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Estimation of Hydrogen Production of a Photovoltaic-Electrolyser direct-coupling system with Fresnel lenses concentrator

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Abstract— **Hydrogen fuel can be produced by using solar electric energy from concentrator photovoltaic (PV) modules for the electrolysis of water without emitting carbon dioxide or requiring fossil fuels. In this paper, an assessment of the technical potential for producing hydrogen from the CPV-EL system is investigated. The present study estimates the amount of hydrogen produced by this system in the site of Bou-Ismail in Algeria using experimental weather data. The system studied in this work is composed of 60 W PV module equipped with Fresnel lenses concentrator connected with units of commercial h-tec 50W StaXX7 PEM electrolyser connected in parallels. The simulation results are presented and discussed.**

Keywords—**Concentrating PV System, Hydrogen production, Modeling, Simulation**

I. Introduction

One of the most promising options for obtaining hydrogen from a clean renewable energy source is by using energy from a photovoltaic generator, via electrolysis. A photovoltaic-hydrogen system (PV-El) usually consists of supplying electric power to a water electrolyser by a PV generator. There are two main kinds of (PV-El) system (Fig.1):

(A) — (PV-El) system with maximum power point tracking (MPPT) system;
(B) — (PV-El) direct-coupling system.

MPPT system usually includes maximum power point tracker and works with direct current/direct current (DC/DC) converter [1,2]. In some MPPT system, an electricity storage device is included [3]. MPPT system makes the whole system more efficient but more complicated and more expensive. From a previous study [pvsec2013, these], the (PV-El) direct-coupling system presents better results in terms of hydrogen production than (PV-El) system with maximum power point tracking (MPPT) system when it is properly configured .

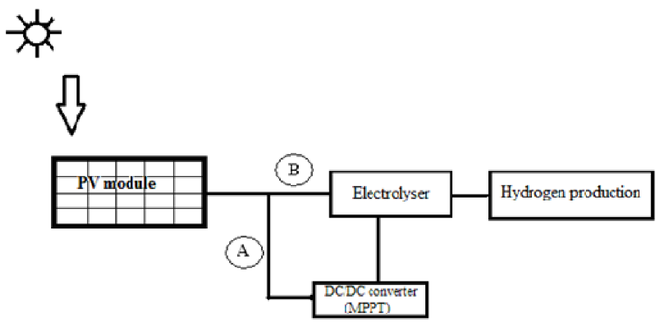

Fig. 1: Schematic of PV hydrogen production system.

The two main components (PV-El) direct-coupling system investigated in this paper are PV array and electrolyser. Besides, improvement of PV collector is important for PV system. One of common methods is to apply a concentrator [4-7]. There are several kinds of concentrators tested in PV systems [8-10]. In literatures, Fresnel lenses concentrator is one of the most common used in concentrating PV (CPV) system [11-12]. Fresnel lenses can generate high solar intensity with smaller focal length, less weight, and lower cost compared to parabolic troughs and dishes, and thick ordinary lenses [12]. The early Fresnel lenses were made of glass and were used mainly for high-temperature applications. More recently, glass Fresnel lenses have been replaced by

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polymer lenses, in particular Poly Methyl Methacrylate (PMMA), which are much lighter and easier to manufacture [13]. Thus a PMMA Fresnel lenses concentrator is applied to a PV-El direct coupling system in this investigation. The PV array receives direct solar irradiation and reflection solar irradiation then delivers electricity energy to the electrolyser. Water is electrolyzed and hydrogen is generated.

For electrolyser, currently most of the commercial water electrolysis technologies use acidic or alkaline electrolyte systems for hydrogen generation. More recently a solid state water electrolysis technology based on polymer electrolyte membrane has been under development and is being commercialised [14-16]. Its operation can be considered to be reverse to that of a PEM fuel cell. The PEM electrolysis systems can respond rapidly to varying power inputs and therefore can be easily integrated with renewable energy systems.

To contribute to the production of hydrogen by renewable energy, this paper proposes to simulate the functioning of a small unit of solar hydrogen production in order to demonstrate the feasibility of such installation and to evaluate the potential of hydrogen production. The hydrogen production unit studied consists of a PV module of 60W equipped with Fresnel lenses concentrator and units of commercial h-tec 50W StaXX7 PEM electrolyser connected in parallels. This work is divided into two parts: a first part devoted to the electrical modelling of each system component followed by a 2nd part on the simulation of the operation. The weather data used in simulation are an experimental data obtained from an experimental setup realize for this study. The simulation results presented in this article are related to the site of Bou-ismail in Algeria.

