engineering proceedings

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Proceeding Paper

Dynamic Response of a Sono-Electrolyzer under PV Supply for Hydrogen Production: A Modelling Approach for the Kinetic and Energetic Assessment under Northern Algerian Meteorological Conditions †

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† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: The experimental work is based on the PV solar powered membraneless KOH alkaline sono-electrolyzer using indirect continuous sonication under real meteorological conditions. The site of the study (36.9° N, 7.77° E) is located at the extreme North-East of Algeria, covering the semester ranging from March to September. A validated semi empirical model for the dynamic assessment of the global incident solar radiation is adopted, in association with a fundamental model based on the electrical analogy of the electrolytic cell. The experimental setup and measurements, coupled to the preliminary numerical model led to a fraction of electrodes' coverage of 37% with a maximum recovery of 13% and 10% in ohmic and cell voltage respectively. The characterization of the sonication system through the calorimetric technique demonstrated an acoustic efficiency of 13.7%.

Keywords: Green hydrogen; sono-electrolysis; cavitation; ohmic resistance; MatLab modeling

Citation: Merabet, N.H.; Kerboua, K. Dynamic Response of a Sono-Electrolyzer under PV Supply for Hydrogen Production: A Modelling Approach for the Kinetic and Energetic Assessment under Northern Algerian Meteorological Conditions. *Eng. Proc.* **2023**, *52*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s): Name

Published: date

1. Introduction

As an energy carrier with the advantages of high efficiency, cleanliness and sustainability, hydrogen has become a research hot topic [1]. Numerous studies have suggested that hydrogen produced from renewable energy sources, such as solar and wind, will have a major influence on global energy supplies in the near future. More specifically, the combination of solar photovoltaic energy with water electrolysis and battery is regarded as the most sustainable, suitable and clean pathway to H_2 production [2]. On an industrial scale, the most utilised and commercialised technologies for water electrolysis are alkaline electrolysis and proton exchange membrane which are based on the water splitting through the following reaction [3]:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

Solar electrolysis hydrogen production has been the subject of several studies, yhere very early, Bilgen [4] has attempted to developpe a mathematical model for the determination and optimisation of the thermal and economic of performance of large-scale photovoltaic electrolyser systems. Sellami et al. [5] also investigated the effect of electrolyte's nature on the amount of produced hydrogen, while Dahbi et al. [6] investigated the possibility of the system's optimization via an MPPT implementation and the controle of water flow injected. Burton et al. [7] reported the means of energy efficiency improvement using magnetic fields and high voltage electric fields, light energy and ultrasonic fields. In our recent study [8], the effect of ultrasound on a Pv solar water electrolysis for hydrogen production was conducted experimentally and by means of modeling for a short period of one day under real meteorological conditions.

In the present study, a modeling study of hydrogen production via membraneless sono-electrolysis under indirect continuous sonication and real meteorological conditions was conducted. 25% KOH electrolyte and nickel plate electrodes were used. a MatLab modeling was used in order to assess the kinetic and the energy efficiency of hydrogen production is based on the mathematical model of solar irradiation, PV panel and the alkaline electrolyzer.

2. Materials and Methods

Two chambers electrolysis cell of 300 mL was used, Table 1 shows the parameters that have been applied.

Table 1. Properties of the adopted system.

Site and Angles Parameters		PV Panel Parameters		Sono-Electrolysis Parameters	
geographical coordinates	36.9° N, 7.77° E	**Cell type**	Monocrystalline	**Electrolyte concentration**	25% *w*/*w*, 4.46 M KOH
Albedo ρ	0.2	**Short circuit current (Isc)**	1.8 A	**sonication**	Indirect continuous
solar declination	$\delta = 23.45 \sin(\frac{360}{365}(284 + N)$	**Open circuit voltage (Voc)**	21.52 V	**Frequency and power**	40 kHz and 60 W_e
Hour angle	$\omega = 15(TST - 12)$	**Maximum power (Pmax)**	30 W	**Electrode's material**	Nickel plates

MatLab modeling

The adopted modeling part is based on the mathematical models of (i) solar irradiation, (ii) PV solar model, (iii) and water electrolysis.

Solar irradiation model

The global radiation on tilted surface G are calculated according to Equation (1) [10]:

$$G = D_\beta + B_\beta + R_g \tag{1}$$

where D_β is the diffuse radiation, B_β and R_g are the beam and reflected radiation In the adopted model, the diffused radiation D_β are estimated according to the anisotropic model of Hay [10] as Equation (2):

$$D_\beta = D_d(f_{Hay}\left(\frac{cos\theta}{cos\theta_z}\right) + (\frac{1 + cos\beta}{2})(1 - f_{Hay}) \tag{2}$$

$$f_{Hay} = \frac{D_b}{E_{xt}} \tag{3}$$

R_g is the reflected radiation which is the fraction of global radiation that is reflected by the Earth's surface and any other obstructing object and is calculated according to Equation (4):

$$R_g = H\rho(\frac{1 - cos\beta}{2}) \tag{4}$$

The direct beam irradiance on an tilted surface can be calculated using Equation (5):

$$D_\beta = r_\beta D_b \tag{5}$$

where r_β represents is the ratio of the hourly radiation received by an inclined surface to that received by a horizontal surface outside the Earth's atmosphere and is calculated using the following equation [10]:

$$r_\beta = \frac{E_{0\beta}}{E_{xt}} \approx \frac{cos\theta}{cos\theta_z} \tag{6}$$

In the previous equations, E_{xt}, θ and θ_z are the extraterrestrial radiation, the incidence angle and the zenith angle that are calculated according to a specific equations [10].

