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Thermoeconomic assessments of green hydrogen production via PV&PEM electrolyzer: a case study for Al-Jufra region in Libya

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ABSTRACT

The study aims to estimate the amount and cost of hydrogen and oxygen that can be produced in the Al-Jufra region (Libya) using photovoltaic panels (PV). The electricity generated by PV is used to power the proton exchange membrane (PEM) electrolyzer. Through the study, the thermal efficiency of the system is calculated, as well as the factors affecting it. The amount of solar radiation that the region receives during the year is also determined, amounting to 81.72 kW/year m^2, with a duration of 3421 daylight hours. With this radiation value, it is possible to produce 1272 and 636 mol/year m^2 of hydrogen and oxygen, respectively, at an estimated cost of $1.42 per mole.

Thermodynamic analysis of PV cells and electrolyzer shows that the electrical efficiency and exergy efficiency of PV cells are 4.8% and 5%, respectively, and vary according to the radiation intensity. The exergy and energy efficiency of the analyzer remained constant at 48% and 39%, respectively, according to the aforementioned arrangement. The decrease in the efficiency of PV energy efficiency affects the overall efficiency of the system and does not exceed 3% in ideal conditions. In addition, the expected cost in 2030 is estimated and found to be 5.77% lower than its current price. Comparing the amount and price of production in the Al-Jufra area with other areas in Libya, it becomes clear that the city of Al-Kufra has a 20% higher annual production amount.

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التقييم الأقتصادي والحراري لمنظومة إنتاج الهيدروجين الأخضر باستخدام اللوح الكهروضوئي والمحلل الكهروكيميائي ذو الغشاء التبادلي للبروتون: دراسة حالة لمنطقة الجفرة بليبيا.

سالم بن يوسف، حمودة قنيفيد، أسعد مزدة.

ملخص: تهدف الدراسة إلى تقدير كمية وتكلفة الهيدروجين والأكسجين التي يمكن إنتاجها في منطقة الجفرة (ليبيا) باستخدام الألواح الكهروضوئية. يتم استخدام الكهرباء المولدة بواسطة الطاقة الكهروضوئية لتشغيل المحلل الكهربائي بغشاء تبادل البروتون (PEM). ومن خلال الدراسة تم حساب الكفاءة الحرارية للنظام وكذلك العوامل المؤثرة عليه. كما تم تحديد كمية الإشعاع الشمسي الذي تستقبله المنطقة خلال العام، حيث تبلغ حوالي 81.72 كيلووات/سنة م^2، بمدة 3421 ساعة نهار. وبهذه القيمة الإشعاعية، من الممكن إنتاج 1272 مول في السنة لكل متر مربع من وقود الهيدروجين و636 مول/سنة م^2 من والأكسجين، بتكلفة تقدر بـ 1.42 دولار لكل مول. أظهر التحليل الديناميكي الحراري للخلايا الكهروضوئية أن الكفاءة الكهربائية والكفاءة الحرارية للخلايا الكهروضوئية تبلغ 4.8% و5% على التوالي، وتختلف وفقًا لكثافة الإشعاع. بينما ظلت كفاءة الطاقة للمحلل الكهروكيميائي ثابتة عند 48% و39% وذالك حسب القانون الأول و القانون التاني لتيرموديناميك , وفقًا للترتيب المذكور أعلاه. واثبتت الحسابات أن انخفاض كفاءة الطاقة الكهروضوئية يؤثر على الكفاءة الكلية للنظام الذي لا يتجاوز3% في الظروف المثالية. بالإضافة إلى ذلك، تم تقدير التكلفة المتوقعة في عام 2030 ووجد أنها أقل بنسبة 5.77% من سعرها الحالي. وبمقارنة كمية وسعر الإنتاج في منطقة الجفرة مع مناطق أخرى في ليبيا تبين أن مدينة الكفرة لديها كمية إنتاج سنوية أعلى بنسبة 20%.

1. INTRODUCTION

Nowadays studies focus on methodologies for hydrogen production, due to its remarkable environmental friendliness and high energy content, which can reach an astonishing level. It is widely recognized that hydrogen is a sustainable, clean and renewable fuel that can be extracted from environmental resources, such as water. Renewable and non-renewable energy sources can be harnessed to facilitate their production. Renewable methods include biomass, hybrid cycle, Photonic energy, wind energy, and hydropower. Each method has its distinctive advantage. Studies show that photonic energy (eg. artificial photosynthesis and photoelectrochemical methods are environmentally preferable to other methods. Likewise, the method of splitting water using electrochemical methods and thermochemical cycles has better environmental properties. In terms of production cost and efficiency, PV electrolysis and photoelectrolysis are not a good choice. Therefore, the development of this method in terms of efficiency and price makes solar hydrogen production a potential option. Hydrogen production using biomass has an advantage in terms of efficiency. Overall, studies indicate that hydrogen production using the hybrid thermochemical cycle method has an advantage as an option in terms of both the environment and cost [1-3].

