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Massive Green Hydrogen Production Using Solar and Wind Energy: Comparison between Europe and the Middle East

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Abstract: This comparative study examines the potential for green hydrogen production in Europe and the Middle East, leveraging 3MWp solar and wind power plants. Experimental weather data from 2022 inform the selection of two representative cities, namely Krakow, Poland (Europe), and Diyala, Iraq (Middle East). These cities are chosen as industrial–residential zones, representing the respective regions' characteristics. The research optimizes an alkaline water electrolyzer capacity in juxtaposition with the aforementioned power plants to maximize the green hydrogen output. Economic and environmental factors integral to green hydrogen production are assessed to identify the region offering the most advantageous conditions. The analysis reveals that the Middle East holds superior potential for green hydrogen production compared to Europe, attributed to a higher prevalence of solar and wind resources, coupled with reduced land and labor costs. Hydrogen production costs in Europe are found to range between USD 9.88 and USD 14.31 per kilogram, in contrast to the Middle East, where costs span from USD 6.54 to USD 12.66 per kilogram. Consequently, the Middle East emerges as a more feasible region for green hydrogen production, with the potential to curtail emissions, enhance air quality, and bolster energy security. The research findings highlight the advantages of the Middle East industrial–residential zone 'Diyala' and Europe industrial–residential zone 'Krakow' in terms of their potential for green hydrogen production.

Keywords: green hydrogen production; solar and wind power plants; Europe and Middle East comparison; alkaline water electrolyzer; comparative regional analysis

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1. Introduction

The world energy systems are in a state of transition. As we continue to grapple with the impacts of climate change and the urgent need to reduce greenhouse gas emissions, alternative energy sources have become increasingly important. One such promising alternative is green hydrogen, which is an emerging technology that uses renewable energy sources, such as solar and wind energy and water, to produce hydrogen via the electrolysis of water without releasing any additional carbon dioxide or harmful gases into the atmosphere. Green hydrogen is a potential solution to many environmental challenges associated with traditional hydrogen production, which is highly dependent on fossil fuels [1]. Green hydrogen production has the potential to reduce greenhouse gas emissions, improve air quality, and reduce dependence on fossil fuels. In addition, green hydrogen could also be used to store and transport energy, providing a more mobile and flexible energy source. This technology is still in its early stages, but its potential is very promising [2,3].

The decarbonization targets set by the Conference of the Parties (COP) are achievable with the production of green hydrogen. However, the renewable production approach is less cost-effective than traditional fossil fuel production [4]. Green hydrogen production from electrolysis is a rapidly growing technology that can be used to create large-scale hydrogen production from renewable energy sources. This technology uses electricity from renewable sources to split water molecules into hydrogen and oxygen. Then, the hydrogen is stored for later use. Generated hydrogen can be used in various ways, including fuel cells, as a transportation fuel, or as a product for many industrial processes. It can reduce the emissions of many of these processes, providing a more sustainable energy source.

Previous studies on the production of massive amounts of green hydrogen have demonstrated that the production of green hydrogen can be significantly increased through renewable energy sources such as solar, wind, and hydropower [5]. Studies have also shown that electrolysis is the most efficient process for the production of green hydrogen [6]. Furthermore, using green hydrogen for energy storage has been identified as a critical factor in a comprehensive energy transition strategy [7]. In addition, the use of green hydrogen to decarbonize the industrial sector has been highlighted as a significant opportunity to reduce emissions and promote economic growth. Developing a green hydrogen infrastructure and integrating hydrogen into the gas network are essential steps for successful energy transitioning (ET) [8].

A review article on massive green hydrogen production presented by Hoisang and Sakaushi [9] discusses important factors for developing electrodes that can be used in the production of green hydrogen through water electrolysis. The authors highlight the need for dimensionally stable electrodes that can operate efficiently and durably at large scales. The article provides insights into the criteria that should be considered when designing such electrodes. The performance of water electrolysis systems based on energy-combination solar photovoltaic modules (PV) and wind turbines (WT) for massive production of green hydrogen was explored by Mazzeo et al. [10]. An interactive design generated a comprehensive dataset representing hybrid hydrogen production at different sites. The results indicated that the yearly and monthly averages and the overall quantity of green hydrogen generation calculated for several sites worldwide are very different. Guerra et al. [11] conducted a conceptual investigation of the electrolysis-based production of hydrogen.

In the assessment, a sensitivity analysis of key factors relevant to the electrolysis plant capacity of the order of megawatts has been conducted. The results of the optimization approach revealed that a 165 MW stack was the most suitable size for an electrolyzer stack, as determined by analyzing the implications of the operating cost and equity investment. The authors show that hydrogen generation in Chile would be technologically possible, profitable, and environmentally beneficial. Furthermore, the sensitivity analysis indicated that the electrical energy price is the primary variable influencing the hydrogen generation cost.

Coming down to Poland, green hydrogen production in Poland is gaining momentum as the country aims to decarbonize its energy sector. With abundant renewable resources like wind and solar, Poland has the potential to become a major player in green hydrogen. Investments are being made in electrolysis technologies to harness renewable energy for hydrogen production. Komorowska et al. [12], in their work, provided a detailed analysis of the LCOH (levelized cost of hydrogen) considering the geographical coordinates of 23 planned offshore wind farms in the Baltic Sea. Furthermore, a comparison was made on hydrogen production costs from offshore and onshore wind parks in 2030 and 2050. The results showed that hydrogen from offshore wind could range between EUR 3.60 and EUR 3.71/kg H_2 in 2030, whereas in 2050, it may range from EUR 2.05 to EUR 2.15/kg H_2.

Franco et al. [13] explored the feasibility of using wind power to produce hydrogen offshore. The study focused on analyzing different offloading pathways for this process, considering both energy and economic factors. The study assesses the efficiency and costs associated with various hydrogen production methods and transportation options. The findings of the study aim to provide valuable insights for decision-makers and stakeholders interested in offshore hydrogen production using wind power. Ulleberg and Hancke [14] focused on assessing the feasibility and economic viability of small-scale hydrogen supply systems for zero-emission transportation in Norway. The study involves conducting techno-economic calculations to evaluate the costs and benefits associated with implementing such systems. The study aims to provide valuable insights into the practicality and potential of using hydrogen as a clean energy source for transportation in Norway, considering both the technical and economic aspects of the infrastructure required. Bhandari and Shah [15] conducts a techno-economic evaluation of decentralized hydrogen production in Germany. The study focuses on assessing the feasibility and economic viability of producing hydrogen in smaller, decentralized facilities. The study analyzed the costs, energy requirements, and overall efficiency of different hydrogen production technologies. The findings provide valuable insights into the potential of decentralized hydrogen production in Germany, considering both the technical and economic aspects of the process. Minutillo et al. [16] focused on assessing the levelized cost of hydrogen production in refueling stations with on-site water electrolysis in Italy. The study analyzed the economic viability of producing hydrogen through this method and considered factors such as capital costs, operating costs, electricity prices, and hydrogen demand. The outcomes provide insight into the cost competitiveness and feasibility of on-site hydrogen production via water electrolysis in the context of the Italian scenario.

Furthermore, analysis of the triangular probability distribution of individual variables suggests that the cost would have been positive 75% of the time at a given confidence level. Milani et al. [17] outlined various hydrogen production pathways and possible scenarios for integrating renewable energy systems, highlighting their potential and capabilities. Their investigation centers on practical and economic integration alternatives in Australia, which could steadily guide the maturation of the hydrogen economy towards mass production for local and international markets. The authors compare techno-economics and performance analysis of diverse production-to-utilization routes, aiming to identify key players and significant challenges and opportunities for solar and wind hydrogen fuel cells to effectively penetrate and progress in the Australian electricity sector. Mosca et al. [18] designed a large-scale scheme for green hydrogen production using transmembrane processors. Various processors and degrees of incorporation for membranes and catalysts were taken into account. They utilized the Aspen tool to evaluate the heat and material balance of the system, its efficiency, and hydrogen production. An economic evaluation was also included to assess the financial feasibility of the proposed method. Lee et al. [19] conducted a techno-economic study for green hydrogen production based on seasonal solar radiation data for single and hybrid systems built as an alkaline electrolyzer and an energy storage system. Their findings suggested that the hybrid power system unit hydrogen production costs were roughly USD 6.55/kg H_2 for a single system. Moreover, the results indicated a preference for the hybrid system when the battery cost is less than USD 78.2/kWh.

In another study, Lee et al. [20] explored a suitable scenario where the electrolyzer could be cost-competitive for hydrogen based on various economic factors, including the average electricity price. Their results indicated that electricity cost is the most influential economic determinant for the hydrogen cost. Weidner et al. [21] examined several methods to produce hydrogen at a rate of 500 Mt/year. Their results suggested that the impact of expected production rates on environmental issues exceeds the planetary limitation by three to five times, with green hydrogen from wind energy remaining under the limit. In addition to the mentioned literature, Table 1 provides a summary of several other studies examining massive hydrogen production in different countries.

Table 1. Literature on massive green hydrogen production.

Country	Target	Investigated Project Details	Evolution Span [Year]	Ref.
US	Green and Blue Hydrogen contextualization	Cost evaluation of alternative options for mitigating climate change	2050	[22]
Germany	Green and blue hydrogen production	Becomes renewable based on 2030 and 2050 projections	2030, 2050	[23]
UK	Green and Blue Hydrogen contextualization	Cost evaluation of alternative options to mitigate climate change and country energy consumption.	-	[24]
Spain	Designed for green hydrogen production	Wind-altering efficiency increases PV efficiency for future massive green hydrogen production.	2030, 2050	[25]
Canada	Green and Blue Hydrogen contextualization	Cost–benefit analysis of solar and fossil sources for climate mitigation and alternative fuels.		[26]
Spain	Designed for green hydrogen production	Reduced investment costs and an increase in renewable energy adoption until 2050.	2050	[27]
Switzerland	Green and Blue Hydrogen contextualization	Various hydrogen production methods with commercialization implications, and energy policy by using green hydrogen.	2030	[28]
Netherlands	Designed for green hydrogen production	Improvement in photovoltaic efficiency and estimation of low future hydrogen costs.	-	[29]
US	Designed for green hydrogen production	Different levels of capture efficiency, leakage rate, and time horizon are compared for green and blue hydrogen.	-	[30]
Germany	Designed for green hydrogen production	Green hydrogen analysis at changing hydrocarbon emission rates for various methods for low green hydrogen cost.	-	[31]
UK	Green and Blue Hydrogen contextualization	Green and blue hydrogen with an evaluation of carbon saved when oil and gas is replaced.	-	[32]
Germany	Designed for green hydrogen production	Green hydrogen analysis at changing hydrocarbon emission rates for various methods.	2030, 2050	[33]

Green hydrogen can greatly contribute to significant emission reductions across various sectors. For instance, in the realm of transportation, green hydrogen can fuel vehicles and ships, effectively replacing fossil fuels and diminishing the carbon footprint of these sectors. Industries can also leverage green hydrogen as a substitute for fossil fuels in processes such as steel and chemical production, as well as cement manufacturing [34,35]. The potential of green hydrogen as a means of decarbonization is remarkable. It can significantly cut greenhouse gas emissions and replace fossil fuels across diverse applications, thus contributing substantially to climate change mitigation. As investment in green hydrogen production and technology escalates, it will further reduce the cost of green hydrogen production, rendering it increasingly accessible and affordable [36]. Green hydrogen production is a pivotal step towards a decarbonized economy and, therefore, warrants comprehensive embrace and support for humanity to effectively combat climate change [37].

Megaprojects for green hydrogen production are currently being developed, with a goal to satiate escalating global demand [38]. Such initiatives frequently employ renewable energy sources like solar or wind energy, along with electrolysis and other innovative technologies, to manufacture green hydrogen. The hydrogen thus generated finds applications in various sectors, such as transportation, heating, electricity generation, and industrial processes [39,40]. These megaprojects not only facilitate a shift away from fossil fuel reliance towards a cleaner, more sustainable energy future but also offer cost-effectiveness, potentially invigorating economic growth [41]. In addition, green hydrogen presents itself as a potential global energy source, thereby ensuring energy security for nations worldwide.

While green hydrogen production megaprojects promise a plethora of advantages, numerous hurdles persist. These encompass the financial implications of the projects, the requisite technology for green hydrogen generation, and the infrastructure essential for hydrogen transportation and storage [42,43]. There are also apprehensions surrounding the safety and security measures of hydrogen production and storage installations. However, with suitable investment backing, these initiatives can facilitate a reduction in fossil fuel reliance, spawn employment opportunities, and stimulate economic advancement [44]. Moreover, they can aid in establishing a cleaner and more secure energy future, bypassing the environmental repercussions associated with conventional fossil fuels. A synopsis of large-scale global green hydrogen production initiatives is provided in Table 2.

