Research Article

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Modelling and analysis of green hydrogen production by solar energy

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Abstract: In the article, the viability of adopting photovoltaic energy systems to convert solar energy into hydrogen in Iraqi four main cities are examined. A 22 kWp off-grid solar system, an 8 kW alkaline electrolyzer, a hydrogen compressor, and a hydrogen tank were modeled for an entire year in order to produce hydrogen. Using hourly experimental weather data from 2021 to 2030, MATLAB/Simulink is used to create a mathematical model of the recommended system behavior. The results revealed a range of annual hydrogen production from 1713.92 to 1891.12 kg, annual oxygen production from 1199.74 to 1323.78 kg, and annual water consumption from 7139.91 to 7877.29 L. Each kilogram of hydrogen costs $3.79. The results indicate that the optimal location for solar hydrogen production systems might be constructed in the central region of Iraq and in other regions with comparable climatic characteristics, particularly those with high radiation levels.

Keywords: hydrogen economy; hydrogen energy; photovoltaic array; solar energy; water electrolysis.

Introduction

Economically, fossil fuels typically outweigh non-fossil fuels in terms of energy supply. According to the British Petroleum Statistics Report on World Energy 2021 (British Petroleum 2021), coal and natural gas made up 25.4 and 22.8%, respectively, of the total energy used globally in 2020. Fossil fuel extraction and its counterparts continue to be the most widely used energy source in the world, with 112.8 million barrels per day produced in 2020 and a predicted increase to 172.4 million barrels per day by 2035 (Ma et al. 2022). Therefore, fossil fuels like coal (39%) natural gas (25%) and oil (70%) account for around 87 percent of total CO_2 emissions (23%).

Renewable and clean energy production is essential to replace fossil fuels as a source of green energy and to address the aforementioned problem. Due to the finite fossil fuel supplies, the growing cost of fuel, and the environmental problems produced by global energy usage, hydrogen can be seen as a promising energy source. Today, the creation of hydrogen from renewable sources is strongly promoted since they are emissions due to the fact that their burning produces CO_2, which plants require for reproduction. However, biomass conversion systems have several limits and are quite energy-intensive (Liu et al. 2020). There are a number of subdivisions of thermal decomposition, such as pyrolysis, hydro-pyrolysis, reforming, gasification, and liquefaction. Gasification is a potential technique for producing synthesis gas and hydrocarbons from biomass feedstocks. Physical and chemical, thermochemical, or biological processes were used to make hydrogen and get rid of carbon, especially for lignocellulosic and second-generation biomass feedstocks (Hassan et al. 2022a). Renewable energy is currently considered to be the cleanest energy available, which is renewed organically over time by humans and natural activity (Hassan 2020). Compared to other fossil fuels, renewable energy sources are created faster than they are used, so the associated favorable energy is encouraging. Similar to fossil fuels, renewable energy sources are used extensively for four distinct applications: commercial, residential, industrial, and transportation power (Ceran et al. 2021; Jaszczur and Hassan 2020). The major benefits of the fast adoption of renewable energy applications are substantial economic gains

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and sustainable energy. The sustainability of renewable energy and its potential for energy efficiency will rely on the vast geological region, such that almost all nations have the opportunity to produce this kind of sustainable energy.

Hydrogen production from water

Water is a molecule that is abundant in nature and is renowned for being a significant source of hydrogen. The thermodynamic of a molecule of water is approximately 285.83 kJ/mol at Standard Temperature and Pressure (STP), but water decomposition by direct-heating works at extremely high temperatures (up to 2000 °C). However, it becomes impossible to separate oxygen from hydrogen at this degree. Utilizing a catalyst and ceramic membrane for decomposing reaction and gas separation, or perhaps a chemical reactant and/or energy, water splitting is a method for producing hydrogen at lower temperatures (Rand and Dell 2007). Figure 1 depicts the electrolysis of water using a typical source of electricity.

Hydrogen production by solar energy

Water electrolysis using solar energy as the source of power is a potential method for replacing the power requirements of conventional sources of electricity and improving overall energy efficiency. One of the most well-known solar technologies is photovoltaic (PV) cells, which convert solar energy (sunlight) into electricity. The process diagram of water electrolysis using solar electricity is shown in Figure 2. Using photovoltaics as a power source enables a considerable increase in total efficiency. However, the cost is higher than conventional electricity (Hassan and Jaszczur 2021).

Literature review

The electrolysis of water requires, on the one hand, a significant amount of electrical energy to be used, and, on the other hand, thermal energy must be turned into electrical energy before the process can proceed. For the electrolytic process to occur, the water that is going to be used must first be heated to a certain temperature, which requires additional heat. This necessitates a significant quantity of thermal energy. The cost of using heat energy accounts for more than 80% of the total cost of producing electrolyzed water (Hassan et al. 2022b). Whereas if excess heat can be utilised as the source of the energy necessary for the procedure of water electrolysis, the cost of producing “green hydrogen” will be far cheaper than the cost of producing hydrogen using fossil fuels.

The water electrolysis process, which is driven by renewable energy, has captured the interest of individuals from around the world due to the possibility that it may one day bring in a global economy that produces no emissions. Even though this hydrogen generation method is environmentally friendly, the accessibility of renewable energy sources is a critical factor in determining the cost of hydrogen production. Several researchers have focused their attention on the efficiency of hybrid hydrogen generation systems as well as their potential applications.

Clarke and colleagues (Clarke et al. 2009) conducted research on the direct connection of electrochemical devices, such as membrane electrolyzers, with matching

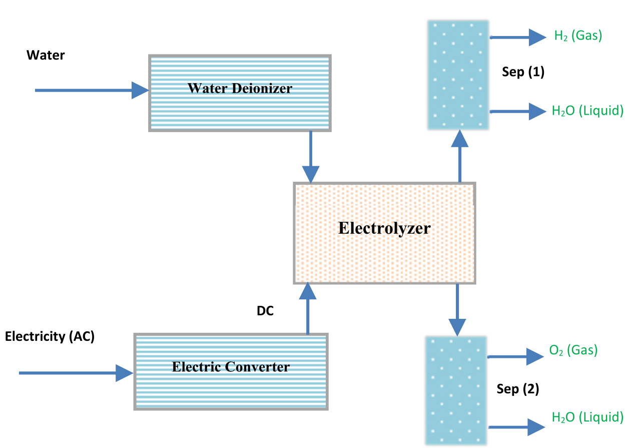

Figure 1: Schematic illustrating the electrolysis of water with electricity provided.

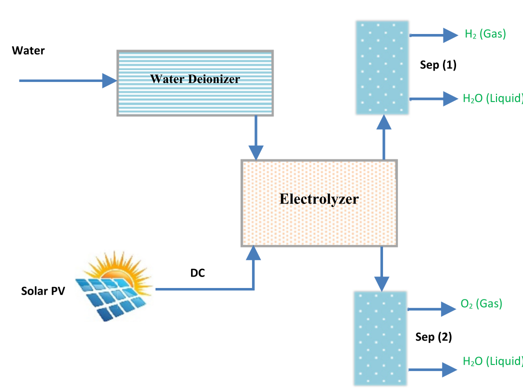

Figure 2: Schematic illustrating the electrolysis of water using solar energy.

solar photovoltaic sources for the synthesis and storage of hydrogen. It has been proved that it is possible to produce hydrogen by the direct linkage of an appropriately matched PV array and a PEMP electrolyzer. This method has also been shown theoretically and practically feasible. Li et al. (2022) examined a hybrid method of producing hydrogen by combining photodynamic collaborative response with photovoltaic/thermal (PV/T) power generation and electrolysis water. This resulted in the creation of hybrid hydrogen. Although the photodynamic collaborative response and the PV/T power generation are both capable of using the whole spectrum of solar energy to generate hydrogen, the electrolysis of water also has the potential to do so. According to the findings, the PV and thermal methods of producing hydrogen have efficiencies of 1.223 percent and 17.339 percent, respectively, in producing hydrogen. In spite of this, the hybrid hydrogen generation process suggested in this study has an efficiency of 18.49 percent while operating under the same circumstances. The findings could provide some food for thought when it comes to the eventual development of full-spectrum solar technologies that are more efficient in producing hydrogen.

