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Feasibility of Photovoltaic-Powered Hydrogen Production for Off-Site Refueling Stations in Iraqi Cities: A Techno-Economic Analysis

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ABSTRACT

The study explores the feasibility of using a photovoltaic (PV) energy system to produce hydrogen for off-site hydrogen refueling stations (HRS) in three Iraqi cities (Karbala, Maysan, and Nineveh), focusing on a comprehensive system model consisting of a 558 MWp off-grid photovoltaic system, a 157.5 MWp proton exchange membrane (PEM) electrolyzer, a converter, and a hydrogen storage tank. Utilizing HOMER Pro software for system simulation and optimizing power output of PV system by NSGA-II algorithm in MATLAB. With a lifespan of 28 years from 2022 to 2050, hourly weather data for 2022 will be incorporated to optimize system performance. The outcomes identify Karbala City as the most cost-effective for green hydrogen production, highlighting the economic benefits of PV technology, which presents the most economical option with a levelized energy cost at 0% capacity shortage of $5,010/GWh. The project is projected to produce 10.61 million kg of hydrogen annually at a production cost of $2.75/kg, with an overall project cost estimated at $372.77 million. A sensitivity analysis is examined based on system dependability and the effect of a 15% capacity shortage for PV power plants with a 5.1% rise in hydrogen production costs. The results are of strategic significance for Iraq transportation sector, supporting the development of a robust green hydrogen infrastructure for HRS. This infrastructure is expected to promote sustainable transportation practices and reduce reliance on fossil fuels, contributing significantly to the energy transition in Iraq. This techno-economic analysis provides a foundational assessment for stakeholders considering investments in renewable hydrogen production and infrastructure development.

1. Introduction

The global landscape is increasingly pivoting towards renewable energy sources to tackle the twin challenges posed by our dependence on fossil fuels and the urgent imperative to address climate change. Climate change is a formidable threat that manifests through escalating global temperatures, melting glaciers, rising sea levels, and an uptick in extreme weather occurrences. These environmental changes have profound implications, impacting human health, agriculture, and economic stability [1]. In 2021, Iraq CO_2 emissions from its electricity production, industrial, transportation, and building sectors totalled 153.18 million tonnes. The International Energy Agency (IEA) reports that fossil fuels in the transportation sector contribute between 27-41% of annual greenhouse gas and CO_2 emissions (Figure 1).

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This underscores the need to monitor the trajectory of CO_2 emissions across various sectors in Iraq from 2000 to 2021 [2]. In the midst of this shift towards renewable resources, Iraq emerges as a pivotal player in the potential for producing green hydrogen using renewable energy. The country is actively pursuing the electrification of transportation, mainly through adopting fuel-cell electric vehicles (FCEV), as part of its strategy to phase out reliance on fossil fuels [3]. This transition is critical for reducing environmental impact and fostering sustainable development in the region.

Green hydrogen, produced via electrolysis using renewable energy sources such as solar power, provides significant environmental and sustainability benefits. This method of hydrogen production dramatically reduces greenhouse gas emissions, directly countering one of the global ecological challenges. For Iraq, endowed with vast solar energy potential, green hydrogen offers a sustainable avenue to address its growing energy demands. As the country looks towards decreasing its dependence on oil and gas, which has historically dominated its economy, transitioning to renewable energy sources for hydrogen production represents a strategic move towards a more diversified and resilient energy sector. This shift supports Iraq energy requirements and aligns with global environmental goals by mitigating the impact of fossil fuels [4]. Moreover, the optimal use of solar and other intermittent renewable energy sources for hydrogen production often involves integrating grid-connected electrolyzers. These systems capitalize on excess renewable energy generated during periods of low demand, enhancing energy use efficiency. Traditional centralized energy systems, decentralized energy generation through such technologies offers increased resilience to geopolitical uncertainties and natural disasters. This decentralization ensures energy independence, which is crucial for maintaining stability in the energy supply despite external disruptions. This approach bolsters national energy security and contributes to a more sustainable and adaptable energy infrastructure, pivotal for long-term planning and development [5-6].

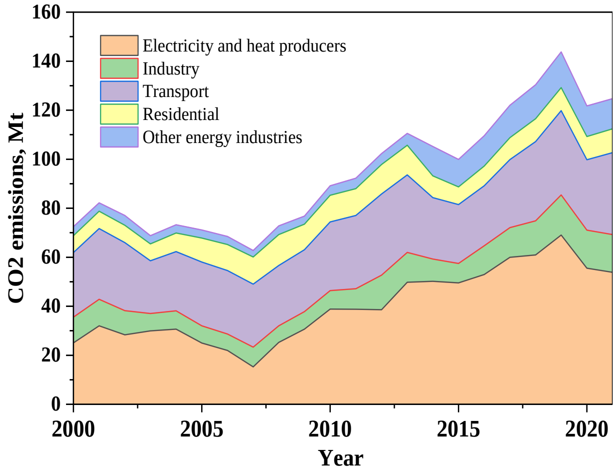

Figure 1. Evolution of CO_2 emissions by sector in Iraq since 2000-2021 [2]

Iraq stands at a crossroads in energy production, with the opportunity to exploit its considerable natural gas reserves for both export and as a feedstock for hydrogen production. Home to one of the largest natural gas reserves globally, Iraq is well-positioned to produce hydrogen via steam methane reforming (SMR), a mature and cost-effective technology. Although hydrogen derived from natural gas, often termed "grey hydrogen," is currently the most economically viable option, it lacks the environmental sustainability of green hydrogen produced from renewable energy sources. Grey hydrogen production offers Iraq an immediate pathway to enhance resource utilization and boost long-term revenue through strategic energy exports. However, the long-term prospects of this pathway may be uncertain as the international community moves towards renewable energy, potentially limiting the future demand for hydrogen produced from fossil fuels [7-9].

Meanwhile, green hydrogen represents a burgeoning frontier in sustainable energy solutions, garnering attention due to its environmentally benign attributes. This alternative, produced through the electrolysis of water, results in a pure hydrogen output and, when utilized, emits only water vapor and heat. It stands out as a zero-emission energy carrier, aligning with global sustainability goals by eliminating greenhouse gas emissions commonly associated with fossil fuel combustion [10-12]. Despite its conceptual simplicity, producing green hydrogen requires sophisticated integration of renewable energy sources and advanced electrolysis technologies. Its versatility and potential to serve as a clean energy carrier has catalyzed interest across various sectors, notably in electricity generation and as a potential replacement for conventional fuels in transportation [13-14].

The global energy landscape is inexorably shifting towards renewable sources, with significant investments signifying its expected predominance. However, the intermittent nature of renewables such as solar and wind energy necessitates flexible energy carriers to manage their variability, especially at scale [15]. Green hydrogen is poised to be a key player in the decarbonization of the transport sector, offering a clean alternative to gasoline and diesel. The establishment of HRS and the production of green hydrogen are crucial for this transition, facilitating the adoption of FCEVs. Nevertheless, while FCEVs offer zero-emission long-distance travel, the high fuel costs and the nascent hydrogen infrastructure pose significant obstacles to market entry [16]. Despite this, Iraq's plentiful renewable resources and the potential for low-cost electricity generation position green hydrogen as a critical element in the country's energy framework. Forecasts by international energy agencies anticipate significant cost reductions in green hydrogen production, with prices potentially falling below $2/kg by 2050, underscoring its viability as a sustainable energy resource for Iraq and beyond [17-18].

In the quest for a sustainable future, the literature concerning renewable energy and green hydrogen production is rich and diverse, marking a significant area of academic and practical inquiry. Scholarly articles encompassing this field delve into renewable energy sources' technical, economic, and environmental facets, focusing on harnessing wind, solar, and hydroelectric power for hydrogen generation. The burgeoning interest in green hydrogen, mainly its production through water electrolysis using renewable energy, is well documented, with research studies examining everything from optimizing electrolysis processes to integrating green hydrogen in existing energy systems. These comprehensive reviews not only chart the progress in the field but also highlight the challenges and potential solutions in scaling up green hydrogen as a cornerstone of clean energy transitions. In the economic analysis of renewable HRS in Sweden, Tang et al. [19] dissected the primary cost factors, paying particular attention to the influence of wind speed and electricity pricing. The findings reveal that integrating solar and wind energy sources can enhance the efficiency of off-grid stations. They determined that the production cost for green hydrogen ranges from $3.78 to $7.77 per kilogram, indicating market competitiveness even without governmental subsidies. Notably, the deployment of solar photovoltaic (PV) technology in the generation of green hydrogen has emerged as a focal point in contemporary research. Nicita et al. [20] offer a comprehensive techno-economic-financial assessment of a green hydrogen production system designed for use by industries and research institutions. Centered on a case study in Messina, Italy, the proposed configuration consists of a 200 kWp of PV array installation coupled with a 180 kW electrolyzer. The analysis underscores the economic potential and investment attractiveness of small-scale, PV-driven hydrogen production facilities, concluding that such ventures can be profitable. Xiang et al. [21] delve into the generation of renewable hydrogen in Pakistan, utilizing the country rich natural resources such as wind, solar, biomass, and geothermal. Their study employs the Fuzzy Analytical Hierarchical Process (FAHP) to evaluate various criteria, including economic viability, commercial prospects, environmental impact, and social acceptability of renewable hydrogen technologies. The results of their assessment point to wind energy as the most favorable option, with biomass as a close second, for the potential production of 6.6 million tons of hydrogen annually. Additionally, the study highlights photovoltaic solar energy capability to produce 2.8 million tons, noting its low installation and production costs as a significant advantage. The research indicates that the cost of hydrogen (COH) could range between $5.30

and $5.80 per kilogram. Okonkwo et al. [22] explored the development of a hybrid energy system in Salalah, Oman, consisting of wind turbines (WT), photovoltaics (PV), fuel cells (FC), and hydrogen storage tanks (HT). Leveraging the HOMER model for the optimization of electric renewables, their investigation confirms the economic feasibility of the PV-WT-FC-HT hybrid system for satisfying both the electrical and hydrogen production demands within the region. This hybrid setup emerged as notably cost-efficient, boasting the lowest Levelized COH at $1.15 per kilogram and a competitive Cost of Energy (COE) at $0.19 per kWh, positioning it as a viable solution for Oman energy needs.

