Fuel economy analysis of fuel cell and supercapacitor hybrid systems

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A B S T R A C T
Fuel cells generally have a higher energy density by a lower power density than batteries, and a fluctuating load can cause unstable operation as well as low efficiency. A hybrid in which a fuel cell is combined with an energy storage element with higher power density, such as a battery or supercapacitor, can enhance the load-following capability of a fuel cell system. We analyze the design space of a proton exchange membrane fuel cell (PEMFC) and supercapacitor hybrid system, and forecast the break-even operating period of the hybrid, at which the additional cost of hybridization is met by reduced fuel costs. The combination of a 100 W PEMFC and a supercapacitor with the earliest cost break-even time uses 6.8% less fuel than a base fuel cell, and has a 50% higher peak power capacity. The additional supercapacitor cost for hybridization is recoverable in 1152 e6480 h of operation, while the typical guaranteed lifetime of a commercial fuel cell is around 3000 h.

Introduction
Portable electric and electronic devices provide the primary market for rechargeable batteries. However, higher power and energy applications, such as electric vehicles, are becoming more common. Most of modern rechargeable batteries generally are able to provide adequate power capacity, but have a relatively lower energy density than petroleum fuel and hydrogen, in terms of both weight and volume. In addition, the problem of slow recharging limits battery application areas.

A recent research directive from the U.S. Department of Energy predicts the energy and power density demands of future portable computing and communication applications [1]. It suggests that requirements will be, at least, a specific energy of 500 Wh kg⁻¹, an energy density of 1000 Wh L⁻¹, and a specific power of 50 W kg⁻¹. Power requirements mobile devices are typically between 0.1 and 25 W, and battery charges are expected to last between 10 and 100 h. Fuel cells largely satisfy these requirements, while providing much higher energy densities than batteries. Fig. 1 compares the performance numbers of electrochemical devices, which are likely candidates for future energy sources [2].

Although the fuel cells have an energy density around 5 times greater than Li-ion batteries, their power density is significantly lower than that of the newest battery technologies. The low power density and low load-following capability
of fuel cells often mean that they are regarded as a secondary energy source, which might be used to charge a battery. But this solution obviously shortens the advantage of the fuel cells, and battery charging and discharging also reduces overall efficiency.

Recent research has led to techniques for hybridizing a fuel cell and a battery which is more effective than the battery charger setup. The fuel cell largely provides power direct to the load, while a small battery helps to meet peak loads, achieving higher fuel efficiency [3,4]. Similar benefits can be obtained by combining a fuel cell with a supercapacitor [5], which is more expensive that a battery but has a much longer cycle life and an extremely high power capacity.

This hybrid approach naturally incurs the cost of the secondary energy storage, and also requires sophisticated control circuitry. Although fuel cell hybrid systems have been intensively studied in recent years, most work has been focused on efficiency and reliability. There has been little study of design optimization based on a cost analysis. To the best of our knowledge, this paper is the first attempt to analyze fuel cell and supercapacitor hybrid system in terms of the tradeoff between extra capital and reduced fuel costs.

We characterize a commercially available proton exchange membrane fuel cell (PEMFC) stack and a supercapacitor, and derive models, which are integrated into a complete system simulator. Although we examine a specific configuration, with a physical prototype, our approach is not limited to a particular type of fuel cell.

The main contribution of this paper is an exploration of the design space of a PEMFC and supercapacitor hybrid system, considering a range of sizes of supercapacitor. We analyze the fuel efficiency of this hybrid system and compare it with the system cost. We attempt to identify the optimal size of supercapacitor by looking for the cost break-even operating period. The configuration with the earliest break-even point is predicted to use 6.8% less fuel, and the cost of the supercapacitor is recouped within the lifetime of the fuel cell.

The rest of this paper is organized as follows. In Section 2, we survey some relevant literature. In Section 3, we introduce the basic of the fuel cell, and the key components of a fuel cell system, and describe a typical fuel cell hybrid system architecture. In Section 4, we describe our simulation model and provide the results of a design space exploration. In Section 5, we describe the implementation of a physical prototype, and discuss experimental results in Section 6.

Related work

The hybridization of fuel cells and other energy storage elements has been widely studied over recent decades. Other studies have examined the improvement of the fuel economy achieved by a fuel cell and battery hybridization [3,6]. The superiority of a fuel cell and battery hybrid power source over a fuel cell alone has been demonstrated in terms of efficiency and flexibility [7].