Obviously, the use of conventional PV technologies is similarly capable of performing the same functions as PV/T.

Depending on the weather in the United Arab Emirates, Ratlamwala, Gadalla, and Dincer (2011) researched a combined PV absorption system for the generation of hydrogen. The direct connection of an appropriately matched PV system and an electrolytic cell was used in this experiment, which resulted in a successful demonstration of both the concept and the practicability of hydrogen generation. In contrast to PV, PV/T has the ability to not only provide electric energy to electrolysis water but also supply heat to electrolytic water. PV can only supply electricity to electrolyte water.

In the same sentence, in comparison to PV, a PV/T system has the ability to lower the temperature of solar cells. It is common knowledge that raising the temperature of electrochemical cell water can improve the effectiveness of producing hydrogen by electrolyzing water (Yilmaz and Kanoglu 2014). It is also common knowledge that lowering the temperature of photovoltaic cells can improve their capacity to convert solar energy into electric energy. As a result, it is recommended that PV/T and the process of electrolytic water reaction be brought into the photothermal cooperative reaction.

Nevertheless, when PV is used, the temperature of the PV cell becomes a significant component that affects the efficiency of the hydrogen generation. If you lower the temperature of the PV cell, the output temperature of the water will also drop, and it will become more in line with the temperature of the electrolytic water. This indicates that the amount of solar energy input will stay the same; but, if the temperature of the PV cell is lowered, the amount of electrical power that can be generated by the PV cell will rise. The efficiency with which it can electrolyze water will decrease (Özcan et al. 2021). Because of this, it is unclear whether or not lowering the temperature of the PV cell may enhance the efficiency of the hybrid hydrogen generation technique suggested in this study by increasing the amount of hydrogen produced by the PV cell. The effects of the temperature of the PV cell on the effectiveness of such a proposed method of producing hydrogen have not been analysed as of yet. This is something that will be addressed in this paper in order to determine how adjusting the temperature of the PV cell can enhance the efficiency of producing hydrogen. Tebibel and Medjebour (2018), provide a performance comparison study of PV hydrogen generation using water, methanol, and hybrid sulphate electrolysis techniques. This research was carried out in order to better understand the capabilities of PV hydrogen production. Electrolyzers that use proton exchange membranes get their electricity from grid-connected photovoltaic systems. The electrical grid is assumed to be a virtual energy storage system in this system architecture. This allows any excess power generated by photovoltaic cells to be injected into the grid before being drawn out to power an electrolyzer. According to the findings, using methanol results in the generation of 65 percent more hydrogen than using water electrolysis. In addition, the quantity of hydrogen that is created is about two times greater when hybrid sulfur is used. The PV/electrolyzer system, it is feasible to create around 25 $g/m^2/d$ and 29 $g/m^2/d$ of hydrogen via methanol and hybrid sulfur, respectively. Chae et al. (2011) investigated the long-term viability of previously disclosed highly efficient electrochemical methods for depositing a cathode and an anode membrane in a PV aided water electrolysis system. The electrodes had low mass loads. The performance of this assembly did not exhibit any discernible signs of deterioration during the first 200 h of operation. However, it began to deteriorate after that point and showed an 18% reduction after 1000 h. In conclusion, we performed a variety of analyses on the electrode surfaces to determine their properties. Nasser et al. (2022) The use of a hybrid renewable energy system consisting of wind turbines (WT) and PV panels for the purpose of producing hydrogen and storing it in five distinct Egyptian towns under varying climatic circumstances is evaluated from a technological and economic standpoint. Both the water electrolyzer and the compressor that are used in the manufacturing and storage of hydrogen are powered by the energy that is generated by using actual photovoltaic panels and wind turbines. According to the results, photovoltaics and wind turbines are both viable options for the generation of hydrogen. In addition, the compressor uses around 3.13 to 3.3 percent of the power that is generated by the PV/wind combination. The yearly hydrogen output is measured at 1972 kg, while the total system efficiency ranges from 7.69 percent to 9.37 percent and the production cost ranges from $4.54/kg to $7.48/kg, respectively.

Ferrari, Rivarolo, and Massardo (2016) conducted research on the unpredictable characteristics of solar radiation and how such characteristics influence the operating parameters of a system as well as the proportion of power that can be harvested from the solar radiation. This investigation was carried out to demonstrate the effectiveness of the electrolyzer under settings that were not designed. According to the results, an increase in the electrolyzer efficiency may be attained by reducing the current. According to the outcomes of research that was carried out by Đukić and Firak (2011), the energy that is generated from PV is not only used to power the electrolyzer but also drives other components. It is possible that these components are water circulation pumps, and when estimating the production and efficiency of the system, you need to take into account this behaviour, which lowers the amount of hydrogen produced. Kovač, Marciuš, and Budin (2019) conducted research on the hydrogen that was created by the direct linkage of PV panels and an alkaline electrolyzer. Based on the results of this experiment, the rate of hydrogen generation is 1.138 g per hour. Additionally, the energy that is generated by this system is able to cut carbon emissions by around 906 kg and provide power to 122 homes. Bilgen (2001), used tracing for PV panels in a system to prevent solar intermittency increases PV efficiency by 5% when compared to fixed PV panels. This is to avoid the problem of solar irradaince intermittency. It is recommended that a battery be added to the system in order to provide temporary energy storage in order to take advantage of the extra energy produced by the sun during times of solar intermittency (Hassan et al. 2022b). Furthermore, by using a bifacial PV rather than a monofacial PV, system efficiency can be increased from 11.55 percent to 13.5 percent. The connection of PV with water electrolyzers as a means of producing solar hydrogen was investigated by Ismail et al. (2019). The results showed that the values obtained and the experimental studies were in reasonable agreement with one another. El-Emam, Ezzat, and Khalid (2022) found that the creation of hydrogen from PV array for the purpose of energy storage is a more environmentally friendly choice than the use of PV/battery systems. Şevik (2022), investigates the feasibility of solar-powered hydrogen production on college campuses without the usage of any energy storage facilities. Using web-based PV system design software, three distinct scenarios were developed in order to carry out the simulation of the PV system (HelioScope). In the simulation, we observed that the low scenario had an installed power of 94.2 kW, the high scenario had an installed power of 123.9 kW, and the high scenario with PV canopy arrays had an installed power of 157.5 kW. The levelized cost of electricity values were $0.061 kWh, $0.065 kWh, and $0.063 kWh, respectively, for the low scenario, the high scenario, and the scenario containing the PV array. Zghaibeh et al. (2022) investigate the viability of converting solar energy to hydrogen through a PV hydrogen station in the southern region of Oman. The capacity of the proposed system components and an estimate of hydrogen generation in a 5 MWp solar power plant are modeled. The results revealed that the proposed system can generate approximately 90,910 kg of hydrogen per year at a total net present cost of €5,301,760. The calculated price of hydrogen at a 2% interest rate is €6,2/kg.

The qualities of Hosseini (2022) ideal fuel for the future include purity, inexhaustibility, and autonomy from external influence. All of these features have been demonstrated by hydrogen fuel, which is advocated globally as an ecologically beneficial alternative to fossil fuels in the commercial and transportation sectors. Egeland-Eriksen, Hajizadeh, and Sartori (2021) reported that although hydrogen energy storage devices are theoretically possible, substantial cost reductions are still necessary for them to be economically viable. Despite the amount of published studies on renewable energy in Iraq, the authors are aware that the notion of sustainable hydrogen generation and its impact on the nation's social health have not been explored or analyzed. Therefore, the goal of this study is to do a techno-economic analysis of solar-powered hydrogen synthesis.

