling infrastructure will only be economical after the widespread deployment of a large hydrogen vehicle fleet. This quandary is one of the most serious challenges facing the adoption of fuel cell technology for transportation. Furthermore, the development of a successful transportation fuel cell market is likely to be a key factor in achieving the high volume fuel cell production rates that will be necessary to reduce costs to economical levels in the stationary fuel cell market. Thus, the development of an approach for the simultaneous deployment of fuel cell vehicles and a hydrogen infrastructure is critical for the success of fuel cell technology. The development of stationary fuel cell systems that co-produce hydrogen for transportation is a promising approach for overcoming this barrier. These systems, referred to here as combined heat, power and hydrogen (HPH) systems include a fuel processor that produces hydrogen, one or more building fuel cell systems, and facilities for storage and refueling of vehicles.

An HPH system can provide heat and power for a building while simultaneously establishing a vehicle refueling infrastructure that can provide hydrogen for transportation services associated with the building (e.g., nearby bus routes, commuter vehicles, etc.) The HPH concept not only facilitates the deployment of a refueling infrastructure but also improves the economic results for a stationary fuel cell application since for a majority of the operating hours hydrogen has a higher value as a vehicle fuel than as an energy source for building heat and power. A prior work has provided an overview of the economic, energy and environmental benefits of an HPH system (Ellis, 2003). The present work focuses on optimizing the operation of the HPH system and on assessing the sensitivity of the results to vehicle fleet size and utility rates.

### 1.1. Status of fuel cell systems for transportation

More than a dozen automakers in North America, Europe and Japan have made major investments in fuel cell technology with the goal of producing a fuel cell power system that provides high efficiency and low emissions at a cost and volume that is competitive with the internal combustion engine. Development efforts have focused on PEM fuel cell technology because of its low operating temperature, high power density and potential for low cost. Today, automakers and fuel cell manufacturers have achieved many of the technical objectives and over 60 designs for light duty fuel cell powered vehicles have been demonstrated (Fuel Cells 2000, 2003). Many of these vehicles have top speeds and accelerations comparable to conventional vehicles. In addition, the volume of the fuel cell powertrain has been reduced to be compatible with existing vehicle platforms. However, cost continues to be a major challenge. While costs have been reduced dramatically over the last few years, the fuel cell system cost must still be reduced by at least an order of magnitude to meet the U.S. Department of Energy's (DOE) target of $50/kW.

In addition to cost reduction, the development of a fuel strategy that is technically and economically feasible is a significant challenge. The fuel for a PEM fuel cell must be pure hydrogen or hydrogen rich reformate that is free of sulfur and carbon monoxide. While development continues for on-board reformers that convert conventional fuels like gasoline to hydrogen rich reformate, most manufacturers foresee off-board reforming with pure hydrogen stored on the vehicle as the most likely long term solution (National Advanced Vehicle Consortium, 2000). Because the fuel cell has a high efficiency (both at design and off-design) and because hydrogen has high energy content per unit mass, the mass of hydrogen that must be stored to yield a vehicle range of 400 km (250 miles) is only about 4 kg. However, due to its low molecular weight, hydrogen gas must be stored at pressures of 34 MPa (5000 psi) or higher to achieve a reasonable storage volume of less than 190 liters (50 gallons). At these high pressures, conventional steel tanks are too heavy to be practical and researchers are focusing on lightweight composite fiber tanks that can withstand pressures this high or higher.

### 1.2. Status of fuel cell systems for building applications

A variety of fuel cell technologies are possible in building applications including phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) and PEMFCs. The PAFC is the only fuel cell technology that has been widely demonstrated in building applications but is not likely to be competitive with PEMFC or SOFC technologies as they mature. Both MCFC and SOFC technologies offer very high operating temperatures that facilitate the simultaneous production of useful heat for building applications. The MCFC system is most commonly considered for relatively large building applications (~ 250 kW to 2,000 kW) and is currently being developed by at least one U.S. company. The SOFC is under development for building applications from 5 to 1,000 kW. Research and development of SOFC systems is underway at a number of companies and is supported by the U.S. DOE through its Solid State Energy Conversion Alliance (SECA) program (National Energy Technology Laboratory, 2003). The high temperatures associated with MCFC and SOFC technologies facilitate the application of MCFC and SOFC systems in hybrid and cogeneration cycles. The higher temperatures also allow these systems to use fuel that has relatively high concentrations of CO and to internally reform light hydrocarbons such as natural gas. Since neither MCFC nor SOFC technologies require pure hydrogen as a fuel, there is less commonality between the fuel needs of these technologies and those of PEMFC systems for transportation. Thus, the concept of an HPH system is likely to be most beneficial for the combination of a stationary PEMFC system in conjunction with a fleet of PEMFC vehicles.

Building energy systems based on PEMFC technology are under development for a range of applications from single family residences (~ 5 kW) to mid-size commercial buildings (~ 250 kW). PEMFC systems are attractive in stationary applications due to their potential for low cost and the prospect for synergy with the transportation application (i.e. the combination of stationary and automotive applications may yield a market that has both early entry opportunities and a very large long-term demand). A large number of manufacturers are currently developing residential PEMFC systems. Larger systems for commercial buildings are being developed by roughly 5 - 10 manufacturers with products currently available for back-up power applications. For buildings, PEMFC systems can be fueled by reformed natural gas. The reformate consists primarily of hydrogen, carbon dioxide, water and small amounts of carbon monoxide (and possibly nitrogen depending on the reformer). The reformate may be processed to remove carbon monoxide only or may be processed using pressure swing adsorption or membrane separation to yield relatively pure hydrogen. While the additional expense of processing the reformate to yield pure hydrogen is essential for transportation applications where the gas will be compressed and stored, it is not essential for

PEMFC systems serving buildings where only carbon monoxide removal is essential. However, PEMFC systems operated on pure hydrogen exhibit higher performance and longer life.

## 2. Analysis

The concept of an HPH system is described here in the context of a 24,100m$^2$ (260,000ft$^2$) laboratory/office building that is part of a relatively large industrial complex in the Newport News, VA area. In the HPH concept, a fuel cell system provides both heat and power to the building while hydrogen extracted from the fuel processor is used to refuel a fleet of vehicles. The industrial facility operates a number of vehicles that are candidates for conversion to hydrogen fuel including a bus, a fleet of vans, light duty trucks and a fleet of automobiles. Many of the issues associated with the development of an HPH system can be illustrated through a case study of this facility including analysis of the incremental values of the various product streams (heat, electricity and hydrogen), evaluation of operating strategies and analysis of life cycle cost.