With the abundance of good solar radiation in the North African region, particularly in Libya, this study focuses on hydrogen production using Photovoltaic-electrolysis devices. The system has been introduced and studied by various researchers and institutions over the years. Development and research in this field have included contributions from scientists, engineers and institutions from around the world[4, 5]. The discovery that electricity could be used to split water into its basic components, oxygen and hydrogen, dates back to 1780. Later, in 1800, Nicholson and Carlisle succeeded in developing this phenomenon and introducing it to the industrial sector [6, 7]. A breakthrough was made in 1939 when a plant was established to manufacture oxygen and hydrogen from water, with an astonishing production capacity of 10,000 Nm^3/h [7]. As science developed, Grimes et all focused on their book topic of water photoelectrolysis, which is a process that uses solar energy to split water into hydrogen and oxygen gases. The authors explore the fundamental principles, materials, and techniques involved in this field and discuss its potential applications for sustainable energy generation [8].

The hydrogen production system consists of solar panels and a chemical analyzer [9]. The system derives energy from the sun through the solar panels, and thus the efficiency of the panels affects the overall efficiency of the system [10]. Numerous studies have contributed to improving the efficiency of the system. In 2001, Khaselev et all investigated the possibility of using a homogeneous, multi-junction cell in the system and found that it had a positive effect on the conversion efficiency of solar energy to hydrogen, reaching up to 16% [11]. Due to the positive advantages of hydrogen production using this method, studies have competed to develop it further. Gibson and Kelly demonstrated the possibility of operating vehicles with fuel cells using this method and achieving a conversion efficiency of up to 12%, by matching the maximum power output and voltage of the photovoltaic cell with the operating voltage of the proton exchange membrane (PEM) analyzer [4]. The same researchers continued their previous study by examining the effect of the analyzer's temperature on system efficiency and were able to increase it to 12.4% [10]. Jia et al. developed their system by using a high-efficiency triple-junction solar cell with two series-connected polymer electrolyte membranes achieving produced hydrogen with an efficiency of up to 30%. By harnessing this remarkable efficiency, the proposed method has the potential to make solar hydrogen economically and commercially possible.

Not only does it promise positive competition in terms of energy production and pricing, but it also paves the way for the establishment of powerful industrial facilities dedicated to its large-scale production [12].

Many studies have been conducted to evaluate the economic aspect of hydrogen production through different methods. Our previous research has shown that it is possible to produce hydrogen by utilising the waste heat of the flue gas to generate electricity and hydrogen through the absorption cycle and PEM electrolyzer at a production cost of 0.049$/kWh and 2.43$/kgH [13]. Özden studied the possibility of hydrogen generation using the PV method in Ankara, within hours of radiation availability. It was used as fuel for the energy cell during dark hours. The results obtained showed the potential of hydrogen generation with a thermal efficiency of up to 4.06%. A solar panel with an area of 300 square meters was used to supply power to an emergency room. The excess energy generated during the day was utilized to produce and store hydrogen. During nighttime and in the absence of radiation, the produced hydrogen was used to power a 5-kilowatt energy cell, which is the required capacity for the load [14].

Nicolaides et al also compared conventional hydrogen production methods with production using sustainable energy. The study showed that hydrogen production through chemical pyrolysis, gasification, and reforming could rival currently approved methods, whose production costs range from 1.3 to 2.27 $/kg. The study also indicated that biological approaches have future potential if obstacles such as low efficiency and high capital costs can be overcome [2].

The accuracy of the data and the method of calculating solar radiation have a significant impact on the efficiency of solar energy systems, including this system. Usually, solar radiation data are not recorded at meteorological stations but are estimated based on other meteorological measurements and calculated in terms of energy per square meter per day. The most important methods for calculating solar radiation include Hargreaves-Samani (HS), Thornton and Ranning (TR), and Weiss et al. (Ws). Ball et all conducted a comparative analysis of previous methods, and they found that a Hs model had the lowest error rate, followed by a TR model. By calculating the solar average for 7 days, it was revealed that all three models provided accurate estimates that could be relied upon to calculate the amount of solar radiation [15].

Since solar radiation is calculated by the amount of radiation falling on a horizontal surface, which is a variable value depending on the time of day and day of the year, and given that Libya is a developing country, records related to solar radiation are very rare and sometimes non-existent. In Libya, there are only fifteen stations that recorded solar radiation over eight years [16]. In this study, the Kreider and Beckman method [17, 18] is adopted to calculate solar radiation, as it was used in previous studies that contain information about solar radiation in the region [16]. In addition, in our previous research on evaluating the economic feasibility of a 12 BTU solar cooling system, we used this method to calculate the amount of solar energy needed to operate the system [19].