PV panel model

The current delivered from the PV panel is represented as given in Equation (7) [11]:

$$I = I_{pv} - I_d - I_{sh} \tag{7}$$

In the expression of I, I_{pv}, I_d and I_{sh} are the light current, diode current and shunt current respectively and can be expressed as follow [12,13]

$$I_{pv} = \frac{(I_{pv0} + K\Delta T)G}{G0} \tag{8}$$

$$I_d = I_0\left(\exp\left(\frac{R_sI + V}{V_ta}\right) - 1\right) \tag{9}$$

$$I_{sh} = \frac{V + R_sI}{R_p} \tag{10}$$

Water electrolysis system

The electrolyzer's voltage U_{cell} is dependent on the current produced from the PV panel, the potential involved E_{rev} the reversible voltage, U_{act} activation voltage, U_{Ohm} ohmic voltage and U_{Conc} concentration voltage which are expressed according to the equations below [14–16]:

$$U_{cell} = E_{rev} + U_{act} + U_{Ohm} + U_{Conc} \tag{11}$$

$$E_{rev}(T,P) = E_{rev}(T) + \frac{RT}{ZF}\ln\left(\frac{{P_v}^*(\mathrm{P} - P_v)^{1.5}}{P_v}\right) \tag{12}$$

$$U_{act} = \frac{2.3026\,RT}{ZFa_a}\log\left(\frac{I_a}{I_{0a}}\right) + \frac{2.3026\,RT}{ZFa_c}\log\left(\frac{I_c}{I_{0c}}\right) \tag{13}$$

$$U_{ohm} = I(R_{cell} + R_{electrodes} + R_{electrolyte} + R_{electrical}) \tag{14}$$

$$U_{conc} = \frac{RT}{ZF}\left(\ln\left(1 - \left(\frac{I}{I_{\lim}}\right)\right)\right) \tag{15}$$

Calorimetric characterization of sono-electrolysis

As the propagation of the ultrasound waves within the electrolyte increases the electrolyte's temperature, an evaluation of the acoustic power transferred to the electrochemical cell was conducted. Where, the power of the ultrasound transmitted to the electrolyte is calculated by means of the equation below [17]:

$$P_s = \frac{m_{KOH}C_pdT}{dt} \tag{16}$$

where m_{KOH} is the mass of the alkaline electrolyte, C_p and dT are the heat capacity of the electrolyte at constant pressure and temperature change within the monitoring time.

Kinetics of hydrogen production

According to Faraday's law [28], the rate of hydrogen gas produced by water electrolysis is equal to the electrical charge consumed by the cell which is expressed according to Equation (17)

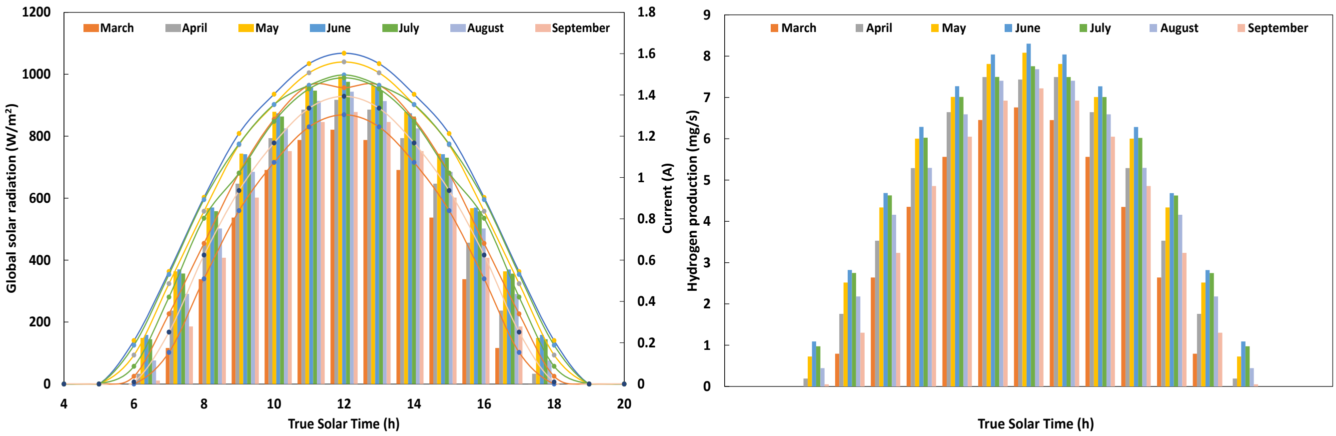
$$\dot{m}_{H_2} = \frac{NIM_{H_2}}{ZF}\eta_F \quad (17)$$

where $\dot{m}_{H_2}$ is the mass flow of hydrogen production by the electrolyzer in g/s, M_{H_2} and N is the cells number of electrolyzer and molar mass respectively and η_F represents the Faraday efficiency.

