batteries

Article

Performance Evaluation of Renewable Energy Systems: Photovoltaic, Wind Turbine, Battery Bank, and Hydrogen Storage

Gheorghe Lazaroiu, **Mohammed Gmal Osman *** and **Cristian-Valentin Strejoiu**

Department of Energy Production and Use, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania; gheorghe.lazaroiu@upb.ro (G.L.); cristian.strejoiu@stud.energ.upb.ro (C.-V.S.)
* Correspondence: mohammed.gmal@stud.energ.upb.ro; Tel.: +40-729662271

Abstract: The analysis aims to determine the most efficient and cost-effective way of providing power to a remote site. The two primary sources of power being considered are photovoltaics and small wind turbines, while the two potential storage media are a battery bank and a hydrogen storage fuel cell system. Subsequently, the hydrogen is stored within a reservoir and employed as required by the fuel cell. This strategy offers a solution for retaining surplus power generated during peak production phases, subsequently utilizing it during periods when the renewable power sources are generating less power. To evaluate the performance of the hydrogen storage system, the analysis included a sensitivity analysis of the wind speed and the cost of the hydrogen subsystem. In this analysis, the capital and replacement costs of the electrolyzer and hydrogen storage tank were linked to the fuel cell capital cost. As the fuel cell cost decreases, the cost of the electrolyzer and hydrogen tank also decreases. The optimal system type graph showed that the hydrogen subsystem must significantly decrease in price to become competitive with the battery bank.

Keywords: hydrogen; electrolyzer; renewable energy; batteries; fuel cell; energy storage; energy challenges; capital cost

check for updates

Citation: Lazaroiu, G.; Gmal Osman, M.; Strejoiu, C.-V. Performance Evaluation of Renewable Energy Systems: Photovoltaic, Wind Turbine, Battery Bank, and Hydrogen Storage. *Batteries* **2023**, *9*, 468. https://doi.org/10.3390/batteries9090468

Academic Editors: George Zheng Chen and Federico Baronti

Received: 7 August 2023
Revised: 11 September 2023
Accepted: 15 September 2023
Published: 18 September 2023

1. Introduction

In recent years, the pursuit of sustainable and reliable power sources for remote sites has gained significant attention. These sites, often located in areas without access to the traditional electricity grid, require innovative solutions to meet their energy needs [1,2]. The utilization of renewable energy technologies, such as photovoltaics (PV) and small wind turbines, coupled with energy storage systems, has emerged as a promising approach to provide power to these remote locations.

The main challenge is supplying remote areas with electricity from renewable energy sources such as wind and solar energy. Because this energy cannot be produced all day long, due to the intermittent nature of energy supply from renewable sources there must be storage methods [3]. To address this challenge, two primary storage options have been explored: battery banks and fuel cell systems. Various battery types are found in solar systems. Lead-acid batteries are reliable, durable, and cost-effective, but less efficient and with a shorter lifespan. Lithium-ion batteries offer high energy density and extended lifespan but are pricier upfront. Nickel-cadmium batteries are durable and suitable for extreme temperatures but come at a higher cost. Flow batteries store significant energy, advantageous for large-scale systems, yet their initial cost is higher. While economic considerations suggest that stand-alone photovoltaic systems using lead-acid batteries are more suitable than those employing lithium-ion batteries, it's noteworthy that lithium-ion batteries offer numerous advantages over lead-acid technology [4]. These benefits include higher energy density, reduced maintenance requirements, and a longer lifecycle other hand, hydrogen storage systems offer an alternative approach by converting surplus renewable power into hydrogen, which can be stored and subsequently used by fuel cells to generate electricity [5].

To evaluate the performance of the hydrogen storage system, a sensitivity analysis was conducted, focusing on variables such as wind speed and the cost of the hydrogen subsystem. By linking the capital and replacement costs of the electrolyzer and hydrogen storage tank to the fuel cell capital cost, the study assessed the impact of changes in fuel cell pricing on the overall system economics [6].

The results of the analysis revealed several important findings [7]. The optimal system type graph indicated that for the hydrogen storage system to become competitive with the battery bank, a substantial decrease in the cost of the hydrogen subsystem is required. Furthermore, in most cases where the hydrogen system was recommended, it was suggested in conjunction with a battery bank, indicating the complementary nature of the two-storage media in providing reliable and efficient power supply to remote sites [8,9], Fuel cell are a promising hybrid power source that can overcome the limitations of batteries. They have strong overload capacity, recyclable energy, and convenient use. They can also overcome the short mileage, poor safety, long charging time, high cost, and frequent load changes of batteries [10].