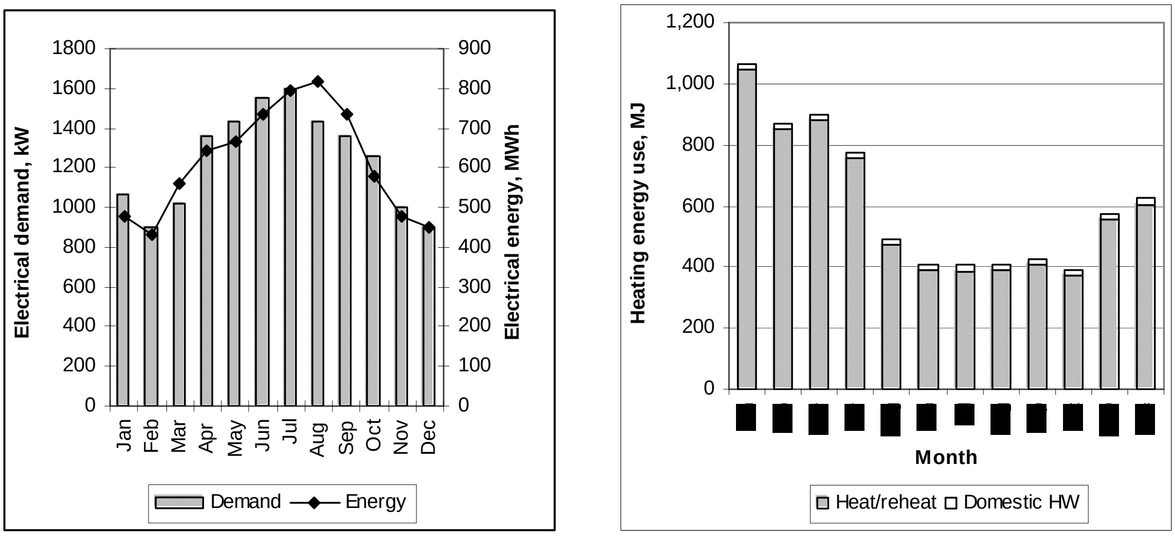
### 2.1 Building energy use profile

The analysis of an HPH system depends on an accurate representation of the electrical use and thermal energy use as functions of time. For the case study facility, electrical energy is used for lights, appliances, fans and air-conditioning equipment. The electrical load profile is typical of those observed for large office facilities and yields an electrical load factor of 53%. Thermal energy is used for water heating, space heating and reheat. The HPH system supplies thermal energy at a sufficient temperature for use in water heating and for space reheat in the summer. In the winter, the building uses heating water at a temperature high enough to preclude the use of thermal energy from the HPH system. The monthly electrical and thermal load profiles are presented in Figure 1. The derivation of these profiles is discussed in detail by Ellis (2003).

Electricity for commercial buildings is priced in a variety of ways. One of the most common approaches is a *demand and energy* price structure. Demand is defined as the peak power in kW required during any prescribed time window (typically 15–30 minutes) of a monthly billing period. Energy charges are based on the electrical energy (kWh) used during the monthly billing period. For the case study considered here, the rate structure can be approximated by a demand charge of \$14.75/kW-month and an energy charge of \$0.02/kWh which is characteristic of a large mid-Atlantic utility. Applied to the facility's electricity use profile, this rate yields an average electricity cost of \$0.056/kWh. Natural gas can also be priced in a variety of ways but most price structures are based on energy use only, not demand. For the case study considered here, natural gas was purchased from the local utility at a market price that averaged \$0.0065/MJ (\$6.90/MCF) during the period October 2001 through September 2002.

### 2.2 Energy use for transportation

In addition to supplying hydrogen to a fuel cell to meet building energy requirements, an HPH system provides hydrogen for vehicle refueling. In the HPH concept, fuel cell powered vehicles (FCVs) visit a refueling station intermittently where they are refueled with high



*(a) Electrical energy use*

*(b) Heating energy use*

*Figure 1. Laboratory/office building energy use.*

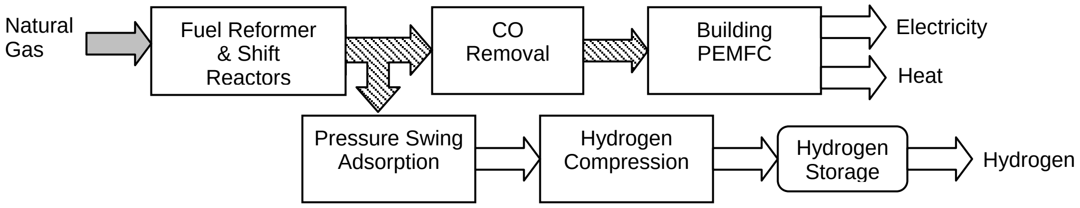
pressure (40 MPa) hydrogen. Assuming that the storage system is large enough and that the vehicle visits are reasonably well distributed, the rate of hydrogen refueling can be modeled as steady over time. The steady rate of refueling is equal to the product of the number of vehicles served and the annual travel distance divided by the fuel economy of each vehicle. In this study, a typical vehicle is considered to be a light-duty vehicle with a fuel economy of 10.2 km/liter of gasoline (24 miles per gallon of gasoline). A light-duty FCV would typically have a drive cycle fuel efficiency of 2.2 times the efficiency of a comparably sized gasoline fueled internal combustion engine vehicle (ICV). Accounting for this efficiency improvement as well as the energy contents of hydrogen and gasoline, the fuel economy of a light-duty FCV is approximately, 85 km per kg-hydrogen (53 miles per kg-hydrogen).

The annual travel distance for a light-duty vehicle varies greatly with the service. A personal vehicle may travel 19,000 to 24,000 km (12,000 to 15,000 miles) per year. A fleet vehicle may travel more or less depending on the purpose of the fleet. For the facility considered in the case study, vehicles typically travel 12,000 km (7,500 miles) per year. Thus, for this study, a standard vehicle served by the HPH system is taken to be a light-duty fuel cell vehicle with a fuel economy of 85 km/kg-$H_2$ (53 miles per kg-$H_2$), that travels 12,000 km (7,500 miles) per year. Other vehicles can be expressed as multiples of this standard vehicle (e.g., the case study facility operates a transit bus for which the annual fuel use is equivalent to roughly 30 standard vehicles).