The economic aspects of on-site HRS are critical to their feasibility and sustainability, encompassing initial capital investment, operational and maintenance costs, and the cost-effectiveness of producing hydrogen on-site versus off-site. Initial costs are significant due to the need for advanced technologies such as electrolyzers and infrastructure for storage and dispensing hydrogen. Operational costs include energy consumption, particularly the electricity needed for electrolysis if green hydrogen is produced, and regular maintenance of high-tech equipment. Economically, on-site HRS can benefit by reducing transportation and logistics costs of delivering hydrogen produced off-site. However, they require a sufficiently high demand for hydrogen at the location to be cost-effective. Moreover, on-site production can leverage renewable energy sources directly, potentially lowering the cost per kilogram of hydrogen compared to more centralized production facilities that rely on a broader mix of energy inputs. Minutillo et al. [23] assessed the economic aspects of on-site HRS in Italy, aimed at producing green hydrogen using renewable energy sources to achieve zero emissions. The study specifically examines HRS powered by grid-connected photovoltaic (PV) installations and electrolyzer units, taking into account a variety of configurations and sources of electricity. Through this analysis, the research investigates the financial and environmental implications of deploying such systems, aiming to identify the most cost-effective and sustainable approaches to green hydrogen production within the Italian context. Minutillo et al. [23] delve into the levelized COH in various configurations of on-site HRS in Italy, particularly those powered by renewable sources. Their analysis determines that the investment costs for such configurations increase with alterations in the electricity mix and hydrogen production capacity. Moreover, their study highlights the influence of operational and maintenance costs on the COH, which they found to range between $10.03/kg and $13.47/kg, reflecting the economic implications of these stations' ongoing upkeep. In a related endeavor, Xie et al. [24] propose an innovative approach to hydrogen production through seawater electrolysis. This method addresses the specific challenges of side reactions and corrosion typically associated with this electrolysis process. This technique is noted for its efficiency and flexibility in terms of system size and scalability, making it suitable for a range of practical applications, including the treatment of water-based effluents, resource recovery, and concurrent hydrogen generation. The research pays particular attention to mitigating electrode side reactions and corrosion, which are prevalent issues in saline water electrolysis, hence advancing seawater electrolysis's potential as a viable hydrogen production method. Saebea et al. [25] explored the functionality of a high-pressure PEM electrolyzer that operates without external compression. This study concentrates on the electrolyzer's capacity to generate high-purity hydrogen directly from the system at substantial pressures. The research incorporates an electrochemical model that accounts for various factors, including hydrogen permeation, cathode pressure, membrane thickness, and the explosive limits of hydrogen-oxygen mixtures. The findings indicate that electrochemical compression within the electrolyzer is beneficial for delivering high-pressure hydrogen while maintaining minimal impact on the overall system performance. This method of hydrogen production presents a significant step forward in optimizing the efficiency and safety of hydrogen delivery systems. Lee et al. [26] conducted a detailed analysis of the economic feasibility of high-pressure polymer electrolyte membrane (PEM) water electrolysis, specifically for its application in distributed HRS across Korea. Their study meticulously calculated that the unit COH production reached $6.24 per kg of ($H_2$) at a production rate of 700 m^3/hr, an output sufficient to service approximately 300 FCEV. The investigation further assessed key economic indicators such as net present value, discounted payback period, and present value ratio, considering varying discount rates and capacity factors. These financial metrics provided a comprehensive evaluation of the economic viability of deploying high-pressure PEM electrolysis technology in the context of Korea expanding hydrogen infrastructure for transportation. Ligen et al. [27] tackled the stringent purity requirements for fuel cell vehicles. They developed a commercial 50 kW alkaline water electrolyzer (AWE) system specifically engineered to eliminate contaminants such as nitrogen, oxygen, and water vapors from hydrogen gas. This system meets the rigorous ISO 14687:2019 hydrogen quality standards with impressive energy efficiency, consuming only 0.5 kWh per kg of H_2 while achieving a product recovery rate of 98.4%. This advancement signifies a significant step forward in providing high-purity hydrogen that is cost-effective and environmentally friendly, which is crucial for the broader adoption of hydrogen fuel cell technologies.

High-pressure PEM water electrolysis represents a promising technology for hydrogen production, offering the advantage of generating hydrogen at pressures suitable for storage and dispensation without the need for external compression. This feature significantly enhances the feasibility of PEM systems for integrating into hydrogen infrastructure, especially in settings where space or additional equipment for compression might be limiting factors. The technology is highly efficient at converting electrical energy into hydrogen, benefits from a fast dynamic response to changing demand and renewable supply conditions, and operates at higher current densities than other electrolysis methods. Moreover, the capability to produce hydrogen at high purity and pressure directly from the electrolyzer reduces the overall complexity and cost of the hydrogen supply chain, making high-pressure PEM electrolysis particularly well-suited for applications requiring high levels of operational reliability and efficiency, such as fueling stations for fuel cell vehicles. Micena et al. [28] explored the potential for establishing a Hydrogen Refueling Station (HRS) in a Brazilian city to replace traditional fossil-fuel-based transportation systems with hydrogen-powered vehicles, mainly focusing on the taxi fleet. Their findings indicate that approximately 185.4 kg of hydrogen per day would be required to power the entire taxi fleet, whereas a smaller-scale conversion involving 10% of the fleet would need just 19.8 kgH_2/day. Notably, the study highlights a critical economic aspect of hydrogen production: the costs are inversely proportional to the capacity of the HRS. Specifically, larger-scale HRS operations could produce hydrogen at a lower cost of $8.96 per kg, while smaller stations face higher production costs, around $13.55 per kg. This inverse relationship underscores the importance of scale in the economic viability of hydrogen fuel infrastructure developments, suggesting larger installations could be more financially sustainable in the long run. Gökçek et al. [29] performed a techno-economic analysis on the feasibility of establishing a HRS on the island of Gokceada, Turkey. This study utilized two hybrid renewable power generation systems to explore the practicality of refueling 25 vehicles daily. Employing HOMER software for simulation, the analysis compared the financial outcomes of these systems. The findings revealed that the levelized COH was $8.92 per kg when utilizing the hybrid systems, which was more cost-effective than $11.88 per kg for the systems combining wind, photovoltaic, and battery storage. This differential highlights the economic advantages of specific hybrid configurations over others in reducing COH production, thereby enhancing the viability of hydrogen as a sustainable fuel option for transportation on the island. Ali Khan et al. [30] have crafted an extensive cost analysis framework to evaluate the economic viability of 10 MW scale alkaline and proton-exchange membrane (PEM) electrolyzers for hydrogen production in Australia. To ensure economic feasibility, the study underscores the importance of maintaining electrolyzer costs below $500 per kilowatt and electricity costs under $30 per megawatt-hour. One of the key strategies identified to reduce production costs involves oversizing the renewable energy capacity by 1.5 times the standard requirements. This approach has led to a 10% reduction in hydrogen production costs. The findings advocate for the upsizing of renewable energy installations to achieve more cost-effective and efficient operations in hydrogen generation, suggesting significant implications for the scaling and sustainability of hydrogen production infrastructure. Wu et al. [31] conducted a detailed economic analysis of HRS to discern the cost implications of various operational modes and transportation methods for hydrogen. The study delineates that while the COH supply significantly affects the COH at off-site refueling stations, the cost of power predominantly influences on-site refueling stations. The analysis reveals that off-site stations utilizing pipelines are the most cost-effective option, mainly when capacity utilization rates are high. For transportation distances, the study finds that long tube trailers are economically viable for distances up to 300 km. Beyond this range and up to 1000 km, transporting hydrogen via liquid hydrogen tankers becomes more feasible. In contrast, on-site hydrogen production through water electrolysis was assessed to be uneconomical, with costs amounting to $4.48/kg, highlighting the economic challenges inherent in adopting this particular method of hydrogen production at current price levels.

