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Journal of Power Sources 144 (2005) 165–169
JOURNAL OF POWER SOURCES
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Short communication

Data results and operational experience with a solar hydrogen system☆

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Received 29 November 2004; accepted 22 December 2004
Available online 21 February 2005

Abstract

A solar hydrogen system is presented able to provide uninterrupted 200 W_e power to an isolated application. It is composed of a photovoltaic generator, a battery set, an electrolyser, a metal-hydride system for hydrogen storage and a fuel cell. Batteries are charged with the photovoltaic array and the fuel cell, and discharged with the electrolyser and the application load. The fuel cell switches on when the state of charge of the batteries is low, until they are recovered to a predetermined level. The electrolyser produces H_2 at 30 bar, enough to feed directly the metal hydrides, avoiding pressurization steps. Metal hydrides work under pressure control in the temperature range 0–40 °C. Kinetics of absorption–desorption of hydrogen is observed as an important limiting aspect for this kind of storage. The system is able to convert about 6–7% of total solar energy irradiated in 1 year. Results and evaluation after 1-year operation are shown. Energy management is found to be a critical issue to improve the behavior of the system.

Keywords: Solar energy; Hydrogen; PEMFC; Electrolyser; Metal hydrides

1. Introduction

Energy storage capacity is a principal issue to increase the conversion efficiency of renewable energies [1]. Storage in batteries is mostly used but their limited capacity and lifetime decrease the utility of renewable systems, for instance, in the case of remote applications with high energy demand. The storage capacity, and with it the efficiency of renewable energies, may be increased with the production of hydrogen from water electrolysis, by adding an electrolyser, a hydrogen storage means and a fuel cell [2,3]. A system like this is described in this work, installed in Madrid (Spain) as the result of a European project [4,5]. The scheme of the system is shown in Fig. 1. It is composed of a photovoltaic generator, a battery set for short-term storage, an electrolyser, a metal-hydride system for hydrogen storage and a fuel cell. Solar energy is converted into constant, uninterrupted, 200–300 W of electricity, intended for a telecommunication system, remote signal or any other application demanding 3–4 kWh daily during all the year. In summer, solar energy is enough to power the application, maintain a high state of charge of the batteries and run the electrolyser to produce hydrogen. Hydrogen is stored in the metal hydrides. In winter, when the state of charge of the batteries is low, the fuel cell recharges the batteries avoiding a cut in electric power to the application. Results and working experiences over 1 year are described below.

2. System description

The photovoltaic generator is composed of 22 panels of thin film chalcogenide ($CuInSe_2$) technology (Würth), with

☆ This paper was presented at the 2004 Fuel Cell Seminar, San Antonio, TX, USA.

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doi:10.1016/j.jpowsour.2004.12.044

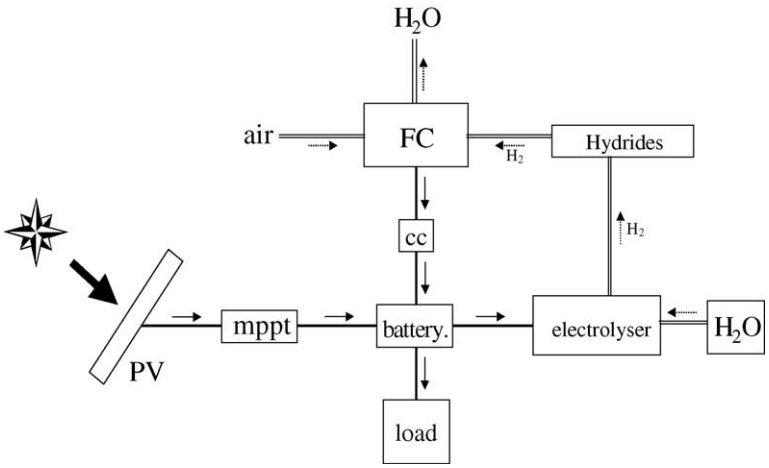

Fig. 1. Scheme of different parts of the solar hydrogen system.

