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Technico-economic estimation of hydrogen production from one PV module in Hassi Messaoud Region – Algeria

***Abstract**. The generation of hydrogen via the use of renewable energy sources, such as solar power, is turning out to be an increasingly appealing alternative for reducing emissions of greenhouse gases. A techno-economic analysis of the generation of hydrogen from a single photovoltaic (PV) panel in the Hassi-Messaoud area of Algeria was carried out for the purpose of this research project. Over the course of the study, consideration was given to a variety of aspects, including the sizing and performance analysis of the PV panel, the expense of the equipment, and the cost of producing hydrogen. According to the findings of the research, the amount of hydrogen that can be produced by a single PV panel in the Hassi-Messaoud area is between 240 and 300 litres per hour at a total yearly cost of 4.53 dollars per kilogram of hydrogen. The cost of production looks to be competitive, and there is the possibility that Algeria may be able to cut its emissions of greenhouse gases and assist the growth of a hydrogen economy that is environmentally responsible*

Streszczenie. *Generowanie wodoru przy użyciu odnawialnych źródeł energii, takich jak energia słoneczna, okazuje się coraz bardziej atrakcyjną alternatywą dla redukcji emisji gazów cieplarnianych. Na potrzeby tego projektu badawczego przeprowadzono analizę techniczno-ekonomiczną generowania wodoru z pojedynczego panelu fotowoltaicznego (PV) w regionie Hassi-Messaoud w Algierii. W trakcie badania wzięto pod uwagę szereg aspektów, w tym analizę wielkości i wydajności panelu PV, koszt sprzętu i koszt produkcji wodoru. Zgodnie z wynikami badań ilość wodoru, którą można wyprodukować za pomocą pojedynczego panelu PV w regionie Hassi-Messaoud, wynosi od 240 do 300 litrów na godzinę przy całkowitym rocznym koszcie 4,53 dolara za kilogram wodoru. Koszt produkcji wydaje się być konkurencyjny, a istnieje możliwość, że Algieria będzie w stanie obniżyć emisję gazów cieplarnianych i wspomóc rozwój gospodarki wodorowej, która jest przyjazna dla środowiska*. (***Szacowanie techniczno-ekonomiczne produkcji wodoru z jednego modułu fotowoltaicznego w regionie Hassi Messaoud – Algieria***)

Keywords: Solar energy, Green Hydrogen, PEM electrolyser, Renewable energy sources Słowa kluczowe:
Słowa kluczowe: Energia słoneczna, Zielony wodór, Elektrolizer PEM, Odnawialne źródła energii Słowa kluczowe:

Introduction

Renewable energy sources including solar, wind, hydropower, and geothermal are clean, plentiful, widely accessible, and long-term. They have the potential to generate new businesses and employment, strengthen national economies, and offer more cost-effective and dependable energy. They also have the benefit of not depleting limited resources, unlike fossil fuels, and may assist to minimize the negative environmental implications of conventional energy. Overall, it is a significant step toward a more sustainable, low-carbon future [1,2]

In recent years, Algeria has made it a priority to encourage the use of energy from renewable sources as a method of lessening its reliance on traditional fuel sources and combating the effects of climate change. The nation has committed itself to achieve a percentage of renewable energy installations equal to 22 gigawatts (GW) of its installed capacity in total by the year 2030. A renewable energy development agency was established, feed-in prices for solar and wind energy were set up, and a national strategy to promote renewable energy was drafted; all of these measures were taken by the government [3-6]

Algeria main plan for developing renewable sources is focused on promoting solar and wind energy sources. They consider research to address the main aspect of developing these resources including efficiency improvement and reducing cost of production [3-6]

Hassi Messaoud is a city located in the eastern part of Algeria and known for its vast oil and gas reservesThe city is also known for its high solar irradiance, which makes it an ideal location for solar energy production [7-10]

The potential for solar energy in Hassi Messaoud is significant due to the high solar irradiance levels in the region. The area receives an average of around 3,000 hours of sunshine per year, with solar irradiance levels reaching up to 6 kWh/m² per day. This makes it one of the best places in Algeria for solar energy production [7-10].