Table 2. Global massive green hydrogen projects [45–49].

Project Name	Project Site	Project Description and Capacity
North Sea Wind Power Hub	The Netherlands, Denmark, and Germany	This massive project uses offshore WT and converts energy into green hydrogen. Renewable energy hubs can produce up to 70 Mt of green hydrogen, with an estimated cost of EUR 47 billion.
South Korean Green Hydrogen Initiative	South Korea	The major green hydrogen initiative is to reduce its dependence on fossil fuels and create a clean energy economy. The project is expected to cost USD 90 billion and produce 15 Mt of green hydrogen annually by 2030.
Vattenfall Hydrogen	Sweden	This EUR 1 billion project will produce 2.5 Mt of green hydrogen in Sweden by 2023. It will produce green hydrogen from wind and solar energy for industrial applications, transport, and energy storage.
Gigastack Project	UK	The project is a collaboration between the UK and Japan for a 5 GWpa electrolyzer to produce green hydrogen worth GBP 1 billion by 2025. The project will produce green hydrogen by combining offshore wind energy, carbon capture and storage technology.
Hydrogen Energy Supply Chain	Japan	The project is a collaboration between Japan and Australia and aims for a 10 GW electrolyzer capacity to generate green hydrogen for 1.5 trillion by 2030. The project will produce green hydrogen from renewable energy sources and will be used for industrial applications, transport, and energy storage.

Table 2. *Cont.*

Project Name	Project Site	Project Description and Capacity
German Hydrogen Strategy	Germany	Germany has announced a hydrogen strategy to produce 5 Mt of green hydrogen by 2030 for EUR 5.5 billion. The project will produce green hydrogen from wind and solar energy and will be used for industrial applications, transport, and energy storage.
Power-to-X	Austria	The project is a collaboration between Austria and Switzerland and aims to produce 3 Mt of green hydrogen for EUR 2 billion by 2027. The project will produce green hydrogen from wind and solar energy and be used as a fuel or energy carrier for energy storage, transport, and industrial applications.
Dutch Green Hydrogen Corridor	Netherlands	The project is a collaboration between the Netherlands and Belgium and aims to produce 5 Mt of green hydrogen for EUR 2 billion by 2027. The project will produce green hydrogen from wind and solar energy and will be used for industrial applications, transport, and storage.
French Hydrogen Valley	France	The project is a collaboration between France and Germany and aims to produce 4 Mt of green hydrogen for EUR 6 billion by 2030. The project will produce green hydrogen from wind and solar energy and will be used for industrial applications and energy storage.
Hydrogen Valley	Norway	The project is a collaboration between Norway and Sweden and aims to produce 2 Mt of green hydrogen for EUR 1.5 billion by 2027. The project will produce green hydrogen from wind and solar energy and will be used for industrial applications, transport, and storage.

While there exists significant literature studying the potential of green hydrogen production via renewable sources, a clear research gap persists in a number of areas that our study aims to address.

- Firstly, there is limited research investigating a direct comparison of green hydrogen production potentials between Europe and the Middle East using both solar and wind energy. This gap is particularly noticeable when it comes to studies based on empirical weather data for specific cities representing these regions. Our study fills this gap by presenting a comparative analysis for Krakow, Poland, and Diyala, Iraq, grounded in experimental weather data from 2022.
- Secondly, most of the existing studies on green hydrogen production do not holistically integrate economic and environmental factors in their analyses. They often neglect to include cost parameters such as labor and land costs, which can significantly influence the feasibility of large-scale hydrogen production. Our study incorporates these economic factors alongside environmental considerations, offering a more comprehensive and nuanced understanding of the hydrogen production landscape in the selected regions.
- Thirdly, the research addressing the optimization of alkaline water electrolyzer capacity, specifically in relation to 3 MWp solar and wind power plants, is sparse. Our study contributes to this underexplored area by optimizing the electrolyzer capacity to maximize the green hydrogen output, thus adding a layer of technical specificity to our comparative analysis.

Therefore, our research contributes significantly to the existing body of knowledge by bridging these identified gaps, ultimately aiding the informed decision-making process regarding the massive production of green hydrogen in diverse geographical and economic contexts.

This study aims to compare the production of green hydrogen using solar and wind energy between Europe (Poland case study) and the Middle East (Iraq case study) to facilitate the implementation of massive green hydrogen production in the region and provide a valuable reference for other regions of the world. This work aims to identify and compare the advantages and challenges of green hydrogen production from solar and wind resources in Europe and the Middle East. The region is abundant in solar and wind resources and is well-positioned to become a large-scale producer of green hydrogen. By analyzing the potential for green hydrogen production in the region, this work will provide valuable information to policymakers and stakeholders looking to develop this clean energy source. This covers various topics, such as the infrastructure, cost, and technical feasibility of green hydrogen production in both regions. The study would also explore the potential for green hydrogen export from the Middle East to Europe. Additionally, it will help identify the best strategies for efficient and effective deployment of green hydrogen production in the region. This type of research has yet to be conducted and would be a valuable contribution to the literature highlighting the potential of green hydrogen in two investigated regions.

The novelty of the research lies in the following aspects:

1. Geographical focus: this is the first study to specifically compare green hydrogen production between Krakow, Poland, and Diyala, Iraq, representing Europe and the Middle East, respectively. This particular comparison illuminates the diverse challenges and opportunities across these two regions, thus contributing to a more nuanced understanding of the global green hydrogen landscape.
2. Dual-energy source utilization: while some studies have explored solar or wind energy for green hydrogen production individually, this research combines these two renewable sources, aligning with the emerging concept of hybrid renewable energy systems. This approach acknowledges the intermittent nature of both solar and wind energy and maximizes the reliability of the power supply for hydrogen production.
3. Detailed economic analysis: the study delves into the detailed economic factors influencing green hydrogen production in the two selected regions, which provided a comprehensive cost breakdown, ranging from the cost of the renewable energy infrastructure to the labor costs. These insights will be valuable for policymakers and investors in understanding the economic viability of green hydrogen production in these regions.
4. Environmental implication assessment: the research also quantifies the potential environmental benefits of green hydrogen production. These findings underscore the environmental sustainability of green hydrogen and highlight its role in addressing global climate change.

2. Methodology

2.1. Materials and Methods

2.1.1. Industrial–Residential Zones

The Krakow industrial–residential zone is located in the city of Krakow, Poland, situated at approximately 50.0647° N latitude and 19.9445° E longitude. Krakow is a historic city in southern Poland and is known for its cultural significance. The industrial–residential zone benefits from its location along the banks of the Vistula River, providing access to water resources that can be utilized for various purposes within the zone. The zone operates within the political framework of Poland, governed by local authorities and subject to national and local regulations and policies. External economic indicators, such as international trade policies, foreign investment, global economic trends, and regional economic integration, play a role in shaping the economic environment of Krakow and its industrial–residential zone.

The Diyala industrial–residential zone is located in Diyala Governorate, situated in eastern Iraq. The Governorate is located between approximately 33.7487° N and 44.6230° E in terms of latitude and longitude coordinates. Diyala Governorate is traversed by the Diyala River, a major water source in the region. This river serves as a vital water resource that can be utilized for various purposes within the industrial–residential zone. The politics of the Diyala Governorate are governed by the national and local authorities of Iraq. It operates within the political framework of the country, which includes relevant regulations, policies, and governance structures. Specific details regarding the local political dynamics within the industrial–residential zone are not provided and would require more specific information. External economic indicators that influence the Diyala industrial–residential zone include factors such as regional and global economic trends, foreign investment, and international trade policies. These indicators contribute to shaping the economic landscape within the zone, attracting businesses, and influencing economic development.

Due to measurement and experimental weather data for both sites, in this study, two locations were selected to analyze green hydrogen production using solar and wind resources. Generally, there is growing interest in green hydrogen production in Europe and the Middle East. Both regions have the potential to produce massive quantities of green hydrogen, but there are a few key differences between the two areas that should be considered.

In Europe, green hydrogen production is developing and has been snowballing in recent years. The region has abundant renewable energy resources and is home to some of the largest renewable energy producers in the world, allowing significant green hydrogen production potential. Europe is already making strides toward becoming a leader in the field [5,50].

Green hydrogen production is a relatively new and growing field in the Middle East. The region has some of the world's most abundant renewable energy resources, making it an ideal location for massive green hydrogen production. However, the region also faces some unique challenges, such as a need for energy storage infrastructure and limited access to financing. Furthermore, political instability could be a significant roadblock to the development of green hydrogen production [51,52].

Europe and the Middle East can produce massive amounts of green hydrogen. However, the two regions face different challenges, and it is essential to consider these differences when looking at the potential of green hydrogen production in each area.

2.1.2. Experimental Weather Data

The experimental data were acquired at a high one-minute resolution for 2022 and for industrial–residential zones: Diyala and Krakow revealing various climate conditions. Figure 1 shows the wind speeds from experimental measurements in Krakow and Diyala for 1 March and 1 August. The wind speeds on 1 March were significantly different, with Krakow having an average wind speed of 0.87 m/s and Diyala having an average wind speed of 4.55 m/s. This difference can be attributed to Krakow's temperate climate and having less wind. In contrast, Diyala is semi-arid and has a higher wind speed. On August 01, the wind speed in Krakow and Diyala was significantly different, with Krakow having an average wind speed of 1.25 m/s and Diyala having an average wind speed of 3.41 m/s.

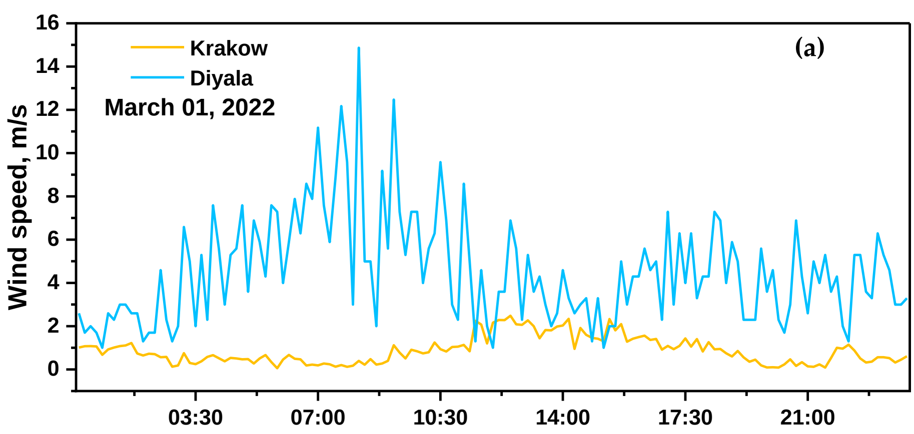

Figure 1. *Cont*.

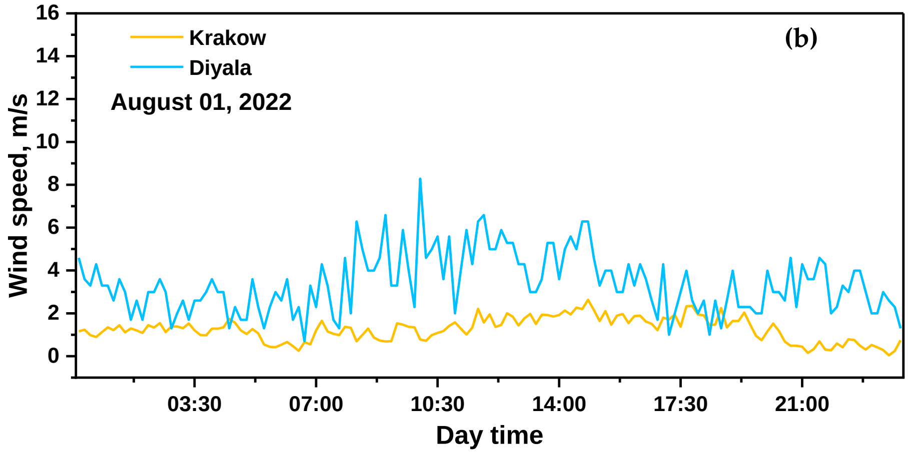

Figure 1. The wind speed from experimental measurements for Krakow and Diyala, results for the days: (**a**) 1 March and (**b**) 1 August of 2022.