1.4 kW_p, and a nominal solar to electricity conversion efficiency of 9.9%. Electricity is primarily stored in a battery set composed of 24 lead–acid units (Tudor), with a 20 kWh total storage capacity. The state of charge of the batteries is continuously calculated by an energy management system, based on an algorithm that takes into account electricity fluxes, temperature and the voltage (Fraunhofer ISE). The electrolyser is of proton exchange membrane (PEM) technology (Fraunhofer ISE), able to consume up to 1 kW [5]. Hydrogen is delivered at 30 bar pressure and stored in seven metal-hydride tanks (Labtech, I. Catálisis – CSIC) of 10 N m^3 capacity each. Hydrogen storage is controlled solely by the pressure at the ambient temperature within a 0–40 °C range. The fuel cell is of the PEM type (Nuvera), delivering 420 W gross power, working in a "dead-end" mode, with air supplied by a compressor, and control of the temperature by fans (Air Liquide). A data acquisition system was set up to record periodically (200 s) different parameters (CIEMAT). Two photographs of the installations in CIEMAT (Madrid) are shown in Fig. 2.

Fig. 2. Photographs of the outside (a) and inside (b) of the building hosting the solar hydrogen system.

3. Results and system behaviour

Values for different parameters over a 1-year test period (June 2003–May 2004) are given in Fig. 3. Solar energy input and photovoltaic conversion (Fig. 3a) reflect monthly conversion efficiency between 3.7 and 10% over the year. Such differences must be attributed to periods of attainment of a full state of charge condition in the batteries that stops the photovoltaic conversion to avoid overcharging. Such a situation is frequent during the months with higher solar irradiation, and could be avoided with an agile energy management able to redirect all the excess solar energy to water electrolysis. Energy management conditions establish the production of hydrogen by electrolysis only at noon hours during summer months (June 2003–September 2003) (Fig. 3b). The hydrogen produced in this period should be enough to cope with the requirements in winter. However, technical problems with the electrolyser system, as well as the frequent full state of charge of batteries (which stops photovoltaic conversion and with it hydrogen production), resulted in a low amount of hydrogen produced at the end of the summer. Therefore, from the 20 N m^3 consumed by the fuel cell in the period November 2003–May 2004, only 13 N m^3 came from electrolysis production in summer (Fig. 3b) (extra hydrogen from pressurized bottles was used to do the test of the system in winter).