Overall, the high solar irradiance levels in Hassi Messaoud, along with the government's policies to support the development of renewable energy, make the region a prime location for solar energy production and a promising area for future solar energy projects. In the other hand, Hydrogen is a key substance for oil and gas industries. it is crucial in the oil and gas industries. Hydrogen production is important for the oil and gas industries for several reasons [7,11-13]

- Decarbonization: in oil and gas industry heat and electricity generally produced by traditional methods (fossil fuels) which produce a considerable amount of CO2. Hydrogen is become an alternative in producing heat and electricity using fuel cells which allow to reducing CO2 emission.
- Carbon Capture and Utilization (CCU): Hydrogen is used along side with CO2 in order to produce methane and reduce GHG emissions of the oil and gas industry [11].
- Refinery and Petrochemical: In the refining and petrochemical processes, hydrogen is used to enhance the quality of gasoline and diesel by eliminating sulphur and other impurities.
- The generation of energy and its storage: the energy production system employs hydrogen as a means for generation (via the use of fuel cells), storage in tanks, and restoration (using electrolysers). It is simple to store hydrogen in high-pressure tanks, and it is also straightforward to transport hydrogen through pipes to far-flung locations such as offshore drilling rigs.

Overall, the generation of hydrogen is significant for the oil and gas sector since it may assist to decrease emissions of greenhouse gases, boost the efficiency of industrial operations, and store renewable energy sources [11-13].

In this study, a techno-economic analysis of hydrogen production from a single photovoltaic (PV) panel in the

Hassi-Messaoud region of Algeria is performed. When assembling a PV panel with a PEM (Proton Exchange Membrane) electrolyser, there are several factors to take into account to ensure the system is efficient and reliable: Efficiency: The production of hydrogen from PV module depends on the efficiency of equipment included in the system. PV module efficiency will highly impact the amount of power being transformed into hydrogen. System Cost: when analysing the cost of production of hydrogen, it is important to explore the initial capital costs, operation and maintenance cost and the replacement cost of each sub-system as well as the frequency of these expenses during the lifespan of the project.

System Modelling

Climate data for Hassi Messaoud Region

The sized system is considered as PV-EL-H2 Tank (see Fig. 1) for Hassi Messaoud city in the south east of Algeria (31°43'09.7"N, 6°03'01.5"E). The region is known by its oil and gas industries in Algeria. In addition, it has a significant solar energy potential due to the high solar irradiance levels in this location.

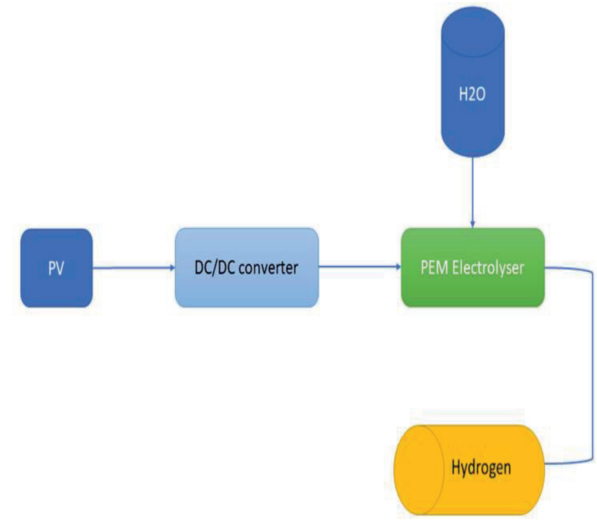

Fig.1.Bloc diagram of hydrogen production system from PV module

The design of the proposed system size is determined as daily average values over one year. Climate data for Hassi Messaoud was obtained from [14]. The daily global irradiance and daily mean ambient temperature data during a one-year period, are presented in Fig. 4