3. Results and Discussion

3.1. Kinetics of Hydrogen Production

Figure 1a shows the simulated hourly solar irradiance and delivered current f for each month. It is clear that the solar irradiation and the delivered current are at their highest values during the summer period. The highest values of solar irradiation 992 W/m² are reached in the summer period during the month of May around solar noon, while the maximum delivered current of 1.6 A was recorded during the month of June.



(**a**) (**b**)

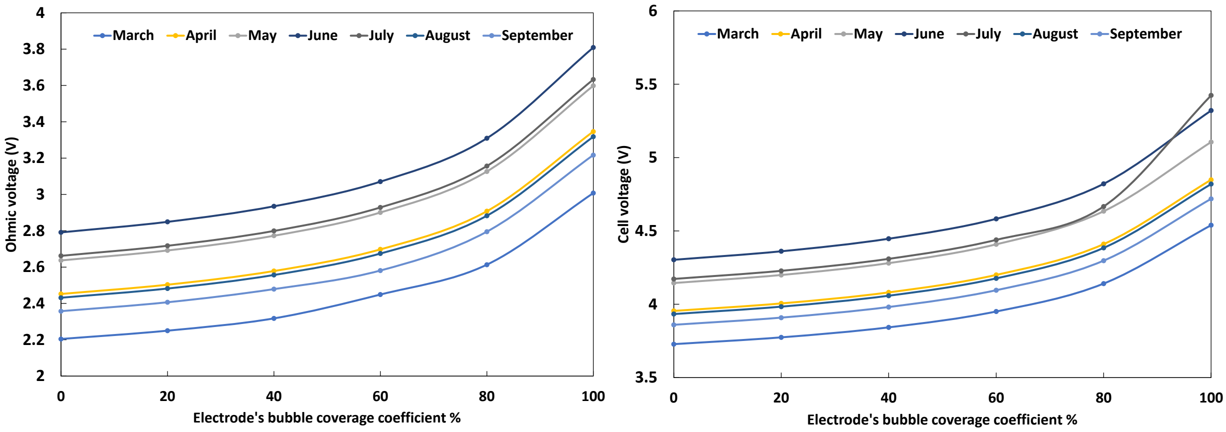
Figure 1. Simulated results of monthly (**a**) hourly solar irradiation and delivered current; (**b**) kinetics of hydrogen production and delivered current.

The kinetic of hydrogen production according to the hourly delivered current is shown in Figure 1b. The kinetic of hydrogen production increases with increasing current according to Faraday's law and reached its maximum of 8 µmol/s in June around solar noon.

3.2. Sono-Electrolysis Results

According to the obtained results and based on the calorimetric study [17], the characterization of the sonication system demonstrated an acoustic efficiency of 13.7% when considering the delivered power of 60 W. This means that the remainder of the power consumed is dissipated as heat to the electrolyte and the surrounding environment.

Figure 2a,b shows the average cell resistance and cell voltage as a function of the coverage of the electrode with air bubbles. The electrode bubble coverage in the presence and absence of ultrasound is 37% and 82%, respectively, based on the previous experimental results [8]. Thus, it can be seen that in the quiescent system, the ohmic voltage and cell voltage range from 2.6 to 3.5 V and from 4.1 to 4.8 V, respectively, depending on the month, whereas under sonication they decrease to 2.25 to 2.8 V for the ohmic voltage and to 3.7 to 4.3 V for the cell voltage.



(**a**) (**b**)

Figure 2. Simulated results of monthly average (**a**) ohmic voltage; (**b**) cell voltage in function of electrode's bubble coverage.

As it is assumed in the literature, the bubble presence in the electrolyte and on the electrode's surface increases the ohmic resistance and voltage and thus the power consumption. It was observed that the higher the current supplied by the solar panel, the higher the hydrogen production kinetic and the higher the bubble and ohmic resistance. The integration of the sonication reduces the ohmic voltage by about 13.5–20% and the cell voltage by 9.7–10.4%, depending on the month. This means that for the same feed current, the hydrogen kinetics described by the mass flow rate is more important due to the effective desorption effect of the sonication.

4. Conclusions

In the present study, hydrogen production via sono-electrolysis powered by a PV solar system was performed using a detailed modeling pathway. The study covered the period of time from March to September under real meteorological conditions during the whole representative days. It was revealed that only 13.7% of the consumed power of sonicator was transferred to the electrochemical cell. In addition, the highest hydrogen production was recorded during the summer where the irradiation reached its maximum. In addition, under sonication conditions, a maximum recovery of 13% and 10% in ohmic and cell voltage respectively was recorded.

Author Contributions:.

Funding:

Institutional Review Board Statement:

Informed Consent Statement:

Data Availability Statement:

Conflicts of Interest:

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