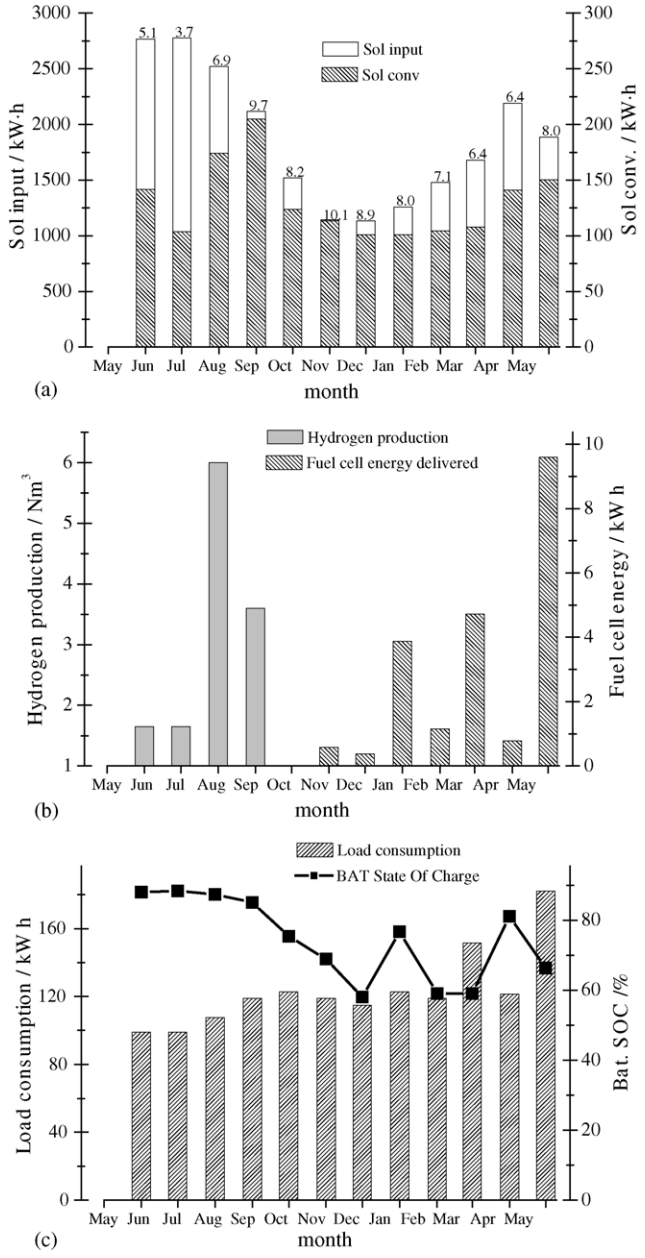

Fig. 3. Data corresponding to the period June 2003–May 2004. (a) Solar energy irradiation and conversion (numbers indicate the efficiency), (b) hydrogen production and fuel cell net energy production and (c) load consumption and average state of charge of the batteries.

Fig. 3c shows the load consumption, which was varied during the year within the range 100–300 W. The average state of charge of the batteries is also given in Fig. 3c, showing a maximum value during summer months.

3.1. Hydrogen production and storage

Hydrogen was produced at an average rate of 0.33 N m^3 per day, during 50 days of summer. During the electrolysis time, the bus voltage was fixed to 56.4 V to polarize the 30 cells of the electrolyser [5]. The energy conversion efficiency was 65% after peripheral consumption (control cabinet, valves). In September, the electrolyser was definitively stopped and hydrogen production terminated. Electrolysis current and hydrogen pressure in the metal-hydride system are shown in Fig. 4. The electrolyser was switched on at noon hours during summer days (Fig. 4a). After the hydrogen generation time, the hydrogen pressure decays within about 6 h, as shown in Fig. 4b for hydrogen storage into one tank. This transient effect is due to the slow kinetics of formation of the hydride. This effect is less acute by increasing the number of tanks to be filled, i.e. the surface of metal hydrides exposed to incoming hydrogen. Fig. 5 shows the isotherm curves corresponding to the metal-hydride alloy used (La, Ce, Ni, Al and Sn) for three different temperatures.

3.2. Fuel cell behavior

Fig. 6 shows the polarization curves of the fuel cell. Working conditions are established at constant current demand, corresponding to 420 W gross power and 280 W net power delivered to the system. Parasitic consumptions by fans, air compressor and control cabinet limits the efficiency to 36%. Single cell voltages are shown for two current demands in Fig. 7. The behavior can be considered optimal, with 0.69 V average voltage under maximum power demand, except for some lower voltage for the first and last cells which is attributed to water accumulation. The fuel cell is started when the state of charge of the batteries is below 35%. In this case, the fuel cell delivers 280 W net power to the system until the state of charge of the batteries is restored above 70%. The hydrogen supply from the metal hydrides is done under pressure control as stated above. The proper delivery of hydrogen in this mode requires fast desorption kinetics of hydrogen from the hydrides, which is attained with a high hydrogen content and ambient temperature within the interval 0–40 °C (Fig. 5). Fig. 8 shows the fuel cell power and hydrogen pressure change in one tank. A steep decrease in the hydrogen pressure is observed when the fuel cell is operating. The transient increase following the stop of the fuel cell reflects the desorption kinetics of hydrogen from the metal-hydride structure. The transient effect limits the availability of hydrogen and should improve by increasing the metal-hydride surface, or by applying heat (this second is not yet considered in the system, but is considered necessary in future).