A battery can only survive a limited number of charge--discharge cycles, and therefore supercapacitors have been used in hybrid power systems; they offer high power density and a virtually unlimited number of cycles [8,9]. In electric vehicles, a supercapacitor can supply extra power for acceleration and store the energy from regenerative braking [10]. A supercapacitor connected to a fuel cell in parallel [11], or by means of a bidirectional DC–DC converter [12].

The benefit of the fuel cell hybrid systems is rarely examined in economic terms. For instance, the electric vehicle simulation tool introduced in Ref. [13] only analyzes the performance and energy efficiency of different sizes of supercapacitor and Li-ion battery. Electric propulsion for small unmanned aircraft systems combining a fuel cell and battery is proposed and examined in Refs. [14,15]. An experimental assessment of fuel cell hybrid propulsion systems for scooters based on a PEM fuel cell/battery and the fuel cell/supercapacitor are explored in Ref. [16]. But, they are mainly concerned about the power capacity and efficiency, not for its economy. To the best of our knowledge, there has been no attempt to analyze fuel cell and supercapacitor hybrid systems in terms of the tradeoff between capital and running cost.

Fuel cell and supercapacitor hybrid systems

Advantages of hybridization

Stability Fuel cells are often considered as a soft power source because their output potential drops significantly by load. Main reason to hybridize fuel cells and other energy storage elements is to compensate for this drawback in the fuel cell. The ability of a fuel cell stack to cope with a variable load current is limited by its maximum power output, which is in turn determined by the effective area of the membrane. Furthermore, the response of the fuel and air supply subsystem may not be sufficiently fast to track the rapid variation in load current even if the load current never exceeds the maximum capacity of the stack. To deal with the load fluctuation with the fuel-cell-based power systems, various kind of fuel cell and battery hybrid systems have been introduced in the literature [3].

Efficiency: Hybridization of a fuel cell with other energy storage elements with higher power densities increases the power density of the overall system. The auxiliary energy storage is expected to meet peak power demands while the
fuel cell provides power corresponding to the average. Thus fuel efficiency is improved by operating the fuel cell close to its maximum efficiency.

Reliability: Hybridization also improves the reliability of a fuel cell. For instance, fuel or oxidant starvation occurs when a fuel cell runs with insufficient fuel or oxidant. This is typically caused by a peak in power demand, leading to high output current and a large voltage drops across the cell. Cell reversal caused by starvation will reduce the service life of a fuel cell [17,18]. Hybridization reduce the occurrence of starvation by smoothing out peak power transients.

**Candidate auxiliary energy storage elements**

An auxiliary energy storage element should provide much higher power density than the fuel cell of which it is linked. As illustrated in Fig. 1, the only commercially available energy storage elements with the power and energy density necessary for a hybrid fuel cell system are batteries and supercapacitors. Both of these possibilities have been studied recent decades, and several commercial fuel cell systems have been introduced that use a battery for auxiliary energy storage [19].

An immediate drawback of a fuel cell and battery hybrid system is the difficulty of connecting the fuel cell to the battery. The voltage of the fuel cell and battery cannot be perfectly matched because of their own unit cell voltages. Therefore, the connection is usually made through a power converter such as voltage or current regulator [3]. Commercial systems typically use a battery charger circuit [19]. Such systems generally suffer from power loss in the cascaded converter and energy loss during charging and discharging cycles of the battery. Another significant drawback of a battery is its limited life cycles. The life of a modern Li-ion battery is approximately 300–400 charge and discharge cycles.

Supercapacitors have several advantages over batteries for use in a hybrid fuel cell system [20]. Supercapacitors have a very low equivalent series resistance (ESR) allowing them to accept and deliver high currents. Supercapacitors can be charged and discharged at high rates that no battery could tolerate. Furthermore, the energy storage mechanism of a supercapacitor requires no chemical reaction, and thousands of charge and discharge cycles can be completed with minimal change in performance. Finally, one of the most practical advantage of the supercapacitor is the ease of connection. Unlike a battery, supercapacitor can be directly connected to the fuel cell without expensive converter circuits because the terminal voltage of the supercapacitor continuously changes with its charge level without unit voltage. The energy-specific cost of a supercapacitor is a bit higher than that of a battery due to its modest specific energy density, but the specific cost of its power capacity is lower than that of a battery.

