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Journal of Power Sources 163 (2007) 916–925
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications

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Received 11 August 2006; received in revised form 22 September 2006; accepted 27 September 2006
Available online 7 November 2006

Abstract

A model of a photovoltaic (PV) powered residence in stand-alone configuration was developed and evaluated. The model assesses the sizing, capital costs, control strategies, and efficiencies of reversible fuel cells (RFC), batteries, and ultra-capacitors (UC) both individually, and in combination, as hybrid energy storage devices. The choice of control strategy for a hybrid energy storage system is found to have a significant impact on system efficiency, hydrogen production and component utilization. A hybrid energy storage system comprised of batteries and RFC has the advantage of reduced cost (compared to using a RFC as the sole energy storage device), high system efficiency and hydrogen energy production capacity. A control strategy that preferentially used the RFC before the battery in meeting load demand allows both grid independent operation and better RFC utilization compared to a system that preferentially used the battery before the RFC. Ultra-capacitors coupled with a RFC in a hybrid energy storage system contain insufficient energy density to meet dynamic power demands typical of residential applications.

Keywords: Reversible fuel cell; Residential power; Dynamic model; Ultra-capacitor; Energy storage; Photovoltaic

1. Introduction

Solar photovoltaic (PV) arrays are becoming more widely accepted in meeting residential electrical energy demand after decades of development and a variety of incentive programs. One of the major challenges for PV systems remains matching the sun dependent intermittent and diurnal power supply with the time dependent power demand of the residence. Operating the PV array in parallel with the electrical grid is one solution to this problem. However, if the PV array is operated independently from the grid, i.e., as a stand-alone power system, some type of energy storage device must be employed. This device must store excess PV energy at times and subsequently deliver power at the desired time and rate. The energy storage device most commonly used with PV systems today is the rechargeable lead acid battery.

With the emergence of reversible or regenerative fuel cells (RFC), one can consider using a new energy storage device that is both analogous to rechargeable batteries and that may have unique advantages in comparison to rechargeable batteries in photovoltaic applications. It is also possible to implement a system design that uses both a RFC and battery together in a "hybrid" energy storage scenario that combines the strengths of each technology. The ultra-capacitor (UC) is another energy storage device that may be used in conjunction with a RFC and/or batteries to form hybrid energy storage systems.

Unitized regenerative fuel cells use a single anode/cathode electrode pair that is bi-functional, allowing RFC operation in both electrolysis and fuel cell modes. This configuration is analogous to a rechargeable battery in that a single energy conversion device can operate under both charging and discharging conditions. In electrolysis mode, the RFC takes in electricity and water to produce hydrogen and oxygen. In fuel cell mode, the RFC takes in hydrogen and oxygen (or air) to produce electricity and water. Regenerative fuel cells have a wide range of potential applications including energy storage devices coupled to renewable energy sources, auxiliary power plants for automobiles and aircraft, and propulsion systems for satellites and other space applications.

Two of the critical questions that pertain to the use of hybrid energy storage systems are:

- What are the best combinations of energy storage devices for a given load profile and duty cycle?

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doi:10.1016/j.jpowsour.2006.09.086

- What are the best control strategies to deploy with respect to the hierarchy in which the different devices are used to meet the load and what are the trade offs of these strategies?

This study addresses these questions in the context of PV energy storage systems consisting of various combinations of a polymer electrolyte membrane (PEM) RFC, batteries and ultra-capacitors given a specific residential load profile spanning 1 week.

2. Background and related work

The main groups that are advancing regenerative polymer electrolyte membrane fuel cell systems are at NASA [1], Lawrence Livermore National Laboratory [2], Proton Energy Systems [3], U.S. Department of Energy [4], and Giner Electrochemical Systems [5]. Other groups that are more focused on bi-functional electrode or MEA development include researchers at AIST in Japan and the Dalian Institute of Chemical Physics in China [6–8]. Few of these research groups have published analyses pertaining to configuration and control of hybrid energy storage systems that contain regenerative fuel cells, batteries and ultra-capacitors as applied to residential solar photovoltaic energy systems as in this effort. However, some recent analyses have addressed related topics.

Kelouwani et al. [9] created a dynamic model consisting of a battery, buck and boost DC converters, electrolyzer, fuel cell and hydrogen storage. Experimentally measured current from a wind generator rectifier and a PV DC regulator are studied as inputs to this energy storage system model. The load on the energy storage system is said to be representative of residential consumption, but the applied residential load and temporal resolution are not described in the paper. The authors claim that the modeled system shows results comparable to the performance of an experimental system with an average deviation of 5%.

Maclay et al. [10] have developed a dynamic empirical model that uses performance curves for a RFC and battery, measured output from a PV array and measured power demand for an individual residence to determine the optimum sizing of the battery and RFC system for a residence with respect to efficiency, load sharing, energy storage capacity and component duty cycle.

Bilodeau and Agbossou [11] build on the work of Kelouwani et al. [9] by using a dynamic fuzzy logic controller to determine suitable hydrogen production and consumption rates based on system power input and output and the battery state of charge. These rates are then implemented to control the operation of the fuel cell and electrolyzer in the model.

Busquet et al. [12] describe an empirical model of a PEM RFC that can calculate cell voltage versus current density (VI) curves by entering measured values of stack temperature and oxygen partial pressure.