Figure 2 shows the daily measured ambient temperature for 1 March and 1 August 2022 for Krakow and Diyala, revealing distinct temperature differences. On 1 March, Krakow's average ambient temperature was 2.1 °C, while Diyala's was equal to 20.5 °C. On August 01, Krakow's average ambient temperature was 21.7 °C, while Diyala's was equal to 42.4 °C. The two cities reveal that Krakow has significantly lower ambient temperatures than Diyala, especially in the winter, which will impact the PV system efficiency.

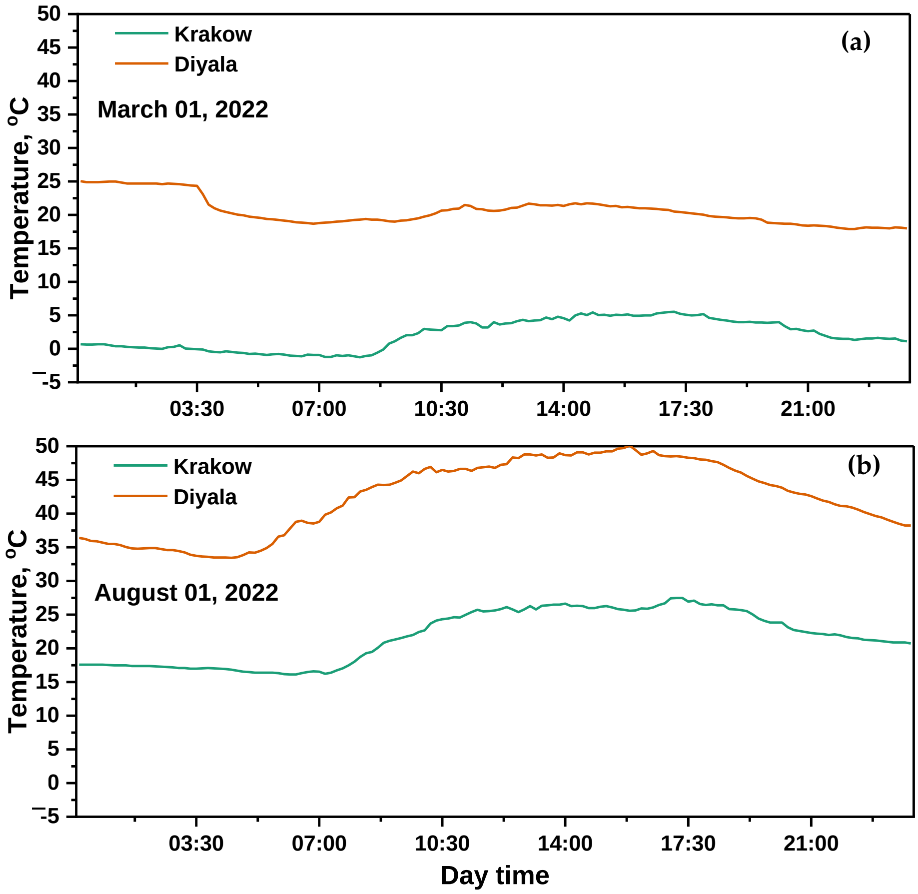

Figure 2. The ambient temperature from experimental measurements for both cities Krakow and Diyala for the days (**a**) 1 March and (**b**) 1 August of 2022.

Figure 3 shows the daily measured solar radiation, in Krakow city, on 1 March 2022. The solar irradiance measured in Krakow for these days was 1.79 kWh/m^2, and in Diyala, it was 1.99 kWh/m^2. This is a relatively low value considering the time of year since the solar radiation is not as high as it can be in the summer months. On 1 August 2022, the solar irradiance measured in Krakow was 2.96 kWh/m^2, and in Diyala, it was 3.77 kWh/m^2. This is a significantly higher value than on 1 March, as the sun radiation is more intensive during the summer months in both cities and the days are longer.

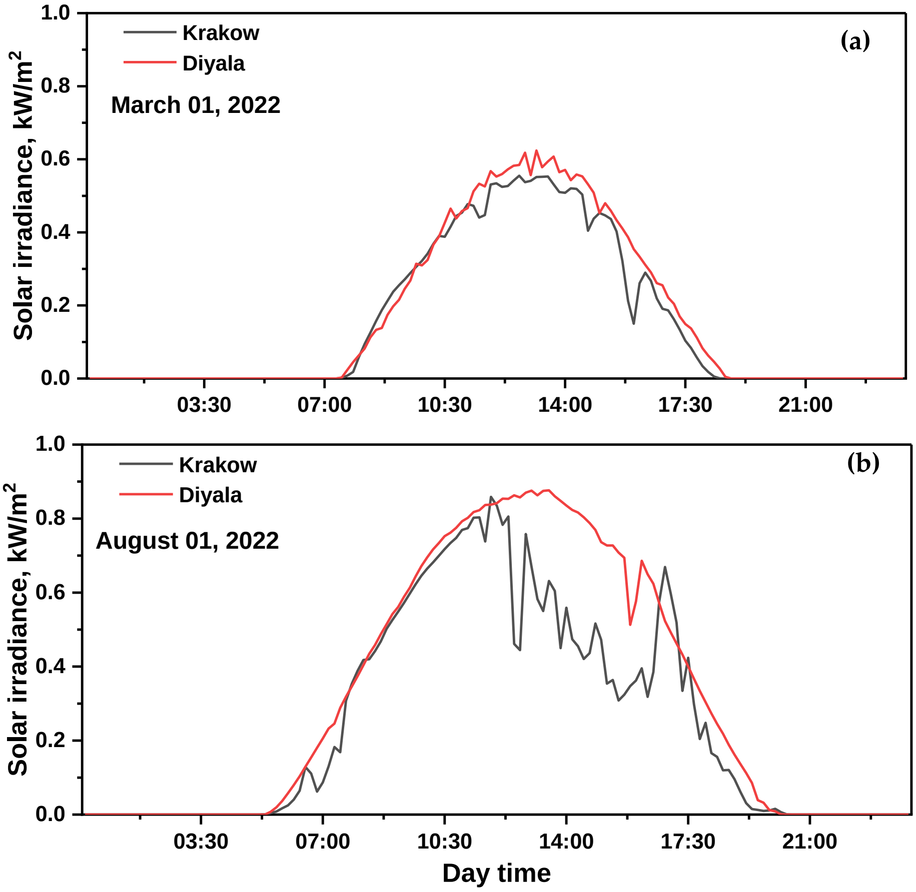

Figure 3. The solar radiation from experimental measurements for both Krakow and Diyala, results for the days: (**a**) 1 March and (**b**) 1 August of 2022.

Table 3 provided the weather data from experimental measurements for the year 2022 for both cities. As expected, the data show that Krakow has a lower wind speed and solar irradiance but also ambient temperature compared to Diyala. This is due to the differences in climate between the two cities. The data from Table 3 will help better understand the weather patterns of both cities and how they may have changed over the year. These data can be used to make more informed decisions about the best preparation for extreme weather conditions in the next analysis.

Table 3. Monthly average weather data from experimental measurements for the year 2022 for both cities.

Month	Wind Speed, m/s		Temperature, °C		Irradiance, kWh/m^2/d	
	Krakow	Diyala	Krakow	Diyala	Krakow	Diyala
Jan	2.02	1.26	2.72	9.79	0.72	1.92
Feb	2.08	1.47	5.55	14.88	1.69	3.04
Mar	1.27	1.92	6.08	20.56	3.58	4.24
Apr	1.48	1.95	9.37	21.69	3.46	5.18

Table 3. *Cont.*

Month	Wind Speed, m/s		Temperature, °C		Irradiance, kWh/m²/d	
	Krakow	Diyala	Krakow	Diyala	Krakow	Diyala
May	1.32	1.63	17.68	28.11	5.69	6.07
Jun	1.25	2.28	22.20	33.20	6.30	6.91
Jul	1.32	2.4	22.06	33.47	5.64	6.84
Aug	1.14	2.14	22.91	34.45	4.67	5.88
Sep	1.18	1.64	15.23	27.49	3.10	4.57
Oct	0.89	0.98	14.02	24.44	2.39	3.04
Nov	1.01	1.05	6.69	19.12	0.91	2.08
Dec	1.18	0.93	2.79	16.66	0.40	1.59

The annual weather data measurements for 2022 in Krakow and Diyala are expected to be quite different, as these two locations are in different climates. The average wind speed for Krakow was approximately 1.3 m/s, and for Diyala, approximately 1.6 m/s; the average ambient temperature for Krakow was approximately 12.3 °C, and for Diyala, approximately 23.6 °C; and the solar irradiance for Krakow was approximately 3.21 kWh/m^2/day, and for Diyala, approximately 4.28 kWh/m^2/day.

2.2. Proposed Model and Governing Equations

The study presented different scenarios of alkaline water electrolysis using two renewable energy sources: photovoltaic (PV) power plants and wind turbines as shown in Figure 4. They focus on two specific locations: Krakow and Diyala.

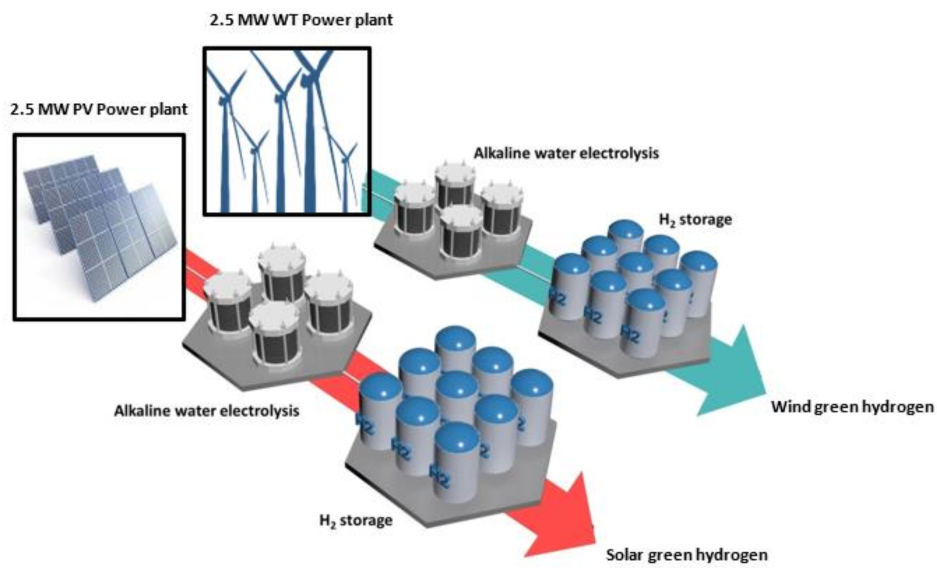

Figure 4. Scenarios of alkaline water electrolysis based on photovoltaic power plant and wind turbine.

For the Krakow case, the PV array is positioned with the optimal yearly adjustment. The tilt angle (β) is set at 35 degrees, and the azimuth angle (γ) is 20 degrees south facing, indicating that the PV panels are oriented towards the south, deviating by 20 degrees from due south. This specific positioning is chosen to maximize solar energy absorption and the generation capacity of the PV array in Krakow. For the Diyala case, the PV array is also positioned with the optimal yearly adjustment. The tilt angle (β) is set at 31 degrees, and the azimuth angle (γ) is 0 degrees south facing. This positioning is chosen to optimize the solar energy absorption and generation capacity specifically for the Diyala location [53]. By analyzing these cases, the authors assess the performance and cost of alkaline water electrolysis based on the PV array configuration and positioning in each location.