As human civilization advances, the demand for energy increases, as it is used in almost all fields. As demand increases, its production increases using conventional methods, which causes environmental pollution and negatively affects public health. From this standpoint, researchers directed their attention towards finding alternative means of producing energy that is natural and environmentally friendly. Libya is an oil-producing country and has good natural energy resources, especially solar energy. Therefore, the idea can be consolidated and start producing clean energy and exporting it to the world instead of relying on oil.

2. SYSTEM DESCRIPTION

Figure 1 illustrates the main components of the system. The system derives energy from the sun and converts it into electricity through the PV. The produced electricity powers the electrolyzer, providing the necessary electrical driving force for the oxidation and reduction reactions (anode&cathod) and the flow of electrons through the water. Thus it is split into its basic elements (hydrogen and oxygen), according to Equation 1,2 [8].

When designing a solar hydrogen system, it is more effective and economical to utilize a single large electrochemical analyzer instead of multiple analyzers. This approach takes into consideration the heat generated in the wires due to the intensity of the current. Consequently, the system under investigation is approved with one PV and an electrolyzer.

$$4H_2O + 4e^- \longrightarrow 2H_2 + 4OH^- \quad reduction \quad ....(1)$$

$$4OH^- \longrightarrow O_2 + 2H_2O + 4e \quad oxidation \quad ....(2)$$

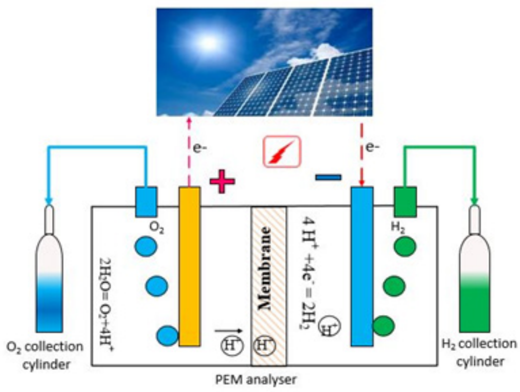

Figure 1. PV-PEM electrolyzer integrated system for hydrogen production.

3. METHODOLOGY AND THERMODYNAMIC ASSESSMENT

Estimating the value of solar energy depends on geographic location. In this research, the Angstrom correlation method is adopted for solar energy estimation. The electricity produced from PV is used in the electrochemical analysis of water using a PEM electrolyzer. The energy and efficiency of the system's devices are analyzed according to the first and second laws of thermodynamics. Furthermore, exergoeconomic analysis is performed according to the specific exergy costing method (SPECO) method [20, 21].

In the realm of mathematical analyses, the Engineering Equation Solution (EES) program reigns

supreme, owing to its remarkable advantages in facilitating an accurate and effortless exploration of variable relationships. With its robust capabilities, EES serves as the go-to tool for conducting intricate mathematical analyses. Its prowess lies in its ability to seamlessly establish connections between variables, enabling researchers to delve into complex systems with precision [22].
To embark on a comprehensive study of the system at hand, Table 1, encompasses the design parameters extracted from prior studies. Additionally, certain assumptions have been carefully incorporated and deemed essential for the thorough examination of the system. These assumptions, in conjunction with the gathered parameters, form the foundation upon which our investigation is built.

Table 1. Input and assumption parameters.

Parameters	Symbol	Values	Ref.
Ambient temperature	T_0	45°C	[19]
Ambient pressure	P_0	101 KPa	[19]
Location		29°.08E, 15°57E	[16]
solar constant	I_{SC}	1.367 kW/m^2	[16, 23]
Day number of the year	D	(1-365)	-
Average value $\left(\frac{\bar{H}}{H_o}\right)$	$\left(\frac{\bar{H}}{H_o}\right)$	0.609 (year average)	[16]
Average value $\left(\frac{\bar{n}}{N}\right)$	$\left(\frac{\bar{n}}{N}\right)$	0.781 (year average)	[16]
PV temperature	T_C	45°C	-
Current density	J	1000 A/m^2	[13]
Water chemical activity	a_{H_2}	0.99	[13]
Faraday constant	F	96490 C/mol	-
Gas constant	R	8.314 kJ/kmol K	-
Annual interest rate	i	2.5	[24]
Plant lifetime	N_{lif}	15 years	[24]
Maintenance factor	μ	1.025	[24]
Annual operation hours	ψ	3420 h	-
Cost of PV	Z_{PV}	310*Area ($)	[24]
Cost of PEM (2023)	Z_{PEM}	384-1071€/kW	[25]
Estimated cost (2030)	Z_{PEM}	63-234€/kW	[25]