El-Sharkh et al. [13] have developed a dynamic electrochemical model of a PEM fuel cell and methanol reformer. The main focus of the study was to characterize the transient response and load following capability of the fuel cell under an actual residential load. The results indicate that the fuel cell is able to rapidly respond to residential load changes.

Tanrioven and Alam [14] describe the impact of load management control on the reliability of residential stand-alone fuel cell systems. Reliability evaluation is performed with a component-based state space model that uses fuzzy set theory and expert knowledge. The smart energy management control is said to increase fuel cell reliability from 95 to 99.93% over a 10 year operational period.

Gigliucci et al. [15] report results from both the demonstration of a residential fuel cell CHP unit and a mathematical model of the system that predicts technical and economic evaluations of system suitability to specific residential customers.

2.1. Approach

As Section 2 suggests, attention and interest in the application of fuel cells for residential use has recently increased. The work contained here expands upon current understanding and addresses the trade-offs associated with different combinations of energy storage devices for residential PV systems. The current work also contributes to understanding and design of control strategies used to dispatch residential PV and energy storage systems as well as providing a present-day capital cost analysis. All system and component analyses are calculated for meeting the full dynamic residential power demand profiles with 5-min temporal resolution. These features of the current study make it unique in its contribution to-date.

In order to analyze the performance of the energy storage devices at the residential level, an empirical model of a PV-energy storage powered home was constructed using MATLAB/Simulink®. The RFC and battery are modeled empirically as described in [10]. The ultra-capacitor is the one component of the model that is analyzed theoretically as opposed to empirically. The details regarding the dynamic PV power output and residential power demand data, data acquisition methods and the major electrical devices that are used within the residence are presented in [10].

2.2. Model

A schematic of the residential PV system and energy storage considered in the current work is presented in Fig. 1.

The model, described in detail in [10], contains nine main components, PV power supply, residential power demand, power management, battery, RFC, UC, utility grid power supply, and H_2 and O_2 storage tanks. The model assumes RFC operation on oxygen not air. The model was run as a stand-alone system where no power exchange with the grid is possible.

The simulated fuel cell operational curves were developed using experimental PEM regenerative fuel cell data for a single cell collected by Giner Electrochemical Systems [16].

Note that the current empirical models accurately account for the most important features of the fuel cell and electrolyzer operation (e.g., voltage, efficiency) as a function of power demand. The simulated battery operational curves were developed using experimental data [17] collected from two Trojan L-16W deep

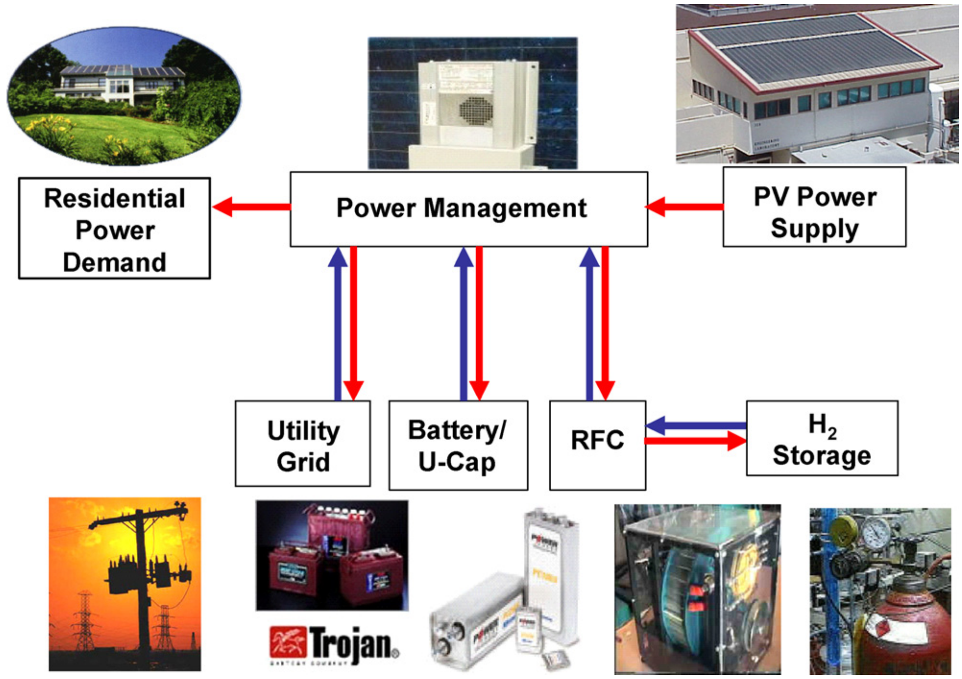

Fig. 1. Schematic of Simulink renewable RFC system model.

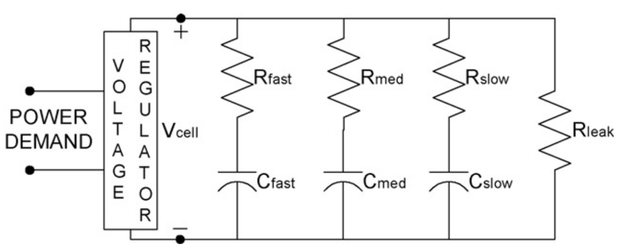

Fig. 2. *R*–*C* model of an ultra-capacitor system.

cycle 6 V lead-acid batteries in series. Further details describing both the battery and RFC models can be found in [10].