Aim of the study

The following constitutes the novelty of this work:

- It looks into whether renewable energy sources can be used to make clean hydrogen and keep it from getting dirty in a number of Iraqi cities with different climates.
- This study provides a thorough examination of the economics associated with the envisioned system.
- The current analysis uses real system parts like photovoltaic panels, electrolysers, etc., so its conclusions can be used.

– It provides a gap in the research of clean hydrogen production from solar energy resources in Iraq, where these resources are abundant. Iraq is one of the nations that could gain the greatest benefits from this study.

Proposed system and site of investigation

As can be seen in Figure 3, 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 approach for the generation of hydrogen is put to the test in four distinct cities throughout Iraq with distinctly distinct environmental conditions (Baghdad, Basra, Duhok, and Rutba). As illustrated in Figure 4 and Table 2, these cities were selected as they offer a comprehensive overview of the variety of environmental parameters (solar irradiance, wind speed, and ambient temperature) that can be found throughout Iraq. The PV array was positioned at the optimum annual adjustment point for each city (see Table 2), where the simulation process was conducted at 1-min resolution. The project life span is nine years, from 2021 to 2030, and the economic assessment is made based on the Iraqi regulation, which means that the annual interest rate is 6%.

Experimental weather data

Both the average monthly wind speed and the monthly incident solar irradiance are given in m/s and kWh/m^2, respectively. Due to their locations in the south and west of Iraq, respectively, the cities of Basra and Rutba get the highest amounts of irradiation when compared with other cities. As a result, it is reasonable to predict that these

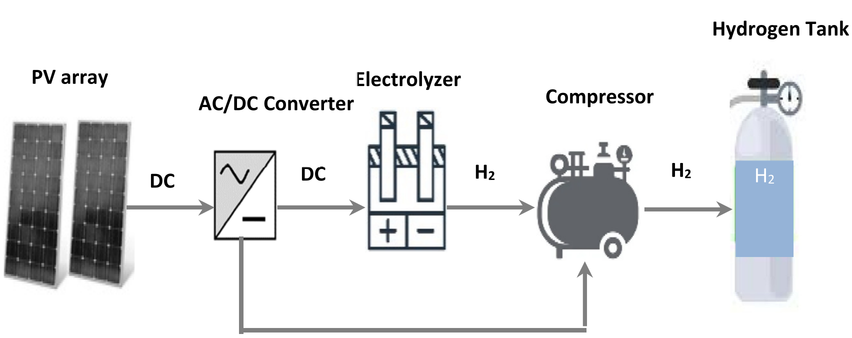

Figure 3: Schematic of the proposed renewable hydrogen production system.

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 (2022)
Electrolyzer	Geemblue	5 kW	>95	700	700	0.03/h	10	Electrolyzer (2022)
Compressor	Doosan	0.8 kW	>93	180	180		20	Compressor and Hydrogen Tank (2022)
Hydrogen tank	Doosan	20	98	100	100	10/year	25	Compressor and Hydrogen Tank (2022)
Converter	Luminous	7 kW	>95	850	900	10	10	Monocrystalline (2022)

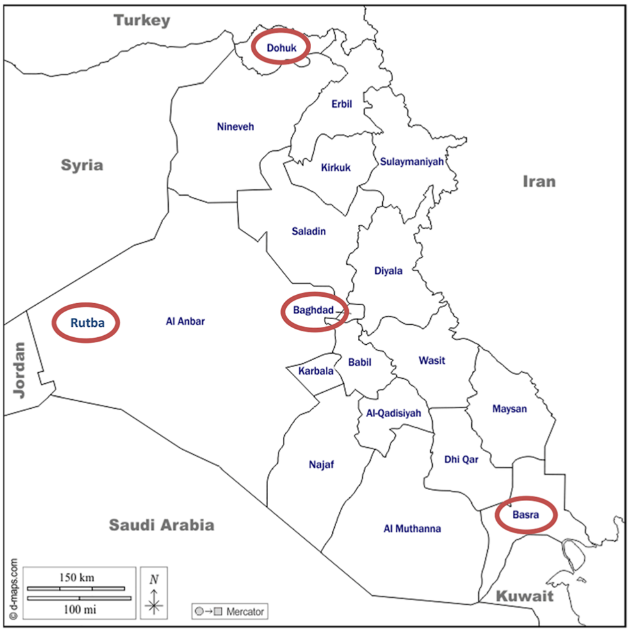

Figure 4: Map of Iraq with highlighted the analyzed cities (Hassan et al. 2021).

metro areas will have the most power generated by solar panels. On the other hand, the sun irradiance in Duhok, which is situated in the northern part of Iraq is quite low. Figures 5 and 6 shows the experimental daily and monthly average of the weather data, respectively. Table 3 shows the daily (June 05, 2021) average of the measured weather data for the investigated cities, for that day the highest solar irradiance was 7.39 kWh/m^2 in Rutba and the lowest was 5.13 kWh/m^2 in Dohuk city, while the highest temperature showed 38.84 °C in Basra and the lowest was 29.35 °C in Rutba.

Figure 6 and Table 4 shows the monthly average of the measured weather data for the investigated cities, the highest solar irradiance was 5.35 kWh/m^2 in Rutba and the lowest was 4.58 kWh/m^2 in Dohuk city, while vthe highest temperature showed 256.06 °C in Basra and the lowest was 18.88 °C in Rutba.

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 (Abbas et al. 2021).

The PV power production is determined according to the amount of incident solar irradiance and other environmental parameters, such as temperature, wind speed, and humidity, etc. The PV output power can be computed as:

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

whereas the PV cell temperature can be determined using solar irradiance, ambient temperature, and wind speed presented as (Hassan et al. 2022c; Jaszczur et al. 2019):

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

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

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

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 2021a)

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

The quantity of electrical energy input needed by the electrolyzer can be calculated as (Farhani and Bacha 2021).

Table 2: Information of the analyzed cities (Hassan et al. 2021).

No.	City site	Site in Iraq	Latitude (*N*)	Longitude (E)	Elevation (m)	PV tilt angle (degree)	PV azimuth angle (degree _south facing)
1	Baghdad	Middle east	33.31	44.36	34	29	0
2	Basra	South	30.52	47.77	5	26	0
3	Duhok	North	36.86	42.98	565	33	0
4	Rutba	Middle west	33.03	40.28	624	28	0

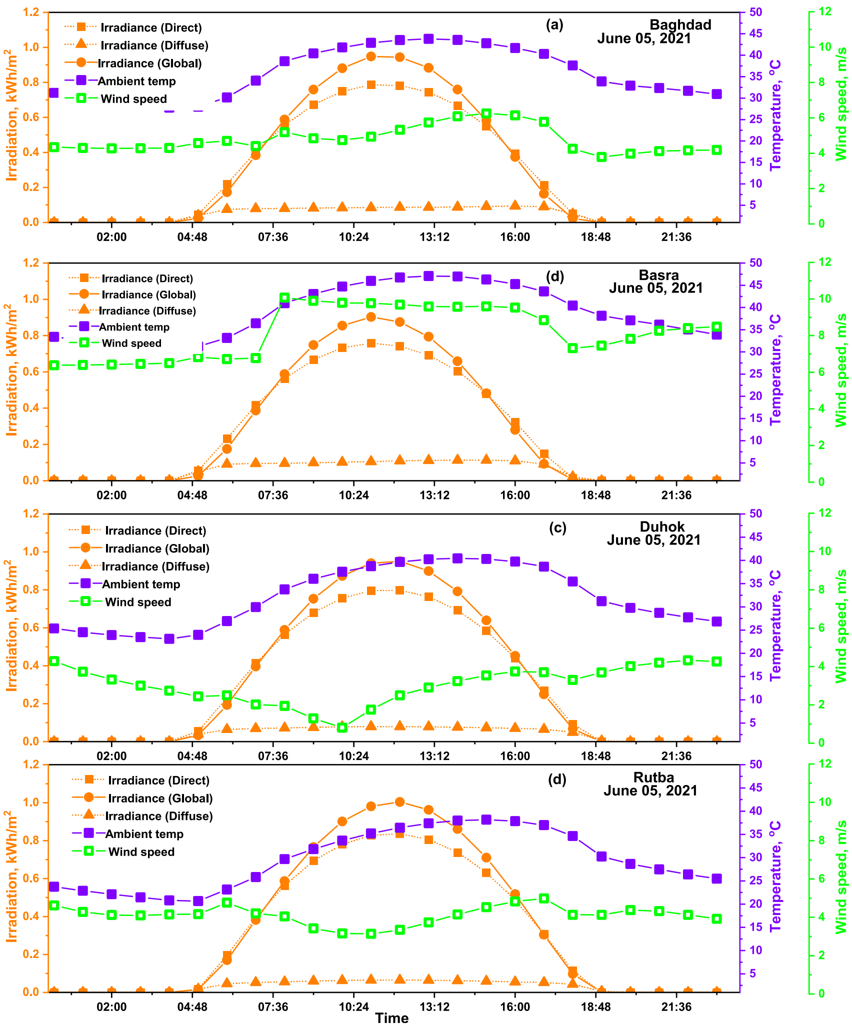

Figure 5: Daily weather data (June 05, 2021) for the analyzed cities.