Table 1 provides a comprehensive overview of research on green hydrogen production. This study integrates important discoveries, methodologies, and geographic considerations from several research teams to provide a comprehensive view of the present status of green hydrogen generation in various situations and regions.

The objective of this study is to conduct a techno-economic analysis of the feasibility of utilizing photovoltaic-powered systems for hydrogen production at off-site refueling stations across various Iraqi cities. The research seeks to model and evaluate a configuration comprising a photovoltaic system, a PEM electrolyzer, converters, and hydrogen storage units to assess their performance and economic viability over 28 years using simulated weather data for 2022. This study will also compare the potential of different cities within Iraq to identify the most cost-effective locations for deploying such green hydrogen infrastructure, aiming to support Iraq transition away from fossil fuels towards a more sustainable energy future.

Table 1: Assessing the viability of green hydrogen generating systems in various parts of the country

Country	Used technology	Objective	Outcomes	Ref.
Tunisia	PV array, Electrolyzer, compressor, converter, and storage tanks.	Economic assessment of PV with capacity 1.89 MWp to produce 150 kg of hydrogen for HRS.	Achieved a minimum COH of $3.58/kg and an NPC of $2.52 million.	[32]
Korea	Case (1) PV-power catalytic cracking green ammonia. Case (2) Solar PV and water electrolyzer.	Techno-economic comparison of two cases leading to H_2 generation for the supply chain of on-site HRS.	Case (1) is cost-effective at $8/kg H_2, while case (2) is high COH at $10/kg.	[33]
Saudi Arabia	Hybrid PV/WT, electrolyzer, storage tank, converter, and lithium-ion battery.	Analyze the feasibility of a hybrid energy system integrated with batteries to produce green H_2 for HRS.	Provide the lowest LCOE at $0.62/kWh, the COH at $9.34/kg, and the NPC at $486,360.	[34]
Chile	PV panels, WT, and water electrolyzer	Investigate the costs of generating green H_2 at various places using a hybrid energy system and evaluate emissions reduction.	The cost ranges from 2.09 to 3.28 $/kg H_2, and the CO_2 emissions are very low, at 1.31 kg CO_2e/kg H_2.	[35]

Greece	Wind farm and AWE.	Examines the viability of combining AWE with 13.8 MWp wind farm electricity supply to generate green H_2.	Reach the lowest COH possible at $6.02/kg.	[36]
Canada	Hydropower and electrolyzer farm.	Explores the use of hydroelectric power with a 3.49 MWp electrolyzer for green H_2 generation.	The hydropower-hydrogen plant achieved a minimum cost of $2.43/kg H_2.	[37]
China	PV array, WT, PEME, and AWE	Analysis of techno-economic integration of renewable PV and WT energy with PEME and AWE.	AWE exhibits the lowest COH, around 3.18-8.74 $/kg, compared to PEME is around 3.33-10.24 $/kg.	[38]
Sweden	Onshore WT and water electrolyzer	Economic analysis of off-grid wind-powered HRS to refuel 200 vehicles daily.	The COH achieved ranges from 5.18 to 7.25 $/kg.	[39]

2. Methodology

2.1 Surveyed area

The research explores the potential for green hydrogen production at HRS throughout Iraq governorates. It emphasizes the region's geographic diversity, examining each area's distinct features. The study provides a detailed analysis of the renewable energy capacity, environmental considerations, and the readiness of existing infrastructure in these areas. The core of the research lies in evaluating the technical and economic feasibility of green hydrogen production in various Iraqi settings. This comprehensive approach will provide a roadmap for establishing HRS tailored to the individual needs of each region. To accomplish this, the study focuses on three strategically chosen Iraqi cities: Nineveh in the north, Maysan in the southeast, and Karbala in the southwest [40]. It considers their specific geographical elevations: Nineveh sits 237 m above sea level, Maysan 14 m, and Karbala 29 m (detailed in Figure 2 and Table 2). The PV panels were positioned at the optimum annual adjustment position azimuth angle facing south at 0 degrees for each city [41]. The meticulously analyzing these locations, the research team can explore the impact of climate, geography, and infrastructure variations on the feasibility and efficiency of green hydrogen production using solar energy systems.

Figure 2. Representation of the three examined cities in Iraq [41]

Table 2 lists the selected Iraqi cities investigated as potential sites for green hydrogen production for HRS. These cities were strategically chosen to represent the country northern and southern regions, ensuring a comprehensive evaluation of green hydrogen production feasibility across Iraq diverse geographic regions.

Table 2. Cities Examined for Solar-Powered Hydrogen Production in Iraq [41]

City site	Latitude (N)	Longitude (E)	PV tilt angle (degree)
Karbala	32.59	44.1	28
Maysan	31.63	47.06	29
Nineveh	36.08	42.05	31

2.2 H_2 Refueling Infrastructure: Development and Performance Analysis

This section analyzes the technological components of a green hydrogen production system specifically designed to supply OSHRS. The system is targeted for a daily production capacity of 1,500 kg for each HRS. Transportation trucks will deliver the hydrogen to a network of 25 strategically located HRS to ensure efficient distribution. These stations will be dispersed based on each Iraqi governorate's detailed population density analysis. This Is the highest demand for hydrogen fuel. In principle, HRS can release green hydrogen up to a purity level of 99.99%. Therefore, it meets the requirements of fuel cells for vehicles and complies with ISO 14687:2-2012 and SAE J2719 standards, which are essential for use in HRS [42]. The HRS relies on high-purity hydrogen gas from a water electrolyzer. The main components of the HRS include solar PV, a water electrolyzer, a converter, and a storage tank. The green hydrogen plant operates as an independent off-grid electrical system. It uses PV solar energy as the primary source of electrical power generation. The power is sent to the AC/DC converter to efficiently manage the electrical load, providing the electrolyzer with direct current (DC). The PEM electrolyzer divides water into oxygen and hydrogen molecules. The hydrogen, with a purity level of up to 99.99%, moves through the PEM. Subsequently, the hydrogen produced by the electrolyzer is stored at pressures exceeding 80 bar in storage tanks [43,44]. The hydrogen is transported from the storage tanks via tankers to off-site HRS. A simplified layout is illustrated in Figure 3. The main components of the green ensure optimal placement to serve the area's hydrogen production system. This investigation extends across three strategically selected Iraqi cities: Karbala, Maysan, and Nineveh, each chosen for its distinct climatic conditions ranging from the moderately hot, solar-rich north to the hot, wind-rich southern regions of Iraq [40]. The study analyzes the main cost components contributing to green hydrogen production and the investment associated with the HRS using HOMER Pro software. Thus, it is solely the aspect of supply.

2.3 Technical and economic specifications

The proposed approach for producing green hydrogen involves photovoltaic solar panels with a capacity of 558 MW as the basic unit. This installed solar capacity is paired with an inverter of 170 MW to supply the 157.5 MW capacity of the PEM electrolyzer. Due to low gas density, the produced gas is collected daily in storage tanks with a capacity of 14,400 m3 [44-47]. Furthermore, transporting gaseous hydrogen by trucks is flexible and can reach areas inaccessible by pipelines. The cost of transporting gaseous hydrogen by trucks includes fuel, maintenance, and labor costs. Hydrogen is often more expensive per unit than pipelines [31]. Revenue from by-products such as oxygen is not factored in. Table 3 displays the economic and technical specifications of the critical components for hydrogen production, including capacities, efficiencies, service life, initial investment, replacement, and operation and maintenance costs. The approach was tested in three cities (Karbala, Maysan, and Nineveh) to assess the impact of solar photovoltaic energy abundance on economic performance. The PV array is positioned optimally for each city. The financial evaluation is based on the current Iraqi system, which has a 6% annual interest rate. The project spans from 2022 to 2050 [48].

