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Research Article

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Sizing electrolyzer capacity in conjunction with an off-grid photovoltaic system for the highest hydrogen production

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Abstract: The electrolysis of renewable energy to produce hydrogen has become a strategy for supporting a decarbonized economy. However, it is typically not cost-effective compared to conventional carbon-emitting methods. Due to the predicted intermediate of low-and zero-marginal-cost renewable energy sources, the ability of electrolysis to connect with electricity pricing offers a novel way to cost reduction. Moreover, renewables, particularly photovoltaics, have a deflationary effect on the value of the grid when they are deployed. This study investigates solar electrolysis configurations employing photovoltaic cells to feed a proton exchange membrane water electrolyzer for hydrogen production. Using experimental meteorological data at 1-min precision, the system has been evaluated in Baghdad, the capital of Iraq. Positioned at the yearly optimum tilt angle for the selected site, the solar array is rated at 12 kWp. Temperature effects on solar module energy loss are taken into account. Several electrolyzers with capacities ranging from 2 to 14 kW in terms of hydrogen production were examined to determine the efficacy and efficiency of renewable sources. MATLAB was utilized for the simulation procedure, with a 2021–2035 project lifespan in mind. The results suggest that a variety of potentially cost-competitive options exist for systems with market configurations that closely approximate wholesale renewable hydrogen. At 4313 h of operation per year, the planned photovoltaic array generated 18,892 kWh of energy. The achieved hydrogen production cost ranges between $5.39/kg and $3.23/kg, with an ideal electrolyzer capacity of 8 kW matching a 12 kWp photovoltaic array capable of producing 450 kg/year of hydrogen at a cost of $3.23/kg.

Keywords: hydrogen economy; hydrogen energy; photovoltaic energy; proton exchange membrane electrolysis; renewable hydrogen.

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Introduction

Fossil fuels have driven industry and societal requirements for more than a century (Aydin, Dincer, and Ha 2021). Currently, a number of variables contribute to the decline in fossil fuel consumption (Razmjoo et al. 2021). As the global population increased and individuals consumed more fossil fuels, their prices rose (Barhoumi et al. 2020). In addition, excessive use of fossil fuels results in substantial environmental contamination, which increases the frequency of intense precipitation (Jaszczur et al. 2020a). Therefore, it is essential to focus on renewable energy sources to alleviate the effects of climate change (Hassan 2021a).

There are numerous and diverse renewable energy sources, including wind, solar, and others (Jaszczur and Hassan 2020). In recent decades, technological advancements have been proposed, and renewable energy sources have become the primary source of electricity (Hassan 2020). However, the intermittent nature of renewable energy sources has a number of detrimental implications on the electricity produced from these sources. Even though batteries are used to store electricity, their high cost prohibits the creation of large and medium-sized renewable energy systems (Ceran et al. 2021).

Hydrogen is expected to account for 12% of world energy consumption by 2050. This increase highlights the importance of low-carbon hydrogen, as it is anticipated that by 2050, two-thirds of total hydrogen will be produced from renewable energy sources and one-third from natural gas combined with carbon capture and storage (Gielen et al. 2021). In order to reach the goals specified in the Paris Agreement, scientists and experts believe that the usage of green hydrogen will be crucial. Direct electrification reduces emissions from the production and transmission of electricity, but the majority of progress is being achieved in energy efficiency and the use of renewable sources.

Hydrogen energy is recognized as the most potential renewable energy source of the 21st century since it is renewable, economical, and sustained. The sustainable hydrogen is characterized as an energy vector sufficient to meet the diverse demands of multiple sectors, including industrial, transportation, energy conservation, and the domestic sector. Meanwhile, most of the raw materials for producing hydrogen come from the chemical reformation of existing energy sources. Unlike the producing hydrogen from fossil fuels, the production of hydrogen by electrolysis of water does not create carbon dioxide (Wu et al. 2021). Despite the fact that the majority of the cost per kilogram of hydrogen generated by electrolysis is due to the cost of power, it is also significant that the cost per kilogram depends on the amount to which electrolyzers are used (Hassan et al. 2022a). So, this study looks into how solar photovoltaic (PV) energy is made using PV technology as a source of energy and how the size of the device affects its absorption coefficient.

Hydrogen production by using water electrolysis is now hampered by a number of factors, notable among them being the drawback of high cost. The majority of the cost of water-electrolytic hydrogen generation comes from investments in fixed assets, power expenses, production and operating expenses. Approximately, 80% of the overall cost is accounted for by electricity indicating that the high cost of energy is the primary cause for the high cost of water electrolysis (Council, H 2020). There are two approaches to minimize the price of producing hydrogen by water electrolysis. the first is to reduce the energy consumption of the electrolysis process, and the second is to reduce the cost of electricity. Consequently, the second kind of approach is the most successful at now. However, given the inequitable distribution of new energy sources, locations with abundant green resources are disadvantaged (dos Santos et al. 2017). Therefore, it is preferable to eat on-site through other methods. In conclusion, the development of solar energy generation for hydrogen production does not relieve the matter of water electrolysis high cost. Therefore, the design and development of solar hydrogen generation facilities must rise in these regions.

Hydrogen production from water

Water is a naturally abundant chemical that is famous as a substantial source of hydrogen. At Standard Temperature and Pressure (STP), the thermodynamic of a water molecule is roughly 285.83 kJ/mol, however water breakdown by direct-heating occurs at very high temperatures (up to 2000 °C). At this temperature, however, it becomes difficult to separate oxygen from hydrogen. Using a catalyst and ceramic membrane for decomposition reaction and gas separation, or a chemical reactant and/or energy, water splitting is a low-temperature process for generating hydrogen (Han et al. 2015; Rand and Dell 2007). Figure 1 illustrates the electrolysis of water using a standard electrical source.

Literature review

Hydrogen can be produced via a variety of techniques, such as electrolysis, chemical reactions, and thermolysis. Even though the most eco-friendly technique of producing hydrogen will eventually be used, electrochemical technologies that rely on power from renewable energy sources are more practical. Following the earliest phases of research on the electrolysis method, various scientists used this method to improve hydrogen production. The main processes for producing hydrogen involve electrolysis technologies, such as alkaline water (Han et al. 2015), and proton exchange membrane (Awasthi, Scott, and Basu 2011; Görgün 2006).

Acar, Dincer, and Naterer (2016) provided a review study on the photocatalytic production of hydrogen. The study assessed the benefits and drawbacks of several

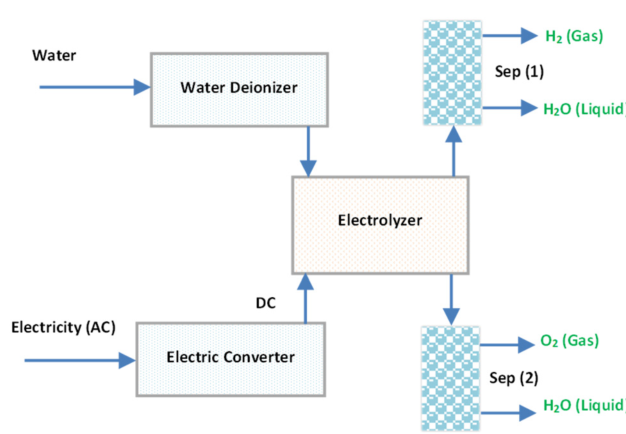

Figure 1: Schematic depicting the electrolysis of water with supplied power.

hydrogen production technologies, with a focus on photocatalytic hydrogen synthesis. In addition, social, ecological, and economic indicators are considered when evaluating certain photocatalyst manufacturing techniques and types. Another review article for solar water splitting technologies presented by Chatterjee et al. (2022).

Review articles examining models that simulate electrolyzer performance and/or specific weather phenomena that occur within a particular electrolyzer component are extremely beneficial to the research community, not only because they provide a clearer understanding of the current state of the art, but also because they provide a variety of input variables and useful guidelines for the creation of new models. Carmo et al. (Grimm, de Jong, and Kramer 2020) published a review on proton exchange membrane (PEM) electrolysis of water that included a section on modeling PEM water electrolysis. Olivier, Bourasseau, and Bouamama (2017) wrote a thorough review of low-temperature electrolysis system designs, which included alkaline and PEM technology solutions. They also put the models they looked at into different groups based on things like the physical domains they involved or how they were modeled numerically.