3.3. Conversion efficiency

Solar energy conversion to electricity may occur by two paths:

(1) direct path:	solar → electricity	η_{PV}
(2) hydrogen path:	solar → electricity → hydrogen → electricity	$\eta_H = \eta_{PV}\eta_{EL}\eta_{FC}$

Fig. 9 shows a scheme of both paths. The efficiency of the direct path (1) is given by the photovoltaic panels, nominally

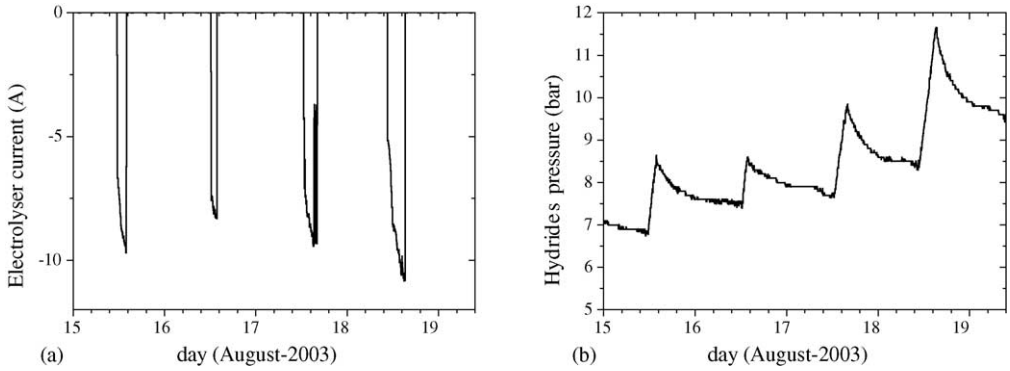

Fig. 4. Electrolyser current and hydrogen pressure evolution when storing the hydrogen in one tank (10 N m^3 capacity) of the metal-hydrides system.

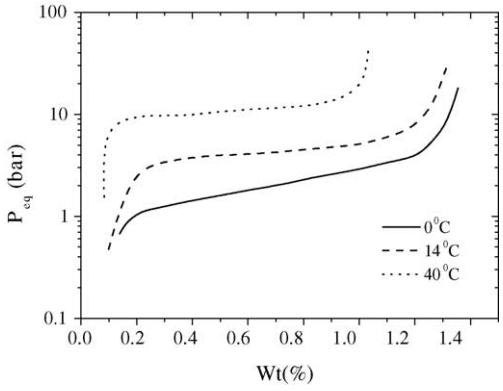

Fig. 5. Isotherm curves of the metal hydrides.

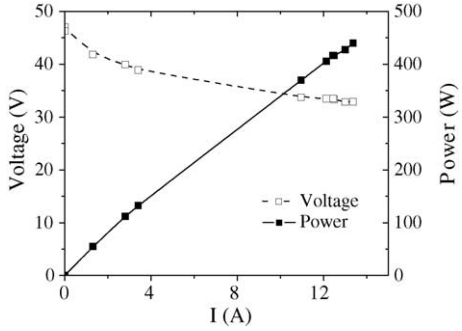

Fig. 6. Polarization curve of the fuel cell.

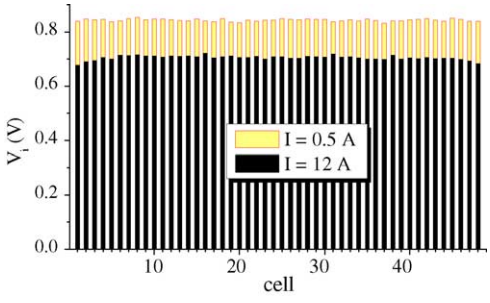

Fig. 7. Single cell voltage for two load currents.

$\eta_{PV} = 0.099$. As for the hydrogen path (2), limitations occur also in the electrolysis and fuel cell conversions, with efficiencies $\eta_{EL} = 0.65$ and $\eta_{FC} = 0.36$, respectively, in both cases including parasitic consumptions. The resulting efficiency of the hydrogen path is $\eta_H = 0.023$. It means that under optimal working conditions, the system is able to convert 9.9% of the solar energy when the direct path is active, and 2.3% when the hydrogen path is active, normally with a high state of charge of the batteries.