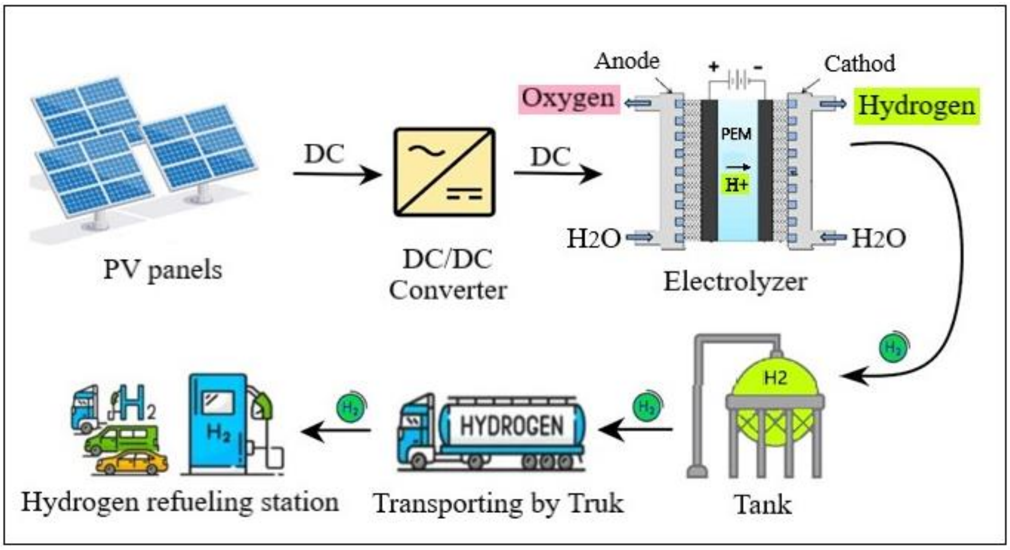

Figure 3. Solar PV-powered hydrogen production for OSHRS

Table 3: Technical and cost data for system components

Component	Model	Capacity	Efficiency (%)	Life span (year)	Capital ($)	Replacement ($)	O&M ($/year)	Ref.
PV panels	Pwsolar	1 MW	20.3	20	90,000	90,000	5,750	[45]
Electrolyzer	Silyzer	35 MW	76	10	34 M	34 M	30,000	[44]
H_2 tank	SL-300	300 m^3	99	28	80,000	80,000	480	[46]
Converter	MCR	20 MW	>97	25	2 M	2 M	2,900	[47]

2.4. Analysis of weather data

Throughout 2022, researchers meticulously collected environmental data to assess the viability of renewable energy sources in various Iraqi towns. Three strategically positioned weather stations with top-of-the-line FT0300 instruments captured vital information every hour [49]. These instruments measured solar irradiance, which indicates the solar energy reaching the Earth surface, ambient temperature, and wind speed. This comprehensive and dependable dataset provides a clear picture of the environmental conditions at each location.

For instance, Table 4 showcases daily average weather data collected from several Iraqi cities on June 27th, 2022. It focuses on three critical metrics influencing renewable energy potential: solar irradiance, temperature, and wind speed. The data reveals variations across the locations.

Table 4: Daily average climate observations for examined Cities on June 27, 2022

City site	Irradiance (kWh/m^2)	Temperature (ºC)	Wind speed (m/s)
Karbala	6.77	39.46	4.98
Maysan	6.68	40.77	7.97
Nineveh	7	36.13	3.75

Figure 4 presents a graph depicting the variations of critical weather conditions throughout 24 hours on June 27, 2022, in the selected cities (Karbala, Maysan, and Nineveh). The graph synchronizes three important weather metrics: solar irradiance, ambient temperature, and wind speed. Examining the trends in each line of the graph, we can gain valuable insights into how these weather elements interacted with each other throughout the day. For instance, periods of high solar irradiance might correspond with increases in ambient temperature. At the same time, strong winds could lead to fluctuations in both temperature and solar irradiance (due to cloud cover).

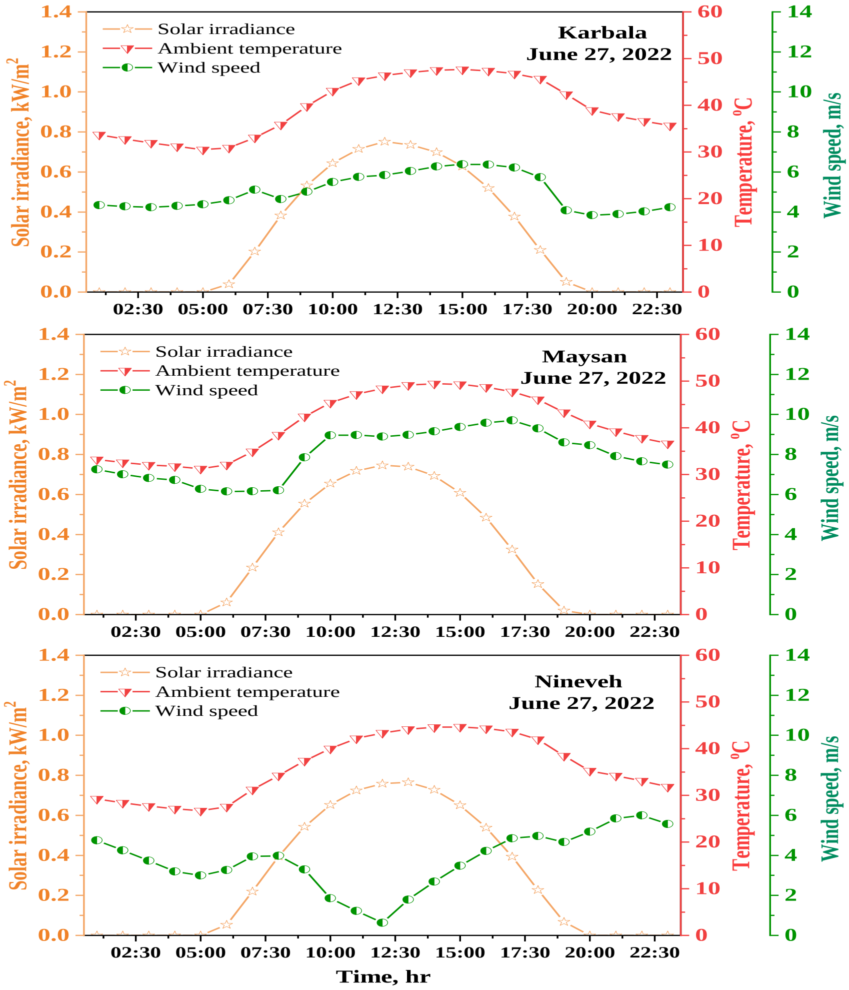

Figure 4. Daily Climate data for Examined Cities on June 27, 2022

Figure 5 dives into the nitty-gritty of weather patterns throughout 2022 in Karbala, Maysan, and Nineveh. It presents monthly averages from real-world solar irradiance measurements (sunshine intensity), temperature, and wind speed. The dissecting weather patterns month-by-month, we gain a richer understanding of the environmental conditions that favor green hydrogen production. The results act as a roadmap, highlighting the months with the most promising potential for solar energy. Solar irradiance in sunnier months reigns supreme during fall and summer. This coincides with longer daylight hours, allowing the sun to blanket the Earth with more intense radiation for extended periods. Conversely, solar radiation dips during spring and winter. The influence of cloud cover and precipitation comes into play. Increased cloudiness and rainfall act as a veil, significantly dampening the amount of sunlight reaching the ground.

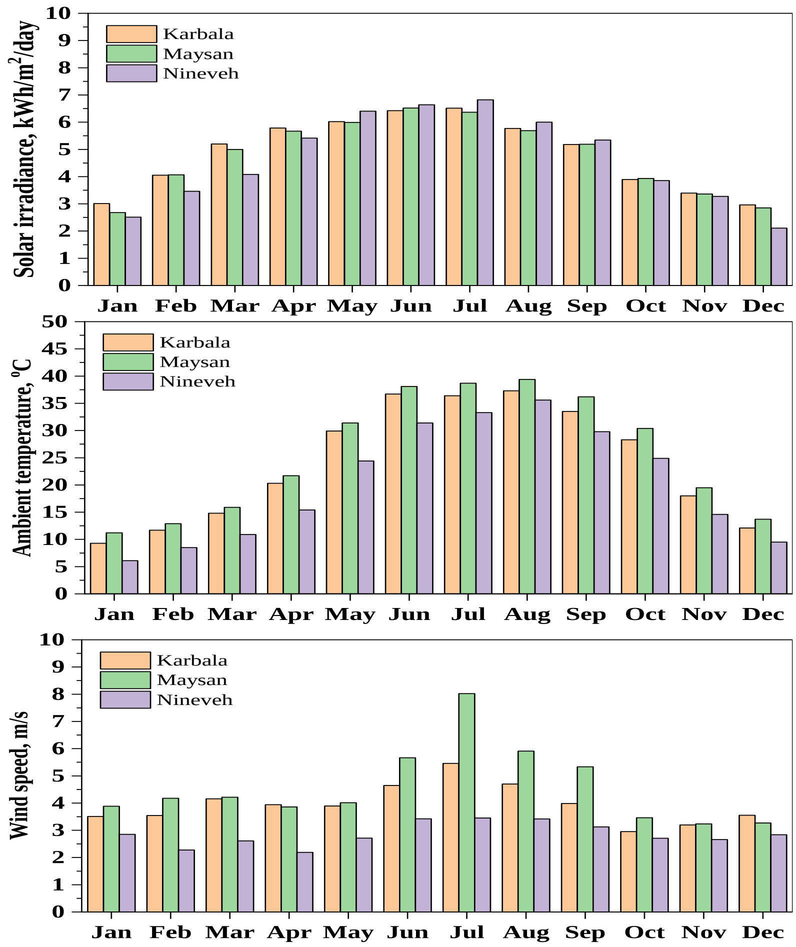

Figure 5. Monthly average observational climate data for the studied cities during the year 2022

Table 5 offers a detailed examination of year-long climate information for 2022 in three strategically chosen Iraqi municipalities: Karbala, Nineveh, and Maysan. This information contains necessary measurements such as average temperature, wind speed, and solar irradiance. Through analyzing these variables, we can acquire valuable perspectives on the present environmental status and how it affects the practicality of implementing renewable energy sources in these areas. This impacts the ability to produce green hydrogen, a sustainable energy carrier. Karbala appears to be a very favorable place for utilizing solar power. The mild average temperatures and the highest levels of sun exposure make for an ideal setting for installing solar panels. On the contrary, Nineveh poses certain obstacles to renewable energy initiatives. Although a cooler average temperature may appear advantageous for solar panels to work more effectively, the region faces the challenge of having the lowest documented ambient temperature and sun brightness, severely hindering solar energy production capacity. Maysan holds a position in the middle. While it has the highest average temperature of the three towns, which could impact solar panel efficiency, its intermediate levels of sun irradiance offer some potential for solar energy development.