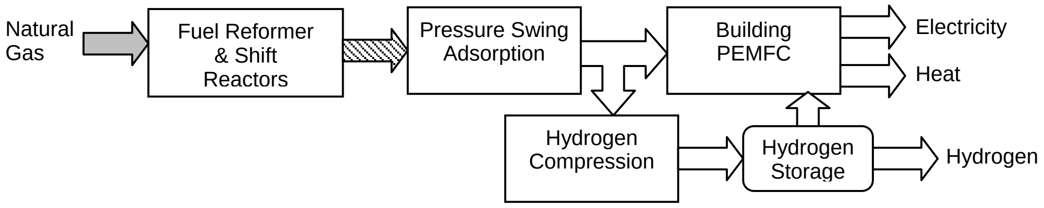
### 2.3 System configuration

Figure 2 illustrates two possible configurations for an HPH system. In configuration (a), reformate from a steam reformer and shift reactors goes to a preferential oxidation reactor where the carbon monoxide is reduced to a level that is acceptable for the stationary fuel cell. The final product, which is a mixture of hydrogen, carbon dioxide and water, flows directly to the PEMFC system which is designed to operate on reformate. A side stream is removed from the reformate stream and purified using a pressure swing adsorption (PSA) process to produce pure hydrogen for compression and storage for vehicle refueling. In theory, this could allow for a smaller PSA subsystem. However, as demonstrated in a later section, hydrogen is most valuable when used for vehicle refueling, thus the PSA subsystem should be sized to match the reformer capacity so that all of the reformate can be used for vehicle refueling if possible. Moreover, the PSA subsystem is likely to have a high fixed cost so that increasing the size to match the reformer capacity may have a relatively small impact on the total cost. Finally, with configuration (a), the fuel cell operates on reformate and, thus, the performance and life may be reduced when compared to a pure hydrogen system.

In configuration (b), all of the reformate is purified through the PSA subsystem. A portion of the hydrogen is used by the building fuel cell system and the rest is compressed and stored for vehicle refueling. With this configuration, the building fuel cell system operates on pure hydrogen and is likely to have higher performance and longer life. In addition, by drawing on the



(a) Purification of transportation hydrogen only



(b) Purification of transportation and stationary hydrogen

▒ Natural gas ▨ Reformate ☐ Hydrogen

*Figure 2. HPH system configurations.*

stored hydrogen, the building fuel cell system can exceed the capacity of the reformer to meet short duration power demands. Furthermore, when electricity for the building is inexpensive, all of the reformer capacity can be directed to producing high value hydrogen for vehicle refueling. Based on these advantages, the configuration depicted in (b) was selected for further study.

### 2.4 Energy and cost models for the HPH system

The energy use and life cycle cost of the HPH system can be evaluated by developing models of the performance of the building fuel cell system and the vehicle refueling system and determining an optimal operating strategy for the complete HPH system.

Development of a performance model begins with the fuel processor which reforms natural gas to yield hydrogen for the building fuel cell and the FCVs. The natural gas energy required per unit mass of hydrogen produced, $e_{ng}$, is given by:

$$e_{ng} = \frac{LHV_{H2}}{\eta_{fp}} \tag{1}$$

where $LHV_{H2}$ is the lower heating value of hydrogen and $\eta_{fp}$ is the hydrogen conversion efficiency of the fuel processor. For an assumed reformer efficiency of 70%, the fuel processor requires 171 MJ of natural gas/kg-$H_2$.

The hydrogen from the fuel processor is at a relatively low pressure, $p_i$, but must be compressed to a high pressure, $p_e$, for storage and vehicle refueling. Assuming that the compressor has N stages each with the same adiabatic efficiency, $\eta_{cp}$, the same pressure ratio, and intercooling to the same ambient temperature $T_0$, the electrical energy on a per unit mass basis required to compress the hydrogen, $e_{cp}$, is given by

$$e_{cp} = \frac{NkR_{H2}T_0}{\eta_{cp}(k-1)}\left[\left(\frac{p_e}{p_i}\right)^{(k-1)/Nk} - 1\right] \tag{2}$$

Based on the system parameters indicated in TABLE I, the energy required for compression is 13.2 MJ/kg-$H_2$.

The amount of hydrogen that must be produced and compressed is related to the number of vehicles supported by the HPH system. Each standard vehicle, as previously defined, requires a mass flow rate of

$$\dot{m}_{fcv,std} = 142 \text{ kg/y} \tag{3}$$

Hydrogen that is not stored or used for vehicle refueling does not require compression and may be delivered directly to the building fuel cell system. The fuel cell system is assumed to operate in an electrical load following mode with thermal energy produced as a by-product. The electrical power delivered by the fuel cell, $\dot{E}_{el}$, is given by

$$\dot{E}_{el} = \dot{m}\eta_{el}LHV_{H2} \tag{4}$$

where $\dot{m}$ is the mass flow rate of hydrogen and $\eta_{el}$ is the electrical conversion efficiency of the fuel cell system. Since the system tracks the electrical load, the rate at which thermal energy from the fuel cell system is used for heating, $\dot{E}_{th}$, is the lesser of the heat required by the building, $\dot{Q}_{th}$ or the heat available from the fuel cell, i.e.

$$\dot{E}_{th} = \min\left[\frac{\dot{E}_{el}\eta_{hr}}{\eta_{el}}, \dot{Q}_{th}\right] \tag{5}$$

where $\dot{E}_{el}$ is the coincident electrical load, $\eta_{hr}$ is the fraction of the fuel cell input energy that is available as thermal energy, and $\eta_{el}$ is the electrical conversion efficiency of the fuel cell[1]. The thermal energy available from the system includes only the energy available from the fuel cell stack coolant (i.e., heat recovery from the reformer is not included).

Thus, the HPH system provides three resources: hydrogen for vehicle refueling, electricity for meeting the building power load, and thermal energy for meeting the building heat load. The value of these resources must be determined along with the cost of producing each so that the net value of the HPH system can be determined. Evaluation of the net value of the HPH system must be accomplished in conjunction with the development of an operating strategy for the system.

