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Solar Energy Storage by Fuel Cell Technology at Abomey-Calavi (Benin)

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Abstract

West Africa has a great amount of sunshine power, varying between 5 $kWh.m^{-2}.day^{-1}$ and 7 $kWh.m^{-2}.day^{-1}$. This power constitutes high energy source in the region. However, several locations in that area have no access to energy because of the lack of suitable technology and projects exploiting the source. The fundamental problem related to sun power or to renewable energies in general is the lack of efficient technology for energy storage. Batteries are generally used for this storage, but once charged, the excess of the energy from the solar photovoltaic panels (PV) is lost. Therefore, it is very important to find a system to recover the excess in order to optimize its use. In this context, hydrogen is considered a very promising candidate to fulfill this function and could become a highly developed energy vector in the future. The very numerous works undertaken over the past decade for the production of electricity by hydrogen fuel cells bear witness to this. The objective of this study is to test a more reliable solar energy storage system by using fuel cell technology. To achieve this, three steps have been necessary: (i) make an electrolyser using materials, (ii) produce hydrogen using a system of PV panels and (iii) convert the hydrogen produced into electricity through a fuel cell. The results obtained indicate a production of 0.020m^3 of hydrogen after 150 min with a yield of 85.86%. The production of electricity by a 2 V fuel cell gives an efficiency of 0.0042%. Even if this value is low, a part of the lost energy has been recovered. In view of these results, the improvement of the device for converting chemical energy into electricity deserves to be deeply explored in West Africa.

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1. Introduction

In recent years, issues related to the energy transition and the carbon-free energy production have aroused several interests and reflections [1]. Indeed, fossil fuels are more than ever, largely responsible for the pollution of the atmosphere and the main cause of global warming. The massive introduction of electricity based on renewable energies such as solar energy in the production of power has therefore become a priority for the states. With the quick industrial advancement and decreasing costs, they will play an important role in future energy frameworks [2]. However, the development of these sources of energy, with an intermittent regime, requires the use of reliable storage means in order to avoid the problem of destabilization of the distribution network and to make this production suitable to consumer's demand [1]. This has therefore led to the emergence of storage as a crucial element in the management

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of energy from renewable sources, allowing energy to be evacuated into the grid during peak hours when it is more valuable. The use of energy storage techniques is then becoming increasingly essential to ensure the accessibility of electrical energy in remote regions [3]. Lead-acid batteries, which are among the most widely used solar components, cannot withstand high cycle rates, nor store a large amount of energy in a small volume [3]. This is why other types of storage technologies are being developed and implemented. In this context, the hydrogen synthesized from this renewable electricity is considered to be a fairly important storage vector [4]. The combination of solar PV and fuel cell power could offer a feasible solution to the challenge of continuous power supply, especially in geographic areas where renewable resources are abundantly available [4, 5], as in West Africa. The depletion of fossil fuel skocks consequently places hydrogen as one of the major energy carriers of the future and the electrolysis of water at low temperature indeed offers prospects for the future with high potential [6, 7]. Discovered by Sir William Grove in 1839, the concern of the fuel cell is not a recent technology. It has been the subject of numerous works since centuries. Today, several researchers and industrial companies are still working constantly, giving much more interest to hydrogen production in order to improve energy storage's performance.