3.1. Solar Radiation and PV Electricity

Estimating the value of the monthly average of daily global solar radiation on a horizontal surface according to the following form:

$$\bar{H} = H_o\left(a + \frac{b\bar{n}}{N}\right) \qquad ....(3)$$

$\bar{n}$ is the monthly mean daily number of hours of observed bright sunshine, N is the mean daily number of hours of daylight in a given month between sunrise and sunset, and a&b are regression coefficients.

$$N = \frac{2}{15\omega_s} \quad ....(4)$$

H_o is the extraterrestrial solar radiation on a horizontal surface on an average day of each month ($Wh.m^{-2}.day^{-1}$).

$$H_o = \frac{24 I_{SC}}{\pi}\left[1 + 0.033.\cos\left(\frac{360D}{365}\right)\right] \times \left(\cos\varphi.\cos\delta.\sin\omega_s \frac{\pi\omega_s}{180}.\sin\varphi.\sin\delta\right) \quad ......(5)$$

Where I_{sc} is the solar constant, φ is the latitude of the site, δ is the solar declination, ω_s is the sunrise hour angle, and D is the number of days of the year starting from the first of January.

$$\delta = 23.45.\sin\left[\frac{360(D+284)}{365}\right] \quad ....(6)$$

$$\omega_s = \cos^{-1}\left[-\tan\delta.\tan\varphi\right] \quad ....(7)$$

The recorded data for $\left(\frac{\bar{H}}{H_o}, \frac{\bar{n}}{N}\right)$ values at the Hun Meteorological Centre in the AL-Jufra region are utilized to calculate the solar radiation value, as indicated by a previous study [16].

By accurately estimating the solar radiation ($\bar{H}$) receives by the PV, it becomes possible to calculate the corresponding electricity output ($\dot{W}_e$):

$$\dot{W}_e = \left(\bar{H}.\eta_{OPT}.\eta_{PV} - \dot{W}_{PAR}\right) \quad ....(8)$$

The optical efficiency and the PV module are represented by (η_{OPT},η_{PV}), while ($\dot{W}_{PAR}$) denotes the parasitic power consumption. The optics efficiencies are assumed to be 0.85. The module efficiency can be expressed as follows [26]:

$$\eta_{PV} = 0.288 - 0.000558\left(T_C - 25\right) \quad ....(9)$$

The consumed parasitic power by the tracking motors is assumed 2.3% of intercepted radiation [27].

The solar exergy input to the PV panels ($\dot{E}_x$) is as follows [28]:

$$\dot{E}_x = \left(1 - \frac{4T_0}{3T_C} + \frac{1}{3}.\left(\frac{T_0}{T_{sun}}\right)^4\right) I_{SC} \quad ....(10)$$

3.2. PEM Thermodynamic Modelling

Dincer and Natere authored a pair of books focusing on water electrochemical analysis. These publications provide comprehensive explanations of the computation of various aspects concerning the thermal efficiency of the analyzer, as per the principles outlined in the first and second laws of thermodynamics [29, 30].

Important values for mathematical modelling of the process using the electrolyzer and their parameter performance are given in Table 2 [29].

Table 2. Modelling and performance parameters for electrolyzer [29].

Parameters and definition	Equations
Thermal nettral potential (V)	$E_{th} = \frac{\Delta H}{2F}$
Reversible cell potential (V)	$E_{rev} = E^0 + \frac{RT}{2F}.\ln(K_{eq})$

The equilibrium constant (Keq)	$K_{eq}=\left(\frac{P_{H_2}P_{O_2}^{0.5}}{a_{H_2}P_{O_2}^{1.5}}\right)$
Current density (A/m²)	$\frac{J}{J_0}=\exp\left(\frac{\alpha FE_{act}}{RT}\right)-\exp\left(-(1-\alpha)\frac{FE_{act}}{RT}\right)$
Activation overpotential (V)	$E_{act}=\left(\frac{RT}{F}\right)\left(\frac{J}{J_0}\right) \quad For \quad J\cong J_0$ $E_{act}=b\ln\left(\frac{J}{J_0}\right), \quad J\rangle J_0$
Concentration overpotential (V)	$E_{con}=\frac{RT}{zF}\ln\left(\frac{1+\frac{J}{J_L}}{1-\frac{J}{J_L}}\right)$
Energy efficiency (%)	$\eta_E=\frac{146.96}{E_{rev}+E_{act}+E_{con}}$
Exerg efficiency (%)	$\eta_{EX}=0.83\eta_E$
PEM Electricity consumption	$P_{PEM}=I_{PEM}.V_{cell}\left(\frac{W}{mol_{H_2}}\right)$
Ecell (V)	$\sum E_{rev}+E_{act}+E_{con}$
PEM current (A)	$I_{PEM}=2F\left(\frac{A}{mol_{H_2}}\right)$