The one component model that is not described in [10] is the ultra-capacitor (UC) model. The UC model used in this study was adapted from previous work by New et al. [18]. The UC is represented by a simple *R*–*C* circuit with three time constant components and a leakage resistance (Fig. 2). A voltage regulator model, comprised of a damping function, was added to the UC model to maintain voltage within acceptable limits.

The single cell UC model (Fig. 2) was further developed to incorporate any number of cells in series so that banks of ultra-capacitors can be simulated as demonstrated by Miller et al. [19]. The resulting expressions governing the resistance and capacitance values for the three time constant components and leakage resistance in Fig. 2 are shown in Table 1. The Simulink® UC model utilized in this work was developed using this approach, and employs component characteristics for a commercial UC available from Maxwell Technologies (BCAP0100, 2600 F, 600 A and 2.5 V).

The UC system must be regulated, however, as the system voltage is highly variable, dependent on SOC and instantaneous power demand. Many wide-range DC–DC converters, such as the design by Todorovic and Palma [20], can readily handle a voltage variation of 2:1. As a result, the current UC system model contains a voltage regulator that does not allow the individual cell voltages to drop below 1.25 V, or one-half of the rated cell voltage. This restriction will limit the energy storage density of the UC, but is a realistic requirement when integrating ultra-capacitors into an energy storage system.

A representative charge/discharge cycle for a simulated UC system containing 100 cells is shown in Fig. 3.

Region I shows the charging region and the resulting drop in UC charging power as the cell voltage approaches 2.5 V. This feature is necessary to protect the UC from over charging, which quickly reduces cell lifetime. In Region II, the system is neither being charged nor discharged; the cell voltage drops during this time due to the leakage current (nominally 2.5 mA for this cell). In Region III, the demand from the UC system is increased to 10 kW; the system is able to meet this demand for approximately 50 s, until the cell voltage drops to the lower limit of 1.25 V.

Table 1
Series expressions for *R*–*C* branch values

Fast		Medium		Slow		Leakage	
R_{fast}	$(2N/3)$ESR	R_{medium}	$(2N/3)\Phi^{-(2k-1)}$ESR	R_{slow}	$(2N/3)\Phi^{-(2k+1)}$ESR	R_{leak}	$950N$
C_{fast}	$(1.05/N)C_0$	C_{medium}	$(1.05/N)\Phi^{(2j+1)}C_0$	C_{slow}	$(1.05/N)\Phi^{(2j-1)}C_0$		

Note: N is the number of cells in series, equivalent series resistance (ESR) = 0.7 mΩ, $\Phi = 0.618$, $C_0 = 2600$ F, $j = 2$ and $k = 8$.

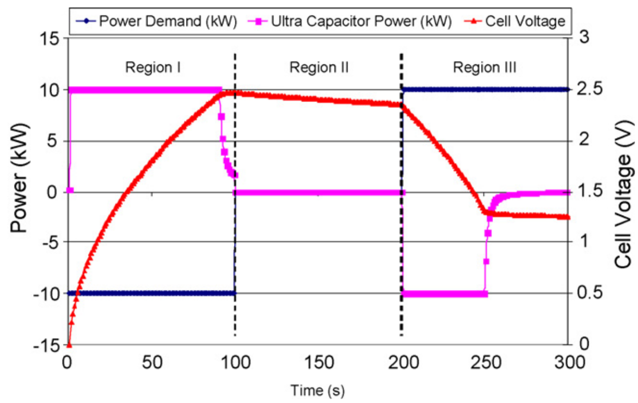

Fig. 3. Representative charge–discharge cycle for a 100 cell ultra-capacitor system.

This analysis shows that the usable energy storage of an individual UC cell as currently simulated is approximately 1.8 Wh, which is an important factor in determining the feasibility of UC integration into energy storage systems. Similar analyses show that each UC cell modeled in this study has instantaneous power storage of approximately 1.4 kW (at a resting voltage of 2.35 V). The UC design is user-defined in the current model in terms of number of ultra-capacitors in series, capacitance in Farads, initial UC cell voltage (0–2.5 V), current limit for each UC in amps and low voltage limit for each UC in volts.

Cost analyses are based on the approximate capital costs of currently available technology (e.g., actual purchase price) for a basis of comparison. The capital cost values used in these analyses are presented in Table 2. Note that these values do not represent the expected future cost of technologies that are currently in the developmental stage (e.g., the RFC).

The unitized reversible fuel cell is assumed to cost US\$ 5000 kW^{-1}. This cost was estimated by the authors based upon actual purchase price information for a polymer electrolyte membrane plus an estimated premium to make it reversible, since there are no commercial RFC systems available at this time. The cost value (US\$ kW^{-1}) is based on fuel cell power output. Battery cost at US\$ 110 kWh^{-1} at $C/5$ is equal to US\$ 191/battery. UC cost of US\$ 70,892 kWh^{-1} is equal to US\$ 160/UC. Since hydrogen is being used to offset the purchase of electricity from the utility grid it is assumed to have a value of US\$ 0.12 kWh^{-1}, a typical cost for electricity in California. It should be emphasized that this cost analysis does not take operating or life cycle costs into account and is only being used in the current paper as a means of comparing capital costs of various system configuration options.

