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Photovoltaic Hydrogen Production with Commercial Alkaline Electrolysers

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Abstract

Renewable energy sources and Electrolysis generate the so-called green Hydrogen, a zero-emission and potentially fossil fuel independent energy source. However, the inherent variability of the renewable energy sources implies a mode of operation for which most current electrolysers have not been designed. This paper analyses the operation of a water electrolyser fed with photovoltaic (PV) generator electric profile. The system, Integrated by a 1 Nm^3/h Hydrogenics alkaline electrolyser and a 5100 W PV generator with 60 BP585 modules, is installed at the Public University of Navarra (Spain). The PV generator profile fed to the electrolyser is emulated by a custom-made apparatus designed and built by the authors of this paper. The profile is designed according to real irradiance data measured by a calibration cell. The irradiance data are converted to the electric power profile that the PV generator would have delivered in case of having been connected to the electrolyser by means of a DC/DC converter with maximum power point tracking (MPPT). Finally, from previously measured power-current electrolyser characteristic curves, the current profile to be delivered to the electrolyser is obtained and programmed to the electronic device.

The electrolyser was tested for two types of days. During the first day, the irradiance was very stable, whereas during the second day, the irradiance was very variable. The experimental results show an average power consumption rate and an efficiency of 4908 Wh/Nm^3 and 72.1%, on the first day, and 4842 Wh/Nm^3 and 73.3% on the second day. The electrolyser performance was particularly good in spite of the high variability of the electric supply of the second day.

Keywords: water electrolysis, hydrogen, photovoltaic energy, power supply.

1 Introduction

Renewable energies currently represent one of the firmest options of a sustainable energy future both for developed countries (like Germany, Japan, United States, Spain and Denmark) and emerging economies (like China and India). In the Spanish case, renewable energy sources reached quotes of 24% of the power generation in 2008 [1], and are projected to reach 30.3% in 2010. Until recently, most of this renewable energy came from wind farming; however, PV plants are rapidly growing, especially in Spain, reaching quotes close to 3500 MW installed at the end of 2008. The situation is similar in Germany and other developed countries.

Currently, the grid integration of the renewable energies implies certain problems due to their inherent variability. In this context, hydrogen generating systems might play a relevant part stabilizing and reducing this variability. Electrolysers coupled with renewable energy sources would need to operate in a completely different way than they currently do. These electrolysers might have to work under variable and dynamic feeding profiles.

Despite the fact that research on hydrogen and PV energy is relatively recent, there are already numerous literature references to studies of both real and theoretical prototype systems, generally isolated [2]-[5]. These systems usually show the experimental feasibility of hydrogen production and PV energy integration and set the base for the up-scaling effort. This paper contributes to the study of the behaviour of an electrolysis system fed with a PV profile, going one step beyond the study of its technical variability. The present study analyses the functioning of an alkaline electrolyser fed by a PV generator power profile highly variable.