### 2.5 Operating strategy

The operating strategy for the HPH system can be developed by establishing the incremental value of each energy resource and optimizing the economic value of the system subject to constraints. The constraints can be physical (e.g., the system cannot use more hydrogen than the fuel processor produces) or functional (e.g., the system must provide hydrogen for 100 vehicles). The incremental value of each energy resource can be evaluated based on the cost of conventional resources to achieve the same effect. For example, the incremental value of the thermal energy from the HPH system is equivalent to the cost of the thermal energy provided by the natural gas boilers. This value can be determined on a per kg of hydrogen basis by

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[1] Since the fuel cell is operated in an electrical load following mode, and since its thermal output is relatively small, thermal energy is only used to supplement the heat provided to the building by the hot water boilers.

$$v^{th} = \frac{c_{ng}\eta_{th}LHV_{H2}}{\eta_b} \qquad (6)$$

which yields a value of \$0.26/kg-$H_2$ for the thermal energy produced as a byproduct of electrical power generation.

TABLE I. HPH SYSTEM FIXED PARAMETERS

| Symbol | Description | Value |
|---|---|---|
| $c_{ee}$ | unit cost of electrical energy, \$/kWh | 0.02 |
| $c_{ed}$ | unit cost of electrical demand, \$/kW | 14.75 |
| $c_{ng}$ | unit cost natural gas, \$/MJ | 0.0065 |
| $c_{fcv}$ | unit cost of hydrogen for vehicle refueling, \$/kg | 3 |
| k | specific heat ratio for $H_2$ | 1.4 |
| $k_1$ | unit conversion constant, MJ/kWh | 3.6 |
| $M_{str,max}$ | maximum storage capacity, kg-$H_2$ | 108 |
| MC | fuel cell unit maintenance cost, \$/kWh | 0.01 |
| N | number of compressor stages | 4 |
| $p_i$ | inlet pressure for the $H_2$ compressor, MPa | 0.101 |
| $p_e$ | exit pressure for the $H_2$ compressor, MPa | 41 |
| $R_{H2}$ | ideal gas constant for $H_2$, MJ/kg-K. | 0.00412 |
| $T_0$ | ambient temperature, K | 298 |
| $\eta_b$ | efficiency of the hot water boiler displaced by the fuel cell | 90% |
| $\eta_{cp}$ | adiabatic efficiency of the compressor | 70% |
| $\eta_{el}$ | electrical conversion efficiency of the fuel cell (see Note 1) | 50% |
| $\eta_{fp}$ | natural gas to $H_2$ conversion efficiency of the fuel processor | 70% |
| $\eta_{hr}$ | fraction of the fuel cell input energy recovered as heat | 30% |
| $\frac{\eta_{fcv}}{\eta_{icv}}$ | ratio of the fuel economy for an FCV to that of an ICV. | 2.2 |
| Notes: 1. The value $\eta_{el}$ is the efficiency for producing electricity *from hydrogen* and is assumed to be constant. | | |

The demand/energy utility rate structure complicates the determination of the incremental value of the hydrogen when it is used to produce electricity. For example, consider a building fuel cell system with a capacity of 100 kW. Figure 3 illustrates the power requirements of the laboratory/office building for the month of July. As indicated in this figure, the power demand peaks at 1,595 kW. With a *peak-shaving* strategy, the fuel cell operates only when the building power demand exceeds 1,495 kW. This strategy yields a reduction of 100 kW of demand and a corresponding demand cost reduction of \$1,475. The amount of electrical energy required to achieve this demand reduction corresponds to the integral of the power curve for power greater than or equal to 1,495 kW and is 800 kWh. Applying the electrical energy unit cost of \$0.02/kWh, the value of this electrical energy is \$16. Based on the LHV of hydrogen and the fuel cell efficiency, the amount of hydrogen used by the fuel cell system to produce this amount of electricity is 48 kg. For the applicable natural gas unit cost of \$0.0065/MJ and the assumed reformer efficiency of 70%, the fuel cost for producing hydrogen is \$1.11/kg. Summing the demand and energy savings and subtracting the cost of the fuel to produce the hydrogen yields \$30/kg as the net incremental value of the hydrogen for producing electricity when the demand exceeds a value of 1,495kW

On the other hand, if the fuel cell system runs continuously during July in a *base-load* strategy, the demand savings is still 100 kW yielding a \$1,475 cost savings, but now the electrical energy savings is the product of 100 kW and the number of hours in the month (744) which when multiplied by the electrical energy cost yields a cost savings of \$1,488. In this case, the amount of hydrogen used by the fuel cell system to produce the demand and energy savings is 4,460 kg. Subtracting the cost of the fuel required to produce this hydrogen yields a net incremental value of \$-0.45/kg-$H_2$ indicating that it is more expensive to operate the fuel cell in a base-load strategy than it is to purchase off-peak utility power.[2]

Comparison of the results for peak-load and base-load operation illustrates the importance of determining the incremental value of the electricity from the fuel cell on an hourly basis rather than on an average cost basis. The average unit cost of electricity for the laboratory is \$0.056/kWh. If electricity is provided from a hydrogen fuel cell with an efficiency of 50%, this implies an incremental value of \$0.93/kg for the hydrogen suggesting that the value of the hydrogen

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[2] Since the contribution of thermal energy to the overall value of the product mix is small, it is neglected in this example. The value of the thermal energy *is* included in the results presented in the next section.

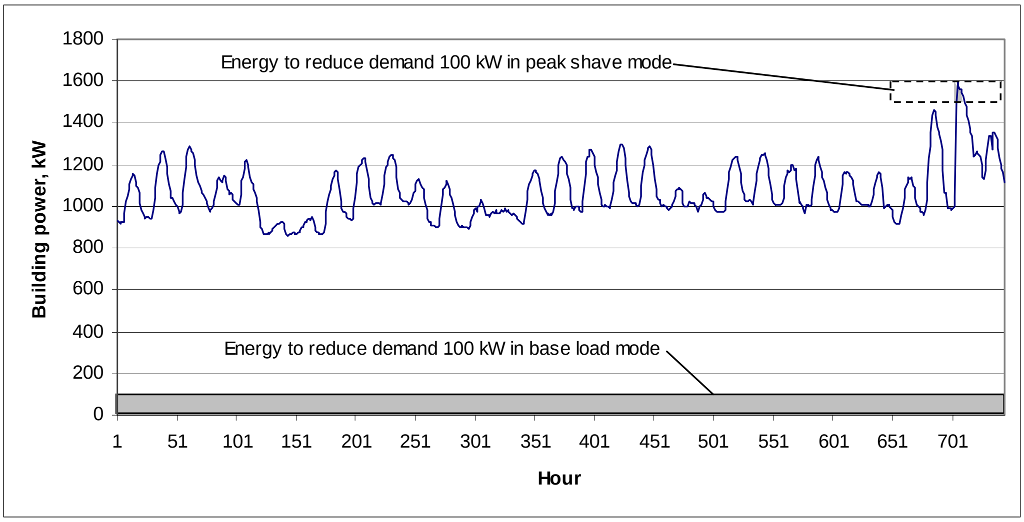

*Figure 3. Hourly power requirements for the case study facility for the month of July.*

does not cover the incremental cost of production (\$1.11/kg-$H_2$). In fact, while this is true during base-load hours, there are other hours during peak loads when the hydrogen is worth considerably more than the incremental cost of production. The HPH system allows hydrogen to be supplied for building use when the electricity rates are favorable and stored for vehicular use when the rates are not favorable.