Authors, such as Faias *et al.* [8], Achkari & Fadar [3], Ibrahim *et al.* [9], Ofualagba *et al.* [10], Zhang *et al.* [11], Staffell *et al.* [12] , Okolie *et al.* [13], Yue *et al.* [14] found that fuel cell technology is too expensive to compete with cheap methods of generating and storing electricity, but its future development and its advantages need its integration into the list of the main suitable renewable energy sources. Other authors have demonstrated the interest of fuel cell application in micro grid systems, based on some attractive characteristics such as being a clean, non-polluting and highly flexible energy resource [5]. Pellow *et al.* [15] estimate that energy storage with a regenerative hydrogen fuel cell represents an attractive technology to reach efficient energy storage. It can lead to the development of more sustainable, efficient and robust hybrid renewable energy systems. According to Singla *et al.* [4] and Belmonte *et al.* [15], Benchrifa *et al.* [1], Derbal *et al.* [17], the production of hydrogen by thermochemical cycles is more promising than the conventional methods of reforming and gasification of fossil resources with the advantage of having lower impact on the environment. Rabih [6] has contributed to a better understanding of the electrochemical phenomena, responsible of the storage and release of electricity as well as the conversion of chemical energy into electrical energy. As for Akinsola *et al.* [18], they constructed a fuel cell using three different materials with different electrodes ((Bitter leaf and Copper electrodes (BCu), Bitter leaf and Carbon electrodes (BC) and Water leaf and Carbon electrodes (WC)). The authors then noticed that the cells made from bitter leaf with a carbon electrode have the highest open circuit voltage, short circuit current and generated power and increase with time. It is clear that the storage of energy from the production of hydrogen by the electrolysis of water and its conversion into electricity via the fuel cell is a technology which deserves special attention for its use in the optimal evacuation of electrical energy produced from renewable energy sources. Unfortunately, in Benin, as in many West African countries the technology is still at an embryonic stage and little work has focused on this domain of research in order to ensure its mastery such as the studies of Fopah-Lele *et al.* [19], Jumare [20]. The objective of this study is to produce hydrogen from the electrolysis of water in order to supply a fuel cell for the production of electricity. The renewable energy source used is a solar field installed to supply the Physics Department in the University of Abomey-Calavi. The electrolyser was made using a well-defined method with suitable materials. The quantity of hydrogen produced according to the chosen experimental protocol is measured using a gas recorder and is stored in an air chamber. From a proton exchange fuel cell (PEM) powered by the air chamber, electricity is produced. Finally, the production yields of hydrogen and electricity are evaluated.

2. Materials and Methods

2.1. Materials

2.1.1. The electrolyser

The production of hydrogen from the electrolysis of water requires the construction of an electrolyser. The material used for this purpose is presented in figure 1. It is composed of plexiglass, vices, nuts, seals, stainless steel plates, a connection pipe, end fittings, a valve and an air chamber.

2.1.2. The Gas logger

The gas recorder used during the experiment is presented in figure 2. Its essential characteristics are as follows: $P_{max} = 0.5bar$; $Q_{max} = 6m^3.h^{-1}$; $Q_{min} = 0.04m^3.h^{-1}$; $Q_t = 0.6m^3.h^{-1}$.

2.1.3. The Fuel cell

Figure 3 shows the fuel cell (*PHYWE, PEM fuel cell, Order Number : 06747.00, Germany*) that was used to generate electricity in this study. It is a proton exchange membrane (PEM) battery with a voltage equal to 2 V.

2.2. Methods

The experimental protocol for the realization of the electrolyser, production and storage of hydrogen as well as the production of electricity is presented in sections 2.2.1, 2.2.2 and 2.2.3. During the experiment, we can enumerate two phases which are not synchronized. First, hydrogen is produced and stored. Then this gas stored at the end of this first phase is used to produce electricity. The yield calculation method for the various operations mentioned above is set out in section 2.2.4.

2.2.1. Realization of the electrolyser

For the realization of the electrolyser, we first took the measurements of various samples of materials. The cutting of the stainless-steel plates and the plexiglass according to the dimensions (1cm by 1cm by 2mn thick for the stainless-steel plates and 13cm by 13cm by 1cm thick for the plexiglass) was carried out. The stainless-steel plates and the two pieces of Plexiglas

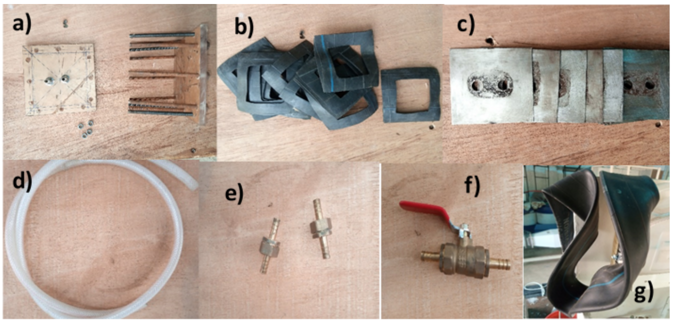

Figure 1: Material used to build the electrolyser (a) Plexiglas, screws and nuts, (b) Gaskets, (c) Stainless steel plates, (d) Connection pipe, (e) End caps, (f) Valve and g) inner tube

Figure 2: Gas Logger

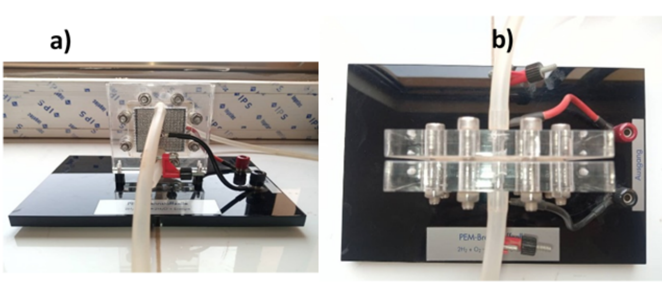

Figure 3: Fuel cell : (a) view from the side and (b) View from the top

have been perforated. The stainless-steel plates were then arranged one after the other, leaving between them approximately 2 mm of space occupied by rubber seals serving as insulation. Everything is held together by the two pieces of plexiglas. We thus obtain the electrolyser illustrated in figure 4.