Gibson and Kelly (2008) determined that the efficiency of the PV-electrolysis system could be maximized by synchronizing the amplitude and peak power production of the PV system to the voltage level of the PEM electrolyzers. The outcomes showed that the optimization procedure boosted the hydrogen production efficiency to 12% for a solar-powered PV/PEM electrolyzer that could produce sufficient hydrogen for a fuel cell automobile. Clarke et al. (2009) investigated the feasibility of directly coupling a PV and PEM electrolyzer for hydrogen production. The results indicated that the judicious matching of the properties of both the photovoltaic and electrolyzer under varying solar radiation is crucial for achieving a maximum hydrogen rate of production. Bhattacharyya, Misra, and Sandeep (2017a) electrolyzed water with yearly hydrogen generation on the order of 10 Nm^3/h. According to their study, a maximum power output of around 120 kW is necessary to produce 10 Nm^3/h of hydrogen. The estimated payback period was 11,6 years based on an economic analysis of the selected site. Qureshy and Dincer (2020) put together an energy system that uses a renewable resource to make hydrogen, as well as a full thermodynamics analysis and evaluation using an energy approach for the solar-water-hydrogen-power cycle. The given results demonstrate that the proposed system obtains an energy efficiency of 25.07%. At 115.86 MW, the energy destruction and entropy production output at the PV panel are at their highest. When the solar receiver is collecting heat at a rate of 1000 MW at 33.53%, it is using the least amount of energy. Beck (2019) illustrate that the integration of PV modules into the system is crucial for optimizing the solar-to-hydrogen conversion efficiency. The study offers a novel paradigm, based on simple transmission concepts, to demonstrate that detaching the PV modules from the electrolytic system via the use of energy monitoring could greatly improve system efficiency. Decoupled systems could also use the current technology of solar cells and the stability of the silicon PV sector to speed up the production of solar hydrogen. Varadhan et al. (2019) described a simple and cost-effective strategy focused on photoelectrodes that operationally and spatially disentangle the light-harvesting aspect of the device from the electrolytic cell part, thereby eradicating parasitic light absorption, reducing costs, and improving the consistency without compromising the efficiency of the hydrogen production. A correspondingly developed epitaxial lift-off was used to produce the monolithically integrated electrolytic cell. The outcomes show that the remarkable efficiency and durability attained here are a consequence of the light-harvesting/catalysis decoupled strategy, which simultaneously enhances the optical and electromagnetic properties and produces hydrogen of high quality. Grimm et al. (2022) provide a circuit comparable model for calculating the steady-state effectiveness of photoelectrochemical cells. The model consists of five distinct photoelectrochemical devices and is based on experimental data. The estimated performance corresponds well with the experimental data of the multiple devices. In addition, the model is expanded to include the influence of light and tilt angle on the effectiveness of hydrogen production. The generated model is used to compare devices for various locations with varying average light levels and tilt angles. The outcomes indicate that the annual average solar-to-hydrogen conversion rate is much lower than the optimal rate. Astakhov et al. (2021) showed that the implementation of batteries in PV-water splitting electrochemical systems is a suitable alternative for smoothing out PV power fluctuations. In particular, the distribution of PV energy across the 24-h period reduces the electrochemical cells power and, consequently, its electrode potential loss. Theoretically and experimentally, the study investigated these possible benefits for a simple parallel connection of PV, electrochemical and rechargeable batteries. Authors demonstrate the viability of the unassisted running of the PV, electrochemical and rechargeable batteries device in a meaningful duty cycle and investigate how the PV, electrochemical and batteries system could function at a better solar-to-hydrogen efficiency than the similar standard PV, electrochemica system, notwithstanding the losses incurred by the batteries. On the basis of the cost of hydrogen, a comparison was conducted to determine two technologies for hydrogen production based on the PV system prepared by Hassan et al. (2022b).

The designs of the PV/electrolyzer (EL) system and the photoelectrochemical system have been compared based on hydrogen production cost and system efficiency. The results demonstrated that the hydrogen cost for the off-grid PV/EL system was determined to be \$6.22/kg with an efficiency of 10.9%, and for the photoelectrochemical system the hydrogen cost was \$8.43/kg with an efficiency of 10%, which was much higher. The research indicated that the potential techno-economic advantages that photoelectrochemical systems have over PV/EL are ambiguous and, in the best-case scenario, modest. Even though research into photoelectrochemical cells is still interesting, there is not much reason to put money into developing and scaling up the technology. Another important article is by Giménez and Bisquert (2016), who investigated the economic and technical feasibility of two distinct photoelectrochemical systems and two types of PV/EL systems. The results demonstrate that the photoelectrochemical system has a lower low hydrogen cost than the off-grid PV/EL. However, the cost estimation of several important components of the photoelectrochemical system was based on commercially available PV components and electrolyzers, which could be significantly different from a true photoelectrochemical system in which both components are combined into a single device. Also, prices have gone down a lot since it was published, especially for PV panels, which means more research is needed. Khouya (2020) studied the synthesis of hydrogen via an electrolyzer powered by a solar-generated electric current. The research was conducted using weather information from the Tangier area of Morocco. The results demonstrate that the electrolyzer electricity consumption rates are 64 kWh/kg of solar energy, respectively. The efficiency of hydrogen generation was 62%, and the prices of electricity and hydrogen fell as photovoltaic capacity increased. This is a great idea for combining the two green sources that have been looked into, as long as the capacity of the electrolyzer that will be installed is enough to boost the production of hydrogen.

Atlam and Kolhe (2011) established an electrically accurate approximation for a PEM electrolyzer based on steady-state experimental data and Faraday law. The model gives an estimate of the hydrogen generation rate, the power-hydrogen production rate, and the feasible electrolyzer efficiency by adjusting the experimental data in the active layer. This model is quite helpful for analyzing the effects of both pressure and temperature on electrolysis performance. Regarding hydrogen production, Sartory et al. (2017) provided a semi-empirical zero-dimensional steady state model of an asymmetric high-pressure PEM water electrolyzer. The empirical characteristics for a 9.6 kW electrolyzer were determined based on experimental research. As a factor of inverter, processing temperature, and output pressure, the model in question can forecast stack voltage, gas production flow rates, water consumption, and stacking effectiveness. The results demonstrated a good degree of measurement and simulated accuracy. Hassani et al. (2020) presented an energy management technique for a PV system with battery storage and an electrolyzer for producing hydrogen. Each subsystem is developed to determine the most appropriate quantity of hydrogen-supplying components. An energy management system was implemented to control these various sources. There was a surplus of solar energy as a result of the suggested oversight, which was utilized to drive an electrolyzer and recharge the batteries. Three important situations were chosen to show how the improvements to the supervision protect the batteries and let us get a steady power load. Yang et al. (2021) are investigating a universal technique for estimating the power redistribution and capacity configurations for a PV power station combined hydrogen production system that is grid-connected, utilizing 100 MW of PV electrical characterization and power to control methods of the hydrogen system process under various storage configurations. The results showed that three sets of 800 Nm^3/h electrolyzers and an annual hydrogen output of 7.01 million Nm^3 were the best ways to set up the hydrogen production system using the grid connection method. This can cut CO^2 emissions by 7.72 million tons.