The net value of the heat and power for the building can also be compared to the net value of the vehicle fuel to determine whether the system should provide building energy or vehicle fuel. The incremental value of hydrogen for vehicle refueling can be established based on the cost of alternative hydrogen sources and an equilibration with the costs of alternative transportation fuels. Thomas et al. (1998) estimated the cost of hydrogen produced and distributed from large-scale steam methane reformer plants to be approximately \$3/kg. This cost includes both the fuel and capital costs and represents the price for which a supplier would be willing to sell hydrogen. Padro and Putsche (1999) estimated the cost of hydrogen produced by electrolysis using power from large fossil fuel plants to be in the range of \$6.15 to \$7.87 per kg. These costs can be compared to the cost of transportation fuels on an equivalent fuel cost per mile basis.

As noted previously, fuel cell powered passenger vehicles are assumed to have a drive cycle fuel efficiency of roughly 2.2 times the efficiency of a comparably sized ICV. Since one kg of hydrogen has a heating value roughly equal to one gallon of gasoline, one kg of hydrogen in a fuel cell vehicle can provide the same driving distance as 2.2 gallons of gasoline. With gasoline costing \$1.50/gallon, the value of hydrogen on an equivalent mileage basis is \$3.30/kg-$H_2$. Thus, on an equivalent mileage basis, hydrogen from a central steam methane reformer plant is less expensive than gasoline while hydrogen produced by electrolysis is likely to be more expensive.

For this analysis, the value of hydrogen supplied by the HPH system for vehicle refueling, $c_{fcv}$, is assumed to be \$3.00/kg-$H_2$ which is equal to the unit cost of hydrogen delivered to the site from a centralized reformer and somewhat less than the cost of gasoline on an equivalent distance basis. This value must be compared to the incremental cost to produce the hydrogen. If the hydrogen is compressed for vehicle refueling, the cost of the electricity to compress the hydrogen must be included in its incremental cost. Assuming off-peak electricity is used for compression, the incremental cost of the hydrogen increases from \$1.11/kg-$H_2$ for low pressure hydrogen to \$1.18/kg-$H_2$ for hydrogen compressed to 40 MPa. Subtracting the production cost from the assumed value of \$3.00/kg yields a net incremental value of \$1.82/kg for hydrogen as a vehicle fuel. On a purely economic basis, hydrogen from the HPH system should go to the building fuel cell if the net incremental value for building heat and power exceeds the vehicle fuel value of \$1.82/kg. However, if the HPH system is the sole source of fuel for a dedicated vehicle fleet, it is probably not acceptable to divert hydrogen for building use if it would mean having insufficient fuel for the fleet. Thus, this analysis is subject to the constraint that hydrogen can be used for the building only if it does not preclude meeting the FCV fleet requirement.

Optimal operation of the heat, power and hydrogen system, subject to the considerations in the preceding discussion, will yield the maximum annual economic value (TABLE II). Achieving the highest annual economic benefit involves maximizing the savings provided by the HPH system for each demand period (i.e. month), d, as expressed by Eq. (7a). Equation (7b) expresses the savings summed over all of the hours of each demand period. The first line of the summation in Eq. (7b) represents the value of the energy from the HPH system including the electricity produced by the fuel cell, the thermal energy supplied by the fuel cell, and the hydrogen supplied for vehicle refueling. The second line in Eq. (7b) reflects the demand savings as the product of the demand unit cost and the change in demand due to the operation of the fuel cell system. The third and fourth lines of Eq. (7b) express the costs associated with the HPH system. Within this summation, the first term is the cost of the natural gas required to produce the hydrogen that is used by the building fuel cell, supplied to the FCV fleet, and added to the storage tank. The second term in this summation (line four) is the electricity required to compress the fuel supplied to the FCV fleet and the fuel added to the storage tank. This expression assumes that the compression is accomplished off-peak and, thus, only the cost of electrical energy is included.

The optimization problem expressed in TABLE II involves determining, for each hour of each demand period, the amount of hydrogen that is used to provide electricity for the building, fuel for the FCVs, and storage for later hours while considering the various production costs and constraints. The assumptions and constraints reflected in TABLE II reduce this problem to an optimization problem in a single variable for each demand period, $\dot{E}_{lim,d}$, which is the electrical demand limit. The electrical demand limit is the building electrical power requirement above which the fuel cell system will supply electricity to the building. As illustrated in Figure 3, selection of a high demand limit provides demand cost savings with relatively few operating hours and little use of hydrogen. Reducing the demand limit increases the demand savings while increasing the amount of hydrogen used for building loads, thus, making less available for storage and vehicle refueling. The desired demand reduction during a particular hour, $\dot{E}_{ddr,i}$, is the amount by which the building power exceeds the demand limit as given by Eq. (7c).

The fuel cell system cannot necessarily meet the desired demand reduction since its power is limited by the fuel cell capacity as well as the amount of hydrogen produced or available from storage during the current hour less that dedicated to the FCV fleet as indicated by Eq. (7d). Once the electrical energy produced by the fuel cell for demand limiting during the current hour is determined by Eq. (7d), the mass of hydrogen used for this purpose is found from Eq. (7e). As reflected by Eq. (7f), hydrogen that is produced but not used for refueling or for demand limiting is stored up to the maximum capacity of the storage tank. This strategy effectively fills the tank as quickly as possible and is based on the assumption that the fuel processor efficiency does not vary with load, and, thus, there is no incentive to balance the output of the fuel processor over the available hours.