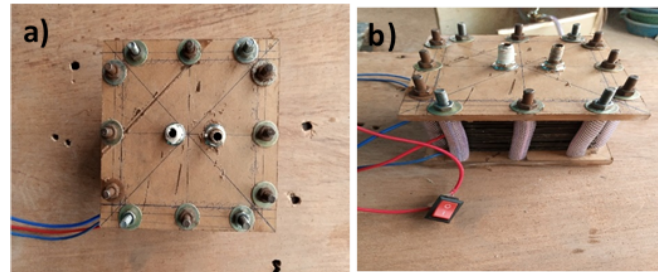

Figure 4: Electrolyser : (a) view from the top, (b) view from the side

2.2.2. *Production of hydrogen by the electrolysis of water*

A very specific protocol was followed for the production of hydrogen:

- Measure a mass m= 4g of sodium bicarbonate in a tank;
- Add 1.5 l of water to the same tank, shake to homogenize;
- Carry out the assembly by placing a voltmeter in parallel with the terminals of the electrolyser to measure the electrical voltage;
- Measure current intensity over time;
- Close the circuit and start the stopwatch;
- During the experiment, check and note the value of the voltage U and the intensity I;
- Measure the amount of gas produced using the gas logger;
- Estimate production time.

The electrolyser is powered by a mini solar field made up of 8 power solar panels of 180 Wc each installed on the roof of the Physics Department. The current supplied by this source varies during the day. Figure 5 shows the assembly carried out as well as the the power source of the electrolyser. Under the effect of gravity, the mixture contained in the tank (1) reaches the level of the electrolyser (5) thanks to the connection pipe (3). This mixture undergoes the action of electric current to form a gaseous mixture consisting essentially of hydrogen and oxygen. This gaseous mixture reaches the bottom of the bottle containing water (7) where part of the oxygen dissolves, but the hydrogen which cannot dissolve rises to the surface creating bubbles. It thus continues on its way through the gas meter (8) to be finally stored in the air chamber (2).

2.2.3. *Production of electricity by the fuel cell*

The production of electricity by the fuel cell takes place in several stages. It is:

- Perform the purge (supply the cell with hydrogen for a few seconds to remove impurities from the cell);
- Close the lower fuel cell valves;
- Connect the hydrogen tank to the pipe on the anode side;

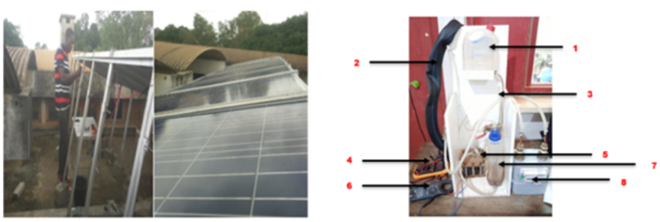

Figure 5: : Hydrogen production and storage system: (1) Electrolytic solution tank, (2) Air chamber, (3) Connection pipe, (4) Multimeter, (5) Electrolyzer, (6) Current clamp, (7) Bottle containing water, (8) Gas logger

- The pipe on the cathode side is supplied with oxygen from the air

The fuel cell is therefore supplied at the anode by the hydrogen produced and at the cathode by the oxygen in the air. The latter mounted in series with a resistor allowed us to know the variation of the voltage and the intensity produced by the battery as a function of time. Figure 6 presents an overview of the test bench made for the production of electricity.

