Article

J. Mex. Chem. Soc. **2007**, *51(2),* 55-58

ISSN 1870-249X

Solar-Hydrogen-Fuel Cell Prototype as a Source of Renewable Energy Generation

Andrés Rodríguez-Castellanos, Ernesto López-Torres, Omar Solorza-Feria*

Departamento de Química, CINVESTAV-Instituto Politécnico Nacional, A. Postal 14-740, 07360 D.F. México.
Mail: osolorza@cinvestav.mx, Tel: (55) 5061 3715, Fax (55) 5061 3389

Recibido el 24 de agosto de 2006; aceptado el 15 de enero de 2007

Abstract: A small renewable energy prototype is presented, integrated by a solar photovoltaic module used for electrolysis of water where the resulting hydrogen was fed to a regenerative fuel cell for a clean electricity generation. A photovoltaic module provided DC power to an electrolyzer, to produce 56 cm^3/min of hydrogen which is fed to a fuel cell and generate electricity. This prototype was designed and manufactured to show the future energy scenario of renewable energy. For water electrolysis, powders of $RuCoO_x$ were used as anode and nanometric Pt powders as cathode catalysts in a polymer electrolyte membrane. Anode catalyst was prepared by pyrolysis processes and annealed at 550°C. The catalysts were applied to an electrode membrane assembly (MEA) and studied galvanostatically and under solar illumination in an electrolysis cell. A high electrochemical performance of the electrolyzer was obtained with 0.25 A cm^{-2} at 1.87 V for each single MEA, at 30 ºC and atmospheric pressure of 585 mmHg in Mexico City. The fuel cell stack prototype was also designed and manufactured with 10 MEAs containing 0.4 mg/cm^2 of 20 wt.% Pt as anode and cathode, to generate electrical energy to power on a portable 3.5 watts TV.
Keywords: Renewable energy, electrolyzer, hydrogen, fuel cell.

Resumen: Se presenta un pequeño prototipo para la utilización de una fuente de energía renovable. Un modulo fotovoltaico fue utilizado para la electrólisis del agua donde el hidrógeno producido fue suministrado a una celda de combustible regenerativa para la producción de electricidad. El módulo fotovoltaico suministra corriente directa, CD, a un electrolizador para producir 56 cm^3/min de hidrógeno el cual es alimentado a una celda de combustible para producir electricidad. El prototipo fue diseñado y construido para mostrar el escenario futuro de una energía renovable. Para la electrólisis del agua se utilizaron polvos electrocatalizadores de $RuCoO_x$ y Pt nanométrico como ánodo y cátodo, respectivamente, integrados a una membrana polimérica. El catalizador anódico fue preparado por pirólisis a la temperatura de 550 °C. Se prepararon ensambles membrana-electrocatalizador, MEAs, los cuales fueron estudiados galvanostáticamente y bajo iluminación en módulo fotovoltaico. Se obtuvo un alto desempeño electroquímico del electrolizador con 0.25 A cm^{-2} a 1.87 V para cada ensamble, a la temperatura de 30 °C y presión atmosférica de 585 mmHg. Un prototipo con arreglos de celda de combustible fue diseñado y construido utilizando 10 MEAs conteniendo 0.4 mg/cm^2 de Pt al 20 % peso como ánodo y cátodo y así generar energía eléctrica para hacer funcionar una TV portátil de 3.5 watts.
Palabras clave: Energía renovable, electrolizador, hidrógeno, celda de combustible.

Introduction

The world now faces tremendous challenges associated with pollution, greenhouse gas emission, climate change and the need for a sustainable development. Production of hydrogen from renewable energy resources has the potential to bring a local energy solution. Water electrolysis is an attractive option to generate renewable hydrogen and oxygen with solar energy without any purification process and is one of the most important energy related electrochemical processes, because water is an inexhaustible natural resource and hydrogen a renewable non-polluted energy source [1-5]. Water electrolysis is a proven method for continuous production of hydrogen by converting the electrical energy into chemical energy. Conversely, a fuel cell is an electrochemical cell which can continuously convert the chemical energy of a fuel into electrical energy.