2.3. Modeling and Economic Setup

2.3.1. Power and Hydrogen Production Model

The PV power production is estimated using a model equation that takes into account factors such as solar irradiance, temperature, PV system characteristics, and losses [54,55]:

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

The degradation of PV power caused by ambient temperature is determined by considering solar irradiance and ambient temperature as factors in the analysis as [56,57]:

$$q_{out,k} = \varepsilon_k \sigma T_k 4 + \rho_k \, q_{in,k} \tag{2}$$

$$A_k \, q_{in,k} = \Sigma \, Aj \, q_{out,k} F_{j,k} \tag{3}$$

The WT power output is determined using Equation (4), which incorporates factors such as the wind speed, turbine characteristics, and efficiency to estimate the electrical power generated by the wind turbine [58]:

$$P_{WT} = 0.5 \cdot \rho \cdot \pi \cdot r^2 \cdot C_p \cdot C_F \cdot v^2 \cdot N_G \cdot N_B \tag{4}$$

The electricity consumption of AWE systems is calculated using Equation (5), which takes into account factors such as the electrical efficiency to estimate the power consumed by the AWE system [59,60]:

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

Equation (6) represents the required electrical power for compressing hydrogen in a tank. It considers parameters such as the compression efficiency, hydrogen flow rate, and pressure differential to estimate the power needed by the compressor motor [61,62]:

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

Equation (7) represents the calculation of the hydrogen tank pressure. It takes into account factors such as the initial tank pressure, hydrogen flow rate, and time to estimate the pressure within the hydrogen storage tank:

$$P_{\tan\ K} = \left(\frac{R \, T_{htci}}{V_{h \ \tan \ K}} \right) \eta_{h \ \tan \ K} \tag{7}$$

The PV array provides DC electricity, but the demand is typically AC; therefore, the converter is required to convert DC power to AC power; in addition, it is applied in the power system to regulate the energy flow. The efficiency of the converter can be calculated as [63,64]:

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

The model equations used to compute the power generated by AWE using solar and wind energy are described as:

(i) using only solar energy:

$$P_{AWE,t} = P_{PV,t} \quad for \quad P_{PV,t} \geq P_{AWE,t} \tag{9}$$

(ii) only using wind energy:

$$P_{AWE,t} = P_{WT,t} \quad for \quad P_{WT,t} \geq P_{AWE,t} \tag{10}$$

(iii) using solar and wind energies:

$$P_{AWE,t} = \begin{cases} P_{PV,t} & for\ \ P_{PV,t}\ \geq P_{AWE,t}; P_{WT,t} = 0 \\ P_{WT,t} & for\ P_{WT,t}\ \geq\ P_{AWE,t}; P_{PV,t} = 0 \\ P_{PV,t} + P_{WT,t} & for\ \ P_{PV,t} + P_{WT,t} \geq P_{AWE,t} \end{cases} \tag{11}$$

2.3.2. Economic Model

The economic model used to compute the cost of hydrogen in USD/kg considers the specifications of 3 MW for the AWE, PV, and WT presented in Table 4. The model takes into account factors such as capital costs, operating costs, energy production, system efficiency, and other relevant parameters to estimate the cost of hydrogen production per kilogram. By analyzing these components and their associated costs, the economic model provides insights into the economic feasibility of hydrogen production using the specified solar and wind power plants.

Table 4. The selected component specifications.

Component	Efficiency (%)	Model	Life Span (Year)	Cost	Ref.
PV module	18.7	Luminous	15	USD 780/kW	[65]
WT	-	Enercon	15	USD 370/kW	[66]
Converter	>95	Luminous	10	USD 450/kW	[65]
AWE	>95	Geemblue	10	USD 601.2/kW	[67]

Water and other expenses are accounted for in different proportions relative to the total capital costs in the given context. Firstly, they represent 0.3% of the total capital costs, indicating that a small fraction of the overall investment is allocated towards water-related expenses. Secondly, in the case of the AWE, 45% of its capital costs are attributed to water and other related expenses, emphasizing the significance of water in the AWE system. Additionally, these expenses account for 2% of the total capital costs, further underscoring their importance. Moreover, the cost of water is specified as USD 0.0015 per liter, likely indicating the unit price for water procurement or treatment. Lastly, there is a mention of 1% of the total capital cost being allocated towards water and other expenses, highlighting their impact on the overall project budget.

The capital recovery factor (CRF) model is represented by Equation (12). This factor is used to determine the present value of future cash flows and assists in calculating the equivalent annual cost or revenue associated with an investment. It considers factors such as the interest rate, project lifespan, and the concept of time value of money. By applying the capital recovery factor, future costs or revenues are converted into their present value equivalent, allowing for meaningful comparisons and assessments of investment profitability or costs over time. It helps in evaluating the financial viability and economic feasibility of projects by considering the impact of discounting future cash flows [68,69].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{12}$$

where i is the discount rate (4%) and n is the 10-year lifespan [70].

The AWE for the hydrogen production rate is calculated as follows:

$$Q_{H_2} = \eta_f \left(\frac{N_C I_e}{2F} \right) \tag{13}$$

The model equation for computing the hydrogen production cost, represented by Equation (14), encompasses various factors to estimate the cost per unit of hydrogen produced. This equation typically takes into account parameters such as capital costs, operating costs, energy consumption, hydrogen production efficiency, and the lifetime of the hydrogen production system. By considering these variables, the equation provides an estimate of the cost required to produce a certain quantity of hydrogen [71–75].

$$HC = \frac{I + \sum_{t=1}^{n} \frac{M_C}{(I+i)^t}}{\sum_{t=1}^{n} H_t} \tag{14}$$

2.4. Optimization Process

The genetic algorithm optimization process is a powerful tool for optimizing the alkaline water electrolyzer capacity for maximum green hydrogen production from solar and wind energy [76]. This optimization process uses a population of individuals to represent different possible solutions to a given problem. Everyone in the population has a set of parameters or variables that define it. The goal of the optimization process is to find the individual in the population with the best combination of parameters to maximize green hydrogen production.

To start the optimization process, an initial population of individuals is created. Everyone is given a set of random parameters, which will determine the individual performance. The population of individuals is then subjected to a series of tests or simulations. During each test, the performance of each individual is evaluated according to the desired goals and objectives. Individuals with the best performance are selected from the population and allowed to reproduce, creating a new generation of individuals. The process is repeated for every new generation of individuals until the best combination of parameters is found. The parameters of the best-performing individual can then be used to optimize the alkaline water electrolyzer capacity for maximum green hydrogen production. This optimization process helps to ensure that the optimal solution is found in the most efficient way possible. This process helps to maximize the efficiency of these systems and to ensure that they can produce the desired amounts of green hydrogen. The flow chart of a simulation of an energy system is shown in Figure 5.

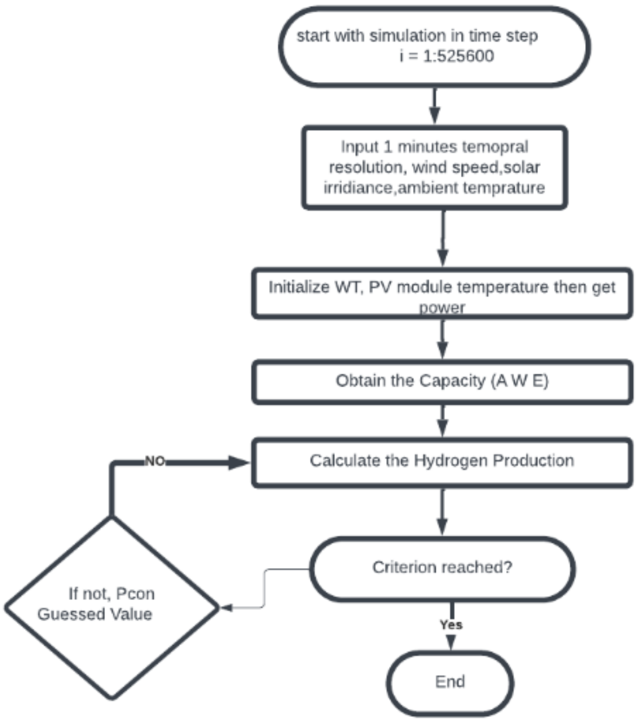

Figure 5. The simulation steps for the proposed system.

3. Results and Discussion

The study used a combination of empirical and computational analysis to optimize the AWE capacity. Empirical analysis was used to determine the optimal operating conditions for the design parameters, while computational analysis was used to model the system and simulate the performance of various configurations. The first scenario involves obtaining the AWE capacity for both cities using a 3.0 MW solar power plant, and the second scenario involves obtaining the AWE capacity for both cities using a 3.0 MW wind power plant. Six AWE capacities (0.5–3.0 MW) were selected to provide the best capacity to match the selected power plant while producing green hydrogen.

The large-scale solar photovoltaic power plant consists of more than 4620 modules (0.65 kWp per module) and uses the latest technology in solar energy generation. For both cities, the photovoltaic modules positioned the optimum year orientation: Krakow (α = 53°, β = 20° south-facing; Diyala (α = 30°, β = 0° south-facing); in providing as much solar energy as possible, the plant also provides economic benefits to local communities by creating jobs in the construction and installation of the solar power plant. The large-scale WT power plant consists of 12 WT units with 250 kW (as described in Table 3) with a hub height of 50 m and uses the latest technology in wind energy generation.

3.1. Energy Production Analysis

Figure 6 shows the daily power production of the specified 3.0 MW solar PV power plant. On 1 March 2022, the solar PV power plant in Krakow generates a total of approximately 17.746 MWh, and in Diyal, approximately 13.356 MWh. On 1 August 2022, the solar PV power plant in Krakow generated a total of approximately 16.257 MWh and 17.972 MWh (see Table 5).

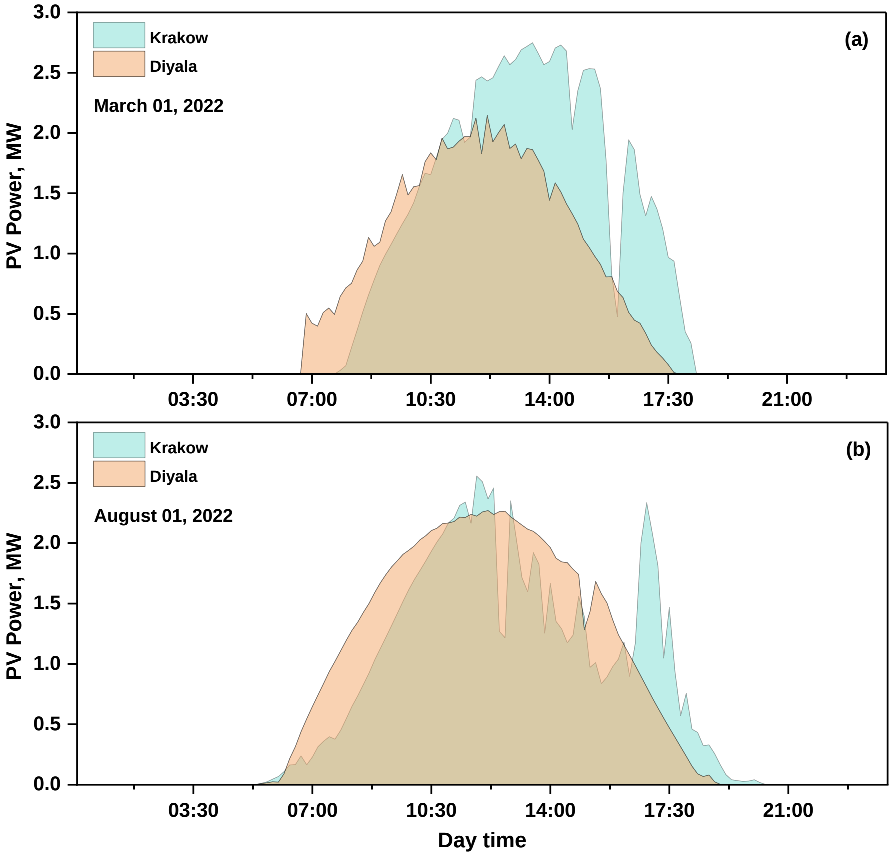

Figure 6. Daily PV power production for the day: (**a**) 1 March and (**b**) 1 August.

Table 5. Daily energy production.

City	PV Energy, kWh		WT Energy, kWh	
	1-Mar	1-Aug	1-Mar	1-Aug
Krakow	17.74	16.25	0.0005	0.0021
Diyala	13.35	17.97	12.57	4.12

Figure 7 shows the daily production of WT power. On 1 March 2022, the WT power plant in Krakow generates a total of approximately 0.00053 MWh, and in Diyal, approximately 12.575 MWh. On 1 August 2022, the WT power plant in Krakow generated a total of approximately 0.00216 MWh, and in Diyala, 4.120 MWh (see Table 5 for reference).