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

Compressor and hydrogen tank

The required power to compress the hydrogen contained in the hydrogen tank can be calculated as (Jaszczur et al. 2021):

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

The predicted pressure within the hydrogen tank can calculated (Jaszczur et al. 2021):

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

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 system to regulate the energy flow. The converter efficiency may be calculated as (Hassan 2021b).

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

System power flow

The power flow distribution between the proposed system components which is generated by PV array and supplies

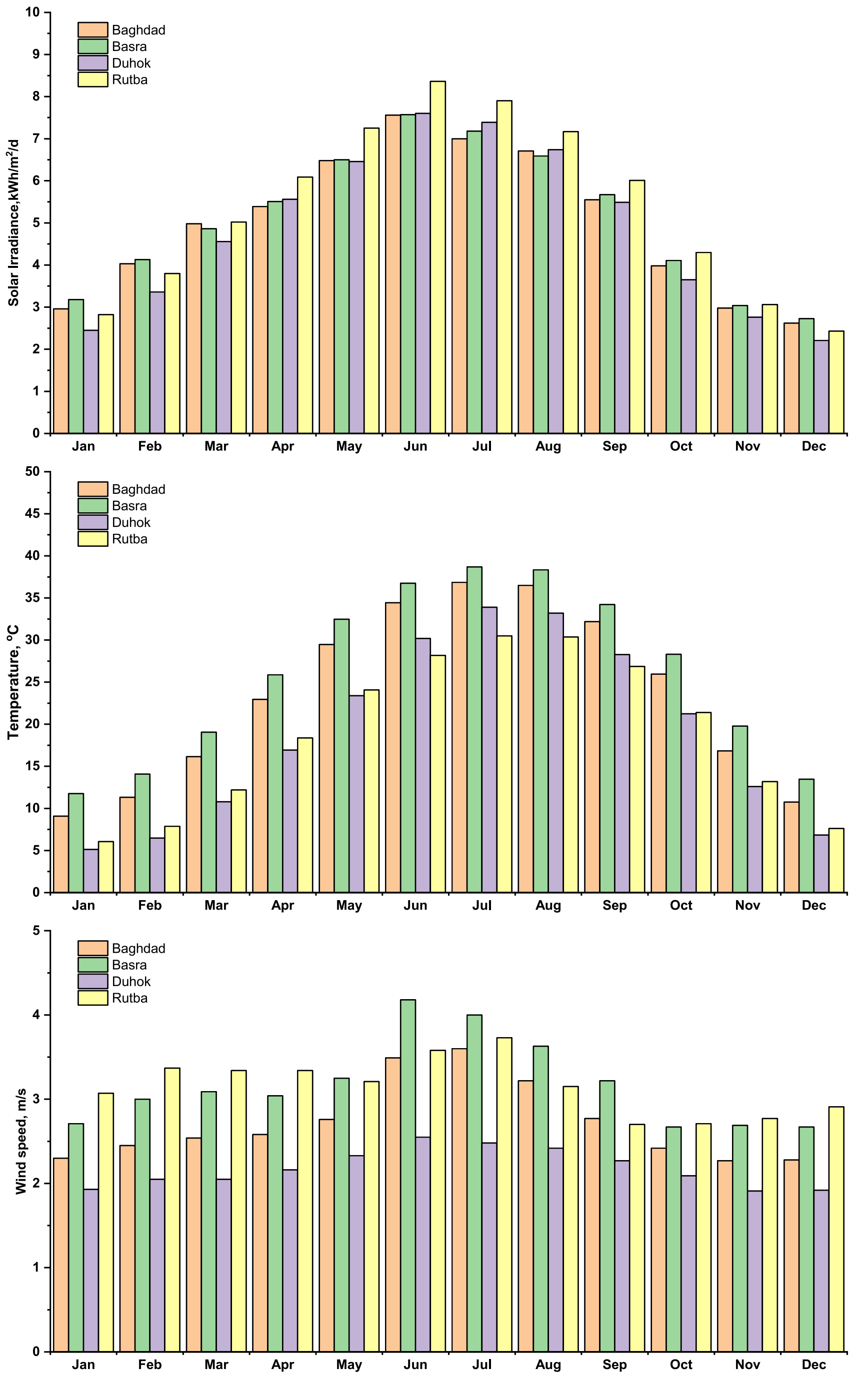

Figure 6: Monthly weather data for the analyzed cities.

Table 3: The daily average (June 05, 2022) of solar irradiance, wind speed and ambient temperature for the analyzed cities.

City	Irradiance (kWh/m^2)	Wind speed (m/s)	Temp. (°C)
Baghdad	6.83	4.77	35.77
Basra	6.43	8.19	38.84
Duhok	5.13	3.05	31.92
Rutba	7.39	4.11	29.53

Table 4: The annual average of solar irradiance, wind speed and ambient temperature.

City	Irradiance (kWh/m^2)	Wind speed (m/s)	Temp. (°C)
Baghdad	5.02	2.72	23.54
Basra	5.08	3.17	26.06
Duhok	4.85	2.18	19.07
Rutba	5.35	3.15	18.88

adequate electricity to the electrolyzer and hydrogen can be presented as following equation (Jaszczur et al. 2021):

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

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 (Jaszczur et al. 2020; Okonkwo et al. 2021):

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

Optimisation framework

The concept of the optimisation procedure is briefly outlined in this section. Figure 7 depicts the optimisation concept procedure diagram based on MATLAB/SIMULINK. Each stage of the optimization procedure, from the defined of design factors to the identification of a solution, is essential for achieving accurate and optimum outcomes. As optimisation begins, the planned hydrogen production system specified requirements need to be met at each successive stage; otherwise, the prior steps must be performed. In the first stage, model parameters are selected; if the generated constraints do not precisely define the system, design variables must be reelected. After successfully completing the second stage, the optimisation procedure will advance to the third. Thus, whenever objective features are not clearly stated in the third stage, the constraints must be altered until the objective functions are in compliance with the optimisation target. If variable boundaries do not satisfy the requirements of the system, the fourth stage can be routed to the first and second stages. The next stage is to choose a suitable optimisation method for the proposed hydrogen generation system. Any obstruction in this phase will reroute the optimisation back to the four stages before it. After successfully performing all of the optimisation of new framework processes, the optimised results are finally achieved. If the required results are not achieved, the optimisation method must be revised or another approach must be used.