Table 5: Annual observational climate data for examined cites

City	Irradiance (kWh/m^2)	Temperature (°C)	wind speed (m/s)
Karbala	4.85	24.1	3.97
Maysan	4.78	25.8	4.59
Nineveh	4.66	20.1	2.86

2.5 Economic evaluation equations

This section delves into the mathematical formulae that support the HRS economic benefits and technological viability. It is necessary to consider several environmental elements that affect solar power production to precisely estimate the amount of energy generated by the photovoltaic (PV) system. These variables include, but are not restricted to, humidity, ambient temperature, and solar irradiation (or the quantity of sunshine received) [50]. Equation (1) determines the PV system power output.

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

Using these three elements, the actual working temperature of PV cells can be estimated, usually better than the standard test condition (STC) of 25°C. This is crucial because the performance of PV cells decreases with increasing temperature [51]. So, knowing the correct running temperature allows expecting the actual electricity output of the solar panels.

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

Established methods can be utilized to assess the effect of temperature fluctuations on photovoltaic (PV) cell performance [52]. The phrase refers to the combined impact of light absorption and transmittance inside the PV cell.

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

The economic viability of PEM electrolysis depends heavily on electrical efficiency. Increased efficiency reduces electricity requirements for hydrogen production, thus lowering operational expenses [53]. Various factors can impact the electrical efficiency of PEM electrolyzers, including:

$$I_e = A_E m_{H_2} + B_E m'_{H_2} \quad (4)$$

PEM electrolysis is a proven technology that generates hydrogen from water (H_2O) with electrical power. Current density and operating temperature play significant roles in hydrogen production [54]. Equation (5) determines the rate at which a PEM electrolyzer produces hydrogen gas.

$$Q_{H_2} = \eta_f \left(\frac{N_C I_e}{2F}\right) \quad (5)$$

Equation 6 describes how to calculate the pressure in a hydrogen storage container. This computation considers multiple factors, such as the speed of hydrogen entering the tank, the starting pressure in the tank, and the length of time the process takes place [55].

$$P_{tank} = \left(\frac{RT_{htci}}{V_{httank}}\right) \eta_{httank} \quad (6)$$

Converting the direct current (DC) generated by the photovoltaic (PV) panels into alternating current (AC) is necessary to power vital components, including gas drying and cooling systems, control systems, and water pumps. The converter is essential to this energy conversion process because it controls how energy moves through the power system [56]. The converter's efficiency, a gauge for how well it transforms and distributes electrical energy, can be expressed using the formula (7).

$$\eta_{con} = \frac{P_{ocon}}{P_{icon}} \quad (7)$$

The power distribution allocation within the envisioned system includes the method by which the PV panels generate electrical energy and then direct that energy toward the PEM electrolyzer and the hydrogen storage system. This guarantees a steady and dependable supply of energy throughout the system. Efficiency and energy losses throughout the conversion and storage processes are considered when calculating the power flow distribution, which is based on the energy needs of the PEM electrolyzer and the hydrogen storage system [57].

$$P_{El} = P_{PV} \left(\eta_{con}\right) - P_{com} \quad (8)$$

The net present cost (NPC) calculation for each component accounts for all pertinent expenditures throughout the component's lifecycle to assess the system's financial sustainability thoroughly. In addition to the original purchase price, there might be additional expected cash flows, installation charges, operating and maintenance costs, and possible salvage value at the end of the product's useful life [58].

$$f_d = \frac{1}{(1+i)^t} \tag{9}$$

$$C_{total,equip,t} = C_{earned,equip,t} - C_{incurred,eqyip,t} \tag{10}$$

The NPC is calculated as in Equation (11):

$$C_{NPC,equip,total} = \sum_{t=0}^{N} C_{total,equip,t} \cdot f_d \tag{11}$$

An essential economic metric for evaluating the feasibility of hydrogen generation, compression, and storage facilities is the COH. It represents hydrogen's delivery price ($/kg), accounting for the HRS capacity [59]. It is calculated as in Equation (12):

$$COH = \frac{I + \sum_{t=1}^{n} \frac{M_C}{(I+i)^t}}{\sum_{t=1}^{n} H_t} \tag{12}$$

A PV system levelized cost of energy, which accounts for the time value of money, is the average cost of power generated by the system throughout its lifetime [60]. It is used to compute Equation (13):

$$LCOE = \frac{C_{ann,total}}{E_{served}} \tag{13}$$

2.6. Optimization technique

Photovoltaic (solar) systems pose a challenge due to their fluctuating power outputs, impacting the stable operation of PEM electrolyzers used alongside them. The frequent starting and stopping of electrolyzers decreases hydrogen production hours and leads to energy wastage and increased hydrogen costs. To address this issue, MATLAB software implements an enhanced version of the NSGA-II algorithm for hourly optimization within the integrated power system. NSGA-II stands out for its capability to identify multiple optimal solutions (Pareto front) for problems with conflicting objectives. This upgraded approach focuses on optimizing the operation of the PEM electrolyzer at total capacity (3000 kg/hr) throughout the day by selecting the suitable solar cell capacity. The energy optimization is further segmented into sub-problems across the 24 hours of a day, ensuring a comprehensive strategy [61]. Where R is the set of data matrices containing all the feasible solutions produced by the NSGA-II algorithm. The methodology utilizes data set R derived from the NSGA-II algorithm is used as input as follows:

$$\varphi(X_J) = Min\left(NPC_{Project}, LCOE, COH\right) \tag{14}$$

Where $\varphi(X_J)$ is the objective function and X_J Is a feasible solution with numbers *J*. Upon obtaining the hourly Pareto fronts, an interactive search strategy is employed to balance the optimal solution per hour and the frequency of the PEM electrolyzer running at total capacity. The overarching aim is to harmonize PV efficiency with electrolyzer capacity. The solutions derived from this approach offer distinct advantages: Solution 1 minimizes peak PEM electrolyzer power, while Solution 2 prioritizes reducing peak power demand at a slightly lower cost. This is achieved by employing larger capacity PV systems and inverters, albeit with a marginal decrease in reliability due to higher NPC. Solution 3, conversely, concentrates on diminishing energy shortage, albeit at the expense of reliability and energy wastage, aligning with real-world climate conditions such as solar radiation intensity and ambient temperature. Figure 6 visually represents the results through a flowchart outlining the proposed NSGA-II algorithm. The goal of evaluating all potential solutions is to identify the optimal approach that minimizes NPC, LCOE, and COH, ensuring an efficient and cost-effective system design.

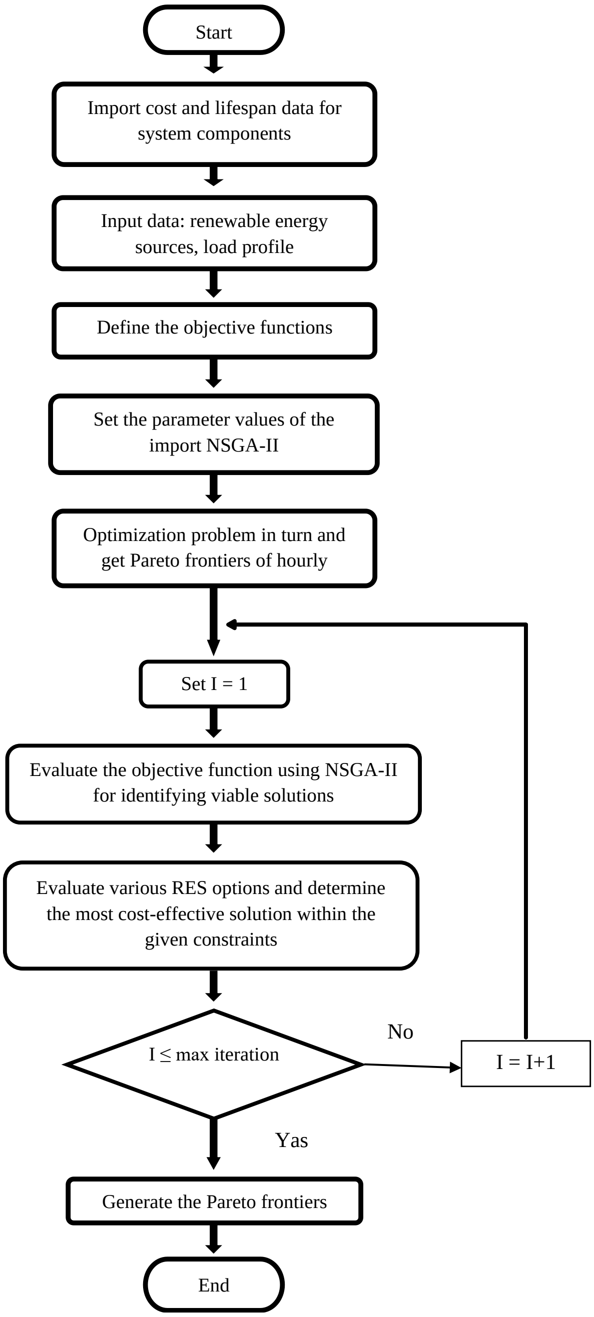

Figure 6. Flowchart of the NSGA-II algorithm process

3. Results and discussion

This section analyzes the performance of a green hydrogen production system specifically designed to supply HRS across Iraq. The system targets a yearly production capacity of 1,500 kg/day for each HRS. Utilized MATLAB and HOMER Pro software to meticulously evaluate the system performance against a backdrop of real-world data, Key Aspects Analyzed:

- Utilized twelve months of weather data collected from weather stations to establish an authentic testing setting.
- The new system was thoroughly assessed in three Iraqi areas, each with unique weather conditions. Utilizing multiple locations provides valuable perspectives on the system's adaptability.
- The efficiency of hydrogen production from the PEM electrolyzer and the energy analysis of photovoltaic cells were focused on, considering the specific environmental factors in Iraq.
- A critical aspect of our analysis involved incorporating a 93% efficiency rating for the PV system. The remaining 7% loss is meticulously attributed to factors such as electrical resistance in wires, temporary cloud cover, and the effects of dust storms, which are common environmental challenges in Iraq.

Moreover, the economic feasibility calculation has been performed using the NPC, LCOE, and COH analysis.

3.1 Evolution of Electric Power Generation

The study commenced by examining the potential energy output of photovoltaic (PV) systems in three key Iraqi cities: Nineveh, Maysan, and Karbala. This evaluation's primary objective was to gauge each system's individual performance and collective efficacy in generating renewable energy. On June 27, 2022, simulation results for these PV systems were analyzed, as depicted in Figure 7. The assessment considered the total capacity of the installed PV panels, which amounted to 558 megawatts (MW).

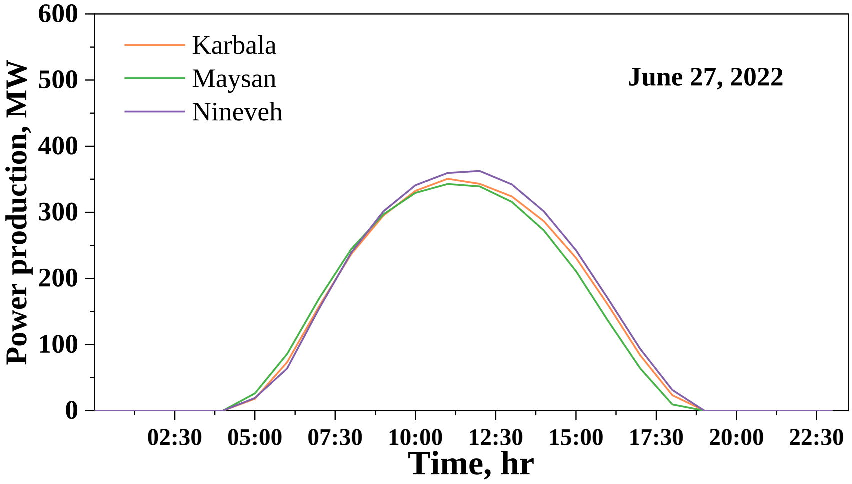

Figure 7. Daily power generation in the examined cities on June 27, 2022

Table 6 illustrates the daily average energy production, revealing that Nineveh emerged as the leading city in daily energy production on that particular day. Conversely, Maysan exhibited the lowest daily output.

Table 6: Daily average energy production in examined cities on June 27, 2022

City	Energy (GWh)
Karbala	3.04
Maysan	2.96
Nineveh	3.15

Tracking variations in solar irradiance (sunlight intensity) across a year, Figure 8 shows the seasonal variations in solar energy potential for a photovoltaic system. These variances directly impact the system's levels of power generation. According to the graph, March is the month of the greatest generation. Karbala achieves an astounding average monthly monthly energy output of 99.58 GWh on sunny days. On the other hand, Nineveh recorded the lowest production in the same month at 80.18 GWh. In addition, January saw a decline in production since there were fewer daylight hours. Karbala's production averages 71.78 GWh at this time, while Maysan's output falls even lower to 61.24 GWh. These variations in solar energy potential demonstrate how crucial it is to consider seasonal variations and meteorological variables when evaluating the performance of PV systems in different regions.

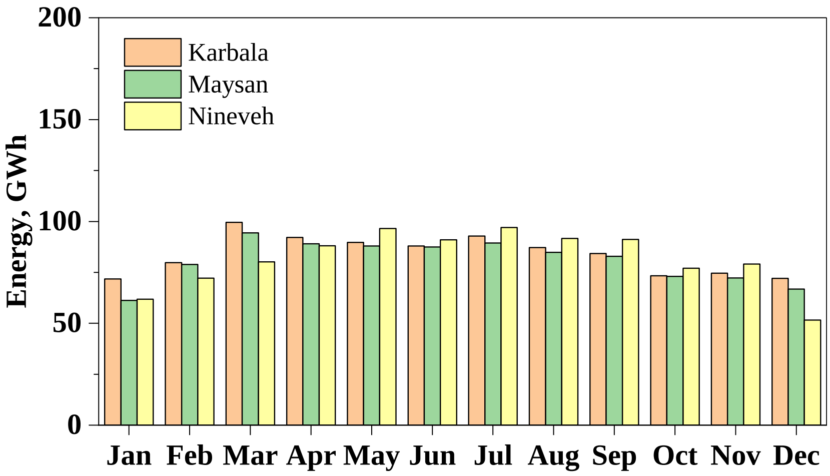

Figure 8. The monthly average of electricity production in 2022 for the cities analyzed

Table 7 provides the yearly production information for the cities that are the subject of the investigation. Karbala emerges as the most prosperous city when considering the larger picture of annual production. Their PV systems produced an astounding amount of power annually, on average. This achievement becomes even more remarkable when considering their comparatively lower power cost. On the other hand, the Maysan had trouble producing energy. The city's power cost was the highest among all the towns with the lowest yearly output. Efficiency and cost-effectiveness are crucial in producing renewable energy, as this difference in production and cost output is clearly shown.

Table 7: Annual energy production with LCOE is used to analyze cities

City	Energy (GWh)	LCOE ($/GWh)
Karbala	1005.21	5,010
Maysan	968.24	5,200
Nineveh	977.22	5,150

3.2 Hydrogen production

This section delves further into the three cities' daily hydrogen production capacities. On June 27, 2022, a typical summer day, Figure 9 and Table 8 give specific insights into the daily hydrogen production capacity of Karbala, Maysan, and Nineveh. This analysis aims to shed light on the efficacy and efficiency of PV green hydrogen generation, particularly emphasizing the hydrogen produced by PEM electrolyzers running on renewable energy sources s such as PV systems. With an average daily output of 35,551 kg, Nineveh is a prominent city in hydrogen production, demonstrating its substantial contribution to green hydrogen generation. On the other hand, Maysan's production rates, at 34,727 kg per day, are significantly lower. The warmer months see the highest point, especially in July and August. The extended daylight hours and increased solar irradiation during the summer are to blame for this rise in output. Furthermore, the daily pattern indicates a significant increase in hydrogen output from 8:30 AM to 5:00 PM, which coincides with the time of maximum solar energy availability, underscoring the impact of solar energy patterns on hydrogen production throughout the day.