Modelling of PV module

PV module circuit model is illustrated in Fig. 2

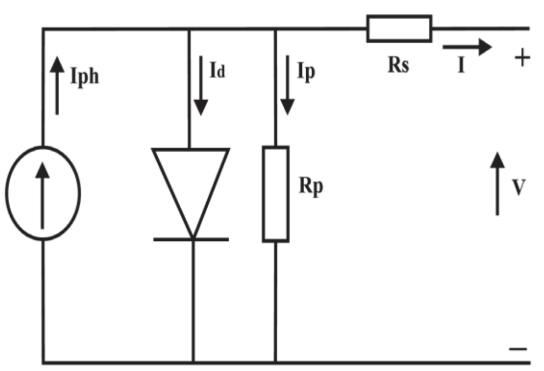

Fig.2.Equivalent circuit of real model for PV panel

The equations that illustrate the model of PV module are expressed in equation bellow [15] :

(1) $$I = N_p \cdot I_{ph} - N_p \cdot I_s \left[\exp\left(\frac{q(V+IR_s)}{N_s K A T_o}\right) - 1\right]$$

(2) $$I_{ph} = [I_{sc} + K_i (T_o - T_r)] \cdot \frac{G}{Gref}$$

Reverse saturation current Irs and Is Saturation current is calculated by using 3 and 4:

(3) $$I_{rs} = \frac{I_{sc}}{exp\left(\frac{q \cdot V_{oc}}{N_s K A T_o}\right) - 1}$$

(4) $$I_s = I_{rs}\left(\frac{T_o}{T_r}\right)^3 \cdot \exp\left(\left(\frac{qE_g}{AK}\right) \cdot \left(\frac{1}{T_r} - \frac{1}{T_o}\right)\right)$$

Electrolyser model

the electrolyser is modelled by its I-V characteristic curve, the data obtained from experimental measurement. The interpolated I-V characteristic curve is given by 5 and showed in Fig. 3 [16]:

(5) $$I_{EL} = \begin{cases} 0 & V \le 10V \\ 128.118 - 33.1587 \cdot V + 2.76617 \cdot V^2 - 0.0732506 \cdot V^3 & V > 10V \end{cases}$$

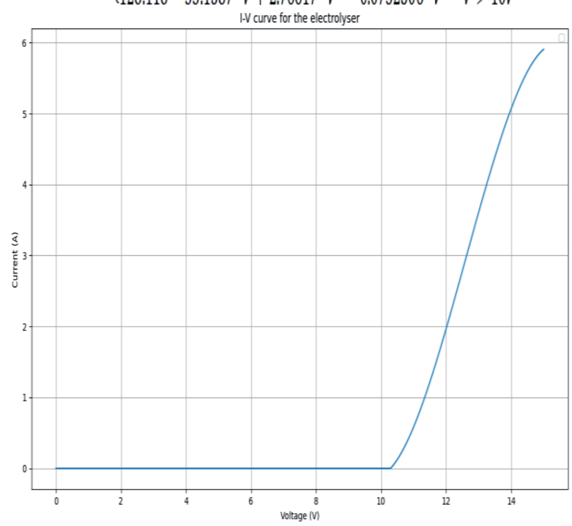

Fig.3. I-V PEM electrolyser characteristic curve

The volume of produced hydrogen is calculated using Faraday's law of electrolysis, the molar flow of the of hydrogen produced by the electrolyser in 1 h can be calculated by :

(6) $$\frac{dn_{H2}}{dt} = \eta_F \cdot \frac{n_c \cdot I_{EL} \cdot A}{z \cdot F}$$

In one hour, the previous equation 6 will become:

(7) $$n_{H2} = \eta_F \cdot \frac{n_c \cdot I_{EL} \cdot A}{z \cdot F} \cdot 3600\ s$$

Hydrogen tank model

Produced H2 from electrolyser was stored in high pressure storage tank in proposed hybrid system. The volume of H2 tank (V) is calculated according to van der Waals Equation (19) [17-19]

The van der Waals equation for hydrogen storage is given by :

(8) $$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

$$\nu = \frac{V_{H2}}{n_{H2}} \quad (9)$$

a is a constant that accounts for the attractive forces between the molecules of the gas acts to reduce the effective pressure. b is a constant that accounts for the finite size of the gas molecules. It represents the volume occupied by the gas molecules themselves. For hydrogen, the constants [18] $a = 24.73\ [kPa \cdot m^6 \cdot mol^{-2}]$ and $b = 0.02654\ (m^3 mol^{-1})$