Table 2
Energy storage capital cost analysis values

	Cost/value (US\$)	Unit	Make and model
Reversible fuel cell	5000	kW	NA
Battery	191	Battery	Trojan (L-16 W, 6 V)
Ultra-capacitor	160	UC	Maxwell (BCAP0010)
Hydrogen	0.12	kWh	California Retail Electricity Rate

3. Results and discussion

3.1. Measured dynamic residential power demand and PV power output

The measured electrical power demand of the residence and the measured electrical power production of the PV array spanning 1 week are presented in Fig. 4. The total electrical energy required by the home was 108.1 kWh and the total energy supplied by the PV array was 224.8 kWh. It is clear from Fig. 4 that most of the power demand for the residence occurs in the morning and evening when there is low solar availability. It is also clear that most of the PV power output goes unused during midday. This time offset between supply and demand leads to only 33.6% (36.3 kWh) of the residential power demand being met directly by the PV, with 66.4% (71.8 kWh) of the demand requiring grid power or some type of energy storage device.

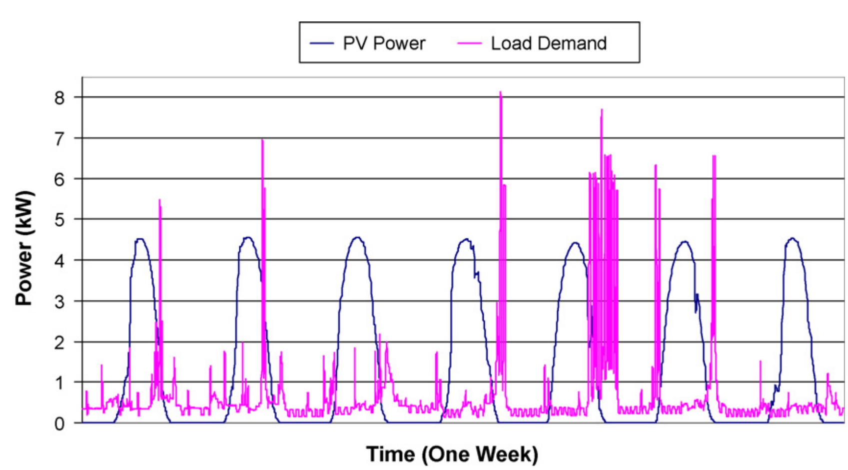

Fig. 4. Electrical load demand for a six-person family home in Irvine, California and photovoltaic electrical power supply from a Unisolar 6 kW DC nominal amorphous silicon array.

Table 3
Stand-alone energy requirements for the residence using a RFC as the only means of energy storage

Peak output (kW)	8.1
System cost (US$)	40,500
H_2 produced (kWh)	50.9
RFC round-trip electrical efficiency (%)	57
System efficiency (%)	71
Fuel cell current density limits (W cm^{-2})	0–0.47
Assumed cost (US$ kW^{-1})	5,000

Table 4
Stand-alone energy requirements for the residence using batteries as the only means of energy storage

Size (Ah)	7910
System cost (US$)	10,439
# battery	54.6
Battery (kWh)	94.9
Peak battery (kW)	8.1
Battery round trip efficiency (%)	77
System efficiency (%)	47
SOC limits (%)	20–100
Charge limits	*C*/10
Cost (US$ kWh^{-1})	110

3.2. RFC-only system simulation

If one were to select a reversible fuel cell (RFC) energy storage device to meet all the residential power demands, including the peak demand of 8.1 kW seen in Fig. 4, the fuel cell must be sized to produce peak power of 8.1 kW. Simulating a RFC that can produce a peak 8.1 kW using the Simulink® model described above leads to the results presented in Table 3. For the case when the RFC is the only means of energy storage in the residential renewable power system, the RFC unit cost is US$ 40,500, produces 50.9 kWh of H_2 over the span of the week and has a system efficiency of 71%.

3.3. Battery-only system simulation

For comparison, a case in which only batteries were used to meet all energy storage needs was simulated using the Simulink® model. The battery-only case required 55 batteries sized to 7910 Ah, leading to the results presented in Table 4. The system costs were determined to be US$ 10,439, with 0 kWh of H_2 produced during the week leading to an overall system efficiency of 47%. These results suggest that batteries can provide all energy storage needs at about one quarter the cost of the RFC. However, the RFC case has a system efficiency that is 51% greater than the case when only batteries were employed. The greater system efficiency arises because the electrolyzer can continuously utilize all the excess PV energy to make H_2, assuming sufficient H_2 storage tank capacity. When solely using batteries, there is a maximum energy storage limit of 100% SOC and batteries must be charged at a rate that does not damage their electrodes (*C*/10 selected in this case). If either of these conditions is exceeded PV electricity is wasted (the PV system goes into "float" or stand-by mode) in the battery-only case. Therefore, the RFC system allows greater PV utilization than the battery-only system by continually producing a valuable hydrogen product. However, this reasoning applies to only to stand-alone systems or grid-connected systems without net metering. If net metering is available, the residence has the opportunity to send excess PV electricity to the grid with potential cost savings and efficiency gains.

