INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 36 (2011) 12130–12140

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Experimental results for hybrid energy storage systems coupled to photovoltaic generation in residential applications

James D. Maclay, Jacob Brouwer, G. Scott Samuelsen*

National Fuel Cell Research Center, University of California, Irvine, CA 92697-3500, United States

ARTICLE INFO

Article history:
Received 18 October 2010
Received in revised form
2 June 2011
Accepted 17 June 2011
Available online 23 July 2011

Keywords:
Dynamic experimental data
Fuel cell
Electrolyzer
Solar-hydrogen
Hybrid energy storage
Renewable residential power

ABSTRACT

An experimental solar-hydrogen powered residence simulator was built and tested. The system consisted of a solar photovoltaic array connected to an electrolyzer which produced hydrogen as a means of energy storage. The hydrogen was used to produce electricity in a fuel cell that operated in parallel with a battery to meet dynamic power demand similar to that found in residential applications. The study demonstrated the technical feasibility of operating such a system under the simultaneous dynamics of solar input and load. Limitations of current fuel cell and electrolyzer designs, as they pertain to both power delivery and energy storage, were identified. The study also established the need to understand and address dynamic performance in the design and application of solar-hydrogen reversible fuel cell hybrid systems. An economic analysis found that major cost reductions would need to be achieved for such systems to compete with conventional energy storage devices.

1. Introduction

Solar photovoltaic (PV) arrays are increasingly being deployed to meet residential electricity needs. One of the major challenges for PV systems remains matching the sun's diurnal and intermittent power supply with the dynamic and non-coincident power demand of a 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 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 them in photovoltaic applications. For example, such systems could produce hydrogen for use as a vehicle fuel or for heating or cooking in addition to energy storage. It is also possible to implement a system design that uses both an RFC and a battery together in a "hybrid" energy storage scenario that combines the strengths of each technology.

Electrolysis is the charge mode of the RFC, where electricity and water are taken in to produce hydrogen and oxygen. The discharge mode uses the fuel cell to take in hydrogen and oxygen (or air) and 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.

* *Corresponding author*. Tel.: +1 949 824 1999x221.
E-mail address: jb@nfcrc.uci.edu (J. Brouwer).

0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2011.06.089

The authors are not aware of prior research that has addressed critical questions that pertain to the use of RFC systems in solar-hydrogen residential applications. These questions are, one, can the electrolyzer be relied upon to consistently produce hydrogen in the presence of dynamic solar input and, two, can the fuel cell be relied upon to deliver power at the dynamic rates typical of residential demand and what are the limitations. This study addresses the technical feasibility of operating a residential solar-hydrogen reversible fuel cell under the conditions of a dynamic source (sun) and sink (load) and establishes the importance of understanding the dynamic requirements of the application and addressing the dynamic performance in design. A cost analysis is also performed to assess the commercial feasibility of such a system.

2. Background and related work

The main groups that are advancing regenerative proton exchange membrane fuel cell systems are at NASA [1], Lawrence Livermore National Laboratory [2], Proton Energy Systems [3], the 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 hybrid energy storage systems that contain regenerative fuel cells and batteries 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 were studied as inputs to this energy storage system model. The load on the energy storage system was 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 an RFC and a 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. This study considered the efficiency, load sharing, energy storage capacity and component duty cycle in the dynamic analyses used to determine component sizes. This work was extended [11] to assess control strategies, sizing, capital costs, and efficiencies of RFCs, batteries, and ultra-capacitors both individually, and in combination, as hybrid energy storage devices. The choice of control strategy for a hybrid energy storage system was found to have a significant impact on system efficiency, hydrogen production and component utilization. Uzunoglu et al. [12], Li et al. [13] and Lagorse et al. [14] describe results for similar models with focuses on sizing optimization and control.

Bilodeau and Agbossou [15] 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 upon 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. [16] describe an empirical model of a PEM RFC that can calculate cell voltage vs. current density (VI) curves by entering measured values of stack temperature and oxygen partial pressure.

El-Sharkh et al. [17] 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 [18] describe the impact of load management control on the reliability of residential standalone 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 ten year operational period.

Gigliucci et al. [19] 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.

Santarelli and Macagno [20] developed a thermoeconomic model of a residential solar-hydrogen reversible fuel cell system. They find that the system has a very high cost but suggest that it may be a viable solution for remote stand-alone applications without electrical distribution infrastructure. The analysis uses average hourly load and solar irradiance data, which will not capture the actual power demand rates that the fuel cell will have to meet or the true solar dynamics that the electrolyzer will be subject to.

Yilanci et al. [21] provide energy and exergy analyses for a model based on a 1.2 kWe Nexa PEM fuel cell unit in a solar-based hydrogen production system. A parametric study on the system and its parameters was undertaken to investigate the changes in the efficiencies for variations in temperature, pressure and anode stoichiometry. Energy and exergy efficiencies were found to increase with pressure, not change with increasing temperature and decrease with increasing anode stoichiometry. The results show that the PEM fuel-cell system has lower exergy efficiencies than the corresponding energy efficiencies due to irreversibilities not considered by energy analysis.

Guizzi et al. [22] describe experimental results for a hybrid energy system for electric wheelchair and industrial automated guided vehicle applications. The main components are a PEM fuel cell, a battery pack and an ultra-capacitor pack as power sources, and metal hydride canisters as energy storage devices. Overall system efficiency is reported to be always higher than 36%. The fuel cell meets low to medium loads, which allows near maximum efficiency operation.

Douceta et al. [23] report the general performance for an auxiliary power unit consisting of a PEM water electrolyzer, a hydride storage tank and a fuel cell. The hydrogen can be