Optimal coupling of PV and PEM Electrolyser using DC/DC converter

Optimal coupling of PV module with PEM Electrolyser encompasses the maximization of energy transfer between them. In fact, energy transfer maximization involves matching (I-V) curve of the Maximum power point of PV array during the climate working condition to the I-V characteristic curve of PEM electrolyser [20]

$$P_{EL} = \begin{cases} P_{PV} \cdot \eta_{conv} & if\ P_{PV} \cdot \eta_{conv} \leq P_{EL_{rated}} \\ P_{EL_{rated}} & otherwise \end{cases} \quad (10)$$

Where $P_{ELrated}$ is the rated power of the PEM Electrolyser. In the case where the Power generated by PV array is greater that the $P_{ELrated}$, the scenario of power management and control in the converter assumes that the PV generator's excess electricity is wasted [16].

Power management

The power management technique in the controller of the DC/DC converter describes the direction of power flow in the suggested system taking into account the maximization of power transfer between the two sub-systems. The chronogram steps for energy flow management adopted for this study are as follow:

1. Acquire climate data for each day of the year (T, G_I)
2. Estimate the PV system MPPT parameters (P_{PV}, I_{mppt}, V_{mppt})
3. Check if $P_{PV} \leq \frac{P_{EL\,rated}}{\eta_{conv}}$ if not set $P_{EL} = P_{ELrated}$ and the excess of electricity is wasted
4. Otherwise calculate $P_{EL} = P_{PV} * \eta_{conv} = V_{EL} * I_{EL}$
5. Compute I_{EL} and V_{EL}
6. Compute the quantity of produced hydrogen

Economical modelling

The cost of installing photovoltaic panels is 350 $ per kilowatt. The price of installing photovoltaic panels is entirely determined by the manufacturer of the equipment. The cost of installing a PV system, which includes all of the necessary components, components, and accessories. It is assumed that the running and maintenance cost of PV panels is equal to ten dollars per kilowatt per year of the installation cost, and that the service life of PV panels is twenty-five years [21,22]

The initial cost of purchasing a PEM electrolyser accounts for the acquisition of all necessary apparatus and components, such as a dehumidifier, deionizer, and other such items. It is anticipated that the initial capital cost of the PEM electrolyser will be 100$ per kilowatt; it is anticipated that the maintenance and operation cost of the PEM electrolyser will be 8% of its capital cost; and it is assumed that the life span of these pieces of equipment will be 15 years with a replacement cost of 100% of the original cost. [21,22]

The economic data of the remaining system components, which are the converter and the tank, are presented in [tab:table1]. It is assumed that the replacement cost of these pieces of equipment will be the same as their initial cost; this is due to the fact that these pieces of equipment will need to be replaced in their entirety when their lifetime comes to an end.

Due to the fact that both the converter and the tank will have to be replaced in their entirety at the end of the system's lifetime, it is anticipated that the cost of replacing either component will be equivalent to the original cost of capital. [tab:table1] displays all of the economic information pertaining to these systems.

Results and discussion

The techno-economic assessment of hydrogen production in Hassi Messaoud, which is located in the southeast of Algeria at (6°37′N, 31°39.7′E), is provided. In the context of this calculation, the assessment of the amount of hydrogen generated utilizing one PV module in conjunction with one or more PEM electrolysers and a DC/DC converter is being carried out. From [14,23] hourly Climatic data are extracted, the daily average values of the temperature and solar irradiance are shown in Fig. 4.

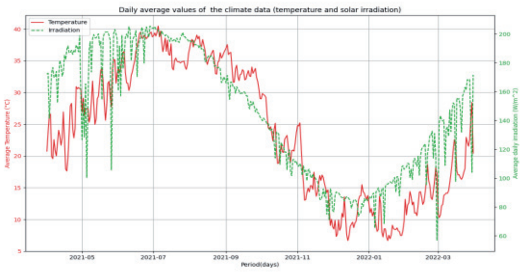

Fig.4. The daily average values of the Climatic data for Hassi Messaoud (6°37′N, 31°39.7′E)

The quantity of hydrogen that the system under consideration in this research produces is evaluated with regard to the climatic condition of selected region. The findings from the simulation are presented at a variety of time scales (daily, monthly). In addition, there is a consideration of economic assessment about the generation of hydrogen. This involves the estimation of the yearly cost of the system ACS as well as the cost of hydrogen COH. As the efficiency of the system is reliant on the design of the system, it is necessary to take into account how the operating margin of the electrolysers may be adapted to work alongside the PV modules. The technical feasibility and financial viability of various configurations are analysed.