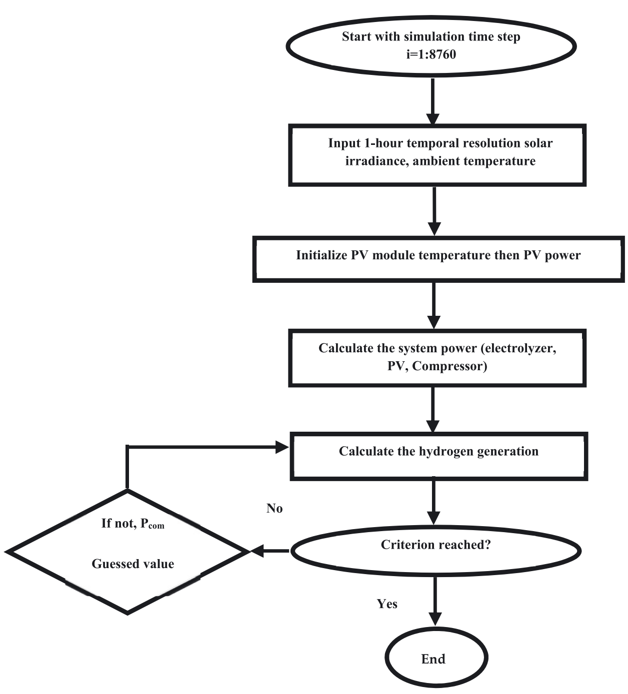

Figure 7: Scheme of the proposed system simulation steps.

Results and discussions

This section displays the outcomes of modelling the weather conditions of four Iraqi cities for producing compressed hydrogen from PV array and. The results are provided for one year span at 1 h resolution. In order to improve modeling and make the decision on whether or not to proceed, it is critical to analyze and appreciate the energy resources available in each specific project in a given region. As illustrated in Figures 5 and 6, as well as the annual solar power generation in the four cities, the solar radiation, ambient temperature, and wind speed at each city vary significantly; thus, the generated power will also vary, as illustrated in Figures 5 and 6. Figures 5 and 6. The PV array derating factor is considered at 95%, where the 5% consideration is the losses in wiring shadow and soiling effects.

Energy produced by PV array

Figure 8 shows the daily PV power and temperature on the selected day of June 05, 2021 for four investigated cities. For the selected day, the generated PV energy varied from 106 kWh for Basra to 115 kWh for Rutba, even though Basra has a higher solar irradaince than Baghdad and Duhok, but it has the highest ambient temperature that causes high energy degradation from the PV array (see Table 5).

Figures 9 and 10 show the monthly and yearly energy generated for the four investigated cities, respectively. The highest annual energy generated was observed at

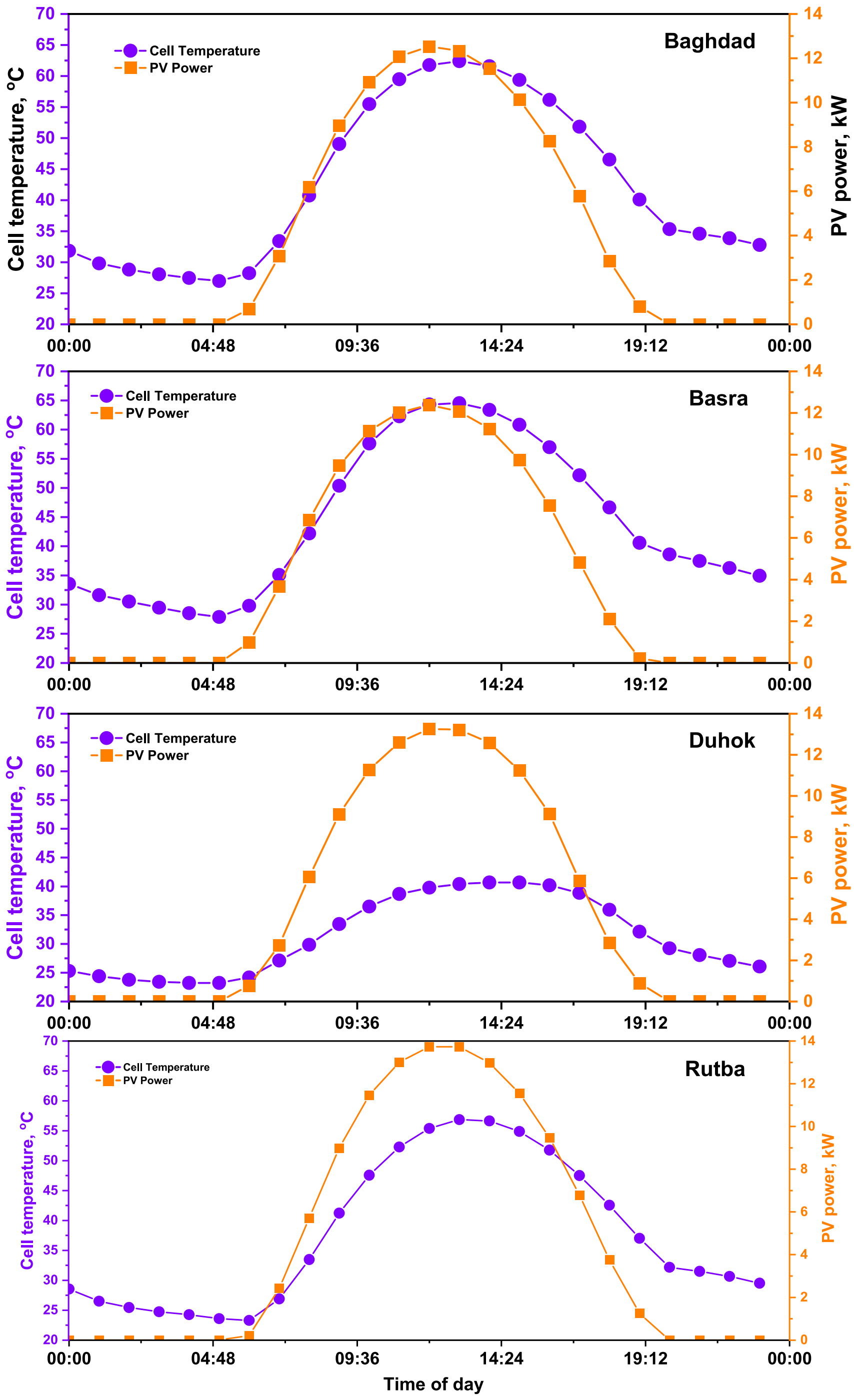

Figure 8: Daily PV power (22 kWp), and module temperature (June 05, 2021) for the analyzed cities.

Table 5: Daily average of PV energy, and module temperature (June 05, 2021) for the analyzed cities.

City	Module temp. (°C)	PV energy (kWh)
Baghdad	42.32	106.16
Basra	43.98	104.31
Duhok	31.34	111.66
Rutba	37.68	115.10

41,372 kWh in Rutba, while the lowest energy observed was at 35,215 kWh in Basra city.

Hydrogen production by electrolyzer

Figure 11 and Table 6 depicts the generation of hydrogen and oxygen in the four cities on June 5, 2021, as well as the

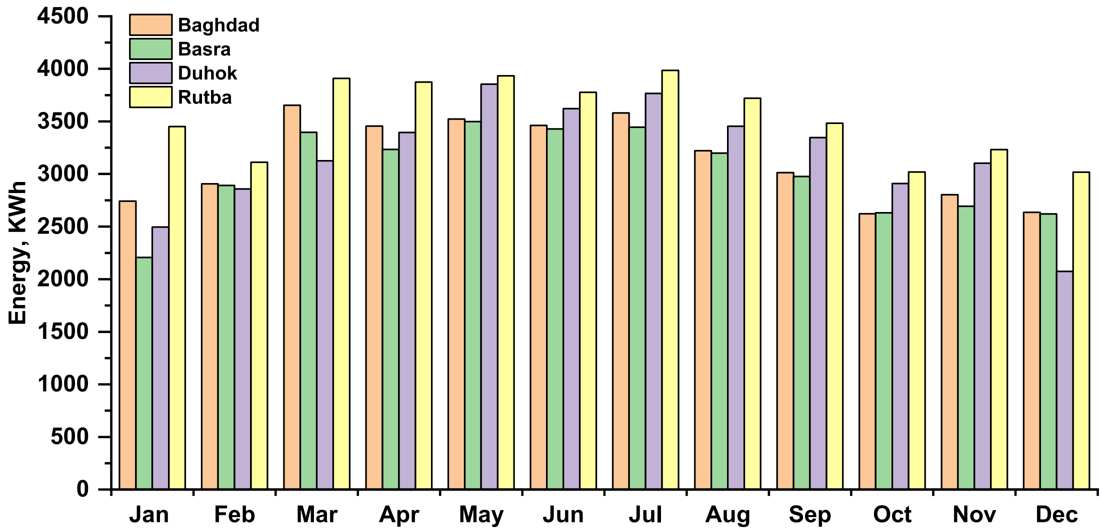

Figure 9: Monthly energy generated by 22 kWp PV array for the analyzed cities.