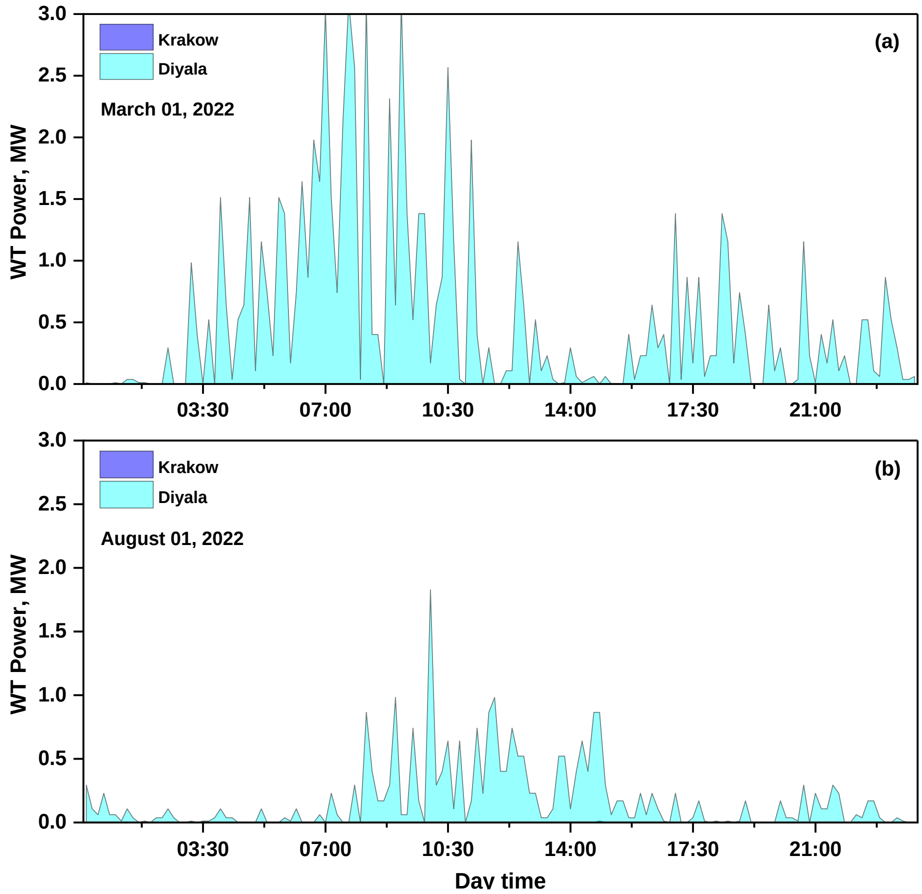

Figure 7. Daily WT power production for the day: (**a**) 1 March and (**b**) 1 August.

Figure 8a,b depict the monthly energy generated by PV and WT power plants for selected cities, respectively. The 3 MW solar PV power plant located in Krakow can generate approximately 3842.817 MWh/year with a daily average of 10.528 MWh. This is enough to power the needs of more than 3000 households combined between the two cities. The 3.0 MW WT power plant located in Krakow can generate approximately 0.127 MWh/year. The 3.0 MW solar photovoltaic power plant located in Diyala can generate approximately 4722.902 MWh/year with a daily average of 12.93 MWh. The 3.0 MW WT power plant located in Diyala can generate approximately 0.401 MWh/year.

In both cities, the WT power plant generated a low amount of energy compared to capacities and investment, thus making it unsupported for either electricity production or green hydrogen. The amount of power generated by the solar PV power plant will vary depending on the weather conditions. During sunny summer days, the plant can produce up to 50% more energy than during overcast winter days. The plant is also capable of producing additional energy during the night, thanks to the production of energy by wind turbines. In general, the 3.0 MW solar photovoltaic power plant located in Krakow and Diyala is capable of generating a reliable and consistent supply of renewable energy, making it an important part of the regional energy mix.

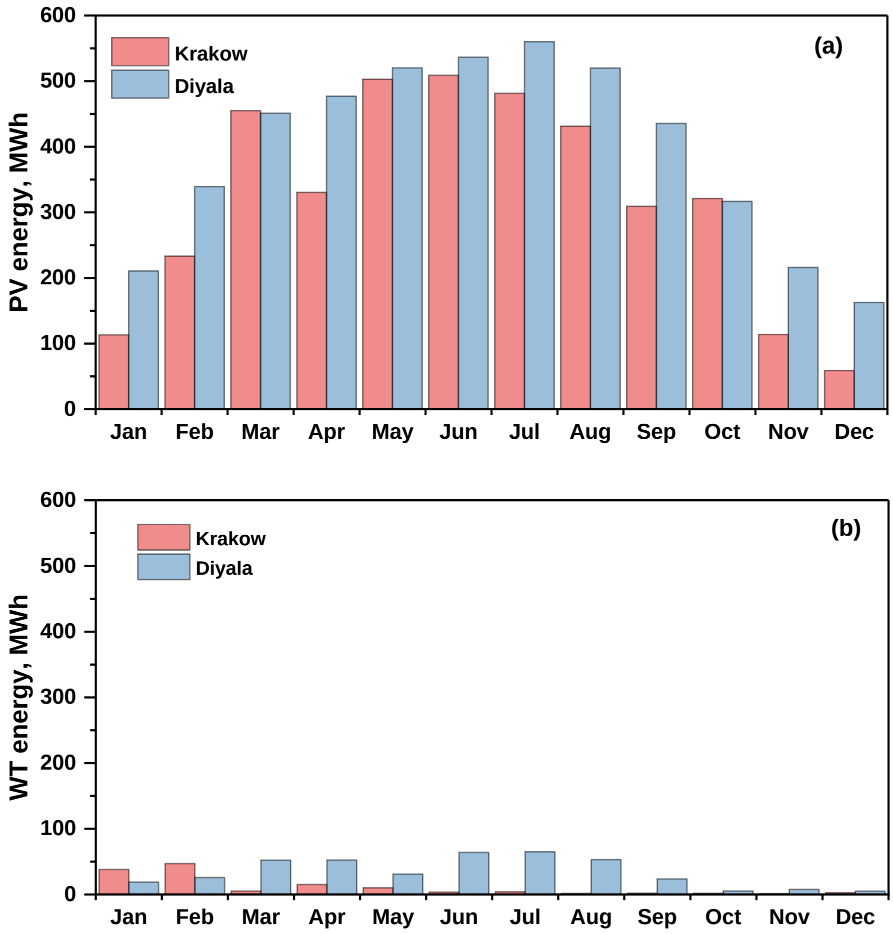

Figure 8. Monthly energy generated for selected location from: (**a**) PV and (**b**) WT.

3.2. Green Hydrogen Production Analysis

3.2.1. Hydrogen Production Using a 3 MW PV Power Plant

The simulation results of the monthly production of green hydrogen using an alkaline water electrolyzer with a capacity of 0.5–3.0 MW based on a 3.0 MW solar PV power plant for both investigated cities are presented in Figure 9. The results show that the maximum monthly hydrogen production of the electrolyzer is dependent on the amount of energy generated by the photovoltaic power plant, which is low during the winter months and high during the summer months for both cities. In addition, the simulation results also showed that the maximum monthly hydrogen production increases with increasing electrolyzer capacity; however, this increase is not linear, and beyond a certain threshold, the saturation process is observed. This shows the importance of selecting an appropriate capacity for the electrolyzer to maximize the hydrogen production rate and minimize costs.

The simulation results of the annual green hydrogen production using an alkaline water electrolyzer with a capacity ranging from 0.5 MW to 3 MW based on a 3 MWp solar PV power plant revealed that the system has high potential. It showed that the production of hydrogen from solar energy could be a promising and viable alternative to more traditional sources of energy, as presented in Figure 10. The green hydrogen produced in Diyala is larger than in Krakow (approx. 20%) for all used AWE capacities due to the higher solar radiation, as presented in Section 2.2. According to the simulation results, the optimal AWE capacity for both cities was 2.5 MW, which can match a 3.0 MW solar PV power plant. The optimized system generated green hydrogen at a rate of approximately 89,762 kg/year in Krakow and 113,337 kg/year in Diyala.

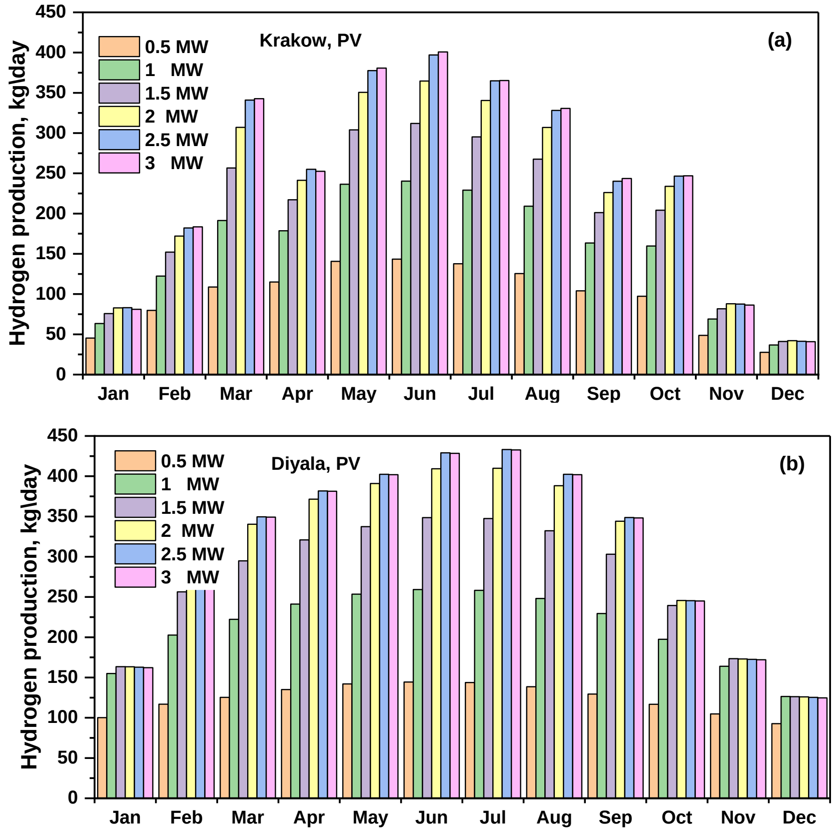

Figure 9. Monthly production of green hydrogen using photovoltaic energy based on a variety of AWE capacities for: (**a**) Krakow and (**b**) Diyala.

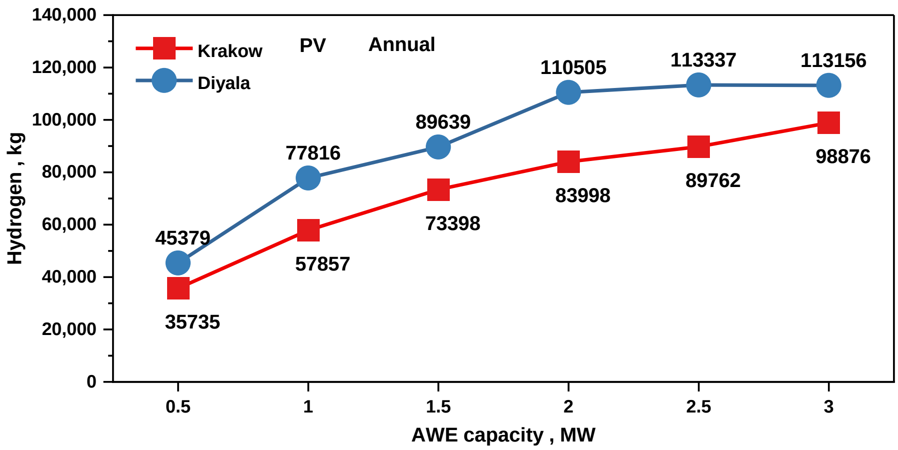

Figure 10. Annual production of green hydrogen based on photovoltaic energy at several AWE capacities for Krakow and Diyala.

3.2.2. Hydrogen Production Using 3.0 MW PV+ 3 MW WT Power Plants

Figure 11 shows the simulation results for monthly green hydrogen production using an AWE with a capacity between 0.5 MW and 3 MW, based on a 3.0 MWp solar PV and 3.0 MW WT power plants, for both cities analyzed. The results indicate that the maximum monthly hydrogen production of the electrolyzer is dependent on the amount of energy provided by the photovoltaic power plant, which is low in winter and high in summer for both cities. In addition, simulation findings revealed that the maximum monthly hydrogen production increases as the electrolyzer capacity usually increases; however, this growth is not linear and not observed for each month. This demonstrates the importance of selecting a suitable electrolyzer capacity to maximize the hydrogen production rate.