Abd Elaziz et al. (2021) establish a technique using artificial intelligence to estimate the performance of PV/EL systems, including electrolytic hydrogen production. The investigation was conducted using two cooling working fluids (water or air), and a model was developed to estimate the effectiveness of the proposed system. Results showed that the proposed system kept making 4.41 kg of hydrogen per day at a high rate. Kurşun and Ökten (2019) developed a photovoltaic system for hydrogen production using a proton exchange membrane electrolyzer plant. The results indicated that the PV system improved energy efficiency and hydrogen production at various rates depending on the parameter settings. According to the conditions, an increase in hydrogen production of between 0.02 kg/h and 0.30 kg/h was realized. The proposal of Nordin and Rahman (2019) is to utilize extra energy to produce hydrogen, which will then be supplied to local customers. Using an adaptive approach, this article compares the optimized design and economic analysis off-grid PV system with/without battery for hydrogen production. For the feasibility assessment of the off-grid PV system with a battery better hydrogen production. Li et al. (2022) assessed the usage of a water electrolyzer fed by PV systems for the production of hydrogen. Different water mass flow rates were used to assess the generation of heat and electrical energy. When the increasing mass flow rate made the electrolyzer temperature drop, this made the maximum electrical efficiencies for water consumption by about 33.8 and 8.5%, respectively. Temiz and Javani (2020) examined the utilization of a floating PV system in the generation of hydrogen. The essential documentation for the investigation was gathered from Mumcular Dam in Turkey. The floating PV system decreased the temperature of the solar panels and enhanced power production. This system produces the majority of its electrical energy without the need for fossil fuels or grid connection. Moreover, a floating PV system reduced the evaporation of water on a 3009-square-meter space. Berrada and Laasmi (2021) study examines the technological and economic effects of producing sustainable hydrogen using solar energy in Morocco. This The distribution of public subsidies has also been researched to determine its influence on the hydrogen price, energy cost, and CO_2 emission reductions. The observed results indicate that the cost of producing hydrogen ranges between \$3.49/kg and \$5.96/kg. The investment site is likely to see a big increase in renewable energy because of the promise of green hydrogen and, in particular, the economic potential of its export.

Akyuz et al. (2011) evaluated solar radiation intensity as a component of a set of variables influencing the performance of photovoltaic systems. In this research, a prototype in Turkey was chosen and its hydrogen production was evaluated based on yearly irradiance measurements. According to this research, one of the parameters estimating the probability distribution of hydrogen production effectiveness is the variable of time. It was stated that the highest hydrogen production was around 600 and 650 W/m^2, that the total energy effectiveness was 8.1%, and that the average energy effectiveness of the examined PEM electrolysis system was 60.5% with a 0.48 A/cm2 current density. In the end, the production of hydrogen in the Balikesir area of Turkey was expected to cost \$43.9 per kilogram. Bhattacharyya, Misra, and Sandeep (2017b) investigated the synthesis of PV-hydrogen under various environmental conditions. Different solar irradiation was shown to result in varying amounts of hydrogen generation. According to the projections, 60 kW of power is needed to produce 10 N m^3 h1 at 70 °C and 5 bar pressures. Laoun et al. (2016) evaluated a solar PV/EL system for hydrogen production and studied the influence of each component on the entire process.

Objective, novelty and paper structure

In previous studies on producing hydrogen, research gaps were found and filled. Numerous researchers have attempted to create hydrogen using various solar energy sources and electrolyzers, but none have looked at an integrated system that hydrogen production using solar energy in Iraqi environment. Additionally, many methods for producing hydrogen have been devised, and efforts have been taken to lower the cycle particular energy usage. The novelty of this paper presents an entire system for producing hydrogen in an environment in Iraq utilizing solar energy.

This study is structured as follows: Proposed system and site of investigation contains the experimental collected data at the investigation location and utilized for the proposed system. Experimental weather data describes the mathematical model used to predict PV power based on observed solar irradiance, hydrogen generation, and cost, the results indexes acquired in Modeling and governing equations, and Results and discussions provides some final observations.

Proposed system and site of investigation

Figure 2 shows the system that has been investigated is made up of four primary parts. The first component is the power generating module, which is comprised of PV panels that are responsible for the production of energy, an AC/DC converter, an electrolyzer, a compressor, and a hydrogen tank. The PV array is responsible for controlling the amount of DC power that is required for the electrolyzer, in addition to feeding the compressor. The water electrolyzer is responsible for the separation of oxygen and hydrogen from water. The proposed system is completed by the hydrogen storage tank and compressor units, which are responsible for compressing and storing the hydrogen that has been created. Table 1 showed the technical and economic specifications for the proposed energy system.

The proposed system for producing hydrogen is tested in Baghdad, Iraq, at coordinates 33.31 N and 44.36 E (see Figure 3). The PV array was positioned at the optimum annual adjustment, and the simulation procedure was performed at a resolution of 1 min. The project has lifespan between 2021 and 2035, and since the economic evaluation is based on Iraqi regulations, the yearly interest rate is 6%.

Experimental weather data

The weather data (solar irradiance and ambient temperature) has been measured for the selected site at 1-min resolution by weather station type (FT0300) for a one-year span of 2021. The daily annual average of the solar irradiance was

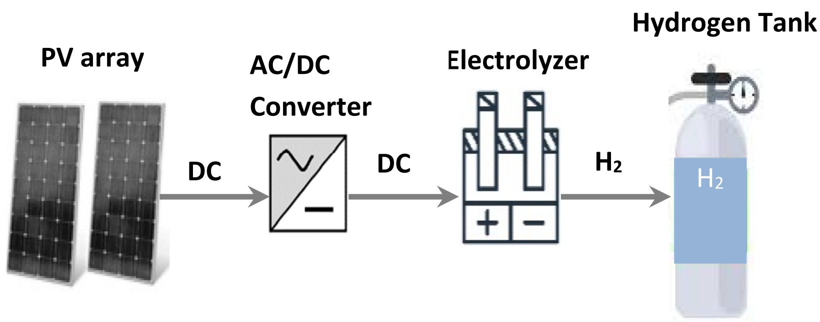

Figure 2: Schematic of the proposed system for producing hydrogen using solar energy.

Table 1: The proposed energy system technical and economic specifications.

Component	Model	Rated Power (kW)	Efficiency (%)	Capital ($/unit)	Replacement ($/unit)	Maintenance ($)	Life span (year)	Ref.
PV module	Luminous	1 kW	19.8	140	140	10/year	20	Monocrystalline
Converter	Luminous	7 kW	>95	850	900	10	10	Monocrystalline
Electrolyzer	Geemblue	5 kW	>95	700	700	0.03/h	10	Electrolyzer
Compressor	Doosan	0.8 kW	>93	180	180		20	Compressor and hydrogen tank
Hydrogen tank	Doosan	–	98	100	100	10/year	25	Compressor and hydrogen tank

recorded at 4.5 kWh/m^2/day and the daily annual average of the ambient temperature was 27.8 °C. Figures 4 and 5 show the daily (for four selected days) and the monthly average for solar irradiance and ambient temperature.

Table 2 shows the daily experimental solar irradiance and ambient temperature for four selected days through the year 2021. Among the selected days the highest solar irradiance and ambient temperature were observed on July 02, which was 7.26 kWh/m^2, 38.3 °C, respectively, and the lowest solar irradiance and ambient temperature were observed on January 02, which was 1.36 kWh/m^2, 11.8 °C, respectively.

Figure 5 shows the monthly average experimental solar irradiance and ambient temperature, which showed the highest during the summer months and the lowest during winter months.

Modeling and governing equations

PV array

The photovoltaic power output is estimated by the amount of incident solar irradiations and other environmental factors such as ambient temperature and humidity, etc. PV output power can be calculated as (Hassan et al. 2021).

$$P_{\mathrm{PV}} = f_{\mathrm{PV}} Y_{\mathrm{PV}} \left[1 + \alpha_P \left(T_C - T_{C,\mathrm{STC}}\right)\right] \left(\frac{S_T}{S_{T,\mathrm{STC}}}\right) \tag{1}$$

whereas the PV cell temperature can be determined using solar irradiance, ambient temperature, and wind speed presented as (Abbas et al. 2021; Hassan et al. 2022c):

$$T_C = T_A + S_T \left(1 - \frac{\eta_C}{\tau\alpha}\right) \left(\frac{T_{C,\mathrm{NOCT}} - T_{A,\mathrm{NOCT}}}{S_{T,\mathrm{NOCT}}}\right) \tag{2}$$

The fluctuation of the PV cell temperatures can be evaluated using (Jaszczur et al. 2019).

$$\tau\alpha S_T = \eta_C S_T + U_L \left(T_C - T_A\right) \tag{3}$$

where $\tau\alpha$ demonstrates the effective absorption transmittance of PV cells.