From the previously mentioned equations, the amount of electricity generated in the PV($\dot{W}_e$) can be calculated. Since the PEM is fed on the electricity produced by the PV, the number of moles of produced hydrogen ($\dot{M}_{H_2}$) can be calculated from the equation [31, 32]:

$$\dot{M}_{H_2}=\frac{W_e}{P_{PEM}} \qquad ....(11)$$

3.3. System Energy and Exergy Efficiency

According to the first law of thermodynamics, the efficiency of a thermal system (energy efficiency) can be expressed as the ratio of the energy input to the power produced by the system. To evaluate the overall efficiency of the system in this study, the production of hydrogen from solar energy is considered. Therefore, the overall energy efficiency of the system can be expressed as follows:

$$\eta_{SE}=\frac{HHV\,\dot{M}_H}{\bar{H}} \qquad ....(12)$$

HHV is the high heat value of hydrogen.

Similarly, the system efficiency, according to the second law of thermodynamics (Exergy efficiency), is defined as the percentage ratio of exergy input ($\dot{E}_x$)to the exergy output (exergy of hydrogen), and can be succinctly expressed as follows:

$$\eta_{EX_S} = \frac{EX_{H_2}}{\dot{E}_x} \quad \text{.............(13)}$$

3.4. Exergoeconomic modelling

The economic analysis of the system uses the Specific Energy Cost Estimation (SPECO) method for economic evaluation [14, 20]. The cost balance equation for any component of the thermal system can be expressed in the following general form:

$$\sum \dot{C}_{in} + c\dot{W} + c_{th}\dot{E}x^{Q}_{in} + \dot{Z}_K = \sum \dot{C}_{out} + c\dot{W}_{out} + c_{th}\dot{E}x^{Q}_{out} \quad \text{....(14)}$$

$\dot{C}_{in}$ & $\dot{C}_{out}$ are the exergy rate ($\dot{E}_x$) of each stream multiplied by its specific cost (c). The subscripts (*th, K*) correspond to thermal, and component, respectively. The component cost rate ($\dot{Z}_K$) is determined by the cost of the equipment.

$$\dot{Z}_K = Z_K CRF\left(\frac{\mu}{\psi 3600}\right) \quad \text{.......(15)}$$

CRF is a capital recovery factor:

$$CRF = \frac{i(1+i)^{N_{lif}}}{(1+i)^{N_{lif}} - 1} \quad \text{........(16)}$$

4. RESULTS AND DISCUSSION

The results analysis revolves around assessing the amount of solar radiation that can be received in the AL-Jufra region and estimating the cost and amount of hydrogen and oxygen that can be produced. Additionally, the parameters that influence the production process, such as the energy and exergy efficiency of the electrolyzer and the PV solar panel are studied. Moreover, the study gives a broader perspective, by comparing hydrogen production in the AL-Jufra region with other regions in Libya.

4.1. Hours and Amount of Solar Radiation

AL-Jafra is located approximately in the middle of Libya, at a longitude of 15.57 and a latitude of 29.08. This geographical location allows it to receive a considerable amount of solar radiation, coupled with a significant number of daylight hours. These are supported by the results in Figure 1, as the actual hours of solar radiation absorption exceed 10 hours per day during June, with a solar energy value reaching more than 0.450 kW/m². This translates to an annual total of approximately 3,421 hours and 81.72 kW/ m².year.

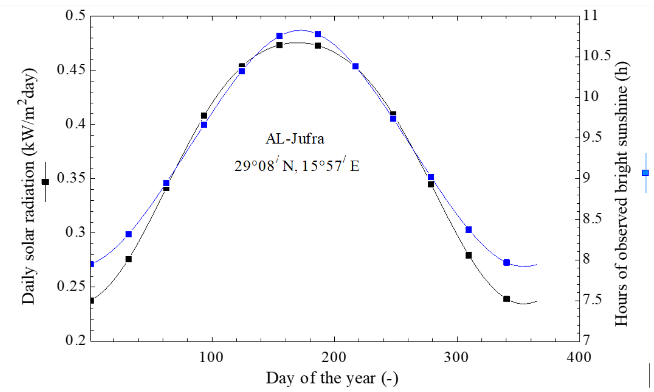

Figure 2. Demonstrates the daily solar radiation and day length.