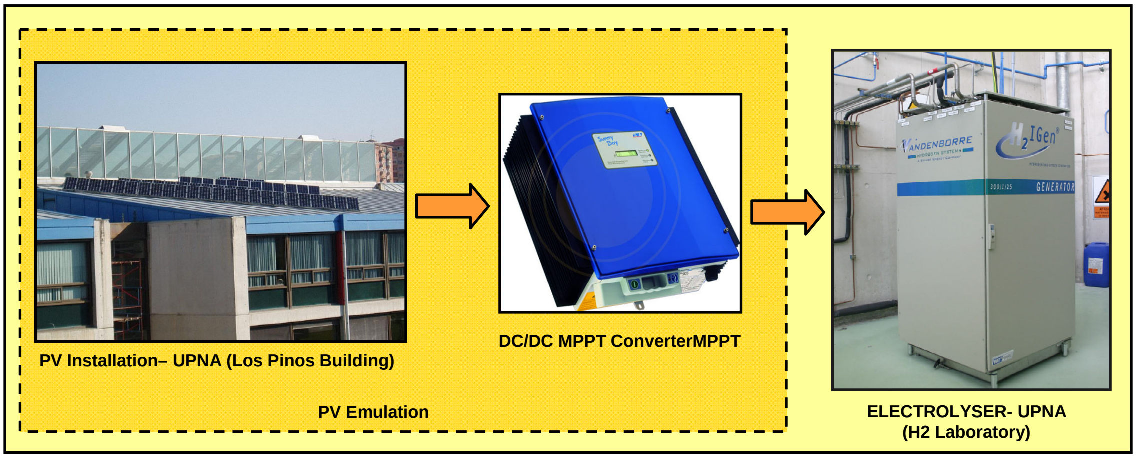

Figure 1: Scheme of the system under analysis.

Figure 1 shows the system under analysis. The system includes a PV system located at the Public University of Navarra Campus (UPNA), a DC/DC converter equipped with maximum power point tracking (MPPT) and an alkaline electrolyser. Considering the variability of PV energy, the system is analyzed at a laboratory scale by means of an emulated PV generator electric profile. As shown in Figure 2, the emulator is an electronic device designed and developed by the authors of this paper with three major functions [6]:

1. To characterize and model alkaline electrolysers
2. To emulate the electric behaviour of renewable energies, particularly, wind and PV, to feed electrolysers and to analyze their response to renewable power supply profiles
3. To emulate different electric profiles from various power supply topologies to evaluate and to compare the influence of the conversion stage on the behaviour and the efficiency of an electrolyser

The 10 kW nominal power emulator enables the simulation of current and voltages up to 250 A and 70 V. It has already been tested to evaluate the functioning of a wind powered electrolyser [7] as well as to compare the efficiency of the electrolyser under various feeding source topologies [8]. In this paper, the device is used to characterize the electrolyser under analysis and to study the electrolyser behaviour if fed by a PV energy source.

The micro-controller of the system enables to customize the electrolyser feeding profile, to sensor and to monitor variables, to manage the data logging and to program the protection actions according to the selected recorded variables. The system has been validated by simulation and experimental tests under different functioning settings [8] and the system capacity to emulate highly variable power sources has previously been demonstrated for renewable and particularly for PV systems.

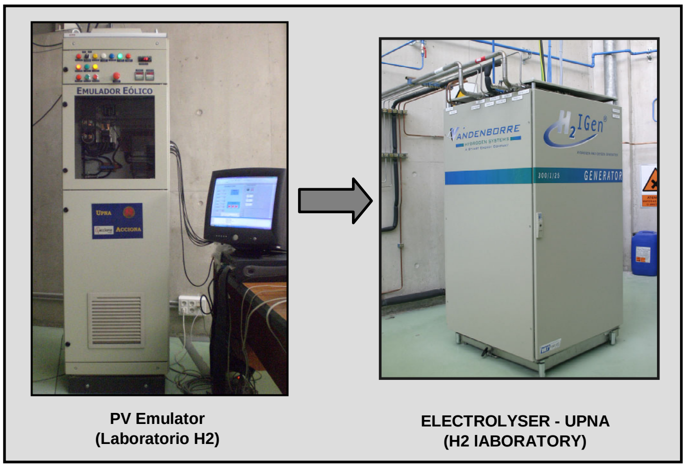

Figure 2: Electronic apparatus to emulate the PV system.

2 Test of an Alkaline Electrolyser Fed by a PV Solar Energy Profile

2.1 System description and characterization

This paper deals with the analysis of the system pictured in Figure 1. The system consists of a PV generator and an alkaline electrolyser to produce hydrogen. Both devices are installed at the Public University of Navarra (UPNA) Campus. The PV modules are installed on the roof of the Los Pinos building (Department of Electric and Electronic Engineering) and are oriented to the South, tilted 30º from the ground. The PV generator, of a peak power of 5100 W, consists of 60 modules BP585.