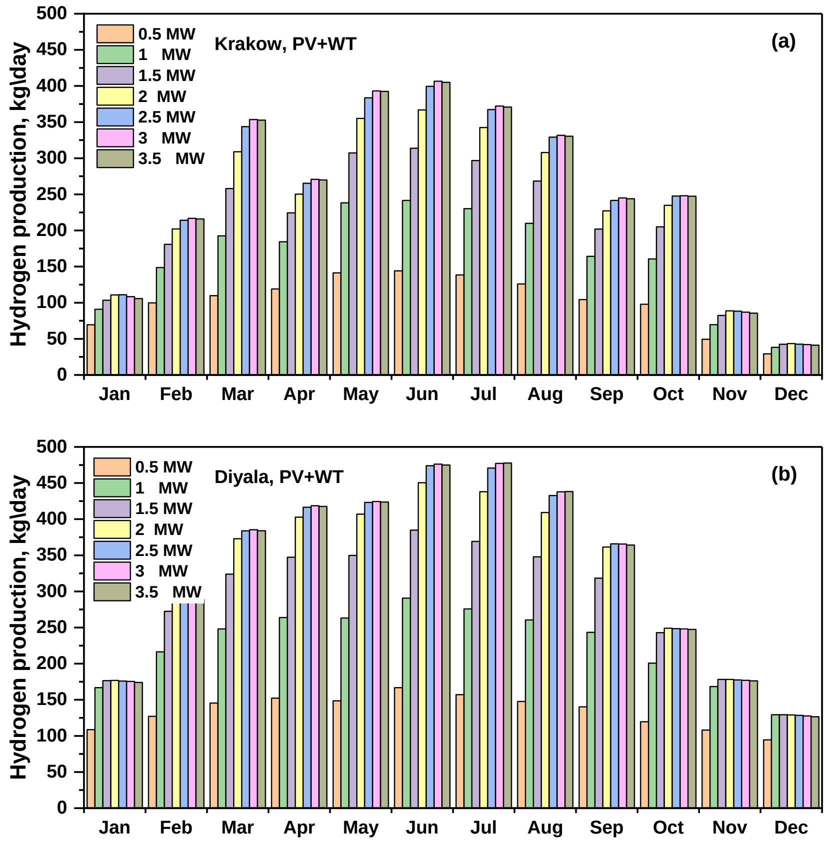

Figure 11. Hybrid system annual production of green hydrogen at different AWE capacities for: (**a**) Krakow and (**b**) Diyala.

3.3. Green Hydrogen Production Cost

The cost of green hydrogen is a crucial factor when considering the feasibility of renewable energy projects. In this section, we discuss the green hydrogen production cost for a 3.0 MWp solar photovoltaic power plant and a 3.0 MW wind turbine power plant for Krakow, Poland; and Diyala, Iraq.

In Krakow, using economic regulations of Poland, the cost of green hydrogen production from a 3.0 MWp solar PV power plant is estimated to be approx. USD 9.88/kg H_2. This is based on the cost of the solar power plant, the cost of the electrolyzer and the cost of storage and transportation. The cost of green hydrogen from the 3.0 MW WT power plant in Krakow is estimated to be around USD 14.31/kg H_2. This is based on the cost of the WT, the cost of the electrolyzer, and the cost of storage and transportation. In Diyala, using the economic regulations of Iraq, the cost of green hydrogen production from a 3.0 MWp solar PV power plant is estimated to be around USD 6.54/kg H_2. This is based on the cost of the solar power plant, the cost of the electrolyzer and the cost of storage and transportation. The cost of green hydrogen from the 3.0 MW WT power plant in Diyala is estimated to be around USD 12.66/kg H_2. This is based on the cost of the WT, the cost of the electrolyser, and the cost of storage and transportation.

The cost of green hydrogen production from the two renewable energy sources varies depending on the location. In Krakow, Poland, the green hydrogen cost of the solar photovoltaic power plant is lower than that of the WT power plant. In Diyala, Iraq, the green hydrogen cost of the solar photovoltaic power plant is lower than that of the WT power plant. It is important to note that the cost of green hydrogen varies depending on the location, size of the power plant, and other factors. Therefore, it is important to consider all of these factors when evaluating the cost of green hydrogen production. Additionally, it is important to consider the long-term cost of green hydrogen production when deciding which renewable energy source to use. Figure 12 shows the sensitivity analysis of the hydrogen production cost using a solar PV power plant.

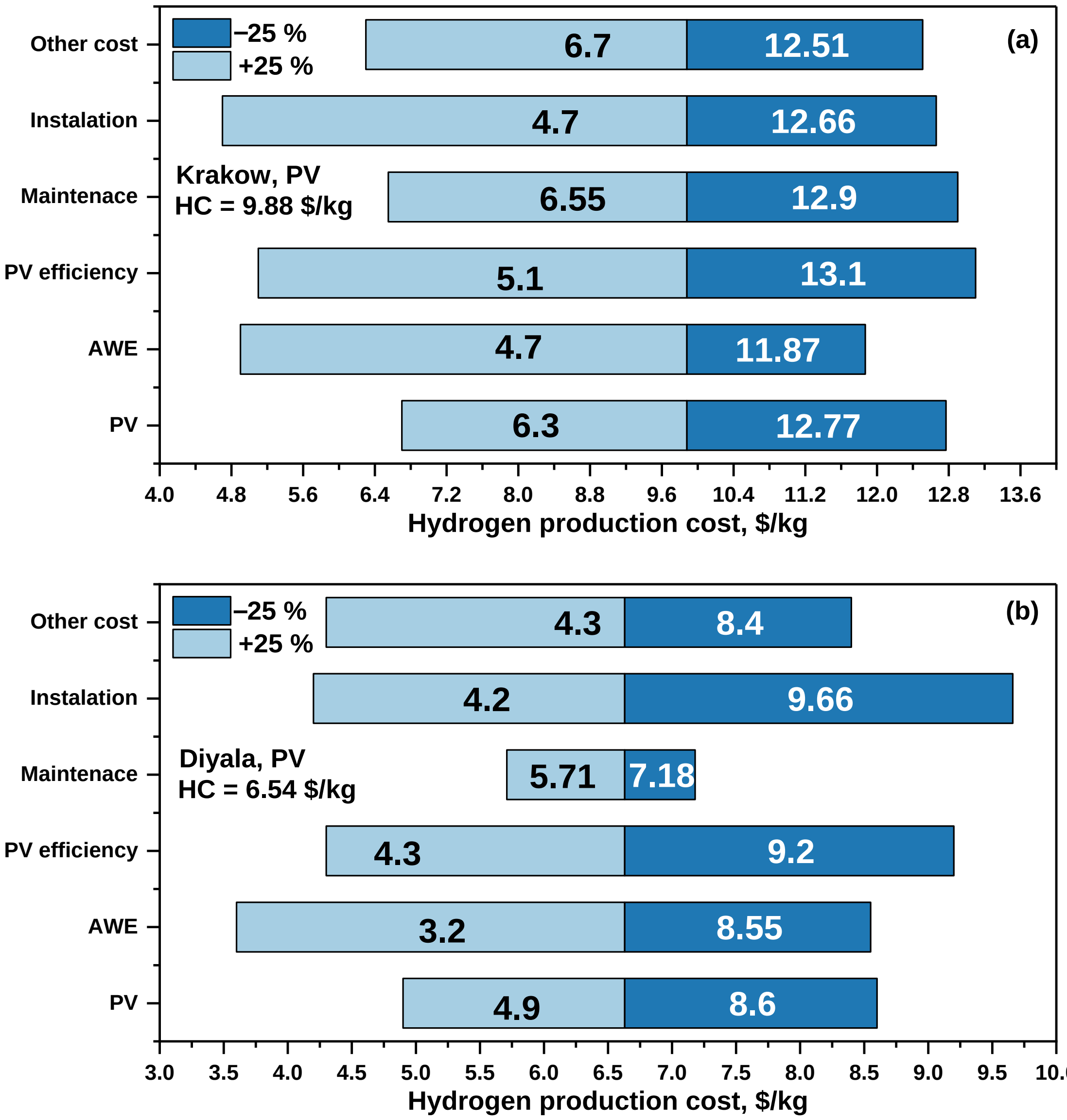

Figure 12. Sensitivity analysis of the hydrogen production cost using a 3MW solar photovoltaic power plant for: (**a**) Krakow and (**b**) Diyala.

Figure 13 shows the sensitivity analysis of different variables on the cost of green hydrogen production using a wind power plant. The results of the analysis indicate that the cost of green hydrogen is affected by the cost of the turbine, the cost of electricity, the cost of labor, and the cost of raw materials. In conclusion, a cost and sensitivity analysis using a 3.0 MW WT power plant for Krakow and Diyala has shown that the cost of green hydrogen production is highly sensitive to the cost of electricity. The analysis also showed that the cost of electricity is the most sensitive variable, followed by the cost of labor and the cost of raw materials. This analysis can be used to determine the best way to reduce the cost of green hydrogen production in both cities.

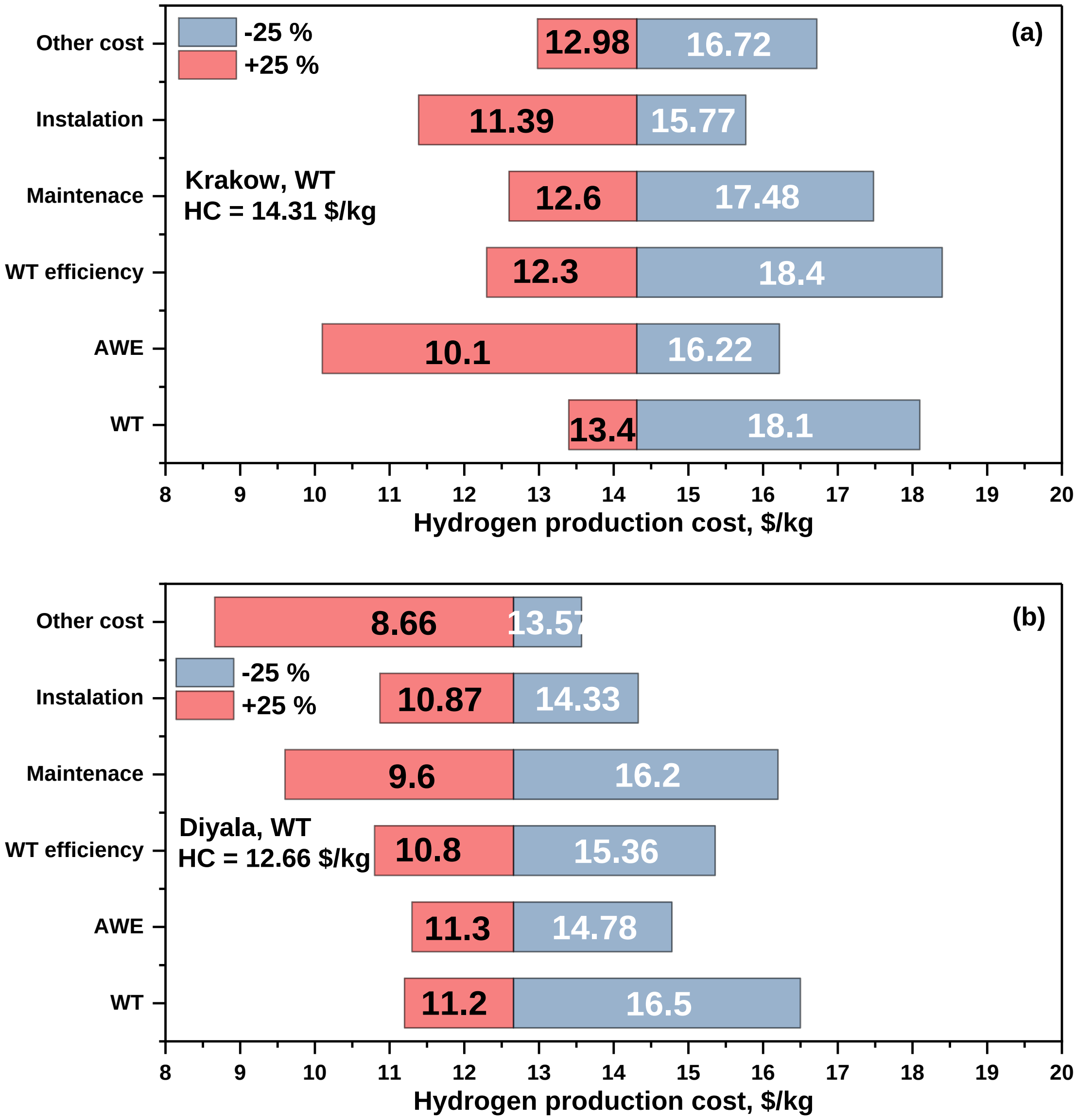

Figure 13. Sensitivity analysis of the hydrogen production cost using a 3.0 MW solar WT power plant in: (**a**) Krakow and (**b**) Diyala.

4. Conclusions

Green hydrogen cost analysis and sensitivity analysis for two cities, Krakow and Diyala, from different climatic zones were carried out. Analyses involved comparing hydrogen production costs using a 3.0 MWp solar PV system and 3.0 MW WT power plant. The analysis shows that the cost of hydrogen production using a solar photovoltaic power plant located in Krakow is significantly higher than the cost of hydrogen production in Diyala due to the higher cost of electricity in Krakow and the lower weather resources (solar and wind).