3.4. Comparison of RFC-only and battery-only systems

Fig. 5 presents the supply and demand power for the RFC system described in Table 3 as applied to the 1-week of dynamic residential power demand data and PV power supply data. The red areas represent all the PV energy that goes directly to meet the residential load demand (36.3 kWh). The yellow areas represent the excess PV energy that goes to the RFC in electrolyzer mode, making H_2 (188.5 kWh). The blue areas represent the energy coming from the RFC in fuel cell mode to meet the dynamic residential load demand (71.8 kWh). Of course, fuel cell and electrolyzer modes never overlap since both are func-

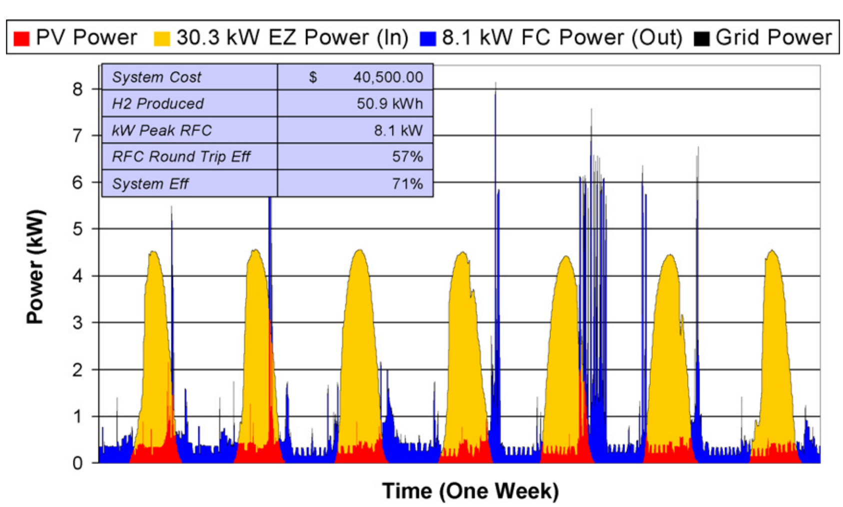

Fig. 5. Supply and demand power flow for a 6 kW photovoltaic array, an 8.1 kW fuel cell, and a 30.3 kW electrolyzer plotted over 1 week.

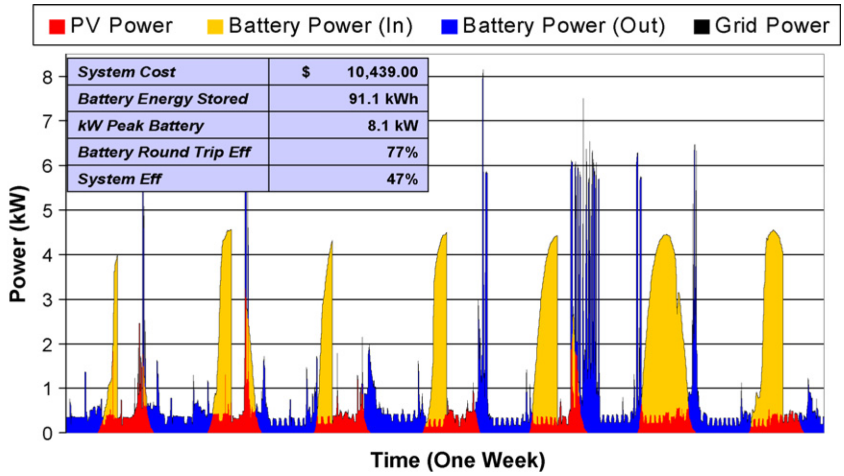

Fig. 6. Supply and demand power flow for a 6 kW photovoltaic array and a 7910 Ah battery plotted over 1 week.

tions of a single RFC device. It can be seen that the majority of the peak demand, which is also highly dynamic, must be met by the RFC in fuel cell mode. The fuel cell must therefore act as both a high energy density device, which is determined by the H_2 storage capacity, and a high power density device. Power coming from the grid to meet power demand is represented by black areas. Note that in Fig. 5 no black areas are present indicating that the sizing and dynamic performance characteristics of the RFC are sufficient to meet all energy storage requirements.

Fig. 6 shows the analysis for the system described in Table 4. This figure is analogous to Fig. 5 except that here the yellow areas represent the excess PV energy that goes to charge the battery and the blue areas represent the energy coming from the battery to meet the dynamic residential load demand. Notice that the battery can only be charged to 100% SOC and then the PV goes into float mode leaving considerable PV energy un-utilized. The SOC was found to range between 70 and 100% during the 1 week of dynamic system operation. Therefore, the battery was considerably under-utilized for its energy storage capacity. But, a battery of this size was required to meet the peak residential power demand of 8.1 kW. The 70–100% SOC range also corresponds to the most inefficient charging conditions of the battery, the absorption and float phases. Thus, the performance of this system could be significantly improved by reducing battery size and developing a control strategy that keeps the battery SOC between 20 and 85% (bulk phase).

To better understand the typical dynamic performance that is required of the integrated renewable RFC system studied herein, a 24-h snapshot of the performance of the RFC-only and battery-only cases is presented in Fig. 7. Note that the battery and RFC energy storage devices are required to respond fairly rapidly to the dynamic residential load profile. Thermostatic cycling of an electric oven (seen in Fig. 7 during hours 16–22) leads to transients on the order of 2 kW s^{-1} for both power ramping and load shed. Note that it is assumed herein that the RFC is capable of meeting these transient demands up to specified power density limits. The battery is assumed to be capable of meeting these transient demands up to specified charge rates. However, more detailed simulation of energy storage device physical, chemical and electrochemical features and capabilities may reveal limi-