However, there was one exceptional scenario identified by the analysis, where the HOMER software (https://www.homerenergy.com/products/pro/index.html, accessed on 7 August 2023) recommended the hydrogen storage system without the battery bank. This scenario occurred when the wind speed was low, and the cost of the hydrogen system was nearly negligible.

Based on the findings, the battery bank currently stands out as the more viable option for remote power supply due to its cost-effectiveness and proven performance [11]. Nonetheless, it is crucial to recognize the dynamic nature of technology and cost trends, requiring continuous monitoring and evaluation of both systems to identify emerging opportunities for improvements in efficiency and cost reduction [12].

The study aims to evaluate the performance of photovoltaic (PV) systems and small wind turbines for remote sites by assessing parameters like capacity, output range, and total production to meet energy demands; analyze energy storage through battery banks and hydrogen systems by examining energy flow, consumption, and storage efficiency; compare PV systems with battery banks, PV systems with hydrogen storage, and small wind turbines with both storage options considering efficiency, costs, and long-duration storage potential, conduct a sensitivity analysis on wind speed and hydrogen subsystem costs to understand their impact on system performance and cost; and provide recommendations for the most efficient, cost-effective power generation and storage approach, considering system performance, cost-effectiveness, and integration possibilities for reliable and sustainable power supply. This analysis considers various factors, including system efficiency, reliability, economic feasibility, and environmental impact [13].

1.1. Literature Review

Energy storage technologies play a pivotal role in enhancing the reliability and efficiency of renewable energy systems. Lithium-ion batteries, as elucidated by Zhang [14], have emerged as a popular choice due to their high energy density and long cycle life. Researchers like Chen and Wang [15], discuss the potential of flow batteries in addressing large-scale energy storage requirements, although cost-effectiveness remains a challenge. Studies by Johnson and Brian [16], delve into the challenges and benefits of grid-connected photovoltaic systems, highlighting the need for robust grid management and energy storage technologies to address intermittent. These studies highlight the diverse range of energy storage options available, each with distinct advantages and challenges, underscoring the necessity of selecting the most suitable technology based on specific application needs. Integrating wind energy has also been a topic of exploration, with Adams [17], discussing the role of advanced forecasting techniques in optimizing wind power utilization. These works collectively underline the significance of a well-designed integration framework, considering grid stability, energy storage, and forecasting methods.

By looking to the previous studies, there has been a lack of comprehensive research on the utilization of renewable energies in remote areas. While individual studies may focus on specific aspects such as solar or wind energy, none have provided an overarching examination. In this study, we have addressed this gap by conducting an analysis of Photovoltaic, Wind Turbine, Battery Bank, and Hydrogen Storage technologies, along with an assessment of their performance and economic aspects in remote areas.

1.2. Sustainable Energy Solutions for Remote Areas

Remote areas face unique challenges when it comes to accessing reliable and affordable energy. These areas often lack access to traditional energy sources and suffer from limited infrastructure. However, sustainable energy solutions offer promising opportunities to address these challenges and improve the lives of people living in remote areas [18].

Renewable energy sources, such as solar, wind, and hydropower, play a crucial role in sustainable energy solutions for remote areas. Solar energy offers immense potential due to the abundant sunlight available in many remote regions. Installing solar photovoltaic systems can provide clean electricity for various purposes, including lighting, heating, and powering essential appliances [19].

In addition to solar energy, small-scale wind turbines can harness the power of wind and generate electricity in areas with favorable wind conditions [20]. Hydropower systems can also be implemented in remote areas with access to flowing water, providing a reliable and renewable source of electricity [21].

Energy storage is another vital component of sustainable energy solutions for remote areas. Battery technologies enable the storage of excess energy generated during peak production periods for later use when renewable energy generation is low. This ensures a more consistent and reliable energy supply, even in periods of low renewable energy production [22].