4.2. PEM Energy and Exergy Efficiency

To deepen the study, the factors affecting the efficiency of the device that uses the electrolysis of water to produce hydrogen and oxygen (water electrolyzer) are analysed. Figure 3a shows the effect of cell pressure and temperature on the device's first and second laws of thermodynamic efficiency. This relationship links the amount of energy produced (hydrogen) to the amount of energy input (electricity). According to the figure: Increasing pressure and temperature leads to a decrease in both efficiencies, which leads to a decrease in the amount of hydrogen produced for the same amount of electrical energy consumed. As a result, there is an increase in energy destruction and hydrogen cost. Therefore, it is desirable to maintain the cell temperature and pressure within possible limits.

Figure 3b shows the amount of energy destruction by the PV panel and the PEM in each month of the year. The amount of energy wasted by both devices is higher during the period of intense solar radiation (April - September). This is due to the large amount of solar energy during this period and some of it being dissipated. It is clear from the figure that the amount wasted by the PV panel is greater than that wasted by the electrolyszr. This is due to the large amount of solar energy that cannot be converted into electricity due to the low electrical efficiency of the PV panel. Efforts can be made to increase the efficiency of both devices, which in turn will increase the amount of hydrogen produced and reduce the costs.

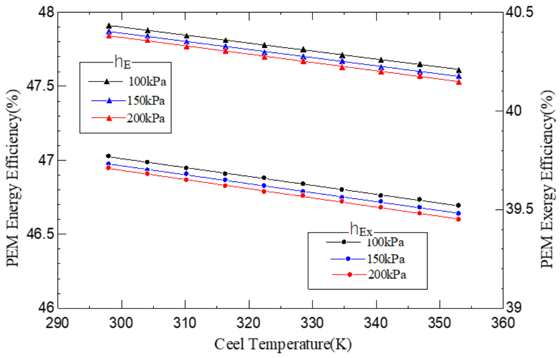

Figure 4a. PV&PEM energy and exergy efficiencies.

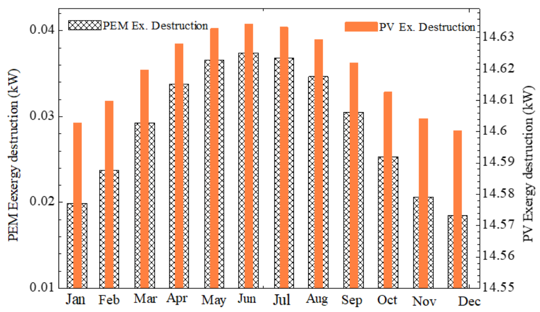

Figure 3b. PEM and PV exergy destruction during the year.

4.3. System Energy and Energy Efficiency

The first and second laws of thermodynamics efficiency (energy and exergy efficiency) of a system represent the system's ability to convert gained energy into useful energy and estimate the losses and irreversible energy. This system uses solar energy as the energy gained and converts it into chemical energy in hydrogen gas. Hydrogen production depends on two main stages: the first involves converting solar energy into electricity through photovoltaic panels, and then the electricity produced is used to produce hydrogen as a final product. The thermal efficiencies of both processes are calculated, analyzed and studied.

In Figure 4a, it is noted that the energy and exergy efficiency of the PV panel varies with the intensity of solar radiation. reach their peak in the middle of the year when radiation is at its highest levels. The highest PV energy and exergy efficiency values just exceed 4.5 and 5%, which are relatively low due to the inability to harness and convert radiation into electricity effectively. This value can be improved by enhancing the panel's efficiency.

As for the thermal efficiencies of the electrolyzer, it does not change over time but rather remains constant. The reason for this is that the ratio between the input energy (electricity) and the output energy (hydrogen) remains constant throughout the production period. It is noteworthy that the energy and exergy efficiency of the electrolyzer is good (39 &48%), which can be attributed to its effective performance in converting electricity into hydrogen.

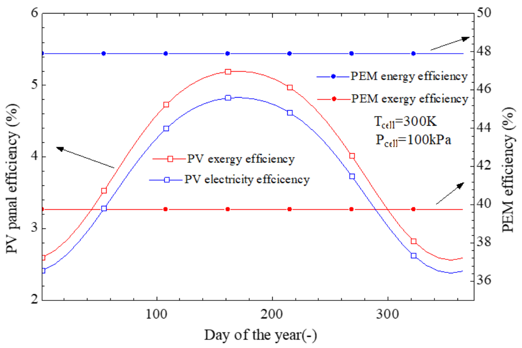

Figure 4a. PV&PEM energy and exergy efficiencies.