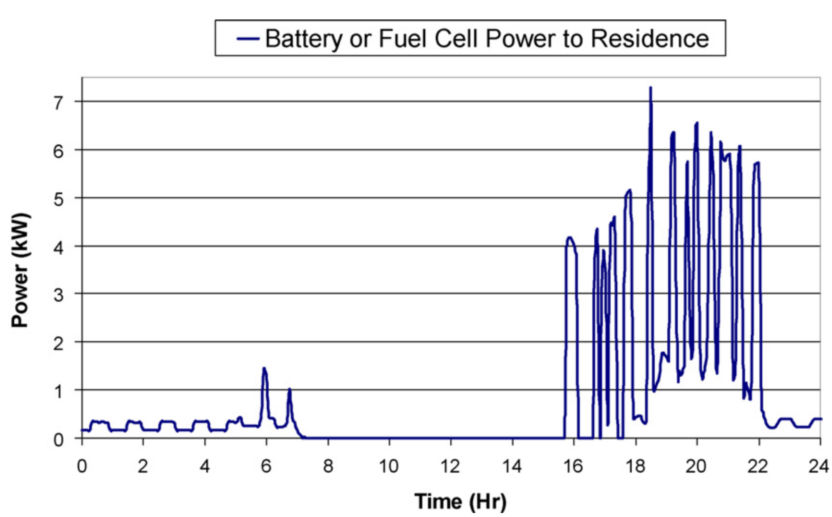

Fig. 7. Twenty-four-hour load demand snapshot to show details of the dynamic performance required by either the RFC (in Fig. 5) or the battery (in Fig. 6) on the fifth day of the week studied.

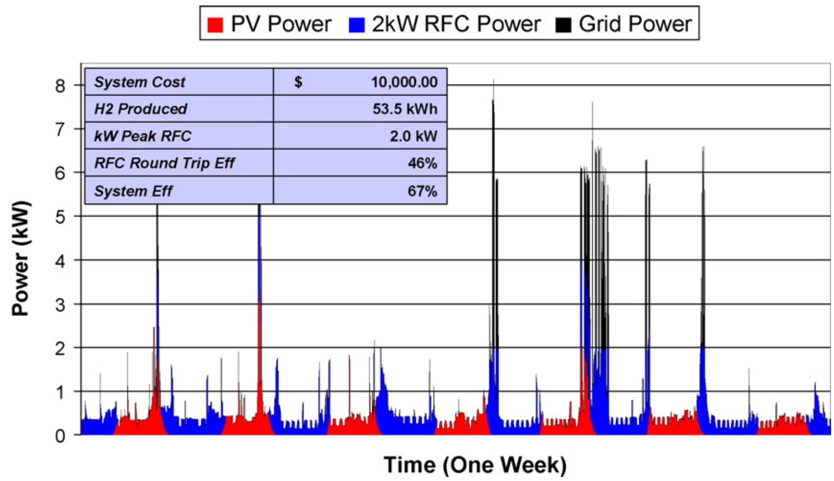

Fig. 8. Residential electrical load demand met by 6 kW photovoltaic array, the grid, 2 kW fuel cell and 7.3 kW electrolyzer with power density limits.

tations that would require further system dynamic performance analyses, design, and control.

3.5. Hybrid battery–RFC system performance

If one was to design a system with a RFC that is comparable in cost to that of the battery bank in the system described in Table 4, the RFC would need to be sized down to have a 2 kW peak fuel cell. The simulation results of such a system can be found in Fig. 8. This system requires some other form of energy storage or the utility grid to meet a large fraction of the dynamic residential load. However, hybrid systems that contain both RFC and batteries or other energy storage devices may offer advantages over systems that use only one type of energy storage. These types of hybrid systems are investigated in more detail in the following analyses.

A hybrid energy storage configuration consisting of a 2 kW fuel cell and 2820 Ah of batteries is analyzed to produce the results presented in Fig. 9. For the hybrid system a control strategy must be devised to determine how the energy storage devices meet the load and what priority is provided to "charging" of the various energy storage devices. For the results presented in Fig. 9, the control strategy requires that the battery is always used to meet the load unless the charge limit of *C*/5 is exceeded or if it reaches its SOC limits of 20–85%. Note that the control strategy for a hybrid system can include limitations on battery SOC to maintain better battery performance with respect to power density and efficiency within the bulk charging phase. The fuel cell is used if the battery exceeds its limits and the utility grid is used if the fuel cell exceeds its power density limits. This configuration presents a comparable cost to the system simulated to produce the results of Table 4. However, it can be seen (Fig. 9) that the fuel cell is rarely used with this system configuration and control strategy and cannot be considered a wise investment of capital as a result. The only time the fuel cell is needed is during peak demand when *C*/5 is exceeded for the batteries and in the early hours of the morning when the battery has been run down to 20% SOC. In the latter case, the fuel cell still cannot meet load demand without exceeding its own power density limits, thus requiring the utility grid to meet this excess power