II. MODELLING

The main components of the (CPV-EL) system are the concentrating photovoltaic (CPV) generator and the electrolyser. In the following sections, the models of the system components are presented.

A. Concentrating Photovoltaic system model

In this study, the PV power generation simulation model consists of two parts, solar radiation on PV module surface and PV generator model.

Solar radiation model on PV module surface

In order to simulate the performance of the hydrogen production system using photovoltaic concentrating energy, it is necessary to have a weather data. In this paper, an experimental study was established to determine the irradiation and temperature under Fresnel lenses photovoltaic concentrator. The apparatus we dispose is constituted of a heliostat (with 02 axes) in which are fixed a PV modules (of poly-Si). On the same plane, other PV modules (of the same technology) are superposed by optical concentrators (Fresnel lenses), in PMMA (Fig. 2, 3 and 4). Type K thermocouples were attached on the top and the bottom of the PV cell. The irradiation was measured using a pyranometer EKO, and using the CM4 pyranometer for concentrated irradiation (~3200w/m², T→ 90°). The data was collected by EKO weather station.

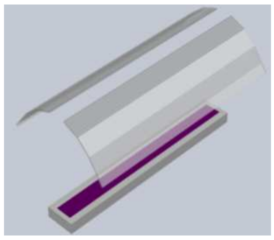

Fig. 2: Fresnel lenses concentrator

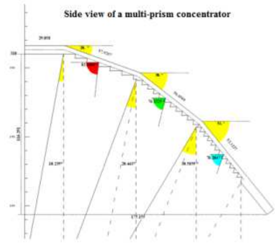

Fig. 3: Side view of a multi-prism concentrator

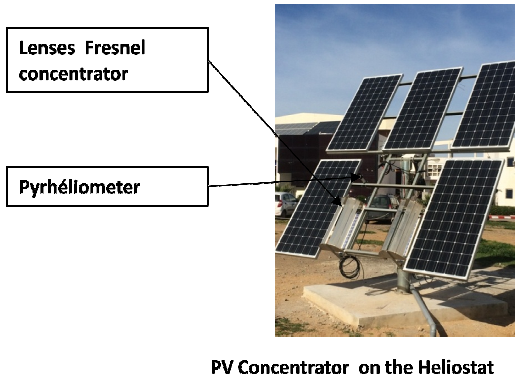

Fig. 4: Scheme of the experimental setup

Photovoltaic generator model

In this study, an explicit model [17] is used to simulate current (I)–voltage (V) characteristics of the modules. The relation between the current *I* and the voltage *V*, in this model, under standards conditions is given by:

$$I = I_{sc,ref}\left[1 - C_1\left(\exp\left(\frac{V}{C_2 V_{oc,ref}}\right) - 1\right)\right] \quad (1)$$

where

$$C_1 = \left(1 - \frac{I_{max,ref}}{I_{sc,ref}}\right)\exp\left(\frac{-V_{max,ref}}{C_2\, V_{oc,ref}}\right) \quad (2)$$

and

$$C_2 = \frac{(V_{max,ref}/V_{oc,ref}) - 1}{\ln\left(1 - (I_{max,ref}/I_{sc,ref}\right)} \quad (3)$$

Under the variable operating conditions of temperature and solar irradiance, the new values of the current (Ipvn) and the voltage (Vpvn) of the PV module/generator are obtained by:

$$I_{pvn} = I + \Delta I \quad (4)$$

$$V_{pvn} = V + \Delta V \quad (5)$$

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ΔI and ΔV represents respectively the variation of the current and voltage according to the temperature and solar radiation, there are given by the following equations [18-20]:

$$\Delta I = \mu_{Isc}\left(\frac{G_\chi}{G_{ref}}\right)\Delta T + \left(\frac{G_\beta}{G_{ref}} - 1\right) I_{sc,ref} \quad (6)$$

$$\Delta V = -0.0539.V_{max,ref}\ \ln\left(\frac{G_\beta}{G_{ref}}\right) - \mu_{voc}\left(T_c - T_{c,ref}\right) \quad (7)$$

$$\Delta T = T_c - T_{c,ref} \quad (8)$$

G_β represents the solar radiation on tilted module plane (W/m^2) and G_{ref} reference solar radiation (1000 W/m^2), $T_{c,ref}$ is reference cell temperature(25°C). μ_{Isc} ,μ_{Voc} are coefficients given by manufacturer's.