The PV system is modular, and is arranged on 15 branches with 4 modules connected in series each. The module electric specifications under standard conditions (T_S = 25ºC and E_S = 1000 W/m^2) are: a peak power P_{MS} = 85 W with a current I_{MS} = 4.7 A and a voltage V_{MS} = 18 V, a short-circuit current I_{SCS} = 5 A, an open circuit voltage V_{OCS} = 22 V, an average efficiency of 13.5% and a power variability coefficient as a function of temperature γ = -0.5%/ºC.

To characterize the electric behaviour of the PV generator, the current-voltage I-V characteristic curve of a module has been analytically modelled according to the 5 parameters that characterize the single exponential equation. Figure 3 shows the characteristic I-V and P-V curves of a BP585 module under standard conditions. The electric characteristics calculated concur with the maker specifications.

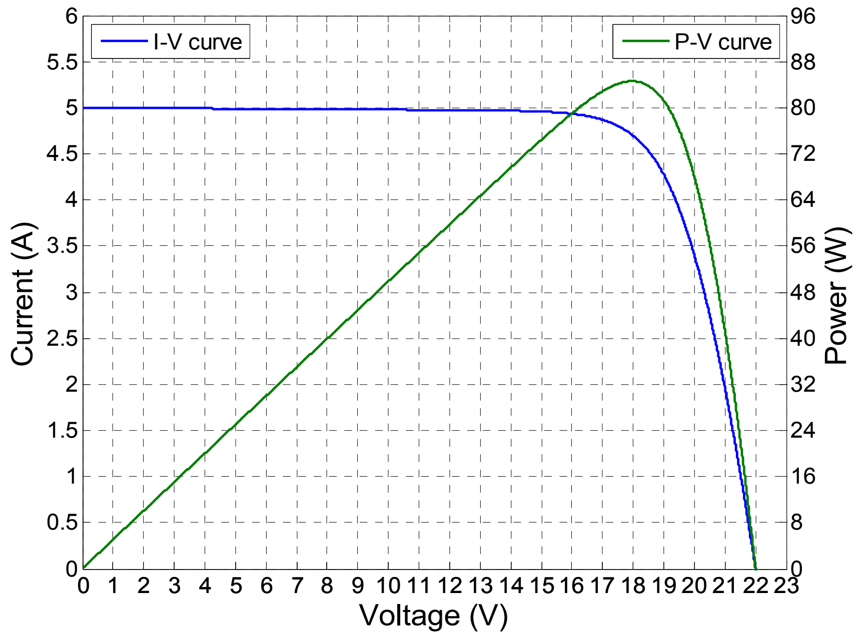

Figure 3: Characterization of the PV BP585 module: I-V and P-V curves under standard conditions.

The electrolyser is a H2 IGen 300/1/25 Hydrogenics model. The apparatus is located at the Hydrogen Laboratory of the UPNA. It is an alkaline electrolyser; the working pressure range goes from 5 to 26 bar and the temperature working range from 2ºC to 65ºC. The electrolysis bipolar stack consists of 22 round cells of 300 cm^2 each, connected in series. Each cell consists of two electrodes (an anode and a cathode) separated by an ion exchange inorganic membrane, assembled on a zero-gap configuration. On a zero-gap configuration the distance between the elements of the stack is minimized in order to maximize its efficiency. The electrolyte is a KOH 30% wg. solution. To maintain the conductivity of the water of the process bellow 5 µS/cm an ion exchange resin bed was set in place. This particular electrolyser model does not require pumps either to recirculate the electrolyte or to replenish water. The nominal hydrogen production rate is 1 Nm^3/h, which is equivalent to a 120 A DC current. The hydrogen production rate ranges from 25% (30 A DC) to 100% (120 A DC). Last, the stack energy consumption rate is 4.3 kWh/Nm^3, whereas the complete system energy consumption rate (including balance of plant and instrumentation) is 4.9 kWh/Nm^3.