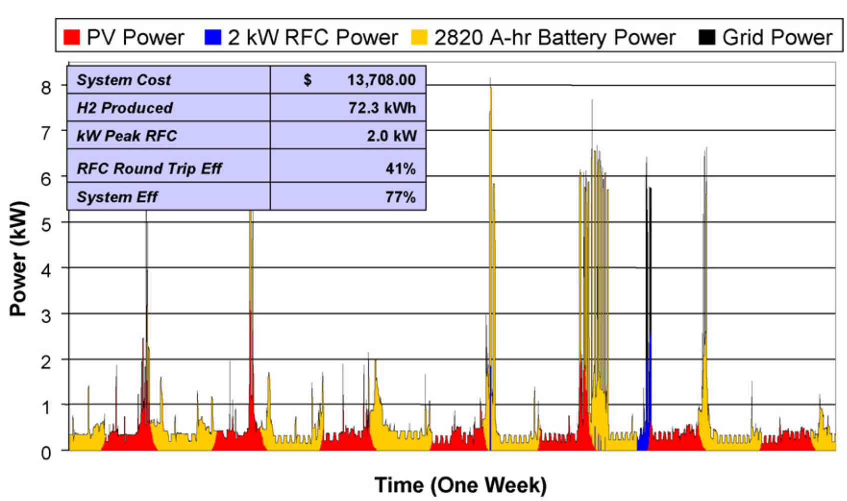

Fig. 9. Residential electrical load demand met by 6 kW photovoltaic array, the grid, 2820 Ah battery, 2 kW fuel cell and 7.3 kW electrolyzer with power density limits. Control strategy uses battery before fuel cell.

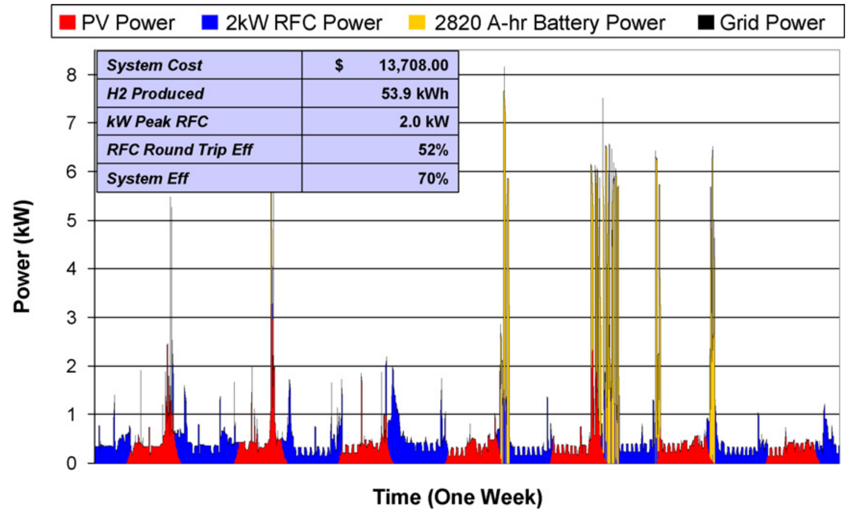

Fig. 10. Residential electrical load demand met by 6 kW photovoltaic array, the grid, 2820 Ah battery, 2 kW fuel cell and 7.3 kW electrolyzer with power density limits. Control strategy uses fuel cell before battery.

demand. The system efficiency is greater than in all previous cases due to the large amount of H_2 generated combined with reliance on the battery (which has higher round trip efficiency than the RFC, especially when controlled to operate only in the bulk charging/discharging phase) as the primary energy storage device.

Fig. 10 presents results from the same hybrid system configuration as that simulated to produce the results of Fig. 9. The only difference is a change in the control strategy. The system simulated to produce the results of Fig. 10 uses a control strategy where the fuel cell is always used before the battery to meet the dynamic residential load demand, unless the RFC power density limits are exceeded. This hybrid system and control strategy results in the combined benefits of low cost, high system and round trip efficiencies and good H_2 production, while utilizing the fuel cell capital investment well. Also, the system can meet all of the dynamic residential power demands without the grid. This shows that a stand-alone hybrid system may be feasible with 25% of the fuel cell and 36% of the battery capacities needed to meet all of the residential power demand compared to either case when only a single energy storage device was used. The major reason for this result is that a battery can be utilized at higher charge rates ($C/5$) when restricted to the bulk phase charging region (SOC = 20–85%) versus the lower charge rate regions on average during the absorption and float phases ($C/10$ and SOC = 20–100%). This essentially makes the battery a higher power density device that, with the current control strategy, is primarily used as such in this hybrid system configuration. A battery could also be operated at $C/5$ and SOC = 20–85% without the RFC, but in this case either less of the PV power would be utilized or the battery size and cost would go up for stand-alone systems.

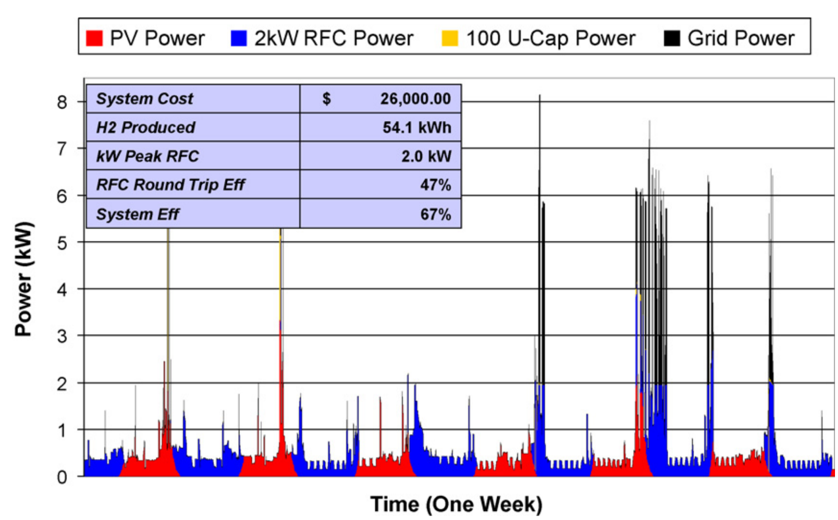

Fig. 11. Residential electrical load demand met by 6 kW photovoltaic array, the grid, 100 ultra-capacitors, 2 kW fuel cell and 7.3 kW electrolyzer with power density limits. Control strategy uses fuel cell before ultra-capacitor.