Microgrids are also essential in remote areas, allowing for the integration of various energy sources and the distribution of electricity within the local community [23]. Microgrids can operate independently or in connection with the main grid, providing localized and resilient energy solutions [24]. To successfully implement sustainable energy solutions in remote areas, a comprehensive approach is needed. This includes assessing the energy demand, resource availability, and infrastructure requirements of each specific location [25]. Additionally, community engagement and participation are crucial for the long-term success of these solutions. Involving local communities in the planning and decision-making process ensures that the energy solutions meet their specific needs and priorities [26].

2. Methodology

This entails addressing challenges encountered in providing reliable and sustainable energy solutions to remote areas, encompassing factors like lack of grid infrastructure, geographical limitations, resource scarcity, fluctuating energy demand, environmental concerns, economic feasibility, and maintenance limitations [27]. Overcoming these challenges involves deploying innovative strategies such as decentralized renewable energy systems, microgrid adoption, energy storage integration, and leveraging smart grid advancements. The development of tailored and sustainable energy solutions is contingent on considering the unique geographical, social, and economic circumstances of each remote area [28]. Sustainable energy solutions for remote areas often involve a combination of renewable energy sources, energy storage systems, and backup power options. In this case, the system consists of a small wind turbine, photovoltaic panels, diesel generator, a DC load, a hydrogen tank with an electrolyzer and a fuel cell-battery hybrid systems [29].

The small wind turbine harnesses the power of wind to generate electricity. It is designed to capture the energy from the wind and convert it into usable electrical energy [30]. This is particularly beneficial in remote areas where there may be consistent wind patterns [31]. PV panels, also known as solar panels, utilize the sun's energy to produce electricity. These panels contain photovoltaic cells that convert sunlight into direct current (DC) electricity. By installing PV panels in remote areas with ample sunlight, a reliable and renewable energy source can be established [32].

To ensure continuous power supply even during periods of low wind or sunlight, energy storage systems are crucial. The diesel serves as a backup power option and can be utilized when the renewable energy sources are not generating enough electricity. These batteries store excess energy produced by the wind turbine and PV panels for later use [33].

In hybrid energy systems that combine fuel cells, battery banks, and diesel engines, it is common to incorporate an integrated hydrogen tank and an electrolyzer. During periods of excess renewable energy generation, like when there is an abundance of wind or sunlight, surplus electricity can indeed be utilized to power the electrolyzer. This process allows us to produce hydrogen, which can later be used as an energy carrier or stored for future energy needs. The electrolyzer splits water into hydrogen and oxygen through a process called electrolysis. The hydrogen gas is then stored in the tank for later use [34]. The stored hydrogen can be utilized in a fuel cell system when there is a high energy demand or when renewable energy sources are not readily available. The fuel cell converts the stored hydrogen back into electricity, providing a reliable and clean energy source for the DC load [35].

In this study, HOMER Pro was used for several reasons. It facilitated comprehensive analyses, optimization, and scenario testing, allowing us to evaluate different technology combinations, including Photovoltaic, Wind Turbine, Battery Bank, and Hydrogen Storage. Additionally, the software enabled financial assessments and provided visual representations, enhancing our ability to communicate findings effectively.

3. Results and Discussion

Figure 1 illustrates the overarching system configuration, portraying a hybrid arrangement comprising both photovoltaic panels and wind turbines to harness energy production. This system further integrates storage batteries and a diesel generator for reserve power. Notably, the energy generated is channeled into a process that facilitates the production of hydrogen. This holistic approach reflects the intricate synergy between various renewable energy sources and storage mechanisms within the context of sustainable energy production and management. By integrating these components into a comprehensive system, remote areas can benefit from a sustainable energy solution [36]. The combination of the small wind turbine and PV panels ensures a consistent renewable energy supply [37]. This system enables the efficient utilization of renewable energy sources, reducing dependence on fossil fuels and promoting environmental sustainability [38].