T_c, cell operating temperature, is approximately proportional to the incident solar irradiance and is given by [23-25]:

$$T_c = T_a + G_\beta\left(\frac{NOCT - 20}{800}\right) \quad (9)$$

Where T_a is ambient temperature and NOCT is the normal operating cell temperature, which is generally given in the manufacturer's specifications.

In this paper, the studied photovoltaic generator consists of a photovoltaic module type SOLAREX MSX60 of 60 W. The electrical characteristics of the module provided by the manufacturer are the open circuit voltage, $V_{oc,ref}$= 21 V, the short circuit current, $I_{sc,ref}$=3.87 A, the maximum power delivered ,$P_{max,ref}$ = 60 W, and the maximum power voltage and current respectively, $V_{mp,ref}$ = 16.8V and $I_{mp,ref}$ = 3.56A.

B. PEM electrolyser model

In this paper, an empirical model is used to approach electrical behavior of unit of commercial h-tec 50W StaXX7 PEM electrolyser. The unit comprises a stack of seven PEM cells in series. The detail parameters of this type of electrolyser are given in Table 1 and a current–voltage characteristic curve for one stack electrolyser is shown in Fig.5.

TABLE I

SPECIFICATIONS OF THE STAXX7 PEM ELECTROLYSER UNIT [21]

Electrode area	7 cells of 16 cm^2 each
Power	50 W at 14 V DC
Permissible voltage	10.5 - 14.0 V DC
Permissible current	0 - 4.0 A DC
H_2 production	230 cm^3/min

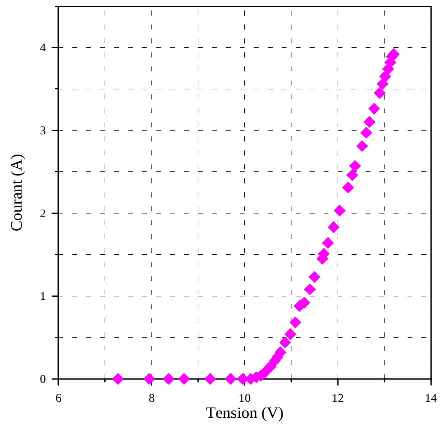

Fig. 5: I-V Characteristic curve of 50 W PEM electrolyser.

In this paper, the I-V characteristic curve of the electrolyser, estabilished in previous study [22], is expressed by a polynomial equation as follows:

$$I_{1S} = \begin{cases} 0 & V_{1S} \le 10 \\ \sum_{i=0}^{4} a_i V_{1S}^i & V_{1S} > 10 \end{cases} \quad (10)$$

Where I_{1S} V_{1S} current and voltage of one stack electrolyser, the a_i are the polynomial coefficients (a_0 = 498,128; a_1 = -159,199; a_2 = 18,828; a_3 = -0,980817; a_4= 0,0191867). with quadratic error, R^2= 0,00192353.

For an electrolyser composed of N_{SEL} stacks in series and N_{pEL} stacks in parallel as shown in Fig.6, the equation (10) can be expressed as follows:

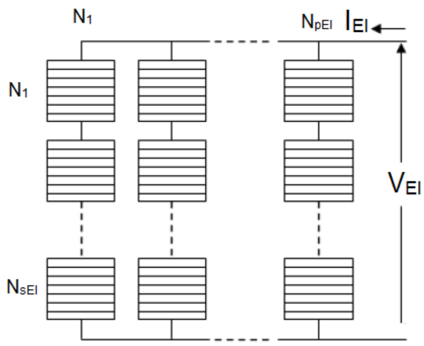

Fig. 6: Block diagram of PEM electrolyser

$$I_{El} = \begin{cases} 0 & V_{El} \le 10 \times N_{sEl} \\ N_{pEl} \times \sum_{i=0}^{4} a_i \left(V_{1S} \times N_{sEl}\right)^i & V_{El} > 10 \times N_{sEl} \end{cases} \quad (11)$$

Estimation of the hydrogen produced

The volume of hydrogen generation (L/h) for one electrolyser stack is estimated by following equation [23]:

$$V_{H_{2,1S}} = 3{,}1939 \times I_{1S} \times \eta_f \quad (12)$$

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Where I_{1S} is the input current of the electrolyser in (A), and η_f is the faradic efficiency of the electrolyser (considered in this study equal to 99%).