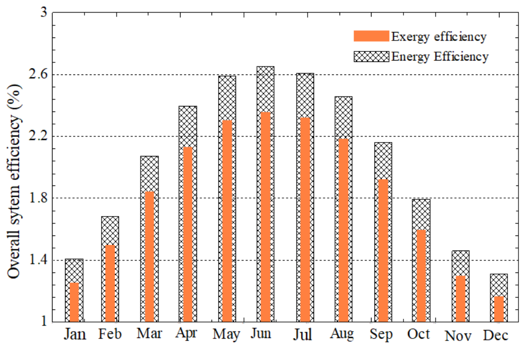

Figure 4b. Overall system efficiency.

Low PV efficiency affects the overall system efficiency and makes it low. It is noted from Figure 4b that the thermal efficiency of the system does not exceed 3% during the annual peak period (Jun). This value varies during months of the year and behaves similarly to the efficiency of solar panels as a result of its effect on the overall efficiency of the system. Based on this conclusion, it is recommended to choose solar panels with good efficiency to enhance the overall efficiency.

4.4. Hydrogen and Oxygen Production

The production rate varies from day to day throughout the year. It depends on the amount of daily sunlight radiation. It can be seen from Figures 5a and b that the amount of hydrogen produced reaches its peak (5 mol/day.m^2) around the middle of the year (July). This is due to longer daylight hours, which results in more absorption of radiation, resulting in greater production of electricity which in turn powers the electrolyzer.

Figure 5b shows the monthly production rate of hydrogen and oxygen. The highest amount produced during July is 170 mole/m^2, followed by June and August. Based on this analysis, it is recommended not to schedule preventative maintenance of the system during these months to avoid downtime during the peak production period. The results indicate that 1,272 mol/m^2 of hydrogen and 636 mol/m2 of oxygen can be produced annually under ideal conditions.

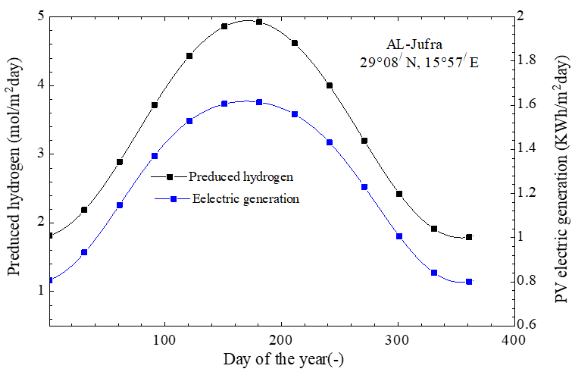

Figure 5a. Amount of daily produced hydrogen and electricity.

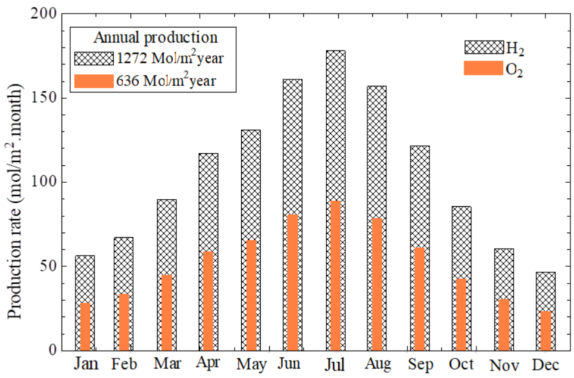

Figure 5b. Value of the monthly production.

4.5. Product Cost

The average cost of the products (hydrogen &oxygen) depends on several factors, including fixed factors such as the capital cost of equipment (solar panels, electrolyzer, etc.) and variable factors such as solar radiation intensity. Figure 6 shows that the cost of electricity and hydrogen decreases with increasing solar radiation. This is due to increased electricity production rate with higher radiation intensity. Calculations show that the average solar radiation the region receives is about 0.37 kW/m^2, resulting in electricity and product costs at 0.5 \$/kWh and 1.42\$/mole.

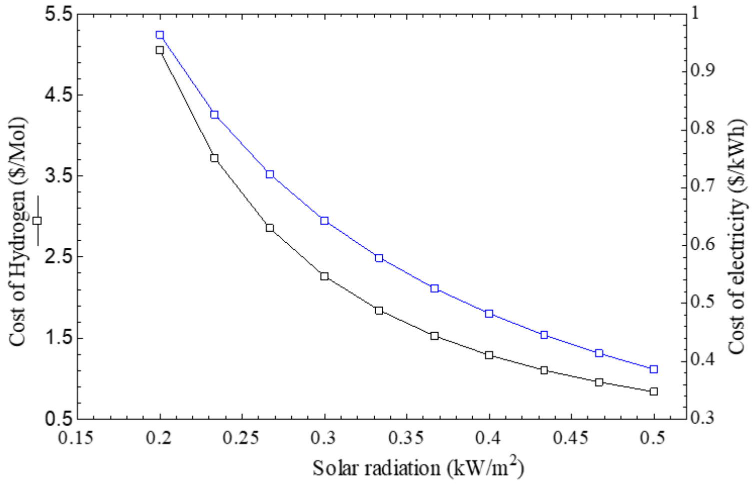

Figure 6. Effect of solar radiation on the product's cost.