The experimental characterization of the electric behaviour of the electrolyser was carried out using the electronic equipment described on Section 1. During the tests the current was swept from 0 A to 120 A (nominal current) at temperatures ranging from 15ºC to 65ºC and the pressure was kept constant at 20 bar. Each test measured both the current and the power of both the stack and the electrolyser. Figure 4 shows the evolution of the power-current (P-I) curves of the electrolyser as a function of temperature.

As shown in Figure 4, as the temperature raises the power consumption decreases, being this effect more noticeable at low temperatures. This trend, especially at high currents (from 50 A to 120 A), is due to the variability of the electrolyte conductivity with temperature. The electrolyte conductivity is directly proportional to the temperature, and as the conductivity of the electrolyte increases the process energy losses decrease. Illustratively, at 120 A the electrolyser power consumption is 5.6% higher at 15ºC (4765 W) than at 65ºC (4495 W).

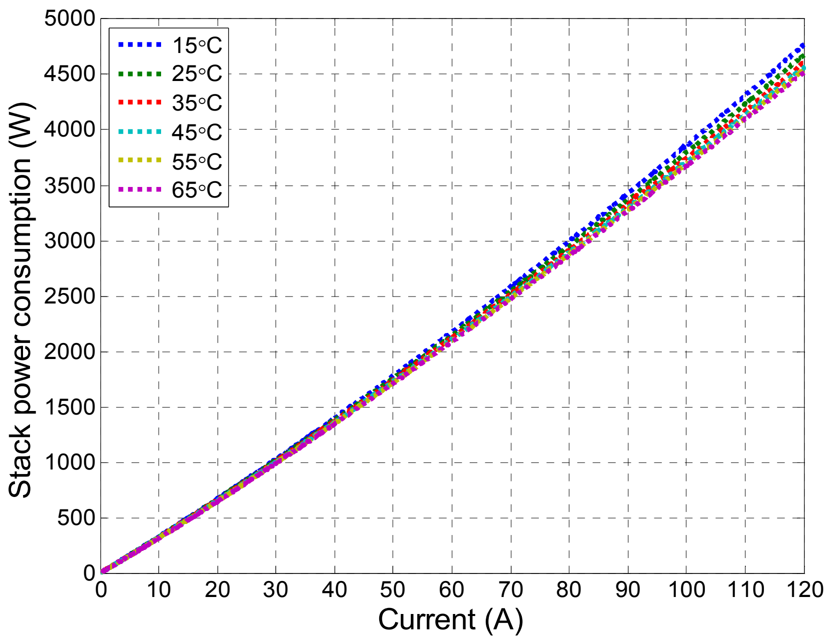

Figure 4: Electrolyser electric behaviour (P-I) as a function of temperature at 20bar.

2.2 Methodology

In order to analyze the electrochemical behaviour of an alkaline electrolyser coupled with a PV power supply, the electrolyser was fed by the supply emulator, assuming the PV generator was connected to a DC/DC MPPT converter as previously shown in Figure 1.

To emulate the PV supply source, the irradiance incident on the PV generator was measured indirectly by means of the short-circuit current I_{SC} of a permanently short-circuited module previously calibrated. Thus, using the digital power meter WT1600, the I_{SC} data were recorded at a frequency of 1 s and stored on a database. The irradiance E at time t can be calculated as:

$$E = \frac{I_{SC}\, E_S}{I_{SCS}} \quad (1)$$

Once the irradiance is known, the maximum power P_M injected to the electrolyser by the DC/DC MPPT converter can be calculated. The PV generator temperature is required. This temperature was obtained from the ETSIA-UPNA meteorological station measurements. The generator PV module working temperature is calculated from the outdoors temperature, T_a, and the irradiance, E, according to:

$$T_m = T_a + \left(\frac{TONC - 20^{\circ} C}{800\ Wm^{-2}} \right) E \tag{2}$$

where TONC is the nominal operation temperature of the modules (47ºC).