**Hybrid fuel cell topologies**

Various ways of connecting a fuel cell and auxiliary energy storage have been reported in the literature, such as: a fuel cell and a supercapacitor connected in parallel [11]; a battery connected to a fuel cell through a bidirectional DC–DC converter [21]; and a supercapacitor connected to the fuel cell through such a converter [12]. A lossless diode-based connection has also been described in Ref. [3]. Commercial products commonly have a constant-current battery charger between the fuel cell and battery [19].

Hybrid topologies can be divided into two groups, depending on the means by which energy flow is controlled: in a passive topology, auxiliary storage is connected without active devices; whereas in an active topology, active devices are used [6]. Passive topologies simply operate at the balance point where the characteristics of each power source matches its load. Active topologies control the power flow with power electronics circuitry. This makes the system more controllable, but it also incurs cost and uses power.

Parallel connection is the most basic hybrid structure but it is practical and efficient. When this form of connection is used with a supercapacitor, we can make good use of its huge power density, whereas an intermediate converter is likely to have limited power-handling ability. Results from system with the simplest topology provide a baseline from which to evaluate other hybrid systems. In this paper, we focus on providing system designers with a perspective on fuel economy. The conceptual topology and behavior of our target system are shown in Fig. 2.
Fig. 2 shows the inefficiency of the fuel cell only system with the pulsed load due to the voltage and current variation by measurement. The load current is controlled within the designed operating range of the fuel cell capacity in this preliminary experiment. Thanks to the dedicated water cooling circuit and air compressor only for stoichiometry regulation, we observe a fast enough response of the fuel cell in that range. However, the voltage of the fuel cell significantly changes, and, in turn, the operating point of the fuel cell varies apart from the optimal point.

Furthermore, high-rated pulse may result in a fuel starvation phenomenon, which influences long-term performance and durability of the fuel cell. When starved from fuel or oxygen, the fuel cell performance degrades and the cell voltage drops. A subsequent cell reversal due to starvation does influence durability of the fuel cell. The problem of starvation can be solved by anticipation of the transient power peak. There are many suggested solutions for this starvation problem, and the hybrid with a fast responding auxiliary power sources also can prevent this problem.

We do not utilize any extra power electronics because we directly connect the fuel cell and supercapacitor in parallel. If we use active power electronics, we can further enhance the performance of the hybrid system. For instance, it is reported that the adoption of current regulator in battery and supercapacitor hybrid systems can enhance the overall efficiency up to 9% for the pulsed load applications [5]. The change of hybrid topology and control policy with power electronics raises another interest in terms of economy analysis, but it is beyond the scope of this work.

System modeling and design-space exploration

System model

We simulated the internal dynamics of a PEMFC and supercapacitor hybrid system using MATLAB Simulink to write the PEMFC model, supercapacitor model, and pulsed load profiles as shown in Fig. 3.

We selected a PEMFC for room temperature operation as our prototype. The theoretical unit cell voltage of hydrogen and oxygen PEMFC voltage at room temperature (25 °C) is given as follows:

$$E = \frac{nF}{2} \frac{237340 \text{ J mol}^{-1}}{96485 \text{ C mol}^{-1}} = 1.23 \text{V},$$

where \(n\), \(F\), and \(E\) are respectively the number of electrons involved in the reactions, Faraday’s constant (96485 C mol\(^{-1}\)), and the Gibbs free energy. However, the output voltage actually drops due to losses when current is drawn from the cell. There are three main losses: activation loss, ohmic loss, and concentration loss.

The activation loss, or activation overvoltage, arises from the need to move electrons, and to break and form chemical bonds at the anode and cathode. Part of the theoretically available energy is lost in driving the chemical reaction that transfers the electrons to and from the electrodes. In low-temperature PEMFCs, the activation overvoltage \(v_a\) can be expressed as follows:

\[v_a = V_0 + V_1 (1 - e^{-a/c})\]

Fig. 3 – PEMFC supercapacitor hybrid simulator in MATLAB Simulink.
where $V_o$ is the open-circuit voltage drop, and $V_1$ and $c_1$ are constants, which can be empirically determined by nonlinear regression for a current $i_f$ [22]. The concentration, or mass transport, loss results from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. The voltage drop due to the concentration losses is given by:

$$v_{fc} = i_f \left( \frac{c_2}{i_{max}} \right)^{c_3} \text{,}$$

(3)

where $c_2$, $c_3$ and $i_{max}$ are constants that depend on the temperature and partial pressures of the reactants.