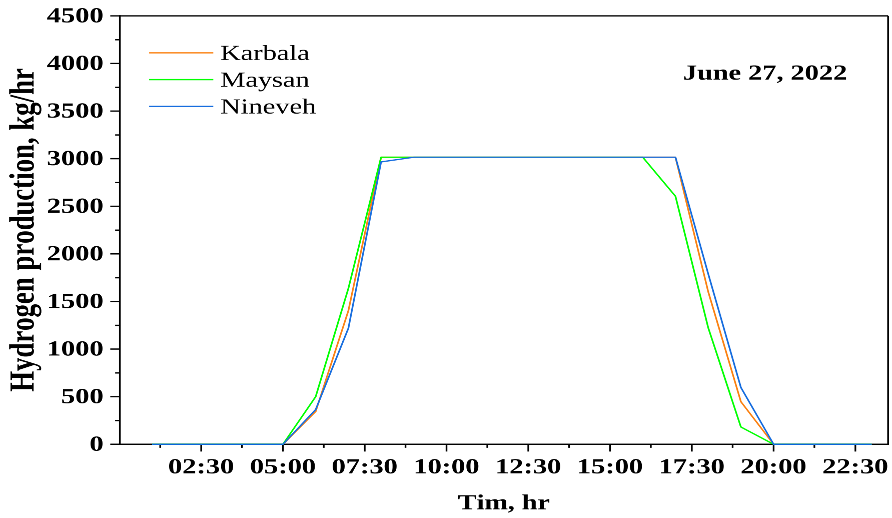

Figure 9. Daily hydrogen production for the analyzed cities on June 27, 2022

Table 8: Daily average hydrogen production for three investigated cities on June 27, 2022

City	Hydrogen production (kg)
Karbala	35,419
Maysan	34,727
Nineveh	35,551

Figure 10 thoroughly examines the monthly hydrogen output in three distinct urban areas throughout twelve months. The differences in hydrogen production efficiency are emphasized and are affected by the seasonal availability of solar resources. The findings suggest that PV systems can boost hydrogen production in months with more sunlight and cooler temperatures. In July, Nineveh saw its highest hydrogen production of 1,048,807.9 kg, demonstrating a clear link between sunlight exposure, longer daylight hours, and the effectiveness of PV systems. On the other hand, Maysan generated the least hydrogen at 1,021,254.4 kg during the same month due to the hot temperature of 43 °C, causing a decrease in power production by the PV array. In contrast, hydrogen production facilities in every city experienced a decline in output during December because of reduced electricity generation from solar PV panels. The main reason for this decrease was seasonal influences such as more clouds and less daylight, which reduced the sunlight needed for solar power generation. Therefore, the effectiveness of hydrogen production systems declined, resulting in a significant decrease in total output compared to times of higher sunlight. Among all cities, Nineveh saw the lowest production rate in December, being particularly affected. The facility could only produce 599,579.1 kg of hydrogen that month, underscoring the significant influence of decreased solar energy. was recorded in July in Nineveh, for example, demonstrating a clear correlation between PV system performance and sunshine exposure and longer days.

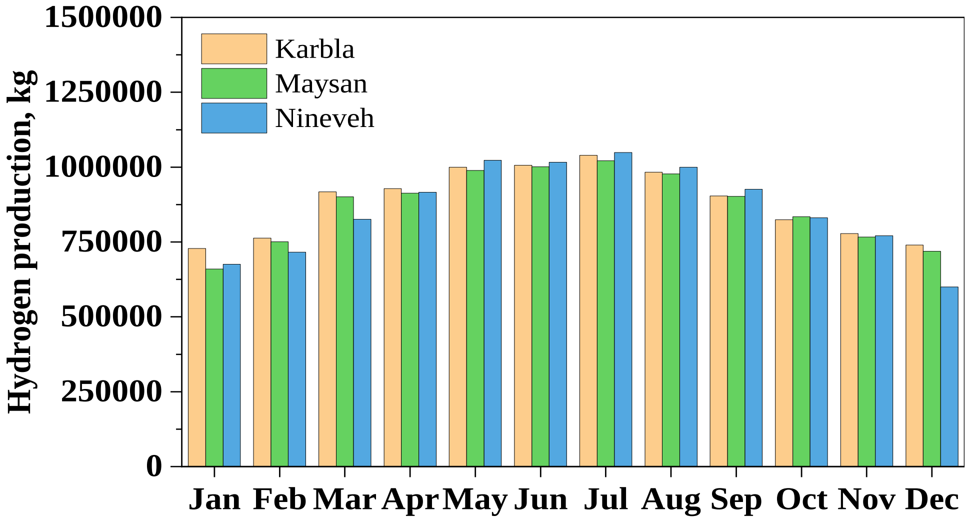

Figure 10. Monthly hydrogen production trends across examined cities

Figure 11 shows the variations in the yearly hydrogen production across the three Iraqi towns of Nineveh, Maysan, and Karbala. Karbala is the top producer, with an annual output of 10,610,981 kg of hydrogen, closely followed by Maysan with 10,435,895 kg. Nineveh is in the rear with an output of 10,348,375 kg.

Karbala's remarkable ability to generate power directly results from its optimal climatic circumstances, contributing to its fantastic hydrogen output. Because of its high solar irradiance, the city has year-round access to plenty of sunlight. Karbala also has pleasant ambient temperatures, which support effective solar energy conversion. Simultaneously, Nineveh has obstacles that prevent it from producing hydrogen. Of the three, the city struggles with the lowest sun irradiation despite experiencing low ambient temperatures. PV panels are adversely affected by the low solar radiation, which reduces the amount of power generated. As a result, Nineveh's hydrogen production is negatively impacted.

Through meticulously evaluating these variables, Iraq may enhance its approach to implementing hydrogen refueling stations and guarantee a more equitable and sustainable hydrogen generation throughout the nation.

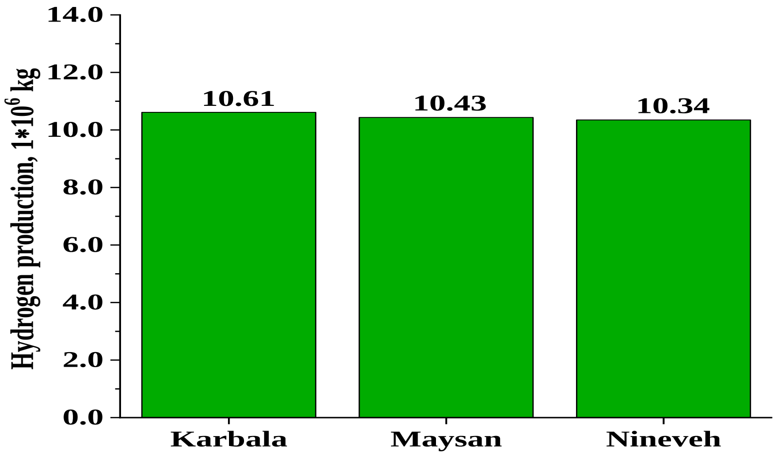

Figure 11. Yearly hydrogen generation in examined cities

3.3 Hydrogen production expense

One of the most critical factors in analyzing off-site HRS systems is the cost of producing hydrogen itself. This analysis considers a projected system lifespan of 28 years. To assess economic feasibility, NPC analysis was employed, with specific equations (Equations (9)-(11)) to evaluate critical financial indicators. Additionally, Equation (12) was used to estimate hydrogen production costs.

Figure 12 delves further into the economics of producing green hydrogen in the three selected cities. The outcome of this analysis will determine whether off-site HRS installation is feasible. It is essential to look at both the technical and economic elements, as Table 3 makes clear. Strategic planning and the efficient deployment of HRS solutions depend on it because it enables a more thorough knowledge of the cost-effectiveness of specific system components. Even with comparable solar-powered hydrogen production systems, the study found noteworthy differences in the costs of producing hydrogen across the cities. The prices in Nineveh were the highest at $2.94/kg and the lowest at $2.75/kg in Karbala. $372.77 million was determined to be the project's NPC. through examining the LCOE, NPC, and COH, Karbala was determined to be the most advantageous place for installing a solar energy system to produce green hydrogen for off-site HRS. Of the places examined, this one had the lowest cost of producing hydrogen. Due to its status as the most economical choice, Karbala is a strong contender for constructing a green hydrogen factory. This result emphasizes the city's ability to take the lead in implementing sustainable energy initiatives.

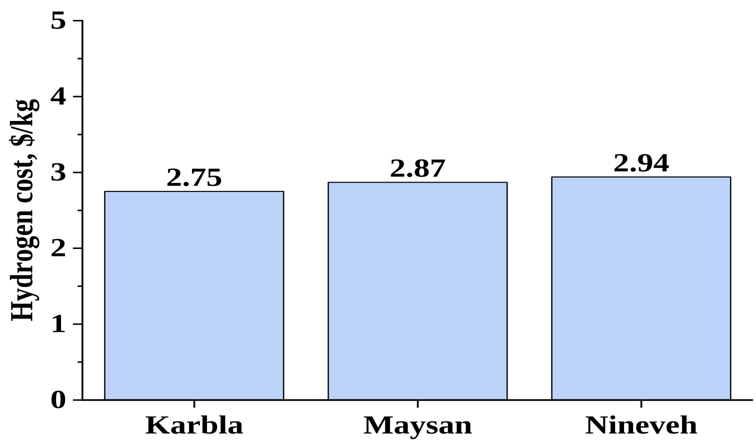

Figure 12. Cost analysis of green hydrogen production for OSHRS in selected cities

Figure 13 reveals significant differences in the cost of producing green hydrogen across various countries. This demonstrates how unevenly the generation of affordable green hydrogen has developed over the world. Due to its plentiful sunshine, which renders solar energy, a crucial component of green hydrogen, extremely inexpensive, China has the most competitive pricing, coming in at $3.45/kg. Whereas the cost of green hydrogen is lower in the UK ($5.66/kg) and Australia ($6.1/kg), this difference may be due to lower levels of renewable energy in those nations, less supportive government regulations, or more extraordinary operating expenses. The present $2.75/kg price in Iraq indicates a budding green hydrogen sector. Germany, South Africa, and Iraq are classified as having mid-range pricing [62–66]. Early-stage infrastructure and technology contribute to this cost, signaling ample room for improvement as these aspects mature. These findings underscore the critical role of local factors such as renewable resources, hydrogen technology investment, and government policies in shaping the economics of green hydrogen production.