Electrolyzer

The electrolyzer hydrogen generation rate is calculated as (Boulmrharj et al. 2020; Hassan et al. 2019)

$$Q_{H_2} = \eta_f \left(\frac{N_C I_e}{2F}\right) \tag{4}$$

The quantity of electrical energy input needed by the electrolyzer can be calculated as (Hassan 2021b).

$$I_E = A_E . m_{H_2} + B_E . m'_{H_2} \tag{5}$$

Figure 3: The map of Iraq with the highlighted analyzed city (Hassan et al. 2022b).

Compressor and hydrogen tank

The required power to compress the hydrogen contained in the hydrogen tank can be calculated as (Farhani and Bacha 2021):

$$P_{\text{com}} = \left[\left(\frac{P_{\text{hto}}}{P_{\text{hti}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\left(\frac{g}{g-1}\right)R\left(\frac{T_{\text{htci}}}{\eta_{\text{htc}}}\right)Q_{H_2} \tag{6}$$

The predicted pressure within the hydrogen tank can calculated:

$$P_{\tan\ K} = \left(\frac{R\,T_{\text{htci}}}{Vh\ \tan\ K}\right)\eta_h\ \ \tan\ \ K \tag{7}$$

Converter

The PV panel provide DC electricity, but the demand is typically AC, therefore, the converter is required to convert DC power to AC power, in addition, applied in the power

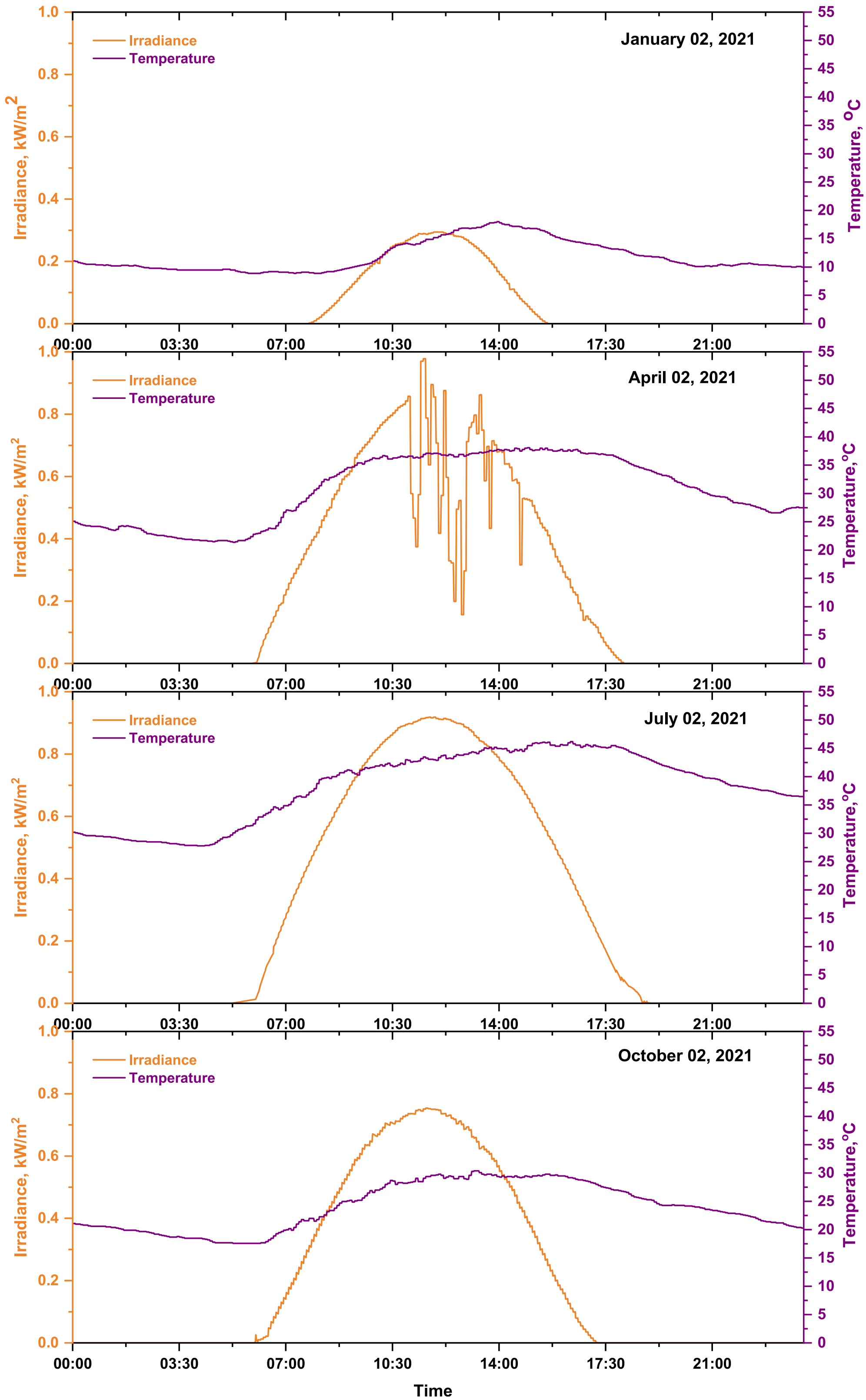

Figure 4: Daily experimental solar irradaince and ambient temperature for four selected days through the year of 2021.

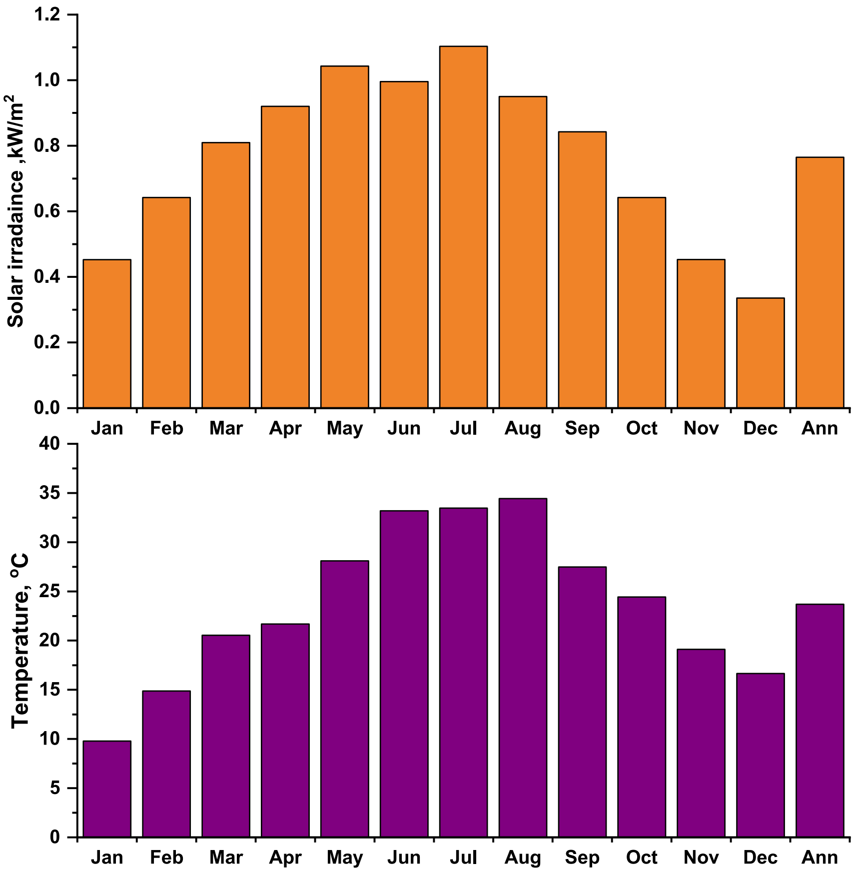

Figure 5: Monthly average experimental solar irradiance and ambient temperature.

Table 2: Daily average experimental solar irradaince and ambient temperature for four selected days through the year of 2021.