Finally, the maximum power P_M is calculated according to the following equation which accounts for the effects of irradiance and ambience temperature upon the power under standard conditions:

$$P_M = N_P\ P_{MS} \left(\frac{E}{E_S} \right) \left(\frac{100 + \gamma\ (T_m - T_S)}{100} \right) \tag{3}$$

where N_P is the number of modules of the PV generator, 59 in this case (since 1 was used to measure the I_{SC}).

To emulate a PV energy source, the renewable energy source emulator has to feed the electrolyser with the P_M calculated according to equation (3), hence the current to be supplied by the emulator to the electrolyser needs to be calculated. The electrolyser characteristic P-I curve can be expressed according to [9]:

$$P_E = (V_{rev} + r\,(T_E)\, I_E + s(T_E) \log(t\,(T_E)\, I_E + 1))\, I_E \tag{4}$$

where P_E and I_E are the electric variables of the electrolysis stack and V_{rev} is the reversible voltage. Parameters r, s, and t, depend on the process temperature (T_E) and are obtained adjusting the P-I curves shown in Figure 4 to equation (4) by non-linear numerical analysis methods. From here, the current that the emulator needs to feed the electrolyser (I_E) is calculated by equalizing the PV power to the electrolyser power ($P_E = P_M$) and then solving equation (4) by numerical iteration.

The calculations described in this section were programmed onto the micro-processor of the emulator system and are calculated online in real time, using the experimental vectors I_{SC} and T_a as seeds. The stack temperature in real time needs to be known in order to calculate the reference current ($I_{ref} = I_E$) to emulate at each instant (1 s).

2.3 Results and Discussion

To evaluate the electrolyser response to various working conditions of the PV generator, two particular days of 2007 were simulated: March 11th (1st day) and April 5th (2nd day). The experimental data (I_{SC} y T_a) were measured from 7:00a.m till 20:00p.m. Figure 5 shows the measured irradiance of both dates. Noticeably, the 1st day was selected because of its unusual irradiance stability; whereas the 2nd day was selected for the opposite reason, since it was a day of particularly high irradiance variability. It can be observed, the foreseeable evolution of the irradiance with the sunlight, and in the 2nd day case, the high irradiance variability due to cloudiness. The variability registered along the 2nd day peaks at 800 W/m^2 (ranging from 300 W/m^2 to 1100 W/m^2) at 12:30pm in less than a minute.

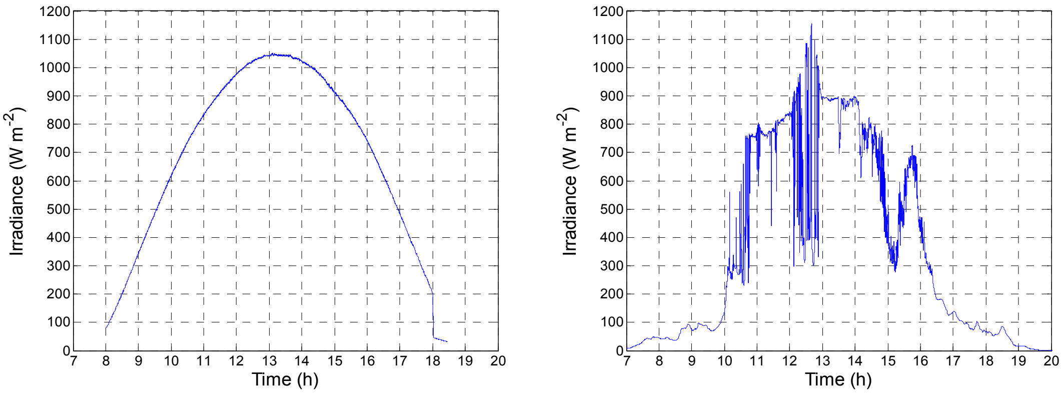

Figure 5: Irradiance. Left: March 11th (1st day). Right: April 5th (2nd day).