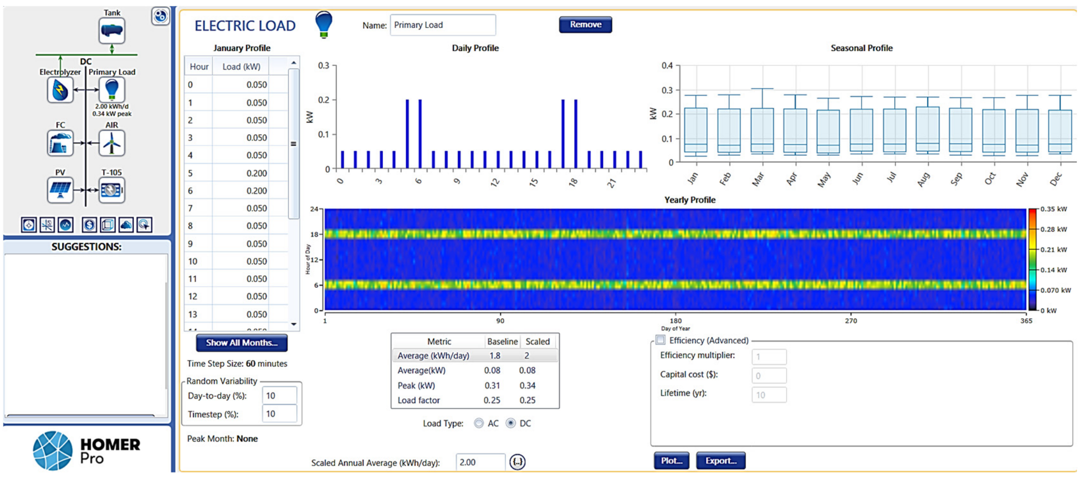

Figure 1. Depicts the comprehensive system design.

The clearness index and daily radiation values provided in Figure 2 give an indication of the solar energy potential throughout the year. Generally, higher clearness index values and daily radiation values suggest sunnier and more favorable conditions for solar energy generation. The data is taken from location (Latitude 44.25, longitude 28.75) from NASA database.

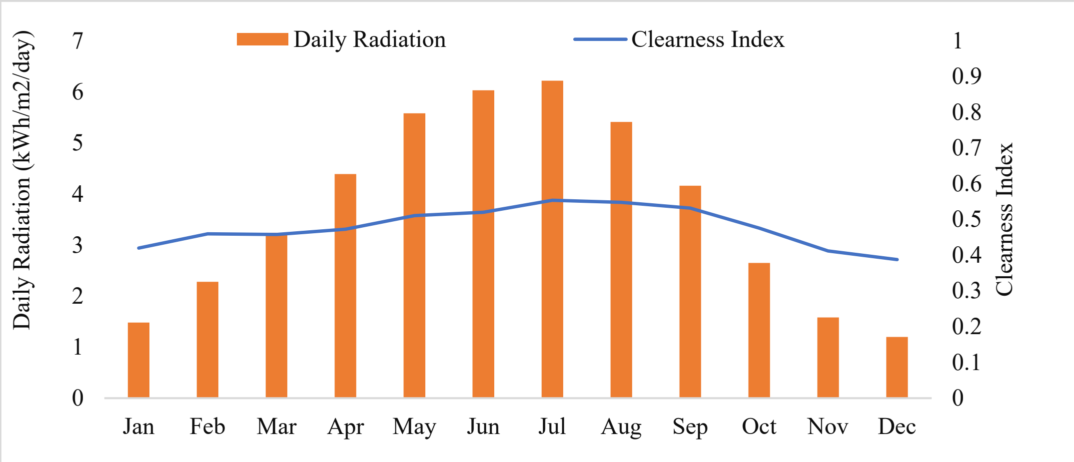

Figure 2. Monthly Average solar Global Horizontal Irradiance in 2021.

Figure 2 shows the Monthly Average Solar Global Horizontal Irradiance. In this figure, two graphs are represented. The first graph consists of the daily radiation reported for the 12 months of the year in kWh/m^2/day. The second graph represents the clearness index also reported for the 12 months of the year.

It can be noted that the clearness index ranges from 0.388 in December to 0.554 in July, indicating that July tends to have the highest proportion of solar radiation reaching the Earth's surface compared to clear sky conditions. Similarly, the daily radiation values show an increasing trend from January to July, peaking in June at 6.03 kWh/m^2/day. After July, the daily radiation values start to decline gradually until December.

Figure 3 shows the daily temperature values for each month of the year. The temperature values are measured in degrees Celsius.