2.2.4. Estimation of the efficiency of the electrolyser and the fuel cell

During electrolysis of water, the amount of hydrogen released responds to Faraday's first law which states that the amount of substance released during electrolysis at an electrode is proportional to time and electric current. The amount of electricity (Q) carried by a current (I) for a duration (Δt) is given by equation 1:

$$Q = I \times \Delta t \tag{1}$$

The experiment lasted for Δt =150 minutes for a average current evaluated at I = 1.64 A and an average voltage of U = 37 V. The hydrogen production yield is given by [21]:

$$r_1 = \frac{V\left(H_2 experimental\right)}{V\left(H_2 theorical\right)} \tag{2}$$

$V\left(H_2 experimental\right)$ is the volume of hydrogen produced by the electrolyser. The theoretical hydrogen volume $V(H_2)theorical$ is evaluated as follows:

$$V\left(H_2 theorical\right) = \frac{nQV_m}{zF} \tag{3}$$

V_m is the molar volume ($V_m = 24L.mol^{-1}$), F the Faraday constant, $F = 96,500C.mol^{-1}$ and z is the number of electrons necessary to produce a gas molecule. For hydrogen ($2H^+ + 2e^- \rightarrow H_2$), $z = 2, n$ is the number of positive plates of the electrolyser. In the case of this study n is equal to 7. The efficiency of the fuel cell is given by the ratio between the energy supplied (E_f) by the cell and that received (E_r) during electrolysis:

$$r_2 = \frac{UI\Delta t}{U_p I_p t} \tag{4}$$

Up is the average voltage of the fuel cell evaluated to 0.5 V and Ip the average current (0.1A), t is the duration of the electricity production experience by the fuel cell (480s).

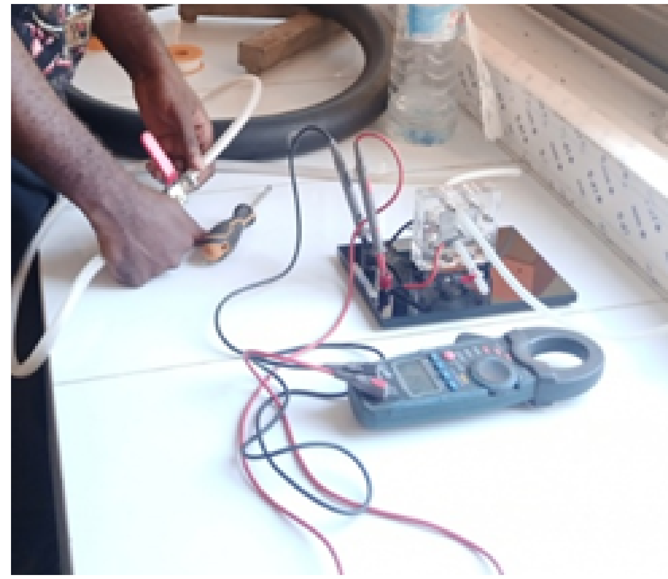

Figure 6: : Electricity production by the fuel cell

3. Results and discussion

3.1. Results

3.1.1. Evolution of hydrogen production

The volume of hydrogen produced noted during the experiment enabled us to collect data on the evolution of this production over time. These data made it possible to obtain the figure 7.

At the end of the 150 min of water electrolysis, a volume of 0.02 m^3 of cumulative hydrogen was produced. This accumulation can be adjusted by simple linear regression. Three production accumulation phases can be reported (0-50min; 50-100min; 100-150min). During the first 50 minutes, the cumulative volume of hydrogen has a lower slope evaluated at $8.8 \times 10^{-5} m^3.min^{-1}$. The hydrogen production at the end of this period is estimated at 0.0044 m^3 according to the graph in figure 7. The following 50 min show a less marked linearity in the hydrogen production with a higher slope of the cumulation estimated at $1.12.10^{-4} m^3.min^{-1}$. Indeed, between 50 and 80 min, there is an increase in the accumulation of hydrogen evaluated at 39.73%. But between 80 and 90 min there is a sudden jump in the total from 0.0073 m^3 to 0.0096 m^3 evaluated at 23.95%. From 90 min to 100 min, there is a very slight increase in the cumulative gas production (0.096 to 0.01 m^3). During the last phase (100 min to 150 min), the production of hydrogen doubled. It went from 0.01 m^3 to 0.02 m^3 with a slope of $2.10^{-4} m^3.min^{-1}$. We therefore observe an increase in the evolution slope of the cumulative hydrogen production from $8.8.10^{-5} m^3.min^{-1}$ to $2 \times 10^{-4} m^3.min^{-1}$ during the three phases. The instantaneous quantity of hydrogen produced and stored is not constant but therefore increases over time. These results are confirmed by the work of Rabih [6].