Since the cost of production varies from one location to another depending on the intensity of solar radiation in the area. Accordingly, a comparison is done between the Al-Jufra region and some other regions in Libya. Figure 7 compares production rates and costs between the Al-Jura, AL-Kufra region and the capital, Tripoli. The region with a higher production rate achieves lower production costs. AL-Kufra, located at a latitude south of AL-Jufra, achieves a 20% higher production rate. In contrast, the capital, Tripoli, located at a higher latitude than Al-Jufra, achieves a lower production rate and a higher cost.

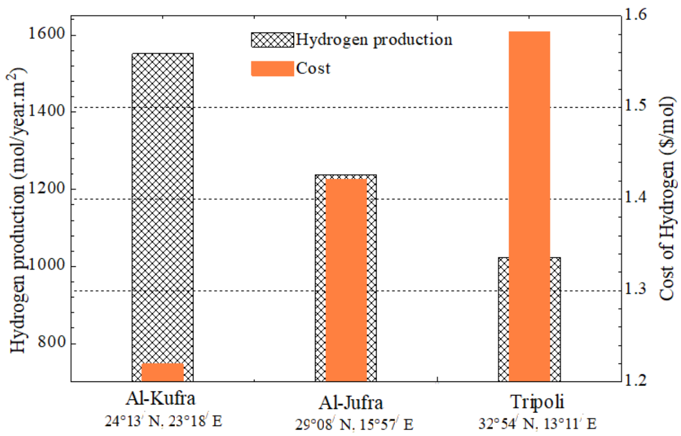

Figure 7. Demonstrates cost and annual production for different regions.

The cost of the electrolyzer is decreasing with advances in manufacturing technology and improved performance, the production cost has been estimated for the next eight years. The price of the analyser is expected to decrease from $728 in 2023 to $149 in 2030. Assuming the price declines at a constant rate over the next eight years, the cost of production for each year has been estimated. It is expected to decrease by 5.77% to $1,388/mall in 2030. It is worth noting that this cost does not include storage and transportation expenses. It is advisable to consider these factors when choosing a location for installing the system. In remote areas far from consumption or export sites, transportation costs will be added to the cost of production.

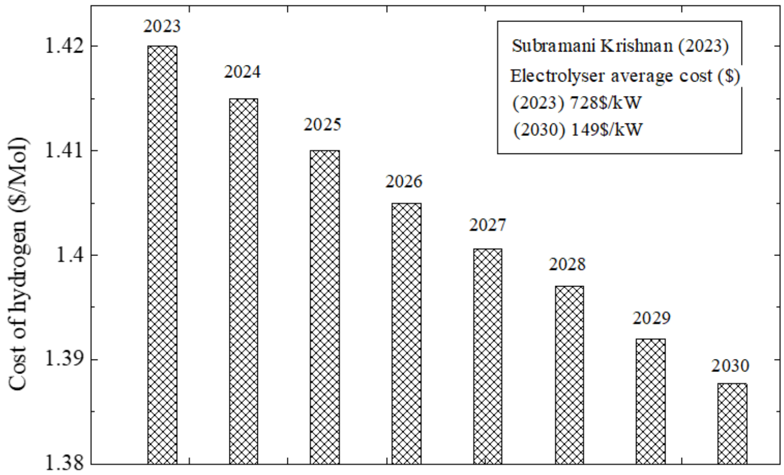

Figure 8. Estimating the cost for the following seven years.

5. CONCLUSION

The study evaluates thermodynamically and economically the solar hydrogen produced in the Al-Jufra area using PV panel technology, as well as studies the parameters affecting the production process. The study concluded the following important points:

- The total solar radiation that the area can receive annually is estimated at 71.82 kW/m2 during 3421 daylight hours.
- 1272 mol/m2 of hydrogen and 636 mol/m2 of oxygen can be produced annually at $1.42/mol.
- The efficiency of the PV panel and analyzer greatly affects the system's overall efficiency.
- The system's overall thermal efficiency is relatively low and does not exceed 3%.
- The system efficiency can be improved by enhancing the thermal efficiency of the PV panel and PEM.
- In the foreseeable future, with advances in technology for manufacturing analyzers and PV with a decrease in their prices, the cost of production can be reduced.
- The areas south of Al-Jufra provide higher production rates and lower prices due to the availability of a greater amount of solar radiation.

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