The sensitivity analysis shows that the cost of hydrogen production using the solar photovoltaic power plant is susceptible to changes in the electricity price. In the case of hydrogen production from the wind turbine plant (due to the lower wind resources), the electricity price is higher than PV, causing higher hydrogen production costs. Additionally, the cost of producing hydrogen for the Krakow location with a solar photovoltaic power plant (USD 9.88/kg H_2) is significantly higher than that estimated for the Diyala site with a solar photovoltaic power plant (USD 6.54/kg H_2). A hydrogen cost production comparison suggests that the solar photovoltaic power plant is the most cost-effective option for producing hydrogen at both locations.

The presented analysis allows us to draw essential conclusions. First, the cost of electricity in Krakow is significantly higher than in Diyala and therefore may only apply to some locations.

Second, the sensitivity analysis does not consider the actual cost of solar photovoltaic and wind turbine power plants, which vary significantly due to market instability and governmental incentives. This may substantially affect the price of hydrogen production.

Third, the analysis shows that the optimum AWE capacity is 2.5 MW for both cities, as the feedstock cost may affect the overall cost of hydrogen production.

The comparison of the green hydrogen cost using a 3.0 MWp solar PV power plant and a 3.0 MW WT power plant for both cities shows that using a solar PV power plant is more cost-effective than the WT power plant in both regions. The sensitivity analysis also shows that the cost of producing hydrogen using the solar photovoltaic power plant is more sensitive to changes in the price of electricity than the cost of producing hydrogen from the WT power plant. However, the cost of electricity in Krakow and the cost of solar photovoltaic and WT power plants have yet to be considered and, therefore, may affect the overall cost of hydrogen production.

5. Future Perspectives

The growing energy demand has led to an increased focus on renewable energy sources such as wind and solar. As a result, many countries in Europe and the Middle East have begun investing in green hydrogen production, solar photovoltaic power plants, and WT power plants. Green hydrogen is produced through electrolysis, which uses electricity to split water into its components, hydrogen and oxygen. Generated hydrogen can then be used in industrial processes and transportation, which is a positive step forward in the effort to reduce our dependence on fossil fuels and mitigate climate change. Countries in Europe and the Middle East seek green hydrogen production solar photovoltaic power plants and WT to reduce their reliance on fossil fuels and carbon footprint. This comparative analysis of green hydrogen production potential in Europe and the Middle East, as represented by Krakow, Poland and Diyala, Iraq, respectively, revealed significant differences between these regions. The research employed a 3 MWp solar and wind power plant model and optimized an alkaline water electrolyzer capacity to maximize green hydrogen production, providing a unique, comprehensive assessment of these energy sources' potential.

The study findings indicate superior potential for green hydrogen production in the Middle East compared to Europe. This conclusion is primarily attributed to the Middle East having a higher prevalence of solar and wind resources and its reduced land and labor costs. More specifically, the research determined that the cost of hydrogen production in Europe ranges between USD 9.88 and USD 14.31 per kilogram, while in the Middle East, the costs span from USD 6.54 to USD 12.66 per kilogram. This difference in cost and resource availability positions the Middle East as a more feasible region for green hydrogen production. Beyond its feasibility, green hydrogen production in the Middle East holds promise for significant environmental benefits, including potential reductions in emissions, enhancements in air quality, and increased energy security. As such, this study underscores the vital role the Middle East could play in the future of global green hydrogen production, emphasizing the need for investment and support in this sector. Future research should explore further region-specific factors influencing the production of green hydrogen, such as the political climate and regulatory environment, to provide an even more comprehensive analysis.

Europe and the Middle East have the potential to become leaders in green hydrogen production. Europe and the Middle East must invest in research and development to reduce the cost of green hydrogen production, which includes optimizing the efficiency of solar photovoltaic and WT power plants, developing cost-effective storage solutions, and improving the process of green hydrogen. Additionally, Europe and the Middle East must invest in educating the public about the benefits of green hydrogen production and promoting its use in industry, transportation, and energy production. By investing in the infrastructure, technologies, and research and development required, Europe and the Middle East capitalized on the potential of green hydrogen to revolutionize the way energy is produced and consumed, which will benefit their economies and help reduce global greenhouse gas emissions and combat the effects of climate change.

There is a need for policy changes and incentives to encourage the development and adoption of green hydrogen production solar PV power plants and WT power plants, which could include tax incentives, subsidies, or other forms of support. It is vital to ensure that the incentives are effective and do not discourage the adoption of renewable energy sources.

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Abbreviations

AWE	Alkaline water electrolyzer
NOCT	Nominal operation cell temperature
PV	Photovoltaic
STC	Standard test conditions
WT	Wind turbines
CRF	Capital recovery factor
List of symbols	
I_e	Electrolyzer current (A)
I_E	Electrolyzer input power (kW)
MC	Maintenance cost in (USD)
m_{H2}	Nominal hydrogen mass flow (kg/h)
n	Project lifetime
NC	Number of cells in series
P_{hti}	Hydrogen tank inlet pressure (kW)
P_{hto}	Hydrogen tank outlet pressure (kW)
P_{com}	Hydrogen compressor input power (kW)
$P_{tank\,k}$	Predicted pressure within the hydrogen tank (kW)
P_{icon}	Converter input power (kW)
P_{ocon}	Converter output power (kW)
$PAWE$, t	Power of AWE (kW)
Q_{H2}	Rate of hydrogen generated by the electrolyser (kg/h)
R	Gas constant (Nm/kg)
S_{STC}	Incident solar radiation at standard test conditions (kW/m^2)
S_T	Incident solar radiation (kW/m^2)
T_C	Temperature of the PV (°C)
T_C, $NOCT$	Cell temperature at which NOCT (°C)
T_{htci}	Hydrogen tank compressor inlet temperature (°C)
Vh_{tanK}	Volume of hydrogen tank (m^3)
Y_{PV}	Nominal capacity of PV (kW)
α_P	Temperature coefficient of power (%/°C)
h_C	Efficiency of PV (%)
$hh\ tan\ K$	Efficiency of hydrogen tank (%)

h_{con}	Efficiency of converter (%)
h_f	Efficiency of AWE (%)
ν	Velocity of the wind (m/s)
C_p	Wind turbine power coefficient
C_F	Capacity factor
N_G	Generator efficiency (%)
N_B	Gearbox efficiency (%)
ρ	Air density (kg/m^3)
Γ	PV module azimuth angle (degree)
B	PV module tilt angle (degree)

References

1. Sazali, N. Emerging technologies by hydrogen: A review. *Int. J. Hydrogen Energy* **2020**, *45*, 18753–18771. [CrossRef]
2. Yu, M.; Wang, K.; Vredenburg, H. Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen. *Int. J. Hydrogen Energy* **2021**, *46*, 21261–21273. [CrossRef]
3. Liu, W.; Wan, Y.; Xiong, Y.; Gao, P. Green hydrogen standard in China: Standard and evaluation of low-carbon hydrogen, clean hydrogen, and renewable hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 24584–24591. [CrossRef]
4. Hassan, Q.; Abdulrahman, I.S.; Salman, H.M.; Olapade, O.T.; Jaszczur, M. Techno-Economic Assessment of Green Hydrogen Production by an Off-Grid Photovoltaic Energy System. *Energies* **2023**, *16*, 744. [CrossRef]
5. Kakoulaki, G.; Kougias, I.; Taylor, N.; Dolci, F.; Moya, J.; Jäger-Waldau, A. Green hydrogen in Europe—A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Convers. Manag.* **2021**, *228*, 113649. [CrossRef]
6. Çelik, D.; Yıldız, M. Investigation of hydrogen production methods in accordance with green chemistry principles. *Int. J. Hydrogen Energy* **2017**, *42*, 23395–23401. [CrossRef]
7. Hirscher, M.; Yartys, V.A.; Baricco, M.; von Colbe, J.B.; Blanchard, D.; Bowman, R.C., Jr.; Zlotea, C. Materials for hydrogen-based energy storage–past, recent progress and future outlook. *J. Alloys Compd.* **2020**, *827*, 153548. [CrossRef]
8. Kovač, A.; Paranos, M.; Marciuš, D. Hydrogen in energy transition: A review. *Int. J. Hydrogen Energy* **2021**, *46*, 10016–10035. [CrossRef]
9. Hoisang, W.; Sakaushi, K. Key criteria for next-generation dimensionally stable electrodes towards large-scale green hydrogen production by water electrolysis. *Curr. Opin. Electrochem.* **2022**, *36*, 101136. [CrossRef]
10. Mazzeo, D.; Herdem, M.S.; Matera, N.; Wen, J.Z. Green hydrogen production: Analysis for different single or combined large-scale photovoltaic and wind renewable systems. *Renew. Energy* **2022**, *200*, 360–378. [CrossRef]
11. Guerra, C.F.; Reyes-Bozo, L.; Vyhmeister, E.; Caparrós, M.J.; Salazar, J.L.; Clemente-Jul, C. Technical-economic analysis for a green ammonia production plant in Chile and its subsequent transport to Japan. *Renew. Energy* **2020**, *157*, 404–414. [CrossRef]
12. Komorowska, A.; Benalcazar, P.; Kamiński, J. Evaluating the competitiveness and uncertainty of offshore wind-to-hydrogen production: A case study of Poland. *Int. J. Hydrogen Energy* **2023**, *48*, 14577–14590. [CrossRef]
13. Franco, B.A.; Baptista, P.; Neto, R.C.; Ganilha, S. Assessment of offloading pathways for wind-powered offshore hydrogen production: Energy and economic analysis. *Appl. Energy* **2021**, *286*, 116553. [CrossRef]
14. Ulleberg, Ø.; Hancke, R. Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway. *Int. J. Hydrogen Energy* **2020**, *45*, 1201–1211. [CrossRef]
15. Bhandari, R.; Shah, R.R. Hydrogen as energy carrier: Techno-economic assessment of decentralized hydrogen production in Germany. *Renew. Energy* **2021**, *177*, 915–931. [CrossRef]
16. Minutillo, M.; Perna, A.; Forcina, A.; Di Micco, S.; Jannelli, E. Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. *Int. J. Hydrogen Energy* **2021**, *46*, 13667–13677. [CrossRef]
17. Milani, D.; Kiani, A.; McNaughton, R. Renewable-powered hydrogen economy from Australia's perspective. *Int. J. Hydrogen Energy* **2020**, *45*, 24125–24145. [CrossRef]
18. Mosca, L.; Jimenez, J.A.M.; Wassie, S.A.; Gallucci, F.; Palo, E.; Colozzi, M.; Taraschi, S.; Galdieri, G. Process design for green hydrogen production. *Int. J. Hydrogen Energy* **2020**, *45*, 7266–7277. [CrossRef]
19. Lee, H.; Choe, B.; Lee, B.; Gu, J.; Cho, H.-S.; Won, W.; Lim, H. Outlook of industrial-scale green hydrogen production via a hybrid system of alkaline water electrolysis and energy storage system based on seasonal solar radiation. *J. Clean. Prod.* **2022**, *377*, 134210. [CrossRef]
20. Lee, B.; Lee, H.; Cho, H.S.; Cho, W.C.; Kim, C.H.; Lim, H. Projected economic outlook and scenario analysis for H_2 production by alkaline water electrolysis on the basis of the unit electricity price, the learning rate, and the automation level. *Sustain. Energy Fuels* **2019**, *3*, 1799–1807. [CrossRef]
21. Weidner, T.; Tulus, V.; Guillén-Gosálbez, G. Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis. *Int. J. Hydrogen Energy* **2023**, *48*, 8310–8327. [CrossRef]
22. Yusaf, T.; Laimon, M.; Alrefae, W.; Kadirgama, K.; Dhahad, H.A.; Ramasamy, D.; Kamarulzaman, M.K.; Yousif, B. Hydrogen Energy Demand Growth Prediction and Assessment (2021–2050) Using a System Thinking and System Dynamics Approach. *Appl. Sci.* **2022**, *12*, 781. [CrossRef]