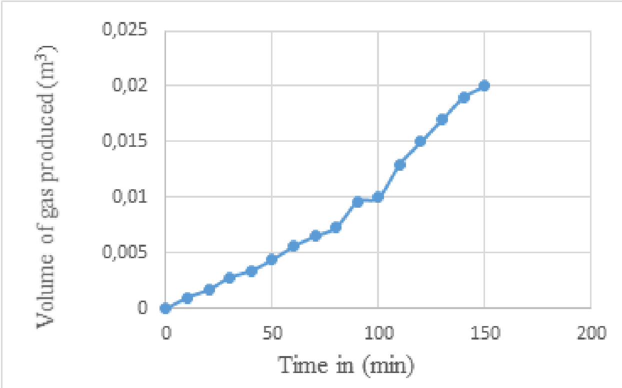

Figure 7: : Evolution of the volume of hydrogen produced as a function of time

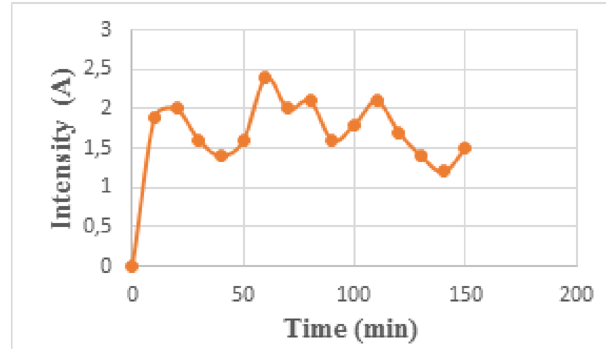

Figure 8: : Current intensity as a function of time

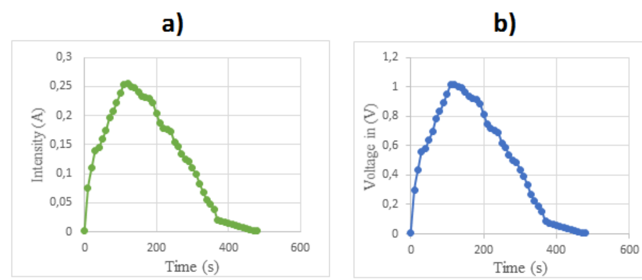

Figure 9: : Electrical quantities measured during the production of electricity by the fuel cell as a function of time, a) Voltage produced by the fuel cell and b) Intensity produced by the fuel cell

3.1.2. *Variation of the intensity of the current at the level of the electrolyser*

During the hydrogen production phase, the intensity passing through the electrolyser varied as a function of time. Figure 8 illustrates this variation over the duration of the experiment.

There is a fluctuation of the intensity of the current over time. It reaches its peak after 60 min of experimentation around 2.4 A. The lowest value of the intensity of the current after the start of the operation is 1.2 A observed after 140 min of hydrogen production. This variation in the intensity of the current at the level of the electrolyser would be due to the intermittence of the sunshine which does not prevent the evolution of the production of hydrogen over time. During the experiment, it was also noticed that a decrease in the intensity of the current lowers the production and that an increase leads to an increase in the production. This observation is true because the volume of hydrogen produced at each moment depends on the quantity of electricity. Moreover, in the work of Yue *et al.* [14], the authors state that a higher current defines a higher hydrogen production rate.

3.1.3. *Production of electricity through the fuel cell*

During the experiment, the supplied current and the voltage at the terminals of the fuel cell were measured. The data collected made it possible to obtain the graphs in figure 9.

The voltage and the current intensity measured from the fuel cell show a variation in the form of a bell over time. These two electrical quantities evolve in an increasing way for a period of about 120 s where they reach their peak evaluated at 1.019 V and 0.25 A. After 120 s, the voltage and the intensity decrease until they cancel out after 480 s. As a result, a strong correlation is observed between these two electrical quantities. The voltage across the terminals of the fuel cell is therefore a linear function of the intensity of the current. These results are consistent with the work of Saïsset *et al.* [22] and Soldi *et al.* [21].

3.1.4. *Efficiency of water electrolysis and power generation*

The values of the efficiency of the water electrolysis operation, of the electricity production by the fuel cell and of the whole system are presented in Table 1.

Table 1: Hydrogen and electricity production efficiency

	Hydrogen production	Electricity production	Fuel cell
	(Electrolyser)	(Fuel cell)	electrolyser
Yield (%)	85.86	0.0042	0.36

The efficiency values of water electrolysis were estimated at 85.86%; that of the fuel cell at 0.0042% and the one of the electrolyser-fuel cell at 0.36%. These values are quite low, in particular those of the cell and consequently of the electrolyser-fuel cell system. This could be due to the different losses recorded during the process of transforming chemical energy into electrical energy.