Day	Irradiance (kWh/m^2)	Temperature (°C)
January 02	1.36	11.8
April 02	5.62	30.7
July 02	7.26	38.3
October 02	5.01	23.9

system to regulate the energy flow. The converter efficiency may be calculated as (Jaszczur et al. 2021).

$$\eta_{\text{con}} = \frac{P_{\text{ocon}}}{P_{\text{icon}}} \tag{8}$$

System power flow

The power flow distribution between the proposed system components which is generated by PV array and supplies adequate electricity to the electrolyzer and hydrogen can be presented as following equation:

$$P_{\text{El}} = P_{\text{PV}}\left(\eta_{\text{con}}\right) - P_{\text{com}} \tag{9}$$

Hydrogen cost

The cost of hydrogen is a method for calculating the cost of producing one kg of hydrogen, and may be computed using the following expression (Hassan 2021c; Jaszczur et al. 2020b):

$$\text{COH} = \frac{I + \sum_{t=1}^{n} \frac{M_C}{(I+i)^t}}{\sum_{t=1}^{n} H_t} \tag{10}$$

Results and discussions

Based on the supplied meteorological data, the simulation procedure was conducted using MATLAB at a 1-min precision. The photovoltaic array comprised 12 modules with a total power of 12 kWp (module specifications presented in Table 1). The array was placed at the annual optimal orientation for the chosen location (tilt angle = 30° and azimuth angle = 0° south facing). Consideration was given to the impact of ambient temperature on the energy generated by the PV array. The PV array derating factor was determined to be 95%, with the remaining 5% representing energy losses in wiring, dust, etc. The electrolyzer is available in a variety of capacities (2 kW, 4 kW, 6 kW, 8 kW, 10 kW, 12 kW, and 14 kW) in order to select the optimal capacity that may be injected into the PV array capacity for the greatest hydrogen generation. The pricing for the proposed system components is based on Iraqi market conditions and an inflation rate of 0.6%.

Power and energy generated by the PV array

Figure 6 depicts the daily power for the specified days as well as the monthly energy produced by the PV array. The day with the maximum solar irradiance is July 2, 2021, and the day with the lowest solar irradiance is January 2, 2021 (see Figure 3). In Figure 6, the maximum monthly energy that can be generated by the proposed PV array in July and the minimum in December, with an annual maximum of 18,892 kWh at 4313 operation hours.

Table 3 shows the daily energy produced by the proposed PV array.

Table 3: Daily energy generated by of PV array for the selected days.

Day	PV energy (kWh)
January 02	15.75
April 02	60.32
July 02	76.02
October 02	55.08

Daily electrolyzer energy consumption and hydrogen production

Figure 7 depicts the daily power usage of the electrolyzer at various capacities during the specified days. Depending on the incident solar irradiance, the PV array begins producing electricity when the sun rises, and its maximum output is possible at midday. The electrolyzer power consumption is heavily dependent on the power provided by the PV array and the electrolyzer capacity; whereas electrolyzer capacity is increased, the power consumption would increase even more.

Table 4 displays the daily electrolyzer energy consumption (kWh) for a variety of capacities on specific days.

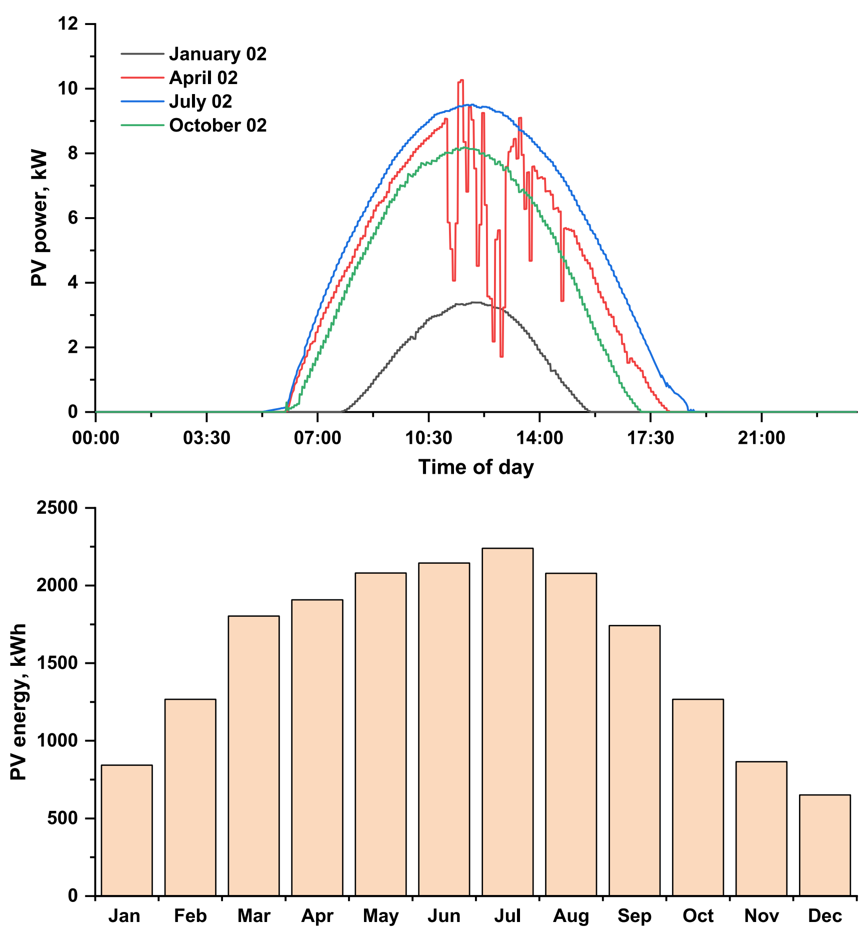

Figure 6: Daily power and monthly energy generated by (12 kWp) PV array.

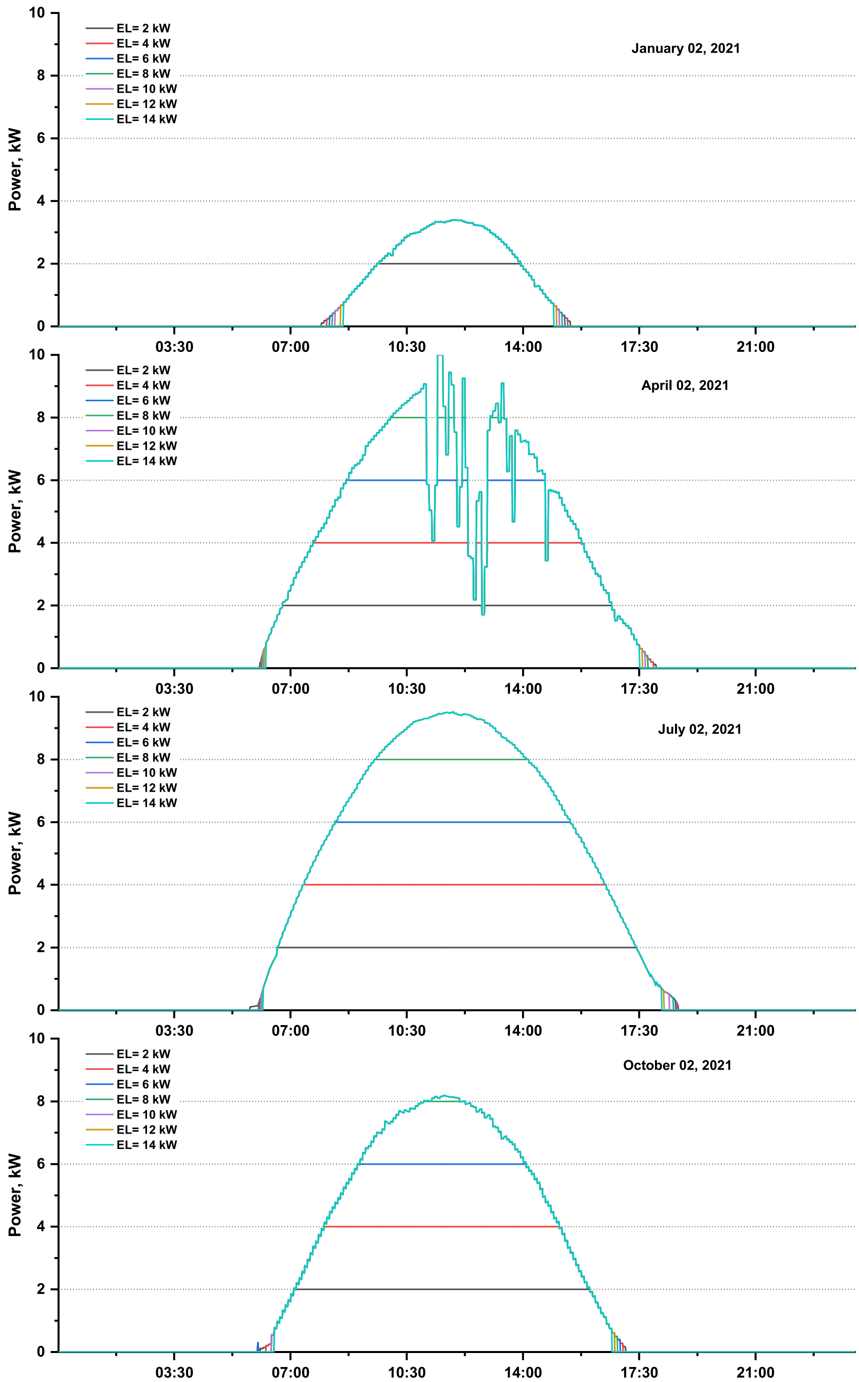

Figure 7: Daily electrolyzer input power at several capacities for the selected days.