TABLE II. OPTIMAL OPERATION OF A HPH SYSTEM

$$\text{Maximize}\ S_{ann} = \sum_{d=1}^{D} S_d \qquad (7a)$$

where:

$$\begin{aligned} S_d = \sum_{i=h_d}^{H_d} & \left[ \dot{E}_{el,i} c_{ee} \Delta t + \frac{k_1 \dot{E}_{th,i}}{\eta_b} c_{ng} \Delta t + \dot{m}_{fcv} c_{fcv} \Delta t \right] \\ & + c_{ed} \left[ \max_{i=h_d \dots H_d} \left( \dot{E}_{el,bld,i} \right) - \max_{i=h_d \dots H_d} \left( \dot{E}_{el,bld,i} - \dot{E}_{el,i} \right) \right] \\ & - \sum_{i=h_d}^{H_d} \left[ \left( m_{bld,i} + \dot{m}_{fcv} \Delta t + m_{str,i} \right) e_{ng} c_{ng} \right. \\ & \qquad \left. + \left( \dot{m}_{fcv} \Delta t + m_{str,i} \right) \frac{e_{cp} c_{ee}}{k_1} \right] \end{aligned} \qquad (7b)$$

subject to constraints:

$$\dot{E}_{ddr,i} = \max\left[ \left( \dot{E}_{el,bld,i} - \dot{E}_{lim,d} \right), 0 \right] \qquad (7c)$$

$$\dot{E}_{dr,i} = \min \left[ \begin{array}{l} \dot{E}_{ddr,i}, \dot{E}_{fc,cap}, \\ \left( \frac{M_{str,i-1}}{\Delta t} + \dot{m}_{fp} - \dot{m}_{fcv} \right) \eta_{el} LHV_{H2} \end{array} \right] \qquad (7d)$$

$$m_{dr,i} = \frac{k_1 \dot{E}_{dr,i} \Delta t}{\eta_{el} LHV_{H2}} \qquad (7e)$$

$$M_{str,i} = \min\left[ \left( M_{str,i-1} + \dot{m}_{fp} \Delta t - \dot{m}_{fcv} \Delta t - m_{dr,i} \right),\ M_{str,max} \right] \qquad (7f)$$

$$m_{str,i} = M_{str,i} - M_{str,i-1} \qquad (7g)$$

$$m_{rsd,i} = \dot{m}_{fp} \Delta t - \dot{m}_{fcv} \Delta t - m_{dr,i} - m_{str,i} \qquad (7h)$$

$$\left\{ \begin{array}{l} \text{if} \ \left( \frac{k_1 e_{ng} c_{ng}}{\eta_{el} LHV_{H2}} + MC \right) < c_{ee} \\ \qquad \dot{E}_{el,i} = \min\left[ \left( \dot{E}_{dr,i} + m_{rsd,i} \frac{\eta_{el} LHV_{H2}}{k_1 \Delta t} \right), \dot{E}_{fc,cap} \right] \\ \qquad m_{bld,i} = \frac{k_1 \dot{E}_{el,i} \Delta t}{\eta_{el} LHV_{H2}} \\ \text{else} \\ \qquad \dot{E}_{el,i} = \dot{E}_{dr,i} \\ \qquad m_{bld,i} = m_{dr,i} \end{array} \right\} \qquad (7i)$$

$$\dot{E}_{th,i} = \min\left[ \frac{\dot{E}_{el,i} \eta_{hr}}{\eta_{el}}, \dot{Q}_{th,i} \right] \qquad (7j)$$

The amount of hydrogen exchanged with the storage tank is given by Eq. (7g). The hydrogen that is left after meeting the FCV requirement, the building demand limit requirement, and after filling the storage tank is called the residual hydrogen and is given by Eq. (7h). If the incremental cost to produce electricity from the fuel cell is less than the unit cost of electrical energy (excluding demand) from the utility, then the residual hydrogen is used to generate electricity. On the other hand, if the incremental cost to produce electricity from the fuel cell exceeds the unit cost of electrical energy from the utility, then the fuel processor flow rate is reduced by the amount of the residual. This logic is depicted in Eq. (7i) which determines the total amount of electrical energy produced and hydrogen used by the building fuel cell system. Finally, the useful thermal energy from the fuel cell is the minimum of what is available from the fuel cell and required by the building as indicated by Eq. (7j).

Maximizing the savings involves determining, for each demand period, the value of the demand limit that maximizes the savings as calculated by Eq. (7b). The optimal value for the demand limit in each period was found using a golden section search technique (Press, 1992). The lower and upper bounds for the search were taken to be the minimum and maximum building power requirements for the demand period of interest. For a fixed electrical demand and energy cost structure such as that considered here, this interval contains only a single maximum.

Optimal operation in a utility price structure that incorporates demand charges requires knowledge of past, present and future power requirements within the demand period. In the optimization problem specified by Eqs. (7a) to (7j), the building power is assumed to be known for each hour of the demand period. In system design studies, this information is provided by historical data. In actual operation, this information is provided by forecasts for power requirements based on historical data or predictive models. The forecast can be updated and the optimization problem solved repeatedly to update the operating strategy as the demand period unfolds.

## 3. Results

The approach outlined in the preceding section was applied to determine the optimal operating strategy for an HPH system serving the office/laboratory facility used here as a case study. The life cycle cost of the HPH system was determined for a variety of combinations of building fuel cell system sizes and FCV fleet sizes. The life cycle cost for each case was based on operating costs calculated in accordance with the procedures outlined in the preceding section and on estimates of first costs for the fuel processor and the stationary fuel cell system, which are summarized in TABLE III.

The fuel processor size, 4.5 kg-$H_2$/h, was based on the size of a product currently under development for on-site reforming of hydrogen in service station applications. The fuel processor costs are based on estimates for an annual production volume of 100-200 units [Thomas, 2003]. Projected costs for complete natural gas fuel cell systems with integral fuel processors range from $500 to $1,500 per kW, which is roughly a factor of four lower than current costs. Assuming a cost of $1,000 per kW and using the estimate from Thomas (2003) that an integral fuel processor accounts for 35% of the system cost, the projected unit cost for a fuel cell system *operating on pure hydrogen* is $650/kW. The site preparation costs are assumed to be 10% of the total system cost. In addition to utility costs, the fuel cell is estimated to have unit maintenance costs of $0.01/kWh which includes a sinking fund for stack replacement. The results of the life cycle cost analysis are calculated on a net present value basis for a rate of return of 8%, a life of 15 years, and a negligible salvage value.