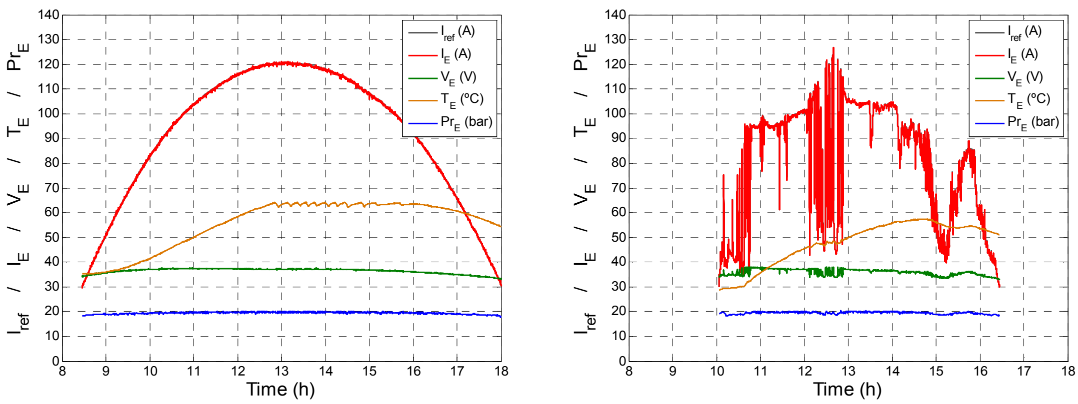

Figure 6: PV tests on both days (Left: 1st day; Right: 2nd day). Reference current (I_{ref}), current (I_E), and voltage (V_E) of the electrolysis stack; temperature (T_E) and pressure (P_{rE}) of the process.

Figure 6 shows the reference current (I_{ref}), the electrolyser electrical variables (I_E and V_E) and the evolution of the temperature T_E and the pressure P_{rE} of the electrolytic process during the tests of both days. First, it can be observed that the graphs depict how the PV energy source has been satisfactory simulated, since I_E, which profile is similar to the irradiance profile, consistently tracks the reference current (I_{ref} is overlapped by I_E). Due to the low limit of the electrolyser functioning settings (corresponding to I_E=30A), hydrogen is produced from 8:27a.m until 17:55p.m during the 1st day, and from 10:03a.m until the 16:27p.m on the 2nd day. The voltage V_E varies similarly to the current due to the electrolyser ohmic behaviour. During the tests, the pressure is kept relatively stable at about 19.5 bar, with a variability of ±1 bar intrinsic to the process; however, the temperature evolution is coupled with the current I_E (actually, with the power) but slower dynamics.

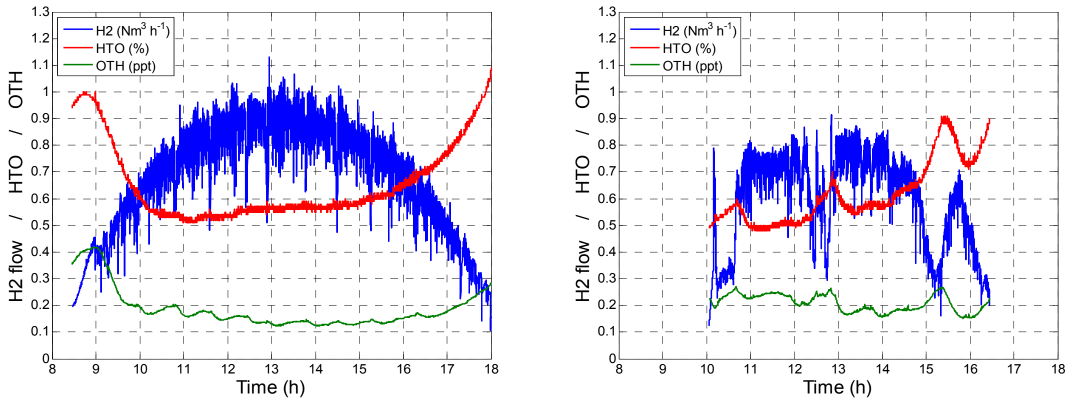

Figure 7: PV Energy source tests for both days (Left: 1st day; Right: 2nd day). Hydrogen production rate (H2), Oxygen purity (HTO) and Hydrogen purity (OTH).