3.2. *Discussion*

The electrolysis of water efficiency values and the production of electricity by the fuel cell are compared with the results obtained in other similar studies encountered in the literature. The different yield values observed are summarized by authors in Table 2.

The values of the production of hydrogen efficiency by the electrolysis of water proposed in the studies of Soldi *et al.* [21] and Laurencelle [24] are between 63 and 85%. These values are

Table 2: Comparison of hydrogen and electricity production yields

Authors	Efficiency of (Electrolyser) (%)	Fuel cell Efficiency (%)	Overall performance (%)
Yilanci *et al.*. [7]	-	-	0.88-9.7
Soldi *et al.* [21]	68.05-85.02	-	4.36-4.99
Tsakiris [23]	-	59	23
Ogawa *et al.* [28]	-	40-55	-
Giddey *et al.* [30]	-	35-45	-
Gautam and Ikram [26]	-	50-60	-
Ceran [27]	-	-	25-45
Pellow *et al.* [15]	-	47	30
Töpler and Lehmann [32]	-	40	-
Hodges *et al.* [31]	-	55	35-39

quite close to that obtained in the present study which is 85.8% and thus confirm our results. In view of these results, the experimental protocol adopted for the realization of the electrolyser can be validated. Several other authors such as Tsakiris [23], Laurencelle [24], Cheung *et al.* [25], Gautam and Ikram [26], Pellow *et al.* [15], Ogawa *et al.* [28], Giddey *et al.* [30], Labbé [29], Hoogers [31], Töpler and Lehmann [32], Hodges *et al.* [33], Stolten *et al.* [34], Srinivasan [35] studied the power generation efficiency of the proton exchange membrane fuel cell. The values proposed by these authors vary from 35% to 60% and are much higher than the yield obtained in this study, evaluated at 0.0042%. It is therefore noted that the greatest losses observed are concentrated during the conversion of chemical energy into electrical energy via the fuel cell. They could be due to the fact that the electrolyser cells do not produce hydrogen at the storage pressure. According to the work of Yilanci *et al.* [7], Soldi *et al.* [21], Tsakiris [23], Laurencelle [24], Ceran [27], Pellow *et al.* [15], Hodges *et al.* [33], Stolten *et al.* [34] the overall efficiency of electricity production from the proton exchange fuel cell is between 0.88% and 39%. This yield, even though low, is much higher than the yield of the present study estimated at 0.36% and is due to the very low yield observed at the level of the battery. However, it should be noted that according to Achkari and Fadar [3], even if the idea of storing energy in hydrogen is not desirable by the authors due to the low yield of the technology, they are convinced that the fuel cell is still likely to play a role in the future due to the large storage potential. Research efforts will undoubtedly lead to its large-scale use in the years to come. The system proposed in this study deserves to be improved in order to increase the efficiency of the conversion of chemical energy into electrical energy. This involves, for instance, reviewing the heat exchange between the electrolyser cells and their environment, monitoring the increase in the operating temperature of the electrolyser and of the battery, which is generally a source of malfunction in system and gas storage pressure.

4. Conclusion

In the present study, electricity was produced by a fuel cell fueled by hydrogen obtained by the electrolysis of water. An experimental protocol was followed both for the realization of the electrolyser and for the production of hydrogen and electricity. The yields of these different operations were evaluated and compared with those proposed in the literature. The main results are as follows:

- After 150 min of experimentation, a quantity of 0.02 m3 of hydrogen gas has been produced and the evolution curve of this production follows a simple linear regression;
- The voltage variation curve as a function of the intensity of the current measured at the terminals of the fuel cell is a linear function;
- The gas and electricity production yields are evaluated at 85.86% and 0.0042% respectively. The overall efficiency of the electrolyser-fuel cell system is estimated at 0.36%. These values except those of the electrolyser are quite low and much lower than those encountered in the literature.

In short, a part of the energy lost by renewable energy systems via batteries can be recovered. The low yield obtained shows that it is necessary to improve the whole system, possibly size and design a fuel cell or optimize the storage of the hydrogen produced. Significant research and development efforts remain to be provided in order to improve the performance of our system and to identify applications that are well suited to their use. Hydrogen, as a storage element and as a fuel, offers a concrete solution to the intermittency of renewable energy sources, energy losses in batteries and the depletion of fossil resources while respecting the environment.

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