TABLE III. FIRST COST ASSUMPTIONS.

| Item | Estimated cost |
|---|---|
| Fuel processor, 4.5 kg-$H_2$/h | $100,000 |
| Hydrogen compressor | $25,000 |
| Hydrogen storage | $31,000 |
| Hydrogen dispenser | $24,000 |
| Hydrogen fuel cell with power conditioning | $650/kW |
| Site preparation | 10% of equipment cost |

The size of the fuel cell system was varied from 50 to 200 kW and the fleet size was varied from 0 to 250 vehicles to determine the most economical system. Each vehicle is assumed to be a “standard” vehicle as described previously with a fuel efficiency of 85 km/kg-$H_2$ and an annual travel distance of 12,000 km. In this analysis, the larger stationary fuel cell systems used stored hydrogen to meet peak loads and incurred the energy penalty associated with hydrogen compression.

The results from the HPH system analysis are presented in Figure 4 for the utility rates currently applicable at the case study facility. As this figure indicates, the vehicle refueling application by itself has a positive net present value (NPV) only for fleet sizes exceeding 90 vehicles. Combining stationary and vehicle refueling applications yields a positive net present value at smaller fleet sizes and increases the net present value at all fleet sizes. As indicated in Figure 4, a 200 kW fuel cell combined with a relatively small vehicle fleet (~ 30 vehicles) can provide a positive net present value. As the fleet grows, the net present value of the system increases. For the case study facility, conversion of the facility’s one transit bus would probably provide sufficient hydrogen demand to justify the investment in the HPH system. On the vertical axis of Figure 4, the net present value of a building only fuel cell system with an integral reformer (without pressure swing adsorption, compression, and storage) and no vehicle refueling is presented. This system has a positive NPV, but for fleet sizes larger than 70 to 80 vehicles the net present value of the HPH system is higher than that of the building-only system.

Results from the optimization confirm that for the rates considered in the case study, the building fuel cell system should be operated in a peak shaving mode with relatively few operating hours. As noted in the development of the operating strategy, the relatively low unit electrical energy cost makes it uneconomical to operate the fuel cell at off-peak conditions. The optimization results indicate that the most economical operating strategy involves only about 900 hours per year of fuel cell operation for the 200 kW system. This relatively limited amount of operation is sufficient to reduce the peak demand by 200 kW during each of the 12 months resulting in an annual demand cost savings of $35,400. The limited number of annual operating hours may also lead to longer fuel cell system life but a number of factors must be considered. For example, age as well as operating time may affect the time-to-failure. Also, the inefficiencies associated with transient system operation must be quantified to determine their effect in a peak shaving strategy.

The sensitivity of the results to electric utility rates is illustrated in Figure 5 which shows the variation of NPV with the electric utility unit cost while the fuel processor size (4.5 kg/h), the fuel cell size (100 kW), the number of vehicles supported by the refueling station (140), and the natural gas cost ($0.0065/MJ) remain constant. As indicated in Figure 5, the HPH system always has a higher net present value than the FCV refueling system alone provided that the demand cost exceeds roughly $7.50/kW. As the electrical energy cost increases, the net present value of a stand-alone refueling system decreases as the cost of compressing the hydrogen rises. The HPH system follows this trend initially. However, once the unit electrical energy cost reaches the point where electricity generated in the fuel cell is less expensive than purchased electricity, the value of the HPH begins to rise. Thus, combining the building fuel cell with vehicle refueling provides a hedge against increasing electrical energy prices.

The critical electrical energy cost above which the fuel cell can provide energy at lower cost than the utility depends on the building load profile and the demand cost. For the load profile in the case study, the critical electrical energy cost lies between $0.065/kWh and $0.075/kWh. If utility rates exceed the critical unit electrical energy cost, optimal system operation will have relatively long operating hours, and thus, the environmental benefits and thermal energy recovery as described by Ellis (2003) will be realized. Below the critical unit electrical energy cost, the system will operate in a peak shaving mode and have very limited operating hours. In this case the primary benefit for the building will be reduced demand cost. Environmental benefits and thermal energy recovery are likely to be very small.

The sensitivity of the results to the unit cost of natural gas is illustrated in Figure 6 for a 4.5 kg/h fuel processor, a 100 kW fuel cell, and demand and energy charges of $15/kW and $0.02/kWh respectively. The HPH system has a

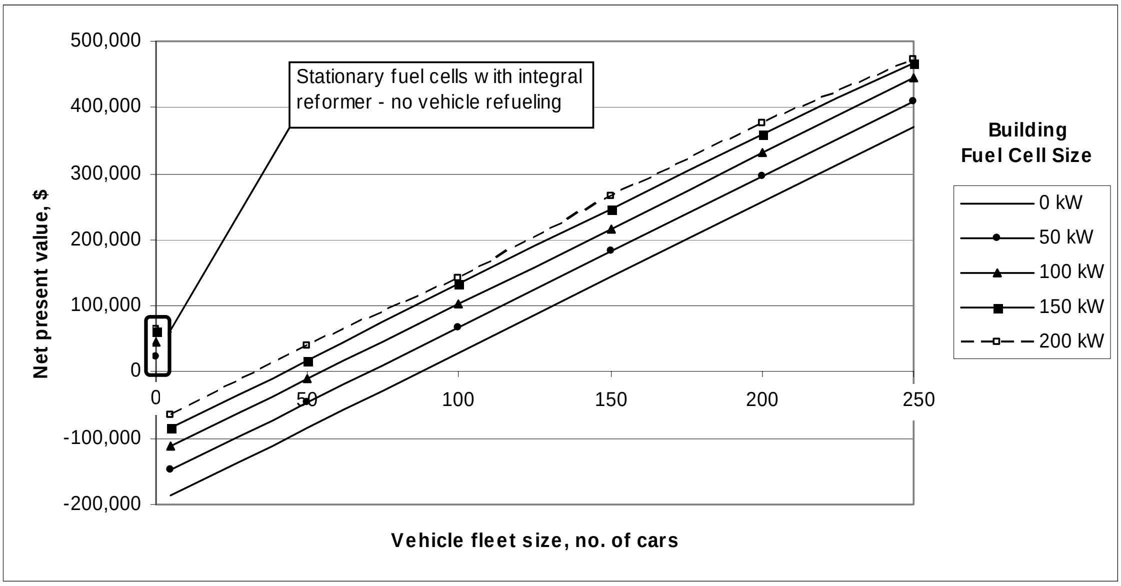

*Figure 4. Economic value of HPH system ($c_{ee} = \$0.02/kwh$; $c_{ed} = \$14.75/kw$; $c_{ng} = \$0.0065/mj$)*

higher NPV than the FCV-only system due to the demand cost savings. Since achieving the demand cost savings requires relatively little natural gas, the difference in NPV between the HPH system and the FCV-only system is not significantly affected by rising gas rates, and the HPH system retains its advantage at all gas rates considered in Figure 6.