The launching of hydrogen and fuel cell technology in the market is now the starting block of renewable energy technology. There are no barriers to the introduction of hydrogen and fuel cells either from a technological perspective or from a safety point. Hydrogen has been produced and utilized in industry for over a hundred years [6], and can be produced by a number of different sources using different techniques. When hydrogen is produced from coal, oil or natural gas, the by-products will be harmful to the environment if they are not handled in an environmentally reliable way.

In the present demonstrative prototype system hydrogen is produced from electrolysis of water with the assistance of photovoltaic panel and the produced fuel is fed to a fuel cell to generate electrical energy. The main electrochemical reactions occurring at the two electrodes of the electrolyzer are [7]:

Anode: (1)

$$2\,H_2O \rightarrow O_2 + 4\,H^+ + 4\,e^-$$

Cathode:

$$4\,H^+ + 4\,e^- \rightarrow 2\,H_2 \tag{2}$$

The global reaction is the addition of both electrochemical reaction plus 237.14 kJ/mol of energy that are required for the reaction to develop. In the fuel cells the chemical energy of the hydrogen is converted directly into electrical energy, contrary to the functioning of an electrolyzer where the electrical energy is transformed to chemical energy. Fuel cells systems have received increased attention in recent years as an available alternative for clean energy generation [8,9]. The direct conversion of the chemical energy of a fuel into electricity may help to reduce the dependence from fossil fuel and contribute to reduce the environmental impacts. The basic physical structure of a fuel cell is similar to that of a typical battery since both are energy conversion devices. However, the fuel cell has the capacity of producing electrical energy for as long as hydrogen and oxygen are supplied to the anode and cathode electrodes, respectively.

In this prototype the clean electrical energy produced from the renewable Solar-H_2-fuel cell has the ability to power a 3.5 watts portable TV.

Experimental

A photovoltaic module integrated by 36 polycrystalline silicon photovoltaic cells was donated for this work by the Electrical Eng. Department of this institution. The performance of this module gives about 11 watts with 0.79 A of photocurrent. The electrolyzer used at the present study was designed and in-home built by our research group. Pt 10 wt.%/C (E-TEK) and $RuCoO_x$ prepared by thermal treatment of $RuCl_3$ and $CoCl_2$ were used as electrocatalysts. The electrode materials were prepared from the mixture of electrocatalysts and Nafion ionomer solution (Aldrich) in an iso-propyl- alcohol. The mixture slurry was thoroughly agitated under ultrasonic condition for 15 min and then deposited by spraying method into 4 cm^2 of each side of the Nafion 115 membrane. The combination of anode/membrane/cathode is referred to as the membrane/electrode assembly, MEA. Prior to each MEA preparation, the Nafion 115 membrane was chemically activated with hydrogen peroxide and sulfuric acid, following the methodology previously described [10,11]. Before spraying, membranes were dried and flattened. The anodic loading catalyst was estimated by the Simplex method, corresponding to a 1.19 mg/cm^2 and a 2.75 mg/cm2 of cathodic charge. After the catalytic ink was deposited on each side of the membrane, a Teflon treated carbon cloth was set on each side of the deposited catalyst and this was hot pressing at pressure of 4 kg/cm^2 at 120°C for 2 min. Each prepared assembly was sandwiched by two current feeders which were made of perforated stainless steel (diam = 2 mm). The total anodic area was 32 cm^2 for both anodic and cathodic electrodes. All 8 assemblies were supported by acrylic plates, with the dimensions 10.4 cm × 6 cm × 6 cm and screwed on. The final solid polymer electrolyte electrolyzer is shown in figure 1. Distilled water was supplied to the electrolyser from two similar glass containers where hydrogen and oxygen were also received. The electrolysis was performed under constant current conditions supplied by the photovoltaic module at room temperature. The current-potential behavior of each and overall assembly was determined using a potentiostat-galvanostat (PARC, Mod 363), under galvanostatic conditions. The hydrogen produced was measured by water displacement of a calibrated burette.

Fig. 1. The solid polymer electrolyte (SPE) electrolyzer designed and manufactured for the removable energy demonstration.