Figure 7 shows the hydrogen production rate (H2) during the PV energy source emulation for both days, as well as the gas purity (Hydrogen: OTH; Oxygen: HTO). It can be observed, how the H2 production rate trails the current profile on Figure 6 although with strong variations of the amplitude due to the repetitive opening and closing of the valves regulating the electrolyte level in the electrolyser. It can also be noted, comparing Figures 6 and 7, that the hydrogen dynamics are decoupled from the I_E, since the electrical dynamics can be significantly faster than those associated to fluids. Concerning the purity of the gases, note how the OTH and HTO trends are inversely proportional to the hydrogen production. The higher the H2 production rate is, the more rapidly the gases are displaced from the stack and the less time the gases stay in the anodic and cathodic compartments; thus, the lower the mixing of the gases diffused through the gas separator membrane is. On the 1st day, the OTH ranges from 0.13 – 0.42 ppt (part per thousand), and HTO ranges from 0.52 to 1.1%. On the 2nd day, OTH ranges from 0.16 – 0.25 ppt, and HTO ranges from 0.5 to 0.9%. Comparing the gas impurity data along the various tests, it is concluded that the HTO is about 40 times higher than the OTH during the 1st day; and about 30 times higher during the 2nd day. The difference between the gas purities is due to the significantly higher diffusion coefficient of hydrogen through the gas separator membrane of the electrolytic cells than oxygen, because it is such a smaller particle (2 g/mol of hydrogen versus 16 g/mol of oxygen).

Last, the average energy consumption rate per Nm^3 (C_E) and efficiency were calculated (η_E). The stack C_E was calculated according to:

$$C_E = \frac{\int_0^{\Delta t} I_E \, V_E \, dt}{\int_0^{\Delta t} H2 \, dt} \tag{5}$$

where Δt is the test time elapsed (9h and 28’ on the 1st day; and 6h and 24’ on the 2nd day). The efficiency (η_E) was calculated based on the hydrogen high heating value (*HHV*, 3.5 kWh/Nm^3):

$$\eta_E = 100 \frac{\text{HHV of 1Nm}^3}{C_E} \tag{6}$$

The results obtained on the test carried out during the 1st day; that is to say, with low irradiance variability, yielded: C_E = 4908 Wh/Nm^3 and η_E = 72.1%. Whereas the results on the 2nd day yielded: C_E = 4842 Wh/Nm^3 y η_E = 73.3%. Comparing both sets of results, it can be concluded that the variability of the working conditions has not negatively affected the electrolyser behaviour. The electrolyser dynamics is coupled to the variations but do not affect the energy efficiency. The minimal difference on the efficiency rate obtained is a result of the electrolyser functioning dependence on the instant current value applied. Finally, it is noteworthy that in any case, the efficiency of both tests was high.

3 Conclusions

This paper studies the behaviour of a 1 Nm^3/h alkaline electrolyser fed by a 5.1 kW PV system. The PV profile is emulated by a custom-made electronic device, capable as well of characterizing and modelling the electrolyser.

The PV supply profile is defined according to real irradiance measurements that are applied to a real PV installation to calculate what the actual generated electric power would be. The electronic device accordingly emulates the PV profile and feeds it to the electrolyser.0

The simulation was carried out for two different days, representative of fundamentally different working conditions. During the first day, the irradiance barely fluctuates; whereas during the second day, the irradiance is highly variable. The experimental results show how the electrolyser is capable of producing hydrogen even under a highly fluctuating electrical supply. The electrolyser behaviour is satisfactory. The electrolyser efficiency is high and none of the electrolyser production restrictions and protections is set off, despite the fact that the electrolyser is not designed, a priori, to be coupled with renewable energy sources, especially if they present a high variability.

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