By raising the electrolyzer capacity, energy consumption rises. The highest consumption for the electrolyzer capacity was 75.82 kWh on July 2, 2021 (10–14 kW).

The daily hydrogen production at various electrolyzer capacities is depicted in Figure 8, for the specified days. The pace of hydrogen production is largely reliant on the amount of PV-generated power consumed by the electrolyzer. By expanding PV power production and electrolyzer capacity, hydrogen production was increased.

Table 5 shows the daily hydrogen production at several electrolyzer capacities for the selected days. The rate of hydrogen production is highly dependent on the power consumed by the electrolyzer that is generated by the PV array. By increasing PV power production and electrolyzer capacity, there will be an increase in hydrogen production. The highest production among the selected days was observed at 1.82 kg on July 02, 2021 at the electrolyzer capacity (10–14 kW).

Table 4: Daily electrolyzer energy consumption (kWh) at several capacities for selected days.

Day	2 kW	4 kW	6 kW	8 kW	10 kW	12 kW	14 kW
January 02	11.78	15.69	15.65	15.59	15.52	15.39	15.28
April 02	21.89	39.41	51.94	58.80	60.16	60.13	60.05
July 02	23.45	43.34	59.57	71.37	75.82	75.82	75.82
October 02	19.75	35.64	47.80	54.81	54.89	54.85	54.79

Monthly electrolyzer energy consumption and hydrogen production

The monthly energy consumption of the electrolyzer at various capacities was shown in Figure 9. The amount of energy consumed by the electrolyzer depends on the amount of energy produced by the solar PV array, which is highest in the summer and lowest in the winter. The energy

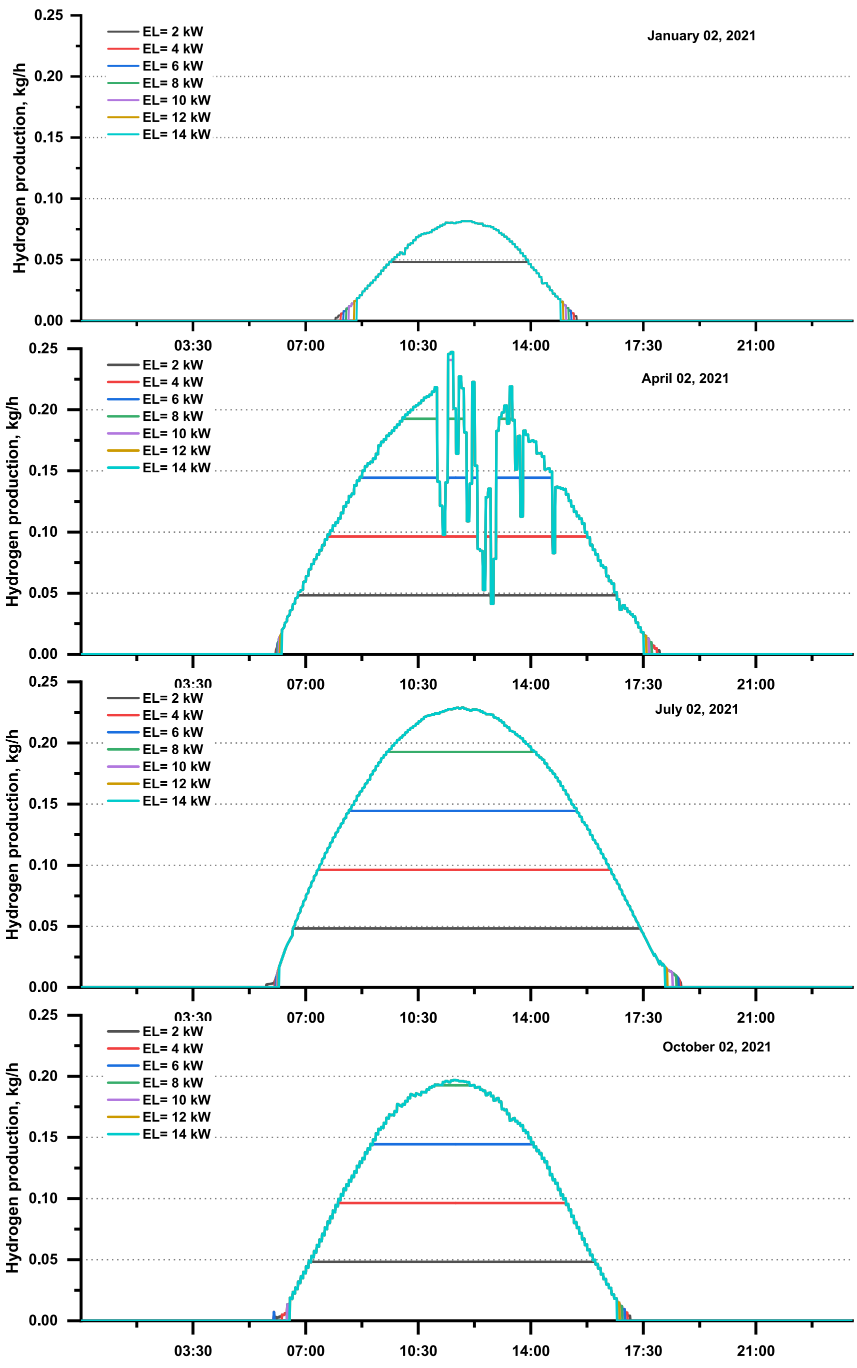

Figure 8: Daily hydrogen production at several electrolyzer capacities for the selected days.

Table 5: Daily hydrogen production (kg) by electrolyzer at several capacities for selected days.

Day	2 kW	4 kW	6 kW	8 kW	10 kW	12 kW	14 kW
January 02	0.28	0.37	0.37	0.37	0.37	0.37	0.36
April 02	0.52	0.94	1.25	1.41	1.44	1.44	1.44
July 02	0.56	1.04	1.43	1.71	1.82	1.82	1.82
October 02	0.47	0.858	1.15	1.32	1.32	1.32	1.31

consumption of electrolyzers increased as their capacity increased; July have seen the highest electrolyzer energy usage it was 2230.43 kWh at the 10–14 kW electrolyzer.

Figure 10 depicts the monthly production of hydrogen by the electrolyzer at various capacities. The amount of hydrogen produced by an electrolyzer is dependent on the amount of energy produced by a photovoltaic array, with summer displaying the maximum hydrogen production and winter the lowest. Hydrogen production by electrolyzers grew as their capacity increased; in June, 10–14 kW electrolyzers produced the most hydrogen, at 53.21 kg.

Based on the daily and monthly statistics, it is very difficult to determine the optimum electrolyzer capacity for a 12 kWp PV array to get the highest hydrogen production at the lowest cost. At least one year worth of data is needed for such a decision.