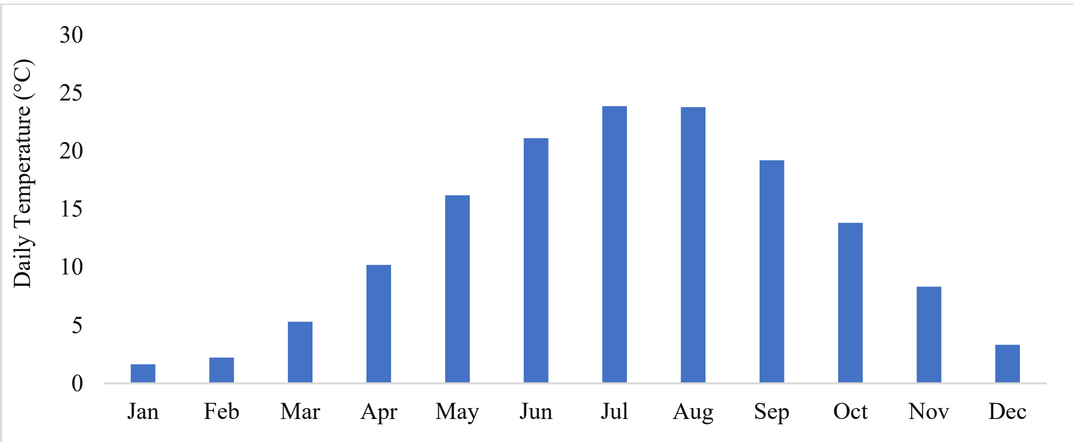

Figure 3. Daily Temperature in 2021.

From Figure 3, it can be observed that the temperatures gradually increase from winter to summer months, with the highest average daily temperature occurring in July and August. This aligns with the typical pattern in many regions where summer months tend to be warmer. Similarly, the temperatures gradually decrease from summer to winter months, with the lowest average daily temperature occurring in December and January [39].

Figure 4 shows the monthly average wind speed values for each month of the year. The wind speed values are measured in meters per second (m/s).

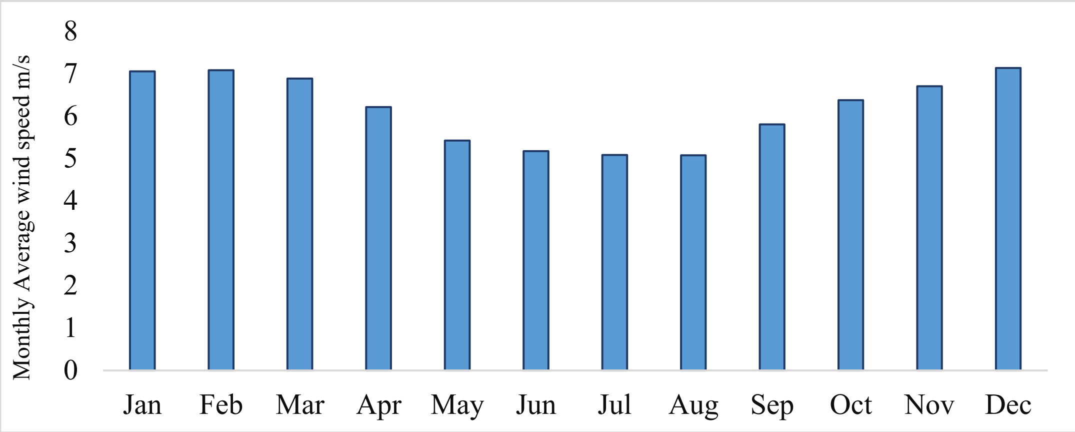

Figure 4. Monthly Average wind speed in 2021.

Figure 4 it can be observed that the wind speeds show some variation but generally remain within a consistent range across the months. The highest average wind speeds are observed in the winter months, particularly in December and January, with values exceeding 7 m/s. This aligns with the expectation that winter months tend to have stronger wind conditions in many regions. On the other hand, the summer months show relatively lower average wind speeds, with values around 5 m/s.

Table 1 shows the annual production of different energy sources in kilowatt-hours (kWh) and their respective percentages. The energy sources listed are PV (Photovoltaic), Fuel Cell, and SW AIR X.

Table 1. Monthly electric production.

Production	kWh/Year	%
PV	571	33.1
Fuel Cell	227	13.1
SW AIR X	928	53.8
Total	1726	100

From Table 1, it can be observed that PV contributes 571 kWh/year, accounting for approximately 33.1% of the total energy production. The Fuel Cell contributes 227 kWh/year, representing around 13.1% of the total. The SW AIR X source has the highest production, generating 928 kWh/year, which makes up approximately 53.8% of the total energy production.