PV module production

The Power output of PV Module depends on module characteristics, solar irradiance and ambient temperature in the study region. The I-V and P-V and maximum power point for different climatic conditions are showed in Fig. 5 and Fig. 6.

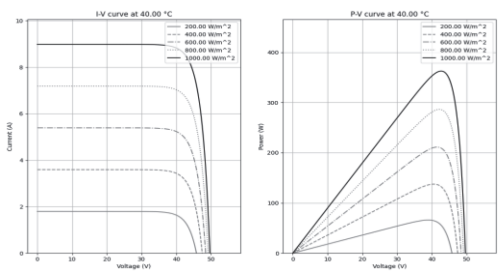

Fig.5. PV module current (left) and power (right) vs voltage curves in different irradiance conditions at 40 C

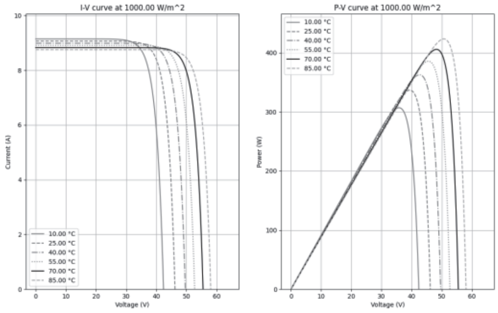

Fig.6. PV module current (left) and power (right) vs voltage curves in different temperatures conditions at irradiance of 1000W/m^2

Coupling PV with Electrolysers

Figure 7 shows the PV module I-V curves superimposed on that of the electrolyser.

DC/DC converter plays a key role in this PV-EL adaptation. Converter control strategy makes both system works at their optimal working point and the power supplied to the electrolyser will be always the power produced by the PV module after deducing the power losses from DC/DC controller/converter defined by η_{conv} [16,17]

Table 1. The economic data of the system components

	Service life	Rated Capacity	Capital	Replacement	O&M yearly
PV	25 years	320 W	$350/kW	100%	$8/kW
PEM EL	15 years	50 W	$100/kW	100%	8%
DC/DC converter	15 years	70 W	$1000/kW	100%	0.5%
Tank	25 years	1 kg	$1/kg	100%	$8

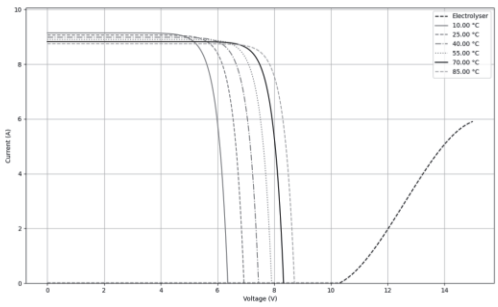

Fig.7. PV module and electrolyser I-V curves

In fact, the DC/DC converter makes the PV works at its maximum power point and ensuring at its output that the V-I values matches the working point of the Electrolyser.

Hydrogen production

The amount of hydrogen that was produced daily by the system that is shown in Fig. 8 for the configuration 03 that was studied. The results of the simulation reveal that the hourly generation of hydrogen is dependent on the amount of solar irradiance that is accessible, and that the system has the potential to create more than 0.020 kg of H2 (242.651 litres at 25° and 1atm) every day between the months of April and August.