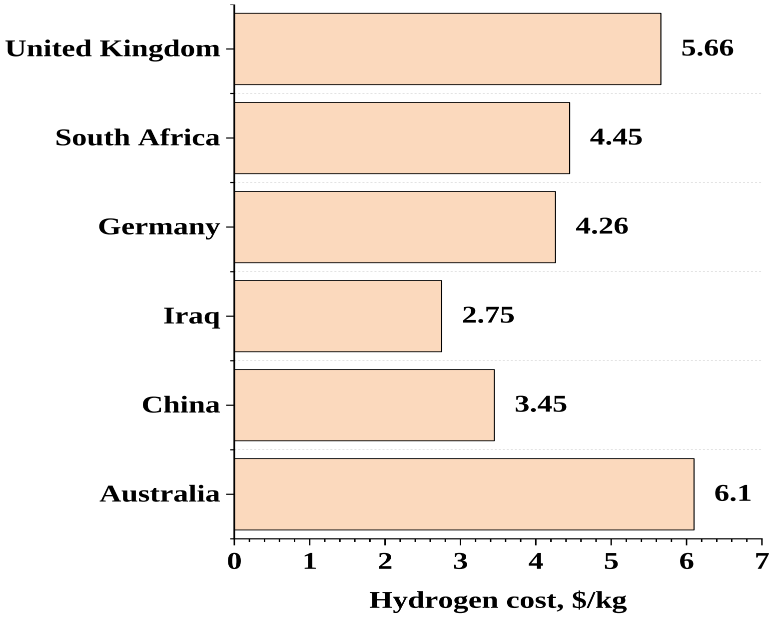

Figure 13. Analysis of green hydrogen cost of production across various nations

3.4 Sensitivity analysis

Sensitivity analysis is performed in HOMER Pro software to prove the permissible power capacity deficiency in supplying demand to the electrolyzer. An analysis of all cities considers the effect of the cost of electricity production and the photovoltaic system on the other parameters. The primary objective is to maximize hydrogen production and minimize the critical parameters of NPC, LCOE, and COH. Moreover, capacity of 900 MWp was selected at random, while the 558 MWp capacity was determined using the multi-objective optimization NSGA-II method. Thus, the capacity shortage can be evaluated at 0%, 15%, 25%, and 40%, respectively. The electrolyzer load of 157.5 MWp is the second parameter, the drug production of which varies depending on the supplied power. To evaluate the effect of the size of photovoltaic plants on the costs incurred when there is a capacity shortage.

Table 9 shows the sensitivity analysis results, with the three cases varying in equipment sizes. When capacity shortage increases, hydrogen production and NPC decrease as LCOE and COH rise. It became less as the capacity shortage decreased. As capacity shortage was at 0%, it was discovered that the COH was lowest at a capacity of 558 MWp. This facility had the lowest LCOE and COH. The reason is that the surplus electricity generated was at its lowest level, with sufficient electrical load. Choosing capacities higher than 558 MWp increases hydrogen production and excess electricity, causing an increase in LCOE, COH, and NPC. Although the NPC is reduced when a capacity shortage occurs, the close connection between hydrogen production and the shortage of electrical supplies to the electrolyzer reduces production and, thus, increases LCOE and COH.

Table 9: Sensitivity analysis on equipment capacity for the PV array in three cities

City	Capacity Shortage (%)	PV (MWp)	LCOE ($/MWh)	NPC ($)	COH ($/kg)	Hydrogen (Kg/year)
Karbala	0	900	6.73	414.5 M	3.59	11,309,072
	15		6.47	400.2 M	3.24	11,095,837
	25		5.74	388.3 M	3.07	10,921,545
	40		5.12	370.1 M	2.83	10,545,389
	0	558	5.01	372.7 M	2.75	10,610,981
	15		5.26	358.9 M	2.89	10,252,869
	25		5.39	346.3 M	3.10	9,965,605
	40		5.65	339.8 M	3.48	9,355,714
Maysan	0	900	6.92	414.5 M	3.73	11,205,994
	15		6.65	400.2 M	3.42	10,970,122
	25		5.91	388.3 M	3.19	10,776.135
	40		5.29	370.1 M	2.95	10,372,309
	0	558	5.20	372.7 M	2.87	10,435,895
	15		5.44	358.9 M	3.01	10,094,589
	25		5.62	346.3 M	3.24	9,151,689
	40		5.84	339.8 M	3.64	8,776,599
Nineveh	0	900	6.87	414.5 M	3.81	11,103,721
	15		6.58	400.2 M	3.50	10,862,937
	25		5.84	388.3 M	3.27	10,674,223
	40		5.23	370.1 M	3.02	10,233,751
	0	558	5.15	372.7 M	2.94	10,348,375
	15		5.39	358.9 M	3.08	9,990,855
	25		5.56	346.3 M	3.32	9,119,841
	40		5.77	339.8 M	3.73	8,677,359

4. Conclusions

This study conducts a technical and economic assessment of off-site HRS using HOMER Pro software to evaluate the generation of green hydrogen from renewable sources. The research involves a multi-objective optimization NSGA-II of the photovoltaic array through MATLAB software, aiming to meet the electrolyzer power requirements efficiently. Hydrogen refueling systems have complex operational constraints, necessitating a tailored operational and control strategy. The model emulates a real-world HRS system with PV solar panels and PEM electrolysis technology.

The hydrogen produced by the PEM electrolyzer meets the stringent requirements for hydrogen fuel cell vehicles, adhering to the ISO 14687:2-2012 and SAE J2719 standards. From a technical and economic perspective, integrating PV panels and electrolyzers facilitates cost-effective electricity and hydrogen production. However, the system power access is confined to daylight hours, which results in intermittent operation of the electrolyzer and fluctuations in production rates and efficiency due to variable solar energy availability. The system configuration includes 558 MWp of PV solar panels, a 157.5 MWp PEM electrolyzer, 14,400 m^3 hydrogen storage tanks, and a 170 MWp converter, spanning an operational forecast from 2022 to 2050. Sensitivity analysis was used to evaluate the efficacy and resilience of the system. The variation was examined for a capacity shortage of PV power. Every city was compared to each other. The findings of the article, taking into account the sensitivity analysis, may be summed up as follows:

- For Karbala city, the amount of hydrogen production was 10,610,981 kg. The COH was $2.75/kg and the LCOE at 0% capacity shortage of 558 MWp was $5,010/GWh.
- For Maysan City, the amount of hydrogen produced was 10,435,895 kg. The COH was $2.87/kg, and the LCOE at 0% capacity shortage of 558 MWp was $5,200/GWh.
- For Nineveh City, the amount of hydrogen production was 10,348,375 kg. The COH was $2.94/kg and the LCOE at 0% capacity shortage of 558 MWp was $5,150/GWh.

The results identify Karbala City as the ideal location for hydrogen production due to its abundant sunshine and moderate temperatures, which are optimal conditions for solar panels to function efficiently and generate maximum electricity for the electrolysis process. In contrast, Nineveh's low temperatures and insufficient sunlight diminish its potential for hydrogen production. The findings underscore the advantages of utilizing renewable energy systems for hydrogen production, presenting a compelling option for supplying HRS across Iraq. The NPC was estimated at $372.77 million. This study aims to provide policymakers with essential information for establishing a green hydrogen production facility that can serve HRS throughout Iraq, suggesting that future research should focus on planning HRS distribution and analyzing hydrogen transportation costs.

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Abbreviations

AC Alternative Current
DC Direct Current
COH Cost of hydrogen
FC Fuel cell
FCEV Fuel cell electric vehicle
HRS Hydrogen refueling station
LCOE Livelized cost of energy
NPC Net percent cost
NOCT Nominal Operation Cell Temperature
O&M Operation and Maintenance cost
AWE Alkaline water electrolyzer
PEM Proton Exchange Membrane
PEME Proton Exchange Membrane Electrolyzer
PV Photovoltaic
PV/T Photovoltaic/Thermal
RES Renewable energy sources
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
PV PV reduction factor
g Polytrophic coefficient
h_f Faraday efficiency
H_t Amount of hydrogen produced per year in kilograms.
i Discount rate
I Initial investment cost
I_e Electrolyser current
M_C 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
T_A	Ambient temperature (ºC)
$T_{A, NOCT}$	Temperature at which NOCT (25 ºC)
T_C	Temperature of the PV (ºC)
$T_{C, NOCT}$	Cell temperature at which NOCT
T_s	Temperature of the PV under standard test conditions (25 ºC)
U_L	Coefficient of heat transfer to the surrounding
$V_{h\ tan\ K}$	Volume of the hydrogen tank
Y_{PV}	Nominal capacity of PV
α_P	Temperature coefficient of power (%/ºC)
η_C	Efficiency of PV
$\eta_{h\ tank}$	Efficiency of hydrogen tank
γ	PV module azimuth angle
β	PV module tilt angle