For an electrolyser composed of N_{sEL} stacks in series and N_{pEL} stacks in parallel, the equation (6) can be expressed as follows:

$$V_{H_2El} = 3{,}1939 \times N_{sEl} \times I_{El} \times \eta_f \quad (13)$$

C. CPV-EL coupling system model

In the case of study, the CPV module is directly connected to the electrolyser. Thus, graphically, the operating point of the system is defined by the intersection of the curve (I-V) of the CPV generator with the I-V curve of the electrolyser [24]. The direct coupling of the CPV generator to the electrolyser allows writing the following two equations:

$$V_{CPV} = V_{El} \quad , \quad I_{CPV} = I_{El} \quad (14)$$

V_{CPV} and V_{EL} are respectively the CPV generator voltage and the voltage of the electrolyzer,
I_{CPV} and I_{EL} are the current of the CPV generator and the current of the electrolyzer respectively.

The resolution of this nonlinear equation can be achieved by two methods either graphically or by the Newton-Raphson method. In this work, the choice fell on the graphical method for its simplicity and especially for its timeliness.

III. Results Simulation

A. Irradiation and temperature results

As mentioned earlier, the study objective is to analyze the performance of (CPV – EL) system for producing the hydrogen.

As the first step, five (5) parameters are experimentally collected namely: — the global solar irradiation on tilted module G_1, — the global solar irradiation on tilted module and under Fresnel lenses concentrator G_{CPV}, — ambient temperature T_{amb}, — Temperatures below and above the module T_1 and T_2 respectively.

The experimentation for data collection was conducted from May 25 to June 15 on the site of Bou-Ismail in Algeria.

As example, the results obtained at the day of May 27, are shown in Figures 7 and 8.

We can notice from the results that the global solar radiation on a tilted plan and under Fresnel lenses concentration almost tripled to reach a value of 2800W/m^2 compared to the global solar radiation on a tilted plan.

These results are used as inputs to the CPV-EL system model.

B. PV results

In this section are represented the simulation results of the current-voltage characteristics curves of the BPSX 60 PV module.

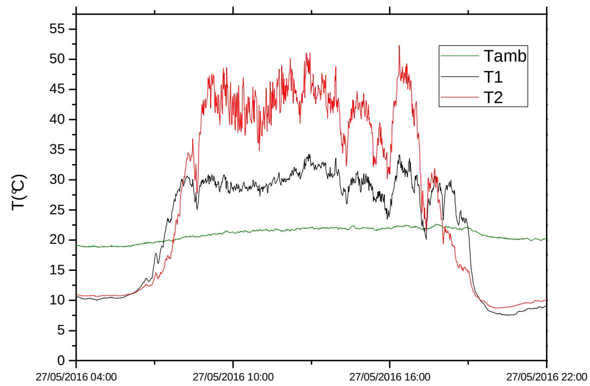

Fig. 7: Experimental measurements of Temperatures of 27/05/2016.

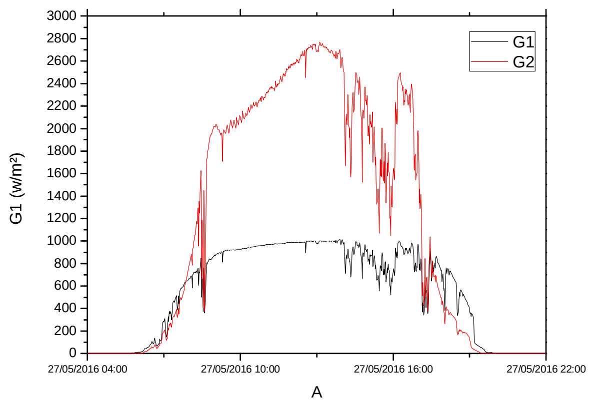

Fig.8**:** Experimental measurements of global irradiation on a titled plane of 27/05/2016

Fig. 9 shows the I-V curves of PV module for different solar radiation levels 100, 300, 500, 700, 900 and 1000 W/m^2. As shown in this figure, at fixed cell temperature, the short circuit current and the open circuit voltage are influenced by the incident solar radiation. The open circuit voltage increases logarithmically by increasing the solar radiation, whereas the short circuit current increases linearly. In addition, under standard conditions, the simulation results closely match those provided in the manufacturer's datasheet.