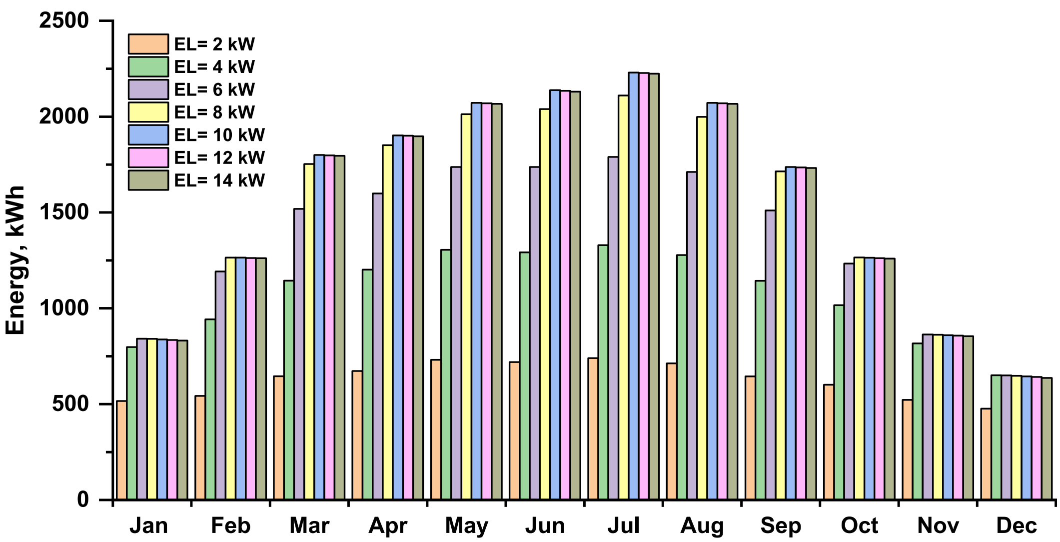

Figure 9: Monthly energy consumption by electrolyzer at several capacities.

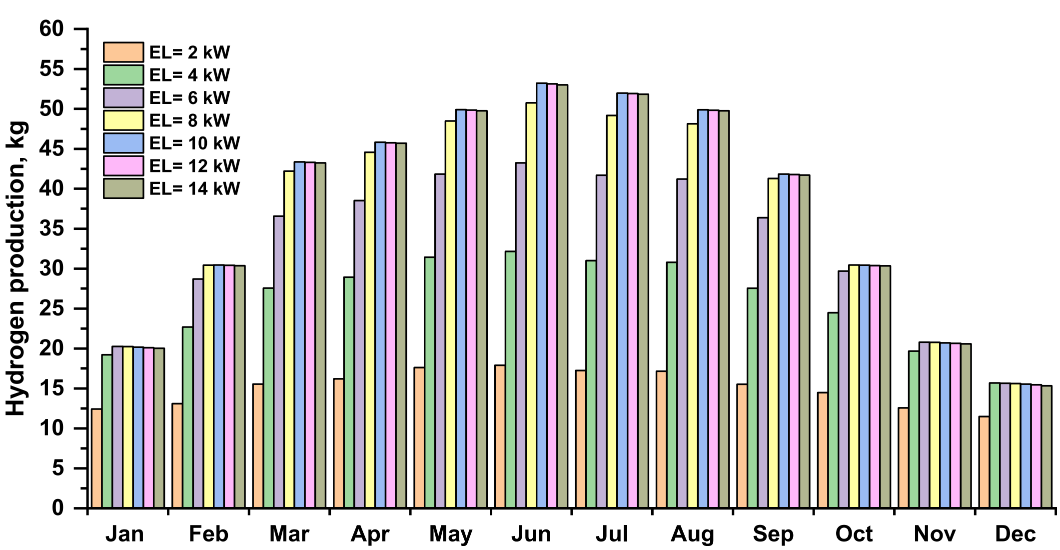

Figure 10: Monthly hydrogen production by electrolyzer at several capacities.

Annual electrolyzer energy consumption and hydrogen production

The annual energy consumption of the electrolyzer at various capacities is shown in Figure 11. The capcity of 10 kW electrolyzer had the highest consumption, at 18,822.98 kWh. As the electrolyzer capacity went up, this value went down, to 18,793.11 kWh for the 12 kW electrolyzer and 18,754.80 kWh for the 14 kW electrolyzer. This is because the efficiency went down because the electrolyzer capacity did not match the PV array capacity.

The annual hydrogen production by the electrolyzer at various capacities is shown in Figure 12. The 14 kW electrolyzer had the highest production of about 456.68 kg. As the electrolyzer capacity went up, this value went up, but the difference in hydrogen production between the electrolyzer capacities of 10 and 14 kW is very poor, just 1 kg/year, which is noticeable that increasing electrolyzer capacity more than 10 kW uses less.

Hydrogen cost

The cost of hydrogen is calculated for one kg of hydrogen using equation (10). The economic setting for the system components is presented in Table 1, and the project life span is taken at 9 years for the period of (2021–2030). Results indicate that the cost of hydrogen varies from \$5.39/kg to \$3.23/kg. The lowest hydrogen cost was observed at an 8 kW electrolyzer (450 kg/year), and this cost increased by

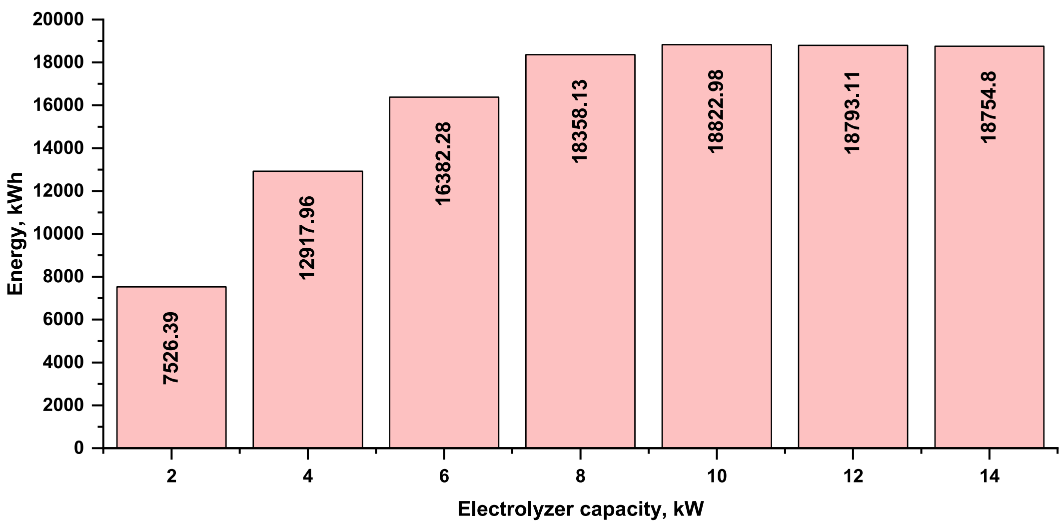

Figure 11: Annual energy consumption by electrolyzer at several capacities.

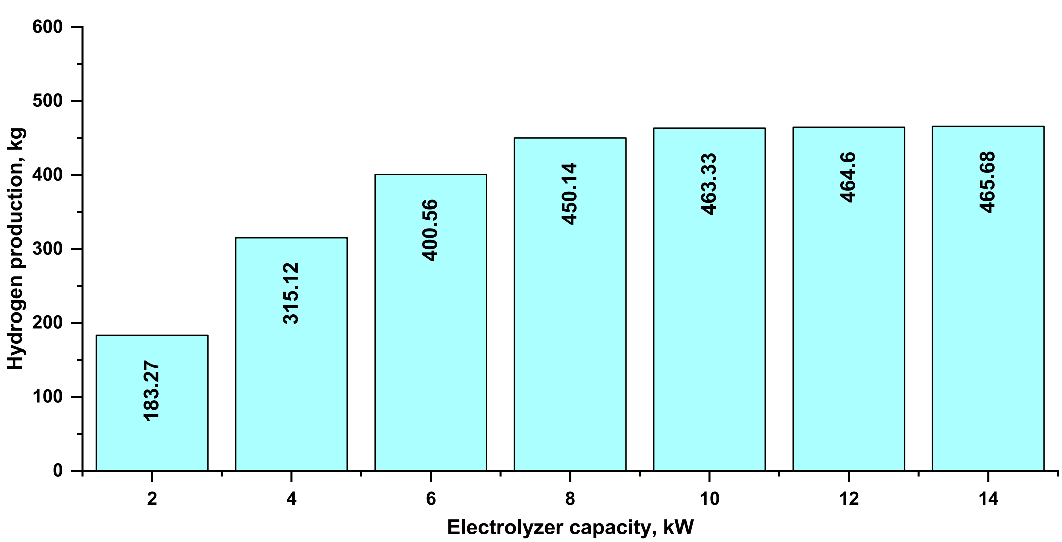

Figure 12: Annual hydrogen production by electrolyzer at several capacities.