All ten membrane electrode assemblies, MEAs, for the polymer electrolyte membrane fuel cell, PEMFC stack were prepared following the same procedure described for the electrolyzer. Nafion 112 membrane was chemically treated and an ink prepared with electrocatalysts containing 20 wt% Pt/C from E-TEK (Electrochem) was sprayed on both sides of each membrane. The load of the catalysts at the anode and cathode was about 0.4 mg/cm^2. Each MEA was prepared by placing the gas diffusion layer (carbon paper, Toray) above electrodes at both sides of the Nafion 112 membrane, followed by hot-pressing of 10 kg/cm^2 at 120°C for 1 min. The effective area for each single MEA was 9 cm^2 being 90 cm^2 the total deposited anodic and cathodic active area. The MEAs were tested with a commercial fuel cell system (Compucell GT, Electrochem). After characterization, each component of the solar-hydrogen-fuel cells system was integrated and the performance of the prototype demonstrated.

Results and discussion

Figure 2 exhibits the photocurrent-voltage characteristics of the photovoltaic module exposed to air under different slopes but the same illumination condition. It is observed that short-circuit current increases with illumination to 1 A, open–circuit voltage of 20 V. This old generation of photovoltaic system was already reported by the manufacturer with efficiency of about 5% in the solar to electricity conversion. This module was used under fixed voltage of solar radiation to obtain 0.72 A and a voltage of 14 V, corresponding to a 10 watts of power output. Figure 3 shows the galvanostatic polarization curve experimentally measured of the electrolyzer containing 8 assemblies with Pt as cathodes and anodes of $RuCoO_x$ at atmospheric pressure and 30 °C. Previously each assembly was characterized and the current-potential average response is similar to that observed in Fig. 2. This behavior is attributed to the homogeneity of the ink deposition. The electrochemical performance of the electrolyzer is reproducible and stable, after operated for around 200 h. The amount of hydrogen produced was determined by water displacement in a burette. The experimental results show that at a current of 1 A and 15 V, the electrolysis of water produce 79 cm^3/min of hydrogen. The current efficiency is defined as the ratio of electrons used for generating hydrogen, calculated using the following equation [12].

$$\eta_1 = \frac{\text{Real } H_2 \text{ product}}{\text{Theoretical } H_2 \text{ product}} = \frac{2 \times 96500 \ \ V^o}{I \times 3600 \times 24.4} 100 \qquad (3)$$

The theoretical hydrogen product is derived by assuming that the hydrogen is an ideal gas and the pressure is corrected by the atmospheric pressure where the experiment was performed. V° is the volume of hydrogen produced under standard conditions. At constant temperature and pressure, the current efficiency increases with current density. The current efficiency is also enhanced by the cell temperature and the operating pressure, because hydrogen dissociation, proton transfer reactivity in the Nafion membrane and the partial pressure of hydrogen, all increase with temperature and pressure. The current efficiency deduced for the production of 79 cm^3/min of hydrogen was up to 95%, indicating that only the hydrogen evolution reaction occurs in the cathode side and oxygen in the anode compartment.

The integrated analysis of the photovoltaic module and the electrolyzer include the current-voltage curve of the photocells and the curve of the electrolyzer. The intersection of these two curves defines the operating point of the system, as illustrated in Fig. 4. The operating point of 0.72 A and 14 V at the output performance of the photovoltaic module produce about 56 cm^3/min of high purity hydrogen from the electrolyzer.

In the fuel cell the chemical energy of the hydrogen is converted to electrical energy. Figure 5 shows the performance (cell voltage-current-power) of the stack containing MEAs with 20 wt% Pt on carbon anode and cathode catalyst. The fuel cell was tested with a commercial fuel cell system (Compucell GT, Electrochem), without pressure and flow rate of 2000 cm^3/min of both gases at cell temperature of 60 ^{0}C. The open-circuit potential is 8.4 V lower than the reversible potential of 12.3 V. This behavior is attributed to the crossover of hydrogen from the anode to the cathode sides and also to a mixed potential that result from the galvanic currents in the oxygen electrode, which is caused by platinum oxidation. At low overvoltage low current arises due to the slow kinetic rate of the oxygen reduction. In the intermediate current the transfer of the conductive protons from the anode to the cathode is