Fig.10 shows the I-V curves of CPV module for different solar radiation levels 500, 1000, 1500, 2000, 2500 and 3000 W/m^2. One can notice that the power delivered by a CPV module varies between 22 W for solar radiation of 500 W/m^2 and 170 W for solar radiation of 3000W/m^2. The latter value is significantly higher compared to the power that can be absorbed by the electrolyser which is equivalent to 50 W. The electrolyser can be damaged. To avoid this, it is necessary to conduct a sizing of CPV-EL system.

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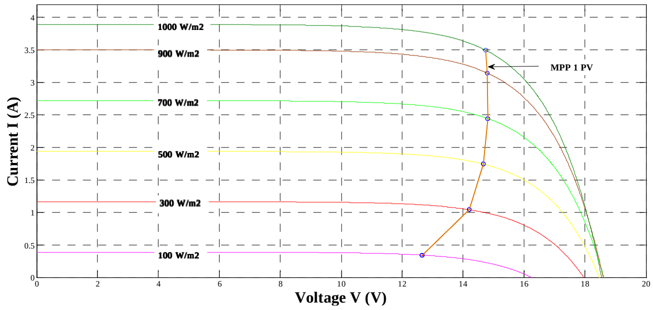

Fig. 9: I-V curves of the BP SX 60 at different levels of solar radiations and a fixed cell temperature of 25 ° C.

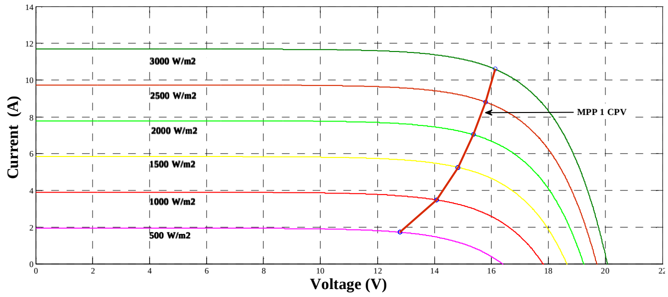

Fig. 10: I-V curves of the CPV module at different levels of solar radiations and a fixed cell temperature of 65 ° C.

C. CPV – EL system sizing results

To match the CPV array output with the electrolyser load, it is first necessary to know the current (I)–voltage (V) characteristic of both the components, to ensure that the PV array is able to supply the minimum cut-in voltage of the electrolyser to initiate the electrolytic action (dissociation of water into oxygen and hydrogen) at all solar irradiances. It is also necessary to ensure that for higher irradiances the output current from the PV array does not exceed the maximum rated current of the electrolyser, since a higher current is likely to damage the electrolyser cell. In this section, some configurations are presented in order to determine the size of electrolyser which can support the CPV module output.

For the combination of one CPV module and one electrolyser stack, the operating curve of the electrolyser and the maximum power point line of the PV output are shown in fig. 11.

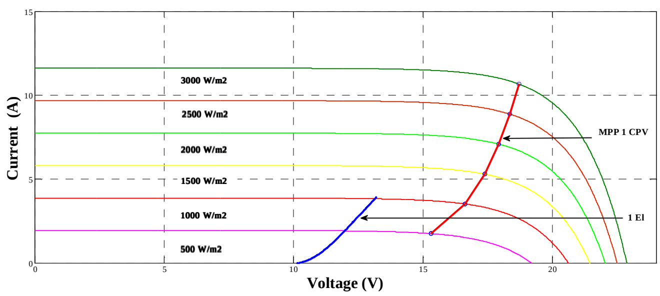

Fig.11: Coupling of one CPV module with one electrolyser stack

From this graph it is clearly visible that for solar irradiance values above 1000 W/m^2 CPV module will deliver more current than the rated values of the electrolyser, which may damage the electrolyser. Hence this combination is not practical.

Since with the previous combination the output of the CPV module is greater than the rated power of the electrolyser at higher irradiances, another electrolyser stack has been added in parallel as a second branch, i.e., one PV module coupled to a bank of two electrolyser stacks connected in parallel (1 CPV–2 ‖ EL). The resulting I-V curves shows that for solar irradiance values above 2000 W/m^2 CPV module will deliver more current than the rated values of the electrolyser, which also may damage the electrolyser. Hence this combination is also not practical.