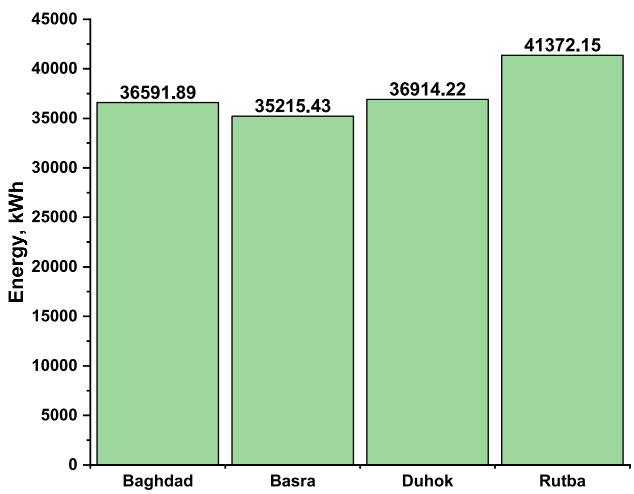

Figure 10: Annual energy generated by 22 kWp PV array for the analyzed cities.

quantity of water utilized by the electrolyzer. This graph demonstrates that Rutba and Duhok produce far more hydrogen, whereas Baghdad and Basra produce the least. In addition, it is evident that the quantity of hydrogen created exceeds that of oxygen.

Figure 12a, b depict the fluctuation in producing hydrogen and oxygen during each month for the analyzed cities, respectively. All cities have the most hydrogen production in the summer months, especially July, since, as indicated earlier, they produce the most electricity during this month. Moreover, it is observed that the production of hydrogen in most cities is particularly high in (May–August) compared to other months. This is due to the comparatively high solar irradiance and longest daytime of the winter months (September–April). The data reveals that the quantity of hydrogen produced throughout the day, mostly between the hours of (9:30 and 16:30), is larger than at other times due to the availability of solar energy during this period (see Figure 12).

Figure 13 depicts the annual hydrogen and oxygen generation for all analyzed cities. As indicated in Figure 13, the yearly hydrogen and oxygen production observed in Rutba was 1891.12 and 1323.78 kg, respectively; Duhok, 1834.60 and 1284.22 kg, respectively; Baghdad, 1756.33 and 1229.43 kg, respectively; and Basra, 1713.92 and 1199.74 kg, respectively. Rutba produces the most hydrogen and oxygen because, as indicated previously, it has the highest value of generated electricity because of its high solar irradiance and low ambient temperature. Basra has the lowest hydrogen and oxygen generation because, as stated before, it has the lowest value of generated electricity owing to its high solar irradiance and highest ambient temperature.

Figure 14 depicts the annual water consumption depicted in Figure 14 for all analyzed cities. Figure 14 shows that Rutba used 7877.29 L of water per year, Duhok used 7641.86 L, Baghdad used 7315.81 L, and Basra used 7139.91 L. The highest water consumption was observed in Rutba and the lowest water consumption was observed in Basra.

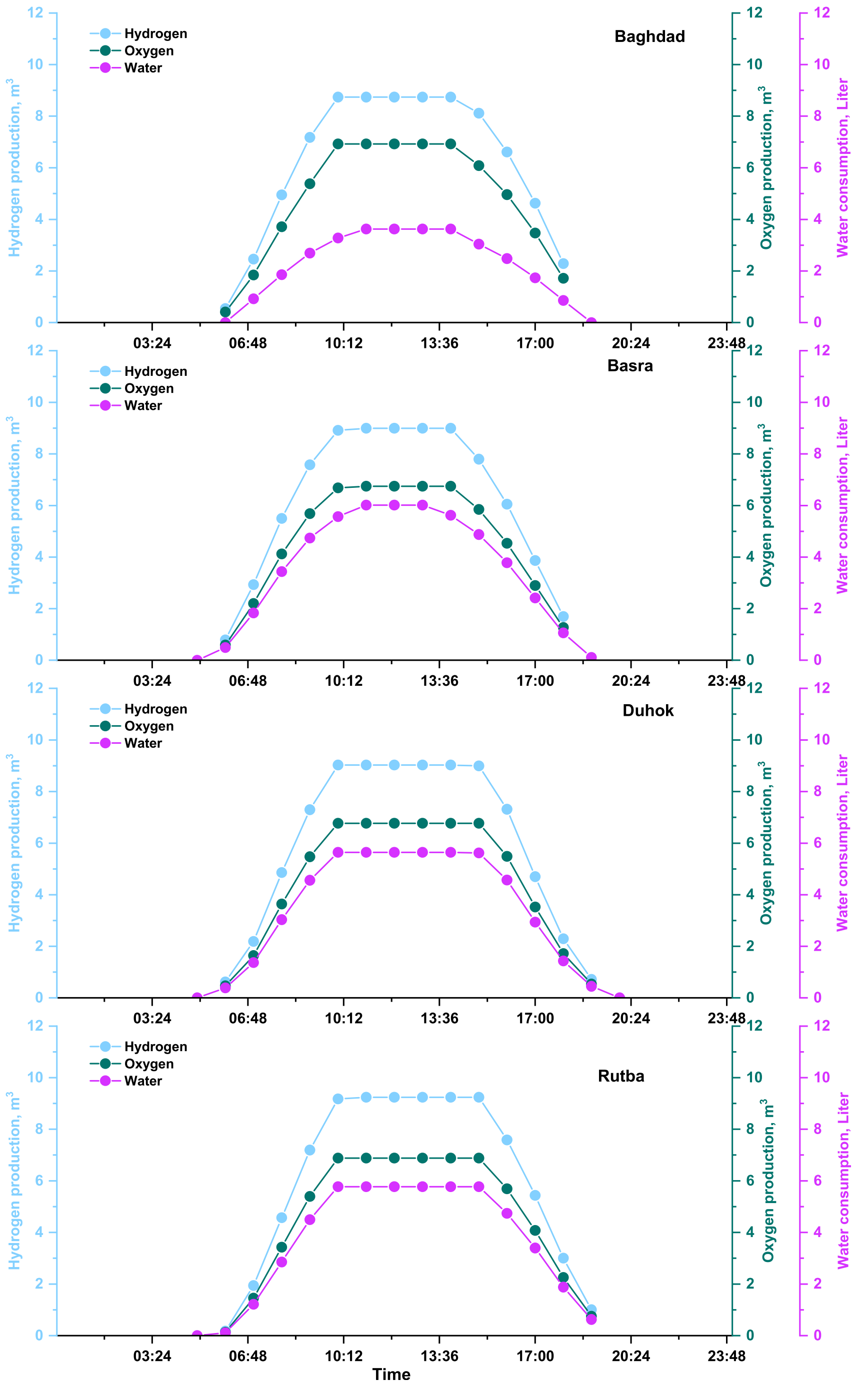

Figure 11: Daily hydrogen and oxygen production, water consumption (June 05, 2021) for the analyzed cities.

Table 6: Daily hydrogen and oxygen production, water consumption (June 05, 2021) for four investigated cities.