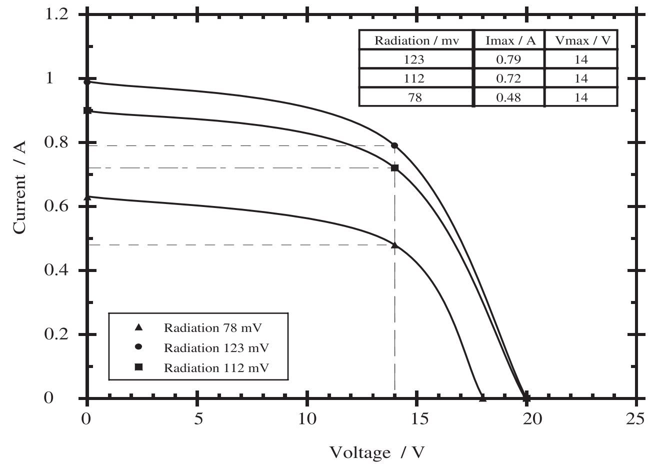

Fig. 2. The photocurrent-voltage curves of a polycrystalline silicon photovoltaic module under different slope and the same radiation.

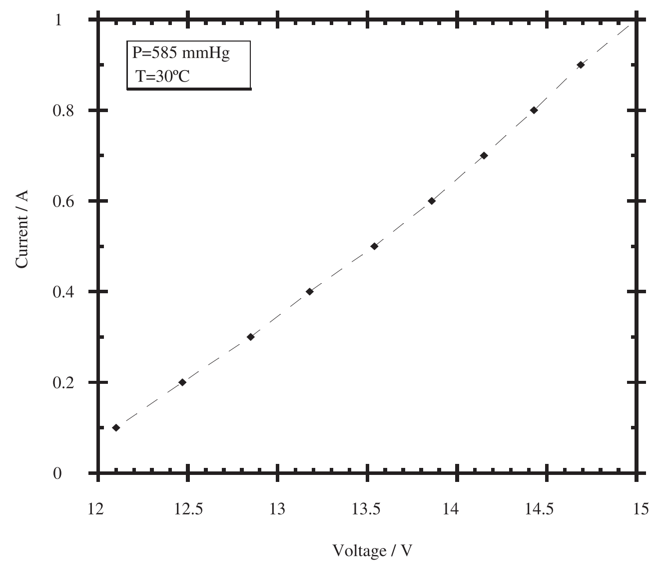

Fig. 3. Current-voltage galvanostatic polarization curve of the electrolysis module.

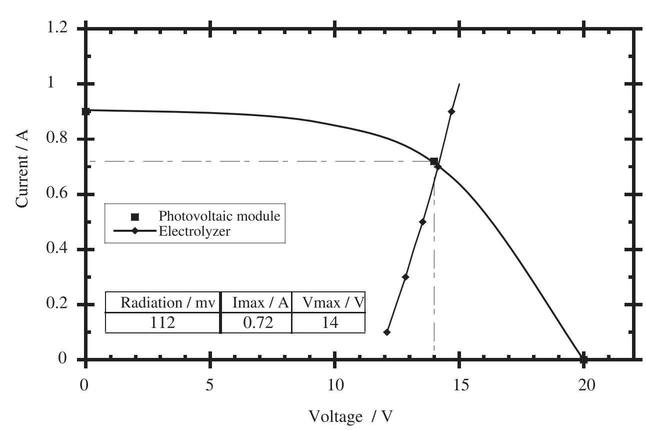

Fig. 4. A schematic representation of the interception between photovoltaic module and electrolyzer responses.

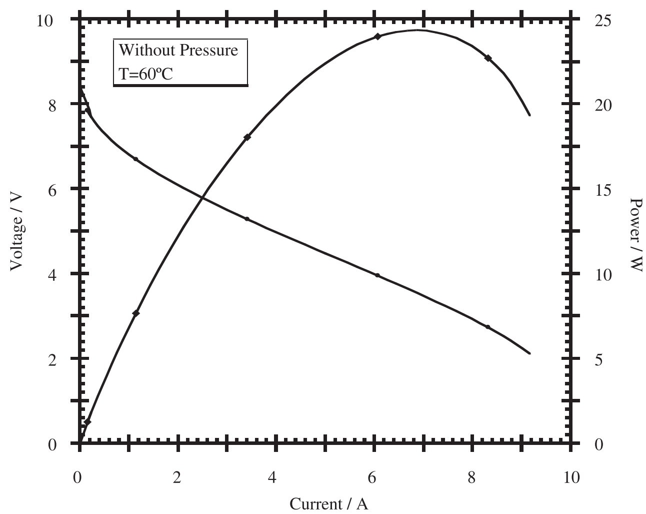

Fig. 5. H_2/O_2 fuel cell performance curves at 60 °C.