For the combination of one CPV module and four electrolyser stacks connected in parallels (1CPV–4‖ EL) the operating curve of the electrolyser and the maximum power point line of the PV output are shown in fig. 12.

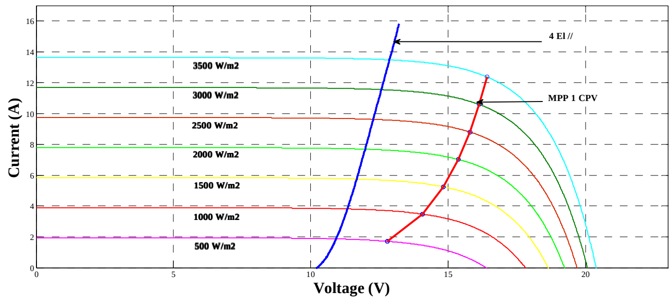

Fig.12: Coupling of one CPV module with four electrolyser stacks connected in parallels

The CPV module is now able to deliver power to the electrolyser at a solar irradiance of 3500 W/m^2 without damaging it.

This is the configuration that has been retained for the simulation of hydrogen production of a CPV-EL system.

D. Hydrogen production simulation results of CPC-EL system

Through modeling previously established, a simulation tool was conducted to estimate the amount of hydrogen production of a CPV system-EL. A flowchart of computer code for estimating the amount of hydrogen production from a CPV-EL system is presented in Fig. 13.

The hydrogen production simulation results of CPV-EL system from 25/05/2016 to 18/05/2016 are shown in fig.13.

The hydrogen production simulation results of CPV-EL system and PV-EL are shown in fig.14 for the day of 05/17/2016 as example. We can see that for the same PV module hydrogen production in CPV-EL systems almost tripled compared to the amount produced by a PV-EL system.

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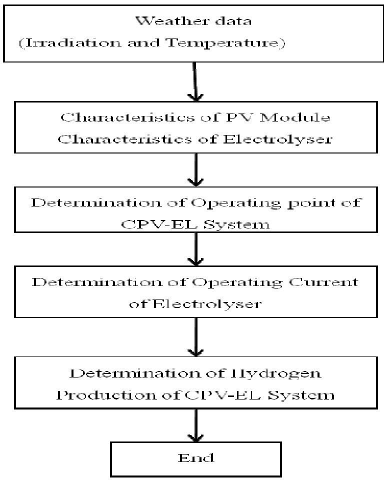

Fig.13 : Flowchart computer code for estimating the amount of hydrogen production from a CPV-EL system

Fig.14: Flow rate of Hydrogen Production of CPV-EL from 25/05 to 18/06/2016

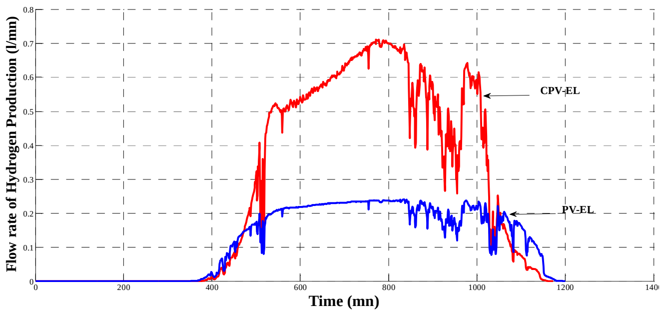

Fig. 14: Flow rate of Hydrogen Production of CPV-El system on 27/05/2016.

IV. Conclusions

Hydrogen can become the energy vector of the future. Regular photovoltaic systems suffer from the problems of low efficiency and high cost. It has been suggested that CPV techniques could be very promising as they could overcome these problems. In this context, this paper presents the performance analysis of hydrogen production system consisting of 60 W PV module equipped with Fresnel lenses concentrator directly coupling with four of 50 W PEM electrolyser connected in series. The objective of this study is to develop a simulation tool to estimate the amount of hydrogen production of CPV-EL system and to compare the results with those obtained from PV-EL system. As results of hydrogen production, the CPV-EL system can increase the production by a factor of 2.5 compared to PV-EL system.

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