City	Hydrogen (kg)	Oxygen (kg)	Water (liter)
Baghdad	3.53	2.65	1.32
Basra	3.47	2.60	2.17
Duhok	3.72	2.79	2.32
Rutba	3.83	2.87	2.39

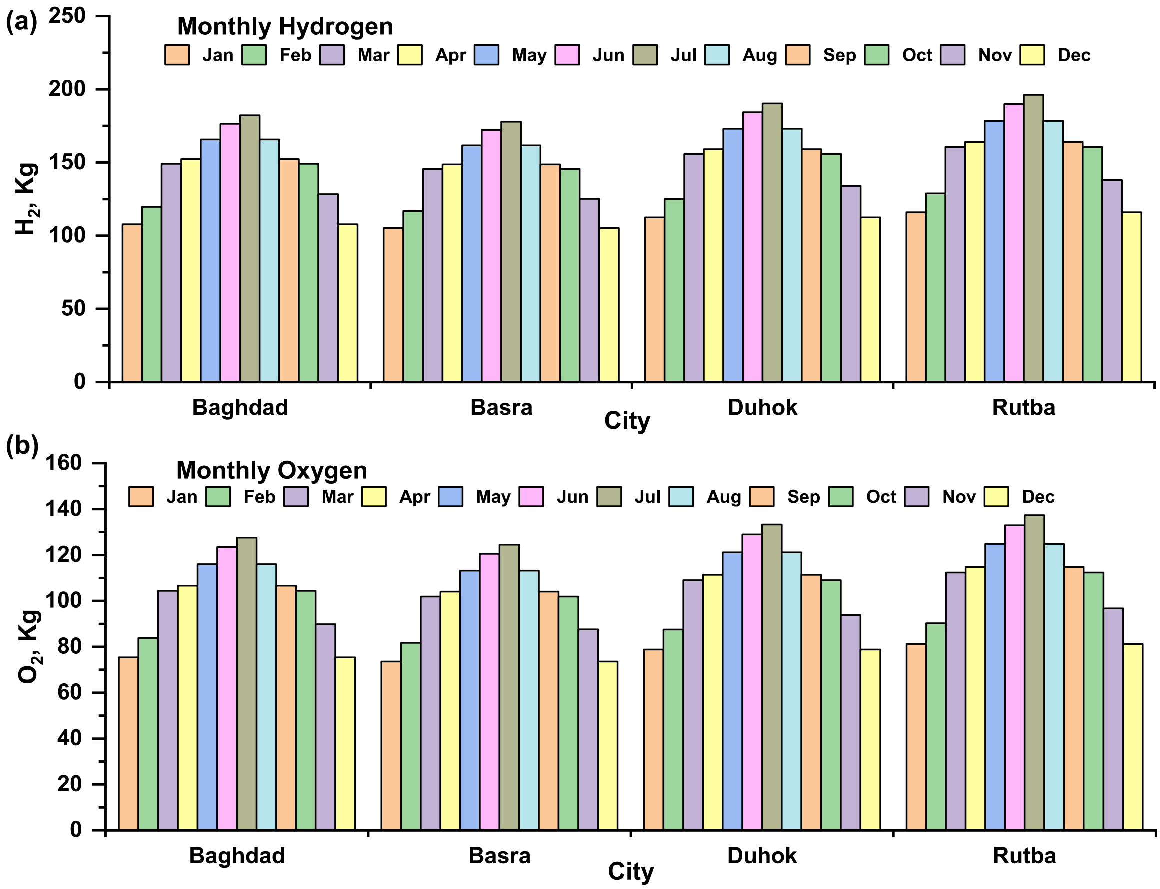

Figure 12: Monthly hydrogen (a), and oxygen (b) production for the analyzed cities.

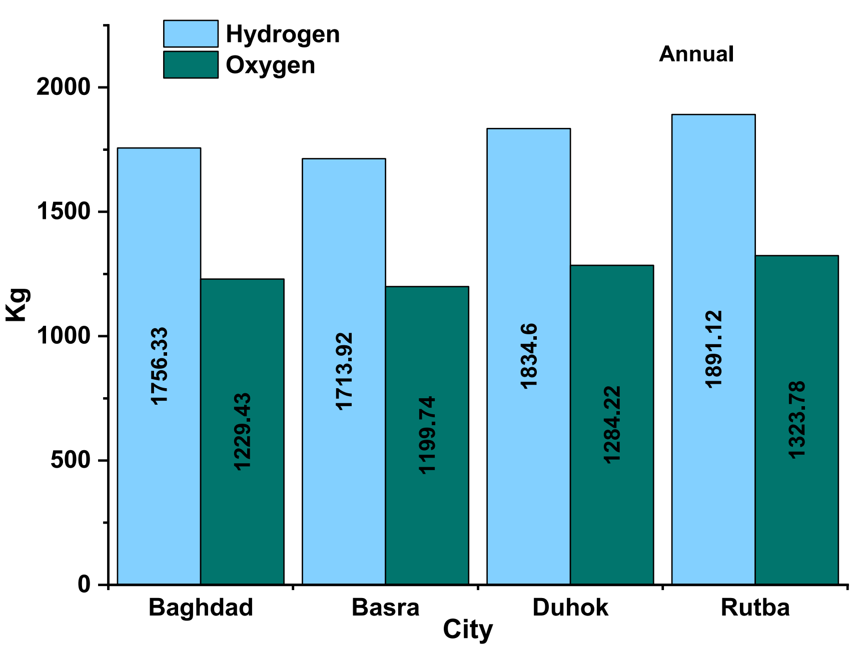

Figure 13: Annual hydrogen, and oxygen production for the analyzed cities.

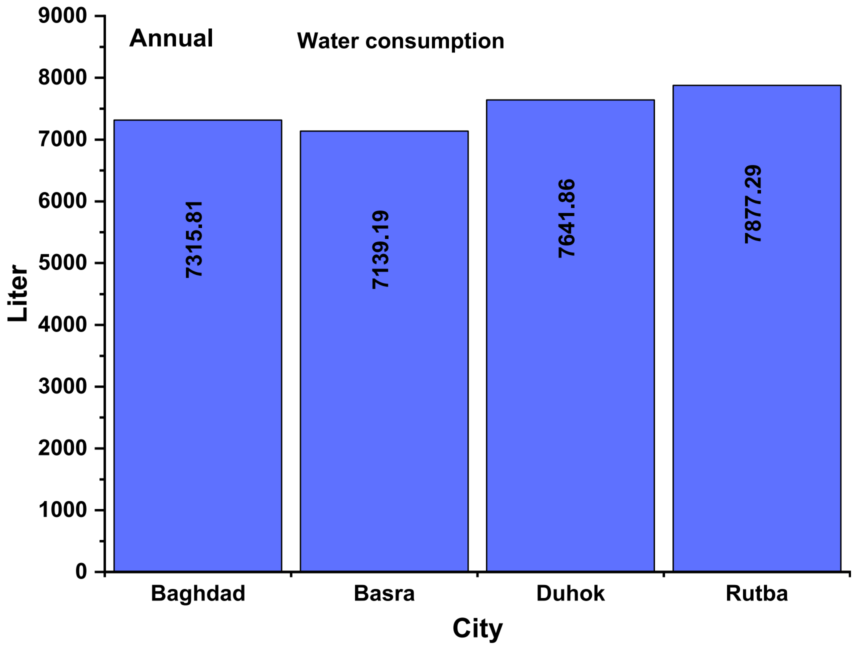

Figure 14: Annual water consumption for the analyzed cities.

Hydrogen cost

The cost of hydrogen is the way to calculate the production cost of one kg of hydrogen, using equation (10). The economic setting for the system components is presented in Table 1. Results indicate that the cost of hydrogen varies from \$4.19/kg to \$3.79/kg, with Basra having the highest cost and Rutba the lowest (see Figure 15).