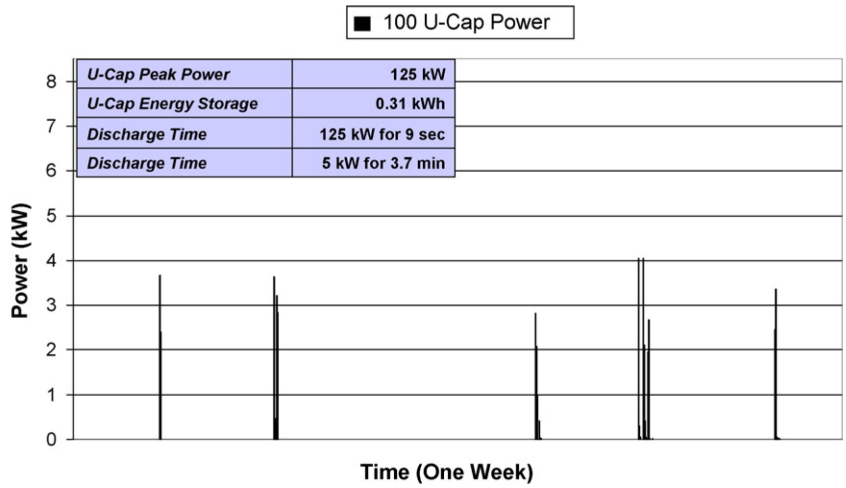

Fig. 12. Portion of residential electrical load demand met by 100 ultra-capacitors.

3.6. Hybrid ultra-capacitor–RFC system performance

Fig. 11 shows results from simulation of a system that is similar to and has the same control strategy as the system used to produce the results of Fig. 10. The only difference is that the hybrid energy storage configuration uses ultra-capacitors (Fig. 11) instead of batteries (Fig. 10). The impetus for this study was to compare the ability of ultra-capacitors, which have higher inherent power density, to that of batteries for meeting peak demand. Initially, 23 ultra-capacitors where simulated to give a total energy storage system capital cost of US$ 13,700, which is equal with the cost of the system used to produce the results of Fig. 10. Results from the dynamic simulation of this configuration showed that the ultra-capacitors were very rarely used because they did not contain sufficient energy to meet much of the peak residential power demand. To address this, the system configuration was changed to include 100 ultra-capacitors with all other features as described above. Results from dynamic simulation of this configuration are presented in Fig. 11. The dynamic simulation shows that even with 100 ultra-capacitors at a capital cost of US$ 16,000, utilization of the ultra-capacitors is very low and the utility grid is required meet most of the residential power demand in excess of what the fuel cell can provide.

For clarity Fig. 12 shows only the fraction of the power demand that is being met by the 100 ultra-capacitors throughout the dynamic simulation. Theoretically this bank of ultra-capacitors can provide a peak power of 125 kW but we see that it only provides about 4 kW. The reason for this is that although the ultra-capacitors possess very high power density, their energy density is very low, only 0.31 kWh (assuming we can extract all of the rated energy, which is impractical). This means that theoretically we could have 125 kW but for only 9 s or alternatively 5 kW for 3.7 min. Once the large peaks in demand appear the ultra-capacitors have already run out of energy to supply them. As a result, ultra-capacitors do not appear to be well-suited for use as primary energy storage devices in residential renewable energy systems of the type investigated herein.

4. Summary and conclusions

A model of a residential home using experimentally determined dynamic load demand and photovoltaic power generation data was developed. Considering a stand-alone system led to the investigation of energy storage in the form of batteries, a reversible fuel cell (RFC), ultra-capacitors and different combinations of these devices in hybrid systems. Batteries were the most cost effective means of meeting the dynamic power demand on a capital cost basis. The main advantage of using a RFC over batteries was that overall system efficiency could be increased due to the greater extent of PV utilization leading to greater energy storage over the long run compared to cases utilizing only batteries.

A hybrid energy storage system comprised of both batteries and a RFC had the advantage of low cost, high system efficiency and H_2 energy production capacity that extended energy storage capabilities. This hybrid system required only 25% of the fuel cell and 36% of the battery capacity needed to meet all power demand compared to cases that used only one of these types of energy storage devices. For a given sized hybrid system, a control strategy that preferentially used the fuel cell before the battery in meeting load demand allowed both grid independent operation and better fuel cell utilization compared to a system that preferentially used the battery before the fuel cell. The control strategy that preferentially used the battery ended up being dependent upon the utility grid to meet peak power requirements and had poor fuel cell utilization.

Systems that combined ultra-capacitors with fuel cells were found to not have an advantage from either a performance or cost basis in the current application. The main reason is the very low energy density of ultra-capacitors. As a result, the ultra-capacitors are depleted of energy before they can meet significant power demand and the grid is needed to support the system.

Acknowledgments

We gratefully acknowledge the support of the U.S. Department of Defense Fuel Cell Program of the Engineer Research and Development Center at the Construction Engineering Research Laboratory, which sponsored this research. We especially acknowledge the support and guidance of the program manager Mr. Frank Holcomb.

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