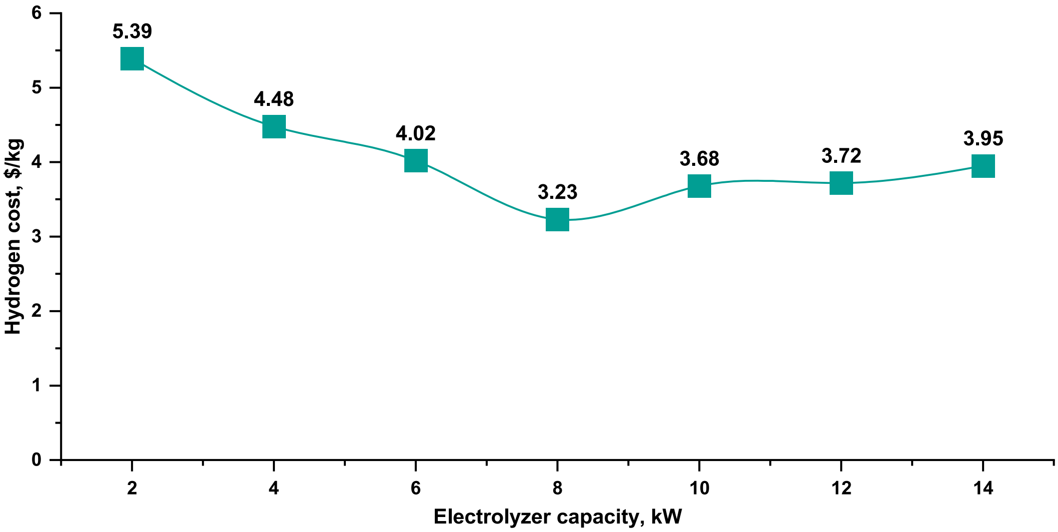

Figure 13: Hydrogen cost at several electrolyzer capacities..

increasing electolyzer capacity, where the annul hydrogen production was raising very low at elecrolyzer more than the 8 kW as presented in Figure 13.

Figure 14 depicts the cost of hydrogen at the chosen location. Due to its low production costs, creating a solar energy system for the generation of green hydrogen was shown. Figure 14 compares the price of hydrogen in the current study to the price of hydrogen in other countries, as shown in (Energy information administration report 2021; Hosseini 2022; Kassem, Gökçekuş, and Furaiji 2022; Liu et al. 2019; Okonkwo et al. 2021).

The outcomes shows the relevance of hydrogen generation and the system utilization factor in determining the total cost of produced hydrogen, and the obtained results demonstrated the yearly hydrogen production, cost, and energy consumption for the investigated site are as follows:.

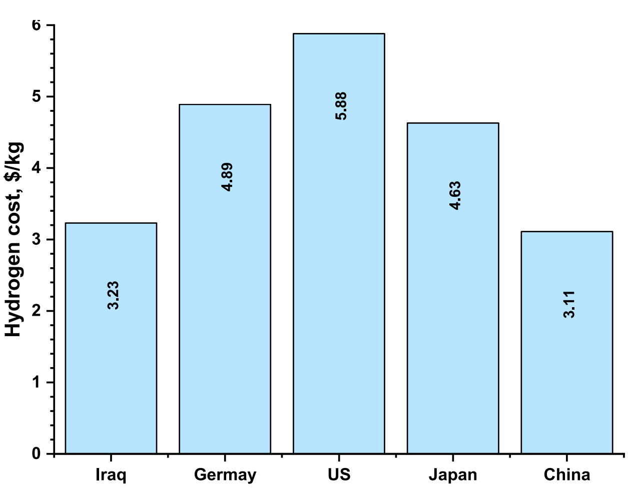

Figure 14: Obtained hydrogen cost compared with other countries.

- For a 2 kW electrolyzer capacity, the annual energy consumption was 7526.39 kWh and the annual hydrogen production was 183.27 kg at a cost of $5.39/kg.
- For a 4 kW electrolyzer capacity, the annual energy consumption was 12,917.96 kWh and the annual hydrogen production was 315.12 kg at a cost of $ 4.48/kg.
- For a 6 kW electrolyzer capacity, the annual energy consumption was 16,382.28 kWh and the annual hydrogen production was 400.56 kg at a cost of $ 4.02/kg.
- For a 8 kW electrolyzer capacity, the annual energy consumption was 18,358.13 kWh and the annual hydrogen production was 450.14 kg at a cost of $ 3.23/kg.
- For a 10 kW electrolyzer capacity, the annual energy consumption was 18,822.98 kWh and the annual hydrogen production was 463.33 kg at a cost of $ 3.68/kg.
- For a 12 kW electrolyzer capacity, the annual energy consumption was 18,793.11 kWh and the annual hydrogen production was 464.6 kg at a cost of $ 3.72/kg.
- For a 14 kW electrolyzer capacity, the annual energy consumption was 18,754.8 kWh and the annual hydrogen production was 465.68 kg at a cost of $ 3.95/kg.

Conclusions

This research emphasizes the role of hydrogen production and system use in determining the eventual price of supplied hydrogen. It has been determined that a photovoltaic system on its own has tremendous potential for producing green hydrogen. This is due to the fact that the electrolyzer can be supplied with energy in an ever-independent and cost-effective approach. Furthermore, the system is only available throughout the day: the electrolysis system must be activated at varying periods of the day, and not all applications are working at full capacity. The variable nature of the solar resource reduces not only the electrolyzer rate of consumption, but also its output and efficiency. An optimal off-grid solar PV system for hydrogen production-based energy systems is proposed for renewable energy generation. The energy system is modeled and simulated in the MATLAB software at 1 min resolution using one year of experience data. The optimum electricity capacity matching the 12 kWp PV array was obtained for the lowest hydrogen cost. The annual energy generated by the specified PV array was 18,892 kWh at 4313 operation hours. The obtained results indicate that a variety of potentially cost-competitive alternatives exist for systems with market combinations that closely resemble renewable hydrogen wholesale, tending to result in a hydrogen production cost range of $5.39/kg to $3.23/kg, with the optimal electrolyzer capacity 8 kW matching a 12 kWp photovoltaic array that can produce 450 kg/year of hydrogen at a cost of $3.23/kg. The study reveals that this solar hydrogen production system is well suited for installation in the central region of Iraq and other regions with comparable climatic conditions, especially those with comparatively elevated solar energy.

Future outlook

This study showed how it is feasible to evaluate single off-grid PV systems for hydrogen production. This study can be expanded upon in the future to derive and quantify optimum designs for the size and configuration of the system. So, by making the system work better, the PV and/or WT system may be able to meet the energy needs of the electrolyzer unit without using the grid. A follow-up study should be conducted to demonstrate that by installing an appropriate energy storage mechanism in each locality, the hybrid renewable energy system can function better, with a higher satisfied load fraction and utilization factor and a lower grid energy interaction factor. In fact, more excess power from the system must be dispersed if the grid is unable to handle it all. On the other hand, if the grid is unable to supply all of the required power, the electrolyser will be able to absorb less electricity and will not be able to create all of the necessary hydrogen. Adding a hydrogen storage tank or a battery storage system can solve this problem.

A different scenario can be thought about, and a thorough techno-economic study should be done to figure out the best place and way to set up the system for future research. It should be mentioned that the cost of producing hydrogen as well as the cost of using wind and solar power on land are not taken into account in future studies. It is possible to compare the economic performance of hydrogen generating systems (such as those with a WT, PV system, electrolysis, battery storage, hydrogen storage, and grid connection) in various places. Each of these optimizations would have the same output need for hydrogen as their main restriction. The sites for making hydrogen would be ranked based on their economic value, as well as the specific capabilities and full load hours of the different parts of the system.

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