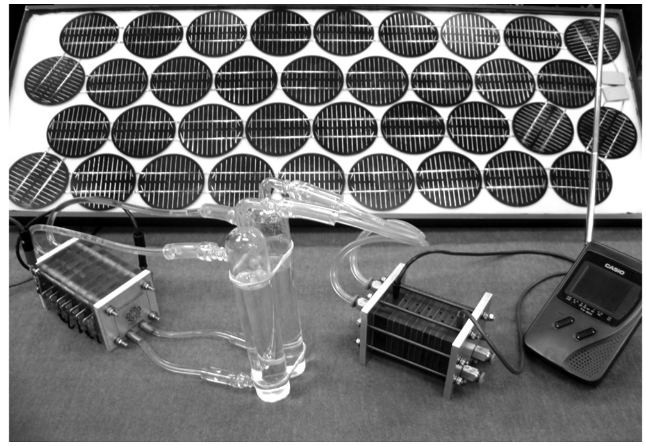

Fig. 6. Demonstrative renewable solar-hydrogen-fuel cell prototype coupled to a portable TV.

predominant. The global power output under hydrogen and oxygen saturation conditions from Fig.5 s is 2.1 A and 12.5 watts evaluated at 6.0 volt.

Figure 6 shows the picture of the integrated photovoltaic module, the electrolizer and the fuel cell connected to the portable TV. The electrolyzer operates with 10 watts from the solar electric module generating enough hydrogen that powered a 3.5 watts portable TV. The efficiency from the electrolyzed to the portable device is 32% which is high enough to make the integrated solar-hydrogen-fuel cell system an attractive technology to use in the renewable energy conversion.

Conclusions

In this paper, we demonstrate how an integrated photovoltaic-electrolyzer-fuel cell prototype can satisfy the electrical energy needs with consumers of small energy consumptions. The water electrolizer converts water to hydrogen and store it at low pressure. The fuel cell runs with the same hydrogen, converting it back to water and simultaneously electrical power to power a portable device. The solar-hydrogen-fuel cell technology will have an impact on the global energy scenario that it is presented as a renewable energy source of energy.

Acknowledgements

This work was supported by grant No. 46094 from Mexican Council of Science and Technology, CONACYT. We thank Prof. Y. Matzumoto by the donation of the photovoltaic module.

References

1. Nowotny J.; Sorrell C.C.; Sheppard L.R.; Bak T. *Int. J. Hydrogen Energ.* **2005**, *30*, 521-544.
2. Orecchini, F.; Santiangeli A.; Dell´Era A. *J. Fuel Cell Sci. Technol*. **2006**, *3*, 75-82.
3. Barbir, F. *Sol. Energy* **2005**, *78*, 661-669.
4. Aurora, P.H.; Duffy, J.J. *Adv. Sol. Energy* **2005**, *16*, 371-421.
5. Grigoriev, S.A.; Porembsky, V.I.; Fateev, V.N. *Int. J. Hydrogen Energ.* **2006**, *31*, 171-175.
6. Barreto, L.; Makihira, A.; Riahi, *Int. J. Hydrogen Energ.* **2003**, *28*, 267-284
7. Plzak,V.; Rohland,B.; Wendt, H. *Modern Aspects Electrochem.* **1994**, *26*, 105-163.
8. Suárez-Alcántara, K.; Rodríguez-Castellanos, A.; Dante, R.; Solora-Feria, O. *J. Power Sources* **2006**, *157*, 114-120.
9. Dante R.; Lehmann, J.; Solorza-Feria, O. *J. Appl. Electrochem.* **2005**, *35*, 327-337.
10. González-Huerta, R.G.; Chávez-Carvayar, J.A.; Solorza-Feria, O. *J. Power Sources* **2006**, *153*, 11-17.
11. Paganin V.A.; Ticianelli, E.A.; González E.R. *J. Appl. Electrochem*., **1996**, *26*, 297-304.
12. Lee, H.K.; Choi, H.Y.; Choi, K.H.; Park, J.H.; Lee, T.H. *J. Power Sources* **2004**, *132* , 92-98.