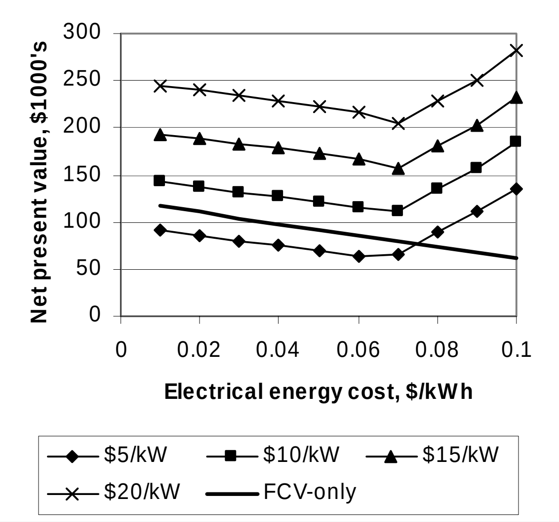

*Figure 5. Effect of electricity rates. (FP = 4.5kg/h; FC = 100 kW; $N_{fcv}$ = 140; $c_{ng}$ = \$0.0065/MJ)*

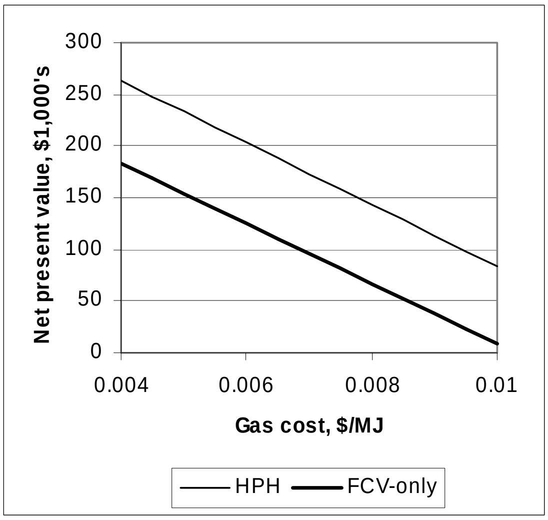

*Figure 6. Effect of gas rates. (FP = 4.5kg/h; FC = 100 kW; $N_{fcv}$ = 140; $c_{ed}$ = \$15/kW; $c_{ee}$ = \$0.02/kWh)*

## 4. Conclusions

Results show that, for the assumed first cost values of the fuel processor and fuel cell, coupling a building fuel cell system to a vehicle refueling system provides economical refueling for smaller vehicle fleets and increases the economic value of the refueling station at all fleet sizes. For larger fleet sizes, the combined HPH system offers higher economic value than a building fuel cell system alone. For applications with high unit demand cost and low unit energy cost, such as the case study considered here, coupling the building fuel cell to a hydrogen compression and storage facility allows the fuel cell system to be sized larger than the reformer, thus, yielding additional synergy with the transportation application.

Sensitivity studies show that provided the unit electrical demand cost exceeds \$7.5/kW, the HPH system provides greater NPV than an isolated refueling system at all utility rates. Furthermore, as energy costs rise, the electricity from the HPH system becomes more valuable providing a hedge against high unit electrical energy costs.

Future work should explore in more detail the system design considerations related to the integration of the fuel reformer, hydrogen purification system and the fuel cell. In particular, the choice of purifying a sidestream for vehicle refueling or purifying the entire reformate stream for use in both vehicle refueling and stationary fuel cells should be evaluated for a variety of application scenarios. The development of a flexible, well integrated HPH system that provides stationary power and vehicle refueling can help to facilitate the introduction of both fuel cells and a hydrogen infrastructure.

## Nomenclature

| | |
|---|---|
| $c_i$ | unit cost of energy resource i. See TABLE I. |
| $e_{ng}$ | natural gas energy per kg of $H_2$ produced, MJ/kg-$H_2$. |
| $e_{cp}$ | energy for compression expressed in MJ per kg of hydrogen. |
| $\dot{E}_{ddr}$ | desired demand reduction, kW. |
| $\dot{E}_{dr}$ | actual demand reduction, kW. |
| $\dot{E}_{el}$ | electrical power from the building FC system, kW. |
| $\dot{E}_{el,bld}$ | building power requirement absent the FC system, kW. |
| $\dot{E}_{fc,cap}$ | maximum electrical power from the building FC system, kW. |
| $\dot{E}_{lim,d}$ | demand limit for period d, kW. |
| $\dot{E}_{th}$ | rate of *useful* heat recovery from the building FC system, $kW_t$. |
| $LHV_{H2}$ | lower heating value of $H_2$, 120 MJ/kg. |
| k | specific heat ratio. See TABLE I. |
| $k_1$ | conversion constant, 3.6 MJ/kWh |
| $\dot{m}_{fcv}$ | average $H_2$ flow rate for refueling, kg/h. |
| $\dot{m}_{fp}$ | fuel processor $H_2$ flow rate, kg/h. |
| $m_{bld}$ | mass of $H_2$ used by the building FC, kg. |
| $m_{dr}$ | mass of $H_2$ used to achieve demand reduction, kg. |

| | |
|---|---|
| $m_{rsd}$ | mass of $H_2$ left after meeting FCV, demand and storage needs, kg. |
| $m_{str}$ | mass of $H_2$ exchanged with the storage tank, kg. |
| $M_{str}$ | mass of $H_2$ in the storage tank, kg. |
| $M_{str,max}$ | maximum capacity of the storage tank. See TABLE I. |
| MC | fuel cell maintenance cost. See TABLE I. |
| N | number of compression stages. See TABLE I. |
| p | pressure, MPa. See TABLE I. |
| $\dot{Q}_{th}$ | rate at which thermal energy is required by the building, $kW_t$. |
| $R_{H2}$ | gas constant for $H_2$. See TABLE I. |
| $S_d$ | net savings for billing period, d, $. |
| $S_{ann}$ | net savings for the year, $. |
| T | temperature. See TABLE I. |
| $\Delta t$ | time increment for analysis, 1 hour. |
| $\eta_i$ | efficiency of device i. See TABLE I. |

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