The in this case is 1726 kWh/year, accounting for 100% of the total energy production.

Figure 5 represents the monthly electricity production graph. It can be seen that we have all 3 types of energy production sources (PV, FC, AIR).

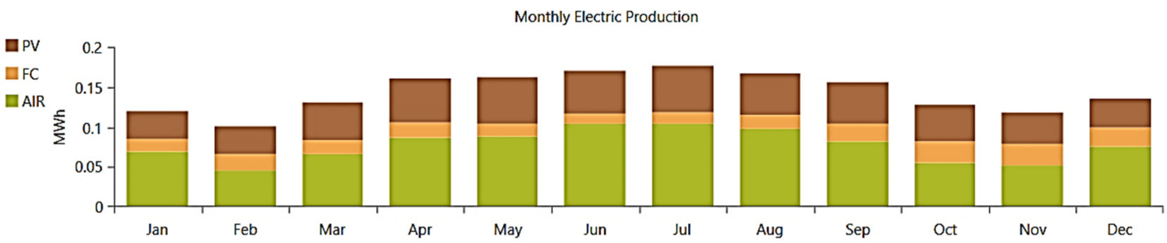

Figure 5. Monthly Electric production in the system in 2021.

An electrolyzer is an electrochemical device used to produce hydrogen gas by splitting water molecules into hydrogen and oxygen through a process called electrolysis. It consists of two electrodes (an anode and a cathode) submerged in an electrolyte solution, usually water or an aqueous solution of an electrolyte [40].

When an electric current is passed through the electrolyte, water molecules at the cathode receive electrons, reducing them to form hydrogen gas (H_2). At the same time, at the anode, water molecules lose electrons, oxidizing them to produce oxygen gas (O_2). The overall reaction can be represented as follows:

$$2H_2O(l) \text{ -> } 2H_2(g) + O_2(g)$$

The process of electrolysis requires an external power source, typically electricity, which provides the energy needed to drive the electrolysis reaction. The efficiency of an electrolyzer is determined by factors such as the design of the electrodes, the type and concentration of the electrolyte, temperature, and operating conditions [41].

Table 2 includes various quantities and values to Electrolyzer input and output power.

Table 2. Electrolyzer input and output power.

Quantity	Value	Units
Rated capacity	0.400	kW
Mean input	0.0847	kW
Maximum input	0.400	kW
Total input energy	742	kw/year
Capacity factor	21.2	%
Mean output	0.00163	kg/hr.
Maximum output	0.00771	kg/hr.
Total production	14.3	kg/year

The system has a rated capacity of 0.400 kW, meaning it can provide a maximum power output of 0.400 kW under normal operating conditions. On average, the system receives an input of 0.0847 kW, with a maximum input of 0.400 kW. Over the course of a year, the total energy input into the system amounts to 742 kWh. The system's capacity factor is 21.2%, indicating that it operates at approximately one-fifth of its maximum capacity on average. In terms of output, the system produces the specified material or substance at an average rate of 0.00163 kg/hr., with a maximum output rate of 0.00771 kg/hr. The total production of the specified material or substance over a year is 14.3 kg.

Figure 6 represents the graph for simulating the electrolysis process. We have a maximum input power of approximately 0.40 kW.

Table 3 consists of the parameters interpreted from the simulation in Figure 6.

The system operates for a total of 2307 h per year, with 958 starts recorded annually. It has an expected operation life of 17.3 years. The capacity factor of the system is 6.47%, indicating that it operates at a relatively low fraction of its maximum capacity on average. The fixed generation cost is $0.008 per hour.

Figure 7 represents the graph for the simulation of the electricity production process. We have a maximum output power of about 0.35 kW.

The system generates a total of 227 kWh of electrical production per year, with an average electrical output of 0.0983 kW. It can deliver a minimum output of 0.0208 kW and a maximum output of 0.307 kW. The system consumes 13.6 kg of fuel, with a specific fuel consumption of 0.06 kg/kWh. The fuel energy input is 454 kWh per year. The mean electrical efficiency of the system is 50%. These values provide insights into the system's operational characteristics, fuel consumption, electrical output, and efficiency.