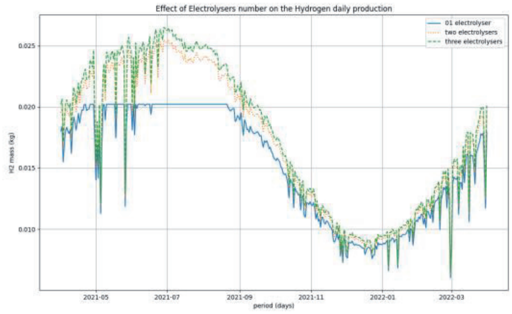

Fig.8. daily hydrogen production over the year

Economic Analysis

It is also clear that the quantity of hydrogen gas generated by a single PV module change according to the number of electrolysers that are taken into account in the calculation. This is due to the DC/DC converter enables the PV module to operate at its maximum power point, so allowing it to harvest the greatest amount of power that is available. Nevertheless, increasing the amount of hydrogen that is produced will drive up the overall system cost. Figure 9 depicts the impact that increasing the number of electrolysers has on the price of hydrogen COH.

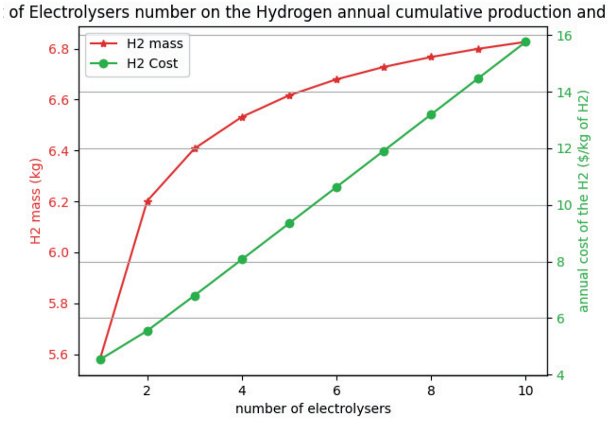

Fig.9. Effect of Electrolysers number on the Hydrogen annual cumulative production and its cost

The price of hydrogen is largely dependent on the cost of each component of the system. The cost of producing H2 may be reduced to its lowest point by using only one electrolyser, which costs 4.5309 dollars per kilogram. The breakdown yearly cost of the system is and shown in the Fig.10 and table2 below.

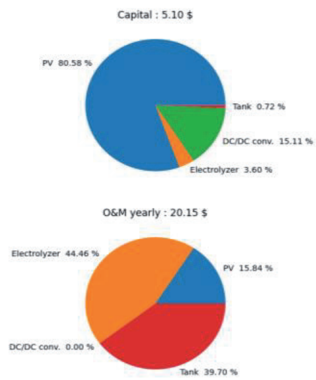

Fig.10. Capital and O&M cost distribution between system sub-equipment's

Table 2. The breakdown yearly cost of the system

	Capital Cost (converted to annual)	Replacement Cost (annual)	O&M Cost
PV	4.111606	0	3.192
PEM Electrolyser	0.183554	0.00403	8.96
DC/DC Converter	0.770926	0.016926	0
Tank	0.036711	0	8

Due to the significant upfront investment required to install PV modules and a DC/DC converter, the initial capital cost of PV modules accounts for 80.58% and 15.11% of the total annual capital cost of the system, which amounts to $5.10 per year. The electrolyser accounts for 44.46% of the system's annual O&M cost, the hydrogen tank for 39%, and the PV module for 15.64%. As the PV module and Hydrogen tank have a lifespan in excess of the system lifespan, they will not incur any replacement costs during that time. With just a single repair of PEM Electrolysers and DC/DC converter required during the project's lifetime, the annual cost of maintenance is minimal.

Conclusion

For the city of Hassi Messaoud in South Est of Algeria, this study provides a techno-economic assessment of hydrogen generation from a single PV module.

A technical and cost-benefit analysis of hydrogen production forecasting is performed. On a technological level, the impact of using several Electrolysers in conjunction with a single PV module being studied to see whether it is possible to increase PV power usage. In contrast, numerical estimations are used to examine the economic evaluation, with the yearly cost of the system, the original capital cost, and the operating and maintenance expenses comprising the backbone of the analysis.

As a further recommendation in this research axis, it is valuable to conduct an optimization process that investigate the hydrogen production in this region taking into account technical, economic, environmental and social key performance indicator.

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