23. Borole, A.P.; Greig, A.L. Life-Cycle Assessment and Systems Analysis of Hydrogen Production. In *Biohydrogen*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 485–512. [CrossRef]
24. Parkinson, B.; Balcombe, P.; Speirs, J.F.; Hawkes, A.D.; Hellgardt, K. Levelized cost of CO_2 mitigation from hydrogen production routes. *Energy Environ. Sci.* **2019**, *12*, 19–40. [CrossRef]
25. Valente, A.; Iribarren, D.; Dufour, J. Prospective carbon footprint comparison of hydrogen options. *Sci. Total Environ.* **2020**, *728*, 138212. [CrossRef]
26. Sadeghi, S.; Ghandehariun, S.; Rosen, M.A. Comparative economic and life cycle assessment of solar-based hydrogen production for oil and gas industries. *Energy* **2020**, *208*, 118347. [CrossRef]
27. Navas-Anguita, Z.; García-Gusano, D.; Dufour, J.; Iribarren, D. Prospective techno-economic and environmental assessment of a national hydrogen production mix for road transport. *Appl. Energy* **2020**, *259*, 114121. [CrossRef]
28. Al-Qahtani, A.; Parkinson, B.; Hellgardt, K.; Shah, N.; Guillen-Gosalbez, G. Uncovering the true cost of hydrogen production routes using life cymonetizationtion. *Appl. Energy* **2021**, *281*, 115958. [CrossRef]
29. Delpierre, M.; Quist, J.; Mertens, J.; Prieur-Vernat, A.; Cucurachi, S. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *J. Clean. Prod.* **2021**, *299*, 126866. [CrossRef]
30. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
31. Bauer, C.; Treyer, K.; Antonini, C.; Bergerson, J.; Gazzani, M.; Gencer, E.; Gibbins, J.; Mazzotti, M.; McCoy, S.T.; McKenna, R.; et al. On the climate impacts of blue hydrogen production. *Sustain. Energy Fuels* **2022**, *6*, 66–75. [CrossRef]
32. Hermesmann, M.; Müller, T. Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. *Prog. Energy Combust. Sci.* **2022**, *90*, 100996. [CrossRef]
33. Schropp, E.; Naumann, G.; Gaderer, M. Prospective Life Cycle Assessment: A Case Study of Hydrogen Production with Water Electrolysis. *Procedia CIRP* **2022**, *105*, 92–97. [CrossRef]
34. Hassan, Q.; Hafedh, S.A.; Mohammed, H.B.; Abdulrahman, I.S.; Salman, H.M.; Jaszczur, M. A review of hydrogen production from bioenergy, technologies and assessments. *Energy Harvest. Syst.* **2022**. [CrossRef]
35. Aneke, M.; Wang, M. Techno-economic analysis of hydrogen production via off-grid photovoltaic-electrolyzer systems in sub-Saharan Africa. *Int. J. Hydrogen Energy* **2019**, *44*, 9385–9405. [CrossRef]
36. Abbas, M.K.; Hassan, Q.; Tabar, V.S.; Tohidi, S.; Jaszczur, M.; Abdulrahman, I.S.; Salman, H.M. Techno-economic analysis for clean hydrogen production using solar energy under varied climate conditions. *Int. J. Hydrogen Energy* **2022**, *48*, 2929–2948. [CrossRef]
37. Hassan, Q.; Abbas, M.K.; Tabar, V.S.; Tohidi, S.; Abdulrahman, I.S.; Salman, H.M. Sizing electrolyzer capacity in conjunction with an off-grid photovoltaic system for the highest hydrogen production. *Energy Harvest. Syst.* **2023**. [CrossRef]
38. Nikolaidis, P.; Poullikkas, A. A comparative overview of hydrogen production processes. *Renew. Sustain. Energy Rev.* **2017**, *67*, 597–611. [CrossRef]
39. Abdalla, A.M.; Hossain, S.; Nisfindy, O.B.; Azad, A.T.; Dawood, M.; Azad, A.K. Hydrogen production, storage, transportation, and critical application challenges: A review. *Energy Convers. Manag.* **2018**, *165*, 602–627. [CrossRef]
40. Aksoylu, A.E.; Dincer, I. A review on hydrogen production through conventional and renewable sources. *Int. J. Hydrogen Energy* **2015**, *40*, 14703–14718.
41. Ceran, B.; Mielcarek, A.; Hassan, Q.; Teneta, J.; Jaszczur, M. Aging effects on modelling and operation of a photovoltaic system with hydrogen storage. *Appl. Energy* **2021**, *297*, 117161. [CrossRef]
42. Hassan, Q. Optimization of solar-hydrogen power system for household applications. *Int. J. Hydrogen Energy* **2020**, *45*, 33111–33127. [CrossRef]
43. Makhloufi, C.; Kezibri, N. Large-scale decomposition of green ammonia for pure hydrogen production. *Int. J. Hydrogen Energy* **2021**, *46*, 34777–34787. [CrossRef]
44. Peschel, A. Industrial Perspective on Hydrogen Purification, Compression, Storage, and Distribution. *Fuel Cells* **2020**, *20*, 385–393. [CrossRef]
45. Li, Y.; Shi, X.; Phoumin, H. A strategic roadmap for large-scale green hydrogen demonstration commercialization in China: A review and survey analysis. *Int. J. Hydrogen Energy* **2022**, *47*, 24592–24609. [CrossRef]
46. Gong, J. A commentary of green hydrogen in MIT Technology Review 2021. *Fundam. Res.* **2021**, *1*, 848–850. [CrossRef]
47. Lebrouhi, B.E.; Djoupo, J.J.; Lamrani, B.; Benabdelaziz, K.; Kousksou, T. Global hydrogen development—A technological and geopolitical overview. *Int. J. Hydrogen Energy* **2022**, *47*, 7016–7048. [CrossRef]
48. Akashi, O.; Yamaguchi, M.; Suzuki, H.; Kato, T. Economic assessment of CO_2 capture, utilization and storage: An overview. *Int. J. Greenh. Gas Control* **2018**, *71*, 111–123.
49. Kopteva, A.; Kalimullin, L.; Tcvetkov, P.; Soares, A. Prospects and Obstacles for Green Hydrogen Production in Russia. *Energies* **2021**, *14*, 718. [CrossRef]
50. Wolf, A.; Zander, N. Green hydrogen in Europe: Do strategies meet expectations? *Intereconomics* **2021**, *56*, 316–323. [CrossRef]
51. Razi, F.; Dincer, I. Renewable energy development and hydrogen economy in MENA region: A review. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112763. [CrossRef]
52. Hai, T.; Ali, M.A.; Dhahad, H.A.; Alizadeh, A.; Sharma, A.; Almojil, S.F.; Almohana, A.I.; Alali, A.F.; Wang, D. Optimal design and transient simulation next to environmental consideration of net-zero energy buildings with green hydrogen production and energy storage system. *Fuel* **2023**, *336*, 127126. [CrossRef]

53. Hassan, Q.; Abbas, M.K.; Abdulateef, A.M.; Abdulateef, J.; Mohamad, A. Assessment the potential solar energy with the models for optimum tilt angles of maximum solar irradiance for Iraq. *Case Stud. Chem. Environ. Eng.* **2021**, *4*, 100140. [CrossRef]
54. Hassan, Q.; Jaszczur, M.; Hafedh, S.A.; Abbas, M.K.; Abdulateef, A.M.; Hasan, A.; Abdulateef, J.; Mohamad, A. Optimizing a microgrid photovoltaic-fuel cell energy system at the highest renewable fraction. *Int. J. Hydrogen Energy* **2022**, *47*, 13710–13731. [CrossRef]
55. Leirpoll, M.E.; Næss, J.S.; Cavalett, O.; Dorber, M.; Hu, X.; Cherubini, F. Optimal combination of bioenergy and solar photovoltaic for renewable energy production on abandoned cropland. *Renew. Energy* **2021**, *166*, 1016–1027. [CrossRef]
56. Jaszczur, M.; Hassan, Q.; Szubel, M.; Majewska, E. Fluid flow and heat transfer analysis of a photovoltaic module under varying environmental conditions. *J. Phys. Conf. Ser.* **2018**, *1101*, 012009. [CrossRef]
57. Jendar, G.A.; Al-Rubaye, L.A.H.; Abdulrahman, I.S.; Hassan, Q. Experimental investigation of soiling effects on the photovoltaic modules energy generation. *Energy Harvest. Syst.* **2022**, *10*, 123–134. [CrossRef]
58. Hassan, Q. Evaluation optimizationtion of off-grid and on-grid photovoltaic power systems for typical household electrification. *Renew. Energy* **2021**, *164*, 375–390. [CrossRef]
59. Abbas, M.K.; Hassan, Q.; Jaszczur, M.; Al-Sagar, Z.S.; Hussain, A.N.; Hasan, A.; Mohamad, A. Energy visibility of a modeled photovoltaic/diesel generator set connected to the grid. *Energy Harvest. Syst.* **2022**, *9*, 27–38. [CrossRef]
60. Abdulateef, A.M.; Jaszczur, M.; Hassan, Q.; Anish, R.; Niyas, H.; Sopian, K.; Abdulateef, J. Enhancing the melting of phase change material using a fins–nanoparticle combination in a triplex tube heat exchanger. *J. Energy Storage* **2021**, *35*, 102227. [CrossRef]
61. Palej, P.; Qusay, H.; Kleszcz, S.; Hanus, R.; Jaszczur, M. Analysis optimization of hybrid renewable energy systems. *Polityka Energetyczna* **2019**, *22*, 107–120. [CrossRef]
62. Hassan, Q.; Pawela, B.; Hasan, A.; Jaszczur, M. Optimization of Large-Scale Battery Storage Capacity in Conjunction with Photovoltaic Systems for Maximum Self-Sustainability. *Energies* **2022**, *15*, 3845. [CrossRef]
63. Hussain, A.N.; Al-Sagar, Z.S.; Al-Tamimi, M.K.A.; Abid, M.; Hassan, Q.; Al-Abbooda, K.S. Comparison of using the photovoltaic system and diesel generator to feed the desired load. In Proceedings of the 4th International Iraqi Conference on Engineering Technology and Their Applications (IICETA), Najaf, Iraq, 21–22 September 2021; pp. 60–65.
64. Alhurayyis, I.; Elkhateb, A.; Morrow, D.J. Isolated and Nonisolated DC-to-DC Converters for Medium-Voltage DC Networks: A Review. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *9*, 7486–7500. [CrossRef]
65. Monocrystalline, Luminous PV Module and Converter. Available online: https://geemblue.com/ (accessed on 3 January 2023).
66. Wind Turbine, Enercon E33 Model and Converter. Available online: https://www.enercon.de/ (accessed on 3 January 2023).
67. Electrolyser Geemblue. Available online: http://www.geemblue.com/ (accessed on 3 January 2023).
68. Turton, R.; Bailie, R.C.; Whiting, W.B.; Shaeiwitz, J.A. *Analysis, Synthesis, and Design of Chemical Processes*; Pearson Education: New York, NY, USA, 2008.
69. Razmjoo, A.; Davarpanah, A. Developing various hybrid energy systems for residential application as an appropriate and reliable way to achieve Energy sustainability. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, *41*, 1180–1193. [CrossRef]
70. Jang, D.; Kim, J.; Kim, D.; Han, W.-B.; Kang, S. Techno-economic analysis and Monte Carlo simulation of green hydrogen production technology through various water electrolysis technologies. *Energy Convers. Manag.* **2022**, *258*, 115499. [CrossRef]
71. Yang, Y.; De La Torre, B.; Stewart, K.; Lair, L.; Phan, N.L.; Das, R.; Gonzalez, D.; Lo, R.C. The scheduling of alkaline water electrolysis for hydrogen production using hybrid energy sources. *Energy Convers. Manag.* **2022**, *257*, 115408. [CrossRef]
72. Hassan, Q.; Jaszczur, M. Self-Consumption and Self-Sufficiency Improvement for Photovoltaic System Integrated with Ultra-Supercapacitor. *Energies* **2021**, *14*, 7888. [CrossRef]
73. Hassan, Q.; Jaszczur, M.; Al-Jiboory, A.K.; Hasan, A.; Mohamad, A. Optimizing of hybrid renewable photovoltaic/wind turbine/supercapacitor for improving self-sustainability. *Energy Harvest. Syst.* **2022**, *9*, 1.
74. von der Assen, N.; Voll, P.; Peters, M.; Bardow, A. Life cycle assessment of CO_2 capture utilization: A tutorial review. *Chem. Soc. Rev.* **2014**, *43*, 7982–7994. [CrossRef]
75. Müller, L.J.; Kätelhön, A.; Bachmann, M.; Zimmermann, A.; Sternberg, A.; Bardow, A. A guideline for life cycle assessment of carbon capture utilization. *Front. Energy Res.* **2020**, *8*, 15. [CrossRef]
76. Styring, P.; Salmi, P.; Bogdan, M. Techno-economic assessment of carbon capture from hydrogen production. *Int. J. Hydrogen Energy* **2019**, *39*, 5207–5215.