Figure 16 depicts the cost of hydrogen in the cities investigated. Due to its cheap production costs, Rutba is the best location to establish a solar energy system for the production of green hydrogen. Figure 16 compares

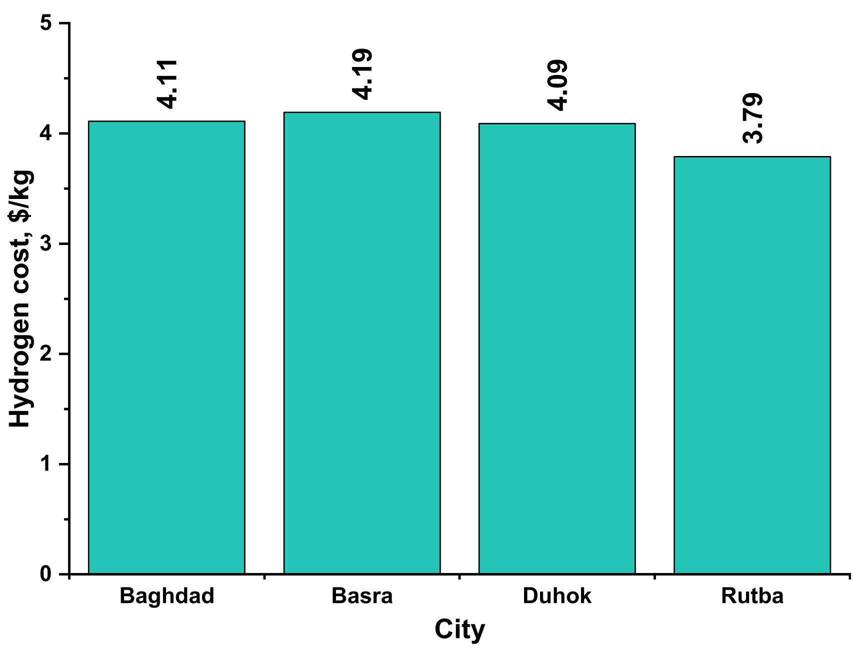

Figure 15: Hydrogen cost for the analyzed cities.

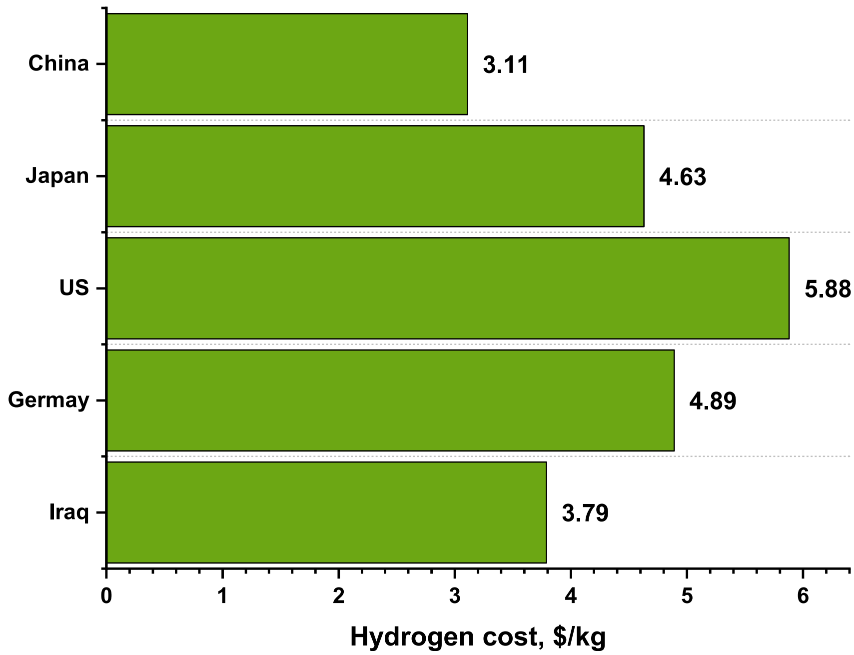

Figure 16: Obtained hydrogen cost compared with other countries.

the price of hydrogen in the current research to the price of hydrogen in other countries, as shown in (Energy Information Administration Report 2021).

Conclusions

This study highlights the significance of hydrogen generation and the system utilization factor in predicting the ultimate price of hydrogen produced. It has been found that a stand-alone photovoltaic system has a lot of potential for making green hydrogen. This is because the electrolyser can be fed energy in an increasingly independent and cost-effective way. However, the system is only accessible during daytime hours: the electrolysis system must be engaged at various times of the day, and not all applications are operating at full capacity. The intermittent nature of the solar source decreases not just the electrolyzer consumption rate but also its production and performance. The proposed system uses 22 kWp of solar energy to create hydrogen via a water electrolysis process using a water alkalin electrolyser (8 kW) driven by these renewable energy sources. The project life span taken 9 years for the period from 2021 to 2030.

As a result of the quantity of solar energy, the research is done in four distinct Iraqi cities (north, south, east, and west). In each of the investigated cities, the PV array parameters are set and adjusted to the annual optimal tilt angle; also, the local weather circumstances are modified. The PV array also powers the electrolyser, which turns water into hydrogen, and the compressor, which stores hydrogen.

The obtained results indicated the annual production/consumption for the analyzed cities was:

- For Rutba city, the hydrogen and oxygen production were 1891.12 and 1323.78 kg, respectively. The water consumption was 7877.29 L, and the cost of hydrogen was $3.79/kg.
- For Duhok city, the hydrogen and oxygen production were 1834.60 and 1284.22 kg, respectively. The water consumption was 7641.86 L, and the cost of hydrogen was $4.09/kg.
- For Baghdad city, the hydrogen and oxygen production were 1756.33 and 1229.43 kg, respectively. The water consumption was 7315.81 L, and the cost of hydrogen was $4.11/kg.
- For Basra city, the hydrogen and oxygen production were 1713.92 and 1199.74 kg, respectively. The water consumption was 7139.91 L, and the cost of hydrogen was $4.19/kg.

Rutba generates the most hydrogen and oxygen because, as stated earlier, its high solar irradiation and low ambient temperature result in the greatest value of produced power. Basra has the lowest hydrogen and oxygen production because, as noted before, its high sun irradiation and maximum ambient temperature result in the lowest value of produced power.

The research indicates that this solar hydrogen generation system is ideal for installation in the central region of Iraq and in other cities with similar climatic circumstances, particularly those with reasonably high solar energy.

Abbreviations

AC	alternative current
DC	direct current
NOCT	nominal operation cell temperature
PV	photovoltaic
PV/T	photovoltaic/thermal
STC	standard test conditions
STP	standard temperature and pressure
WT	wind turbines

List of symbols

A_E, B_E	coefficient of the consumption curve (kW/kg/h)
F	Faraday constant
f_{PV}	PV reduction factor
g	polytrophic coefficient
h_f	Faraday efficiency
h_{htc}	hydrogen tank compressor efficiency
H_t	amount of hydrogen produced per year in kilograms.
i	discount rate
I	initial investment cost
I_e	Electrolyser current
I_E	electrolyser current
M_C	is the operation and maintenance cost in ($)
m_{H2}	nominal hydrogen mass flow (kg/h)
n	project lifetime
N_C	number of cells in series
P_{hti}	hydrogen tank inlet pressure
P_{hto}	hydrogen tank outlet pressure
P_{icon}	converter input power
P_{ocon}	converter output power
Q_{H2}	rate of hydrogen generated by the electrolyzer
R	gas constant
S_{STC}	incident solar radiation at standard test conditions (kW/m^2)
S_T	incident solar radiation (kW/m^2)
$S_{T,\ NOCT}$	incident solar radiation which NOCT (1 kW/m^2)
t	time in the year
T_A	ambient temperature (°C)
$T_{A,NOCT}$	temperature at which NOCT (25 °C)
T_C	temperature of the PV (°C)
$T_{C,NOCT}$	cell temperature at which NOCT
T_{htci}	hydrogen tank compressor inlet temperature
Ts	temperature of the PV under standard test conditions (25 °C)
U_L	coefficient of heat transfer to the surrounding
$V_{h\ \tan\ K}$	volume of hydrogen tank
$Y_{\ PV}$	nominal capacity of PV
α_P	temperature coefficient of power (%/°C)
η_C	efficiency of PV
$\eta_{h\ \tan\ K}$	efficiency of hydrogen tank
γ	PV module azimuth angle
β	PV module tilt angle

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