The total efficiency for solar energy conversion η_T can be calculated from the energy consumed by the load (E_C) and the solar energy input (E_S):

$$\eta_T = \frac{E_C}{E_S} = \frac{\eta_{PV} E_{PV} + \eta_H E_H}{E_{PV} + E_H + E_0} \quad (1)$$

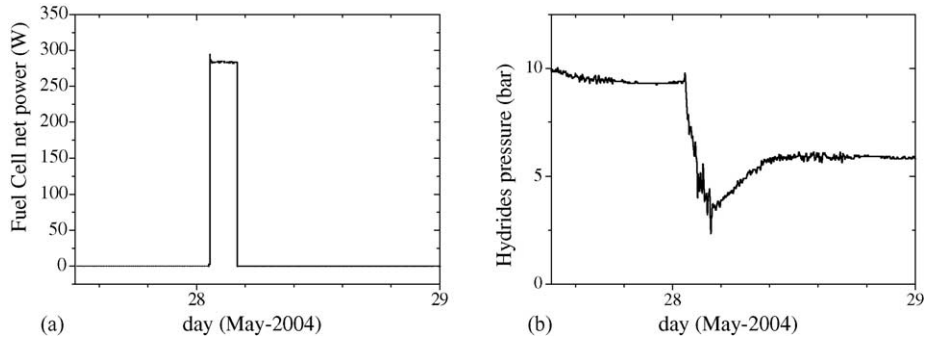

Fig. 8. Fuel cell current and hydrogen pressure evolution in the metal-hydrides system when delivering the hydrogen from one tank.

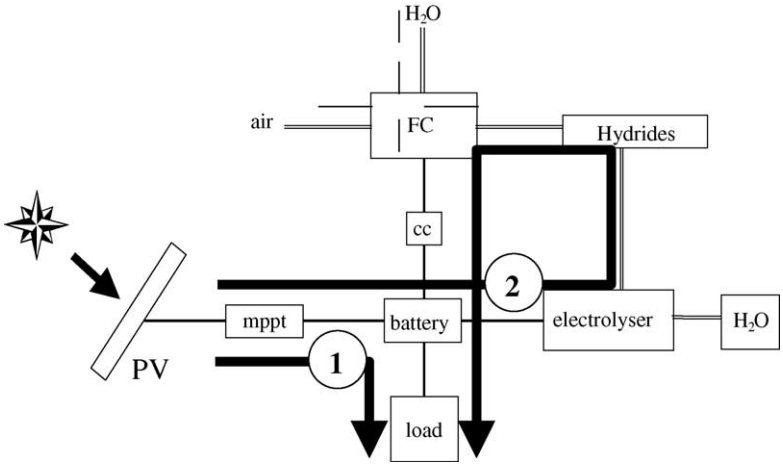

Fig. 9. Scheme of the system showing two paths for energy conversion: (1) the direct path and (2) the hydrogen path.

where the total solar energy input (E_S) is divided into three terms depending on the active conversion path, i.e. $E_S = E_{PV} + E_H + E_0$, E_{PV} being the energy input when direct path is active, E_H when hydrogen path is active and E_0 when there is no energy conversion. The energy management must be able to minimize E_0 by directing efficiently all the solar energy input to a combination of the photovoltaic and the hydrogen conversion paths. For the system described here, $\eta_T = 6$–7% although more precise estimation requires a longer test without the technical problems occurred in this year.

4. Conclusions

The system described has been working for 1 year delivering uninterrupted energy of 3–5 kWh daily to an electronic load. It has converted about 6–7% of the solar energy irradiation in this year, with a partial 9.9% efficiency for the direct photovoltaic path and 2.3% efficiency for the hydrogen path. This second path, although less efficient, however, makes possible the use of temporary surpluses of solar energy to maintain the power supply without interruption. A critical issue for improvement of system behavior is energy management.

Acknowledgement

This work has been financed by a European project (FIRST, ERK5-CT-1999-00018).

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