The ohmic loss has two components: resistance to the flow of electrons through the material of the electrode, and resistance to the flow of protons ($H^+$) through the membrane. The membrane resistance is a function of the water content in the membrane and the stack current. We use the ohmic resistance $R_o$ to represent the ohmic loss, by assuming that the PEMFC is operating stably. The voltage drop $v_o$, corresponding to the ohmic loss is proportional to the current:

$$v_o = i_f R_o \text{,}$$

(4)

Finally, the following equation describes the PEMFC output voltage $v_f$ at a steady state:

$$v_f = E_{fc} - v_{oa} - v_{ol} - v_e \text{,}$$

$$v_f = E_{fc} - (V_o + V_1 (1 - e^{-c_1 i_f})) - i_f \left( \frac{c_2}{i_{max}} \right)^{c_3} - i_f R_o \text{.}$$

(5)

Fig. 4 shows an equivalent circuit for a PEMFC that can be used to predict its dynamic characteristics. A fuel cell shows a concentration resistance $v_{fc}$ expressively. We can now obtain the activation resistance $R_a$ and the concentration resistance $R_c$ from (2) and (3), as follows:

$$R_a = \frac{1}{i_f} \left( V_o + V_1 (1 - e^{-c_1 i_f}) \right) \text{,}$$

$$R_c = \left( \frac{c_2}{i_{max}} \right)^{c_3} \text{.}$$

(6)

And thus the output voltage of the PEMFC $v_{fc}$ can be expressed as follows:

$$v_{fc} = E_{fc} - v_{cap} - i_f R_o \text{,}$$

(7)

where

$$i_f = C_{fc} \frac{dV_{cap}}{dt} = \frac{v_{cap} - V_o}{R_a + R_c}$$

(8)

and $v_{cap}$ accurs the voltage of the equivalent capacitance. The MATLAB Simulink model is shown in Fig. 3.

Exploring the design space

Load profile: The design of a hybrid system strongly depends on the power profile of target applications. Applications such as electric vehicles and mobile computing systems typically exhibit rapid load fluctuation in response to user demand [5]. We, therefore, use a pulsed load in exploring the design space with our prototype. Specifically, we have assumed electric vehicles as a target application in this work. Which often equips the supercapacitor hybrid system to enhance the performance during acceleration and regenerative braking. We select an electric-assisted bicycle among the candidates where it is within an affordable range of implementation and instrumentation. Figure 5 shows a power profile of the electric-assisted bicycle during riding cycle from Ref. [23]. Unfortunately, the exact data values were not available. Therefore, we extract the data from the plot by using graphical analysis of it. We digitize the plot points and extract the difference between the points. The power profile shows 422 times of sudden increase and 492 times of sudden decrease during 530 s. Note that we only choose the meaningful range of changes by ignoring the values smaller than 1 W. Obviously, it does not mean that we intentionally make such a frequent acceleration and braking in our daily riding. It can be regarded as a result of the interaction among the pedal action, motor assistant, terrain, and riding speed. If it is a fully motorized bicycle, the characteristics may be simpler than this.

We mimic the profiles with sequence of pulse load current based on the profile characteristics. 422 times of increase and 492 times of decrease during 530 s correspond to around 0.8 Hz
of pulse frequency. The average increase-to-increase and decrease-to-decrease durations are 1.26 s and 1.06 s, respectively. We choose 1 Hz of pulse considering these characteristics. We change the duty of pulse for the design space exploration where the length of pulse period varies in the real profile.

Fig. 6 shows how a pulsed load can be expressed as a power profile. Each profile contains peak and idle periods. It is reported that an electric-assisted bicycle consumes around 130 W on average [23]. We scale down the load profile according to the limit of prototype power capacity. Our power profile is a 1 Hz pulse train with a 70 W average power for safety, while our target PEMFC stack has a nominal 100 W output power. The duty ratio of the load profile is determined by the peak power, which we will use to identify load profiles. Of course, the pulsed load profile that is used in our experiment does not completely reflect the actual profile. We analyze the load profile and reflect its characteristics to the pulsed load profile that can be manipulated by a typical active load device. The presented analysis framework, however, can be easily extended to the other load profile from the other kind of applications without loss of generality.

We expect two advantages from supercapacitor hybridization, when the load profile is pulsed: fuel should be saved by reducing the IR loss during peak power periods; and the peak power capacity is improved by the supercapacitor. The metric that we use in exploring the design space is the operating period required to amortize the supercapacitor cost by saving fuel cost. We also examine power capacity.

**Fuel cost model:** We calculate the consumption of hydrogen from the number of charge required by the fuel cell to provide the load power. The weight of hydrogen per unit time (flow-rate) can be expressed as follows:

\[
W_{H_2} = \frac{M_{H_2} N_{cell} I_{cell}}{2F} \text{ (kg s)}.
\]

(9)

where \(M_{H_2}\) is the molar mass of \(H_2\), which is \(2.015 \times 10^{-3} \text{ kg mol}^{-1}\). \(N_{cell}\) is the number of cells in the stack, which is 10. The price of hydrogen is reasonably stable at about $100 kg^{-1} [24]$. Thus the cost of fuel can be expressed as:

\[
\text{Cost}_{\text{fuel}} = 100 \int_{0}^{t_{\text{run}}} W_{H_2} dt,
\]

(10)

\[
\text{Cost}_{\text{fuel}} = 100 \frac{M_{H_2} N_{cell} I_{cell}}{2F} \int_{0}^{t_{\text{run}}} I_0 dt (\$),
\]

where \(t_{\text{run}}\) is the time in s over which the system operates.

**Supercapacitor cost model:** We use information about commercial supercapacitors to estimate the cost of supercapacitor. The price list from Maxwell Technologies [25] indicates that the cost is roughly proportional to the capacitance, leading to the following formula for cost in dollars:

\[
\text{Cost}_{\text{scap}} = 0.06 \times C_{\text{scap}} + 1.79 (\$),
\]

(11)

where \(C_{\text{scap}}\) is the size of a supercapacitor.

We use (9)–(11) to analyze operating time required to break even.

**Prototype implementation**

A PEMFC system typically includes the following subsystems: oxygen or air supply, hydrogen or hydrogen-rich gas supply, heat management, water management, and instrumentation and controls. Oxygen or air is supplied by a fan, a blower (for low-pressure systems) or an air compressor (for pressurized systems). Hydrogen is commonly supplied from a pressurized tank. Water and heat are byproducts of fuel cell operation, and
the supporting system must include means for their removal. Fig. 7 shows a typical configuration of a hydrogen-air fuel cell system, which matches our prototype implementation.

Our prototype has a 100 W nominal, 144 W maximum, 9 V open-circuit-voltage PEM fuel cell stack manufactured by BCS FC Systems [26]. The PEMFC stack requires hydrogen to be supplied in the anode at 3\text{ psig} from a tank, through a pressure regulator at the input of the stack. The stack is usually operated with a 15 s dead-end and a with 0.35 s release time. We use P30C-0002R air pump from Oken Ltd. to match the pressure at the anode and cathode for the prevention of the pressure mismatch over the membrane. Note that the pressure mismatch may damage the membrane, which results in a permanent degradation of the fuel cell performance. It has flow rate of 10 L min\(^{-1}\) at with 6 psig. A water cooling system keeps the operating temperature around 66–67 °C.

Fig. 7(b) shows the prototype. The main controller board is shown in Fig. 7(c). A Texas Instrument TMS470 microcontroller provides analog-to-digital converter channels for the sensor inputs and PWM

![Fuel cell](image1.png)

![Supercapacitor](image2.png)

![Load](image3.png)

![Load](image4.png)

**Fig. 8** – Behavior of the prototype with a pulsed load.
output drivers for the actuator control. The output power is supplied through a DC–DC converter circuit, which is selected to meet the voltage requirement of the target load. The prototype hybrid system control software runs on a tiny real-time OS called μC-OS II. The control program consists of five main threads for system boot up, temperature control, water management, monitoring, and housekeeping.

The behavior of the prototype with supercapacitors of 6.25 F and 40 F is shown in Fig. 8. As expected, with the same pulsed load the output current is more stable with the larger supercapacitor.

Experiments

We assembled supercapacitors from Maxwell Technologies and Nesscap into array modules for the experiments (Fig. 9(a)). Each module has a cell balancing circuit. The fuel cell assembly is connected to the supercapacitor array modules through a protection circuit. A programmable load device emulates a load that matches power profiles. Fig. 9(b) shows the whole experimental setup.

Model characterization and verification

We characterized the target PEMFC stack used in the prototype system. The equivalent circuit representation of the ohmic conduction is found from the stack’s response to step load. We derive $R_U$ from the immediate voltage drop caused by a pulse, and obtain $C_{fc}$ from the RC constants. Fig. 10(a) shows the response of our fuel cell stack. Next, we measured the voltage and current with various constant loads. The results are summarized in Table 1, and Fig. 10(b) shows the current–voltage curve of the stack.

We compared measurements from the prototype to the simulation model, using the sample load profiles, which have peak power of 150 W, 120 W, 100 W, and 80 W with 43%, 55%, 67%, and 86% duty ratio to achieve the same average power. Fig. 11 shows the estimated and measured fuel consumptions. We performed simulations and made measurements with a range of power profiles and sizes of supercapacitor.

<table>
<thead>
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<th>Table 1 – Simulation parameters.</th>
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<td>Parameter</td>
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curves are estimates from the simulation, and the markers are the measured values. The error is small: 1.18% maximum and 0.2% on average.

There is less reduction in fuel consumption with a smaller peak load because there is less variation in the load profile to be observed by the supercapacitor. Naturally the system with only a fuel cell cannot meet a power demand above its capacity: 120 W and 150 W peak load profiles. A hybrid system with 10 F supercapacitor cannot satisfy the profile with a 150 W peak.

Cost break-even time analysis

Fig. 12(a) shows the result of a break-even time analysis performed by simulating a range of peak power profiles and sizes of supercapacitor under continuous exploration. Fig. 12(b) shows a cross-section of the resulting surface, which has readily identifiable minima. Break-even usually occurs in less than a year.

We observe that the optimal size of supercapacitor, for which break-even comes nearest, lies between 20 F and 40 F for our load profiles. The optimal size of supercapacitor naturally increases with peak power demand because we need a larger supercapacitor to reduce the effect of load fluctuations. We performed experiments with the prototype which tracked the simulation results. We found that the target PEMFC stack with a 20 F supercapacitor has an average 6.8% better fuel efficiency than the fuel cell alone, and 17.5% at best. We also confirmed that the peak power capacity of the hybrid system is up to 50% better than that of the base fuel cell. The hybrid system with a 20 F supercapacitor can meet a 150 W peak load, even though he nominal output of the fuel cell is only 100 W.

The break-even time analysis shows that the cost of a supercapacitor is recouped within 1.6–9 months (1,152–6,480 h), depending on the load profile. The typical guaranteed lifetime of a commercial fuel cell is around 3,000 h [19]. This implies that the cost of a supercapacitor is unlikely to be recouped during the lifetime of a fuel cell unless the hybrid is properly designed. A supercapacitor has a much longer lifetime than a fuel cell, and may therefore be reusable, but the cost of such recycling must be considered. However, it is also not free because the reassembling of the supercapacitor or fuel cell in the system incurs extra cost.

It is widely agreed that a hybrid system has significant advantages over a base fuel cell in terms of power capacity and fuel efficiency. Hybridization can be expected to enhance system-level power capacity and reduce the fuel cost by improving fuel efficiency while exploiting the high energy density of the fuel cell. However, it is not always an economical solution. Our break-even time analysis suggests that commercially available fuel cell and supercapacitor technology requires proper hybrid design and optimization to make hybrid system an economically feasible solution.
Conclusions

The fuel cell is a promising next-generation power source, providing the high energy density that is likely to be required by future applications. But fuel cells have a significantly lower power density than batteries. Hybridization with high power capacity energy storage elements has been regarded as a practical way of providing both high energy and power density. However, the hybrid approach incurs extra cost. In this paper, we attempt to analyze the economics of a hybrid system consisting of a PEMFC and a supercapacitor.

We characterized a PEMFC by prototyping, and explored design space to find the optimal size of supercapacitor in terms of earliest time at which the saving in fuel cost pays for the supercapacitor. A supercapacitor sized to bring forward this break-even time as far as possible also increases the maximum peak power capacity. We implemented a PEMFC-supercapacitor hybrid system to assess the accuracy of our to the design space exploration. This system uses 6.8% less fuel than a base fuel cell on average, and 17.5% at best, with a 50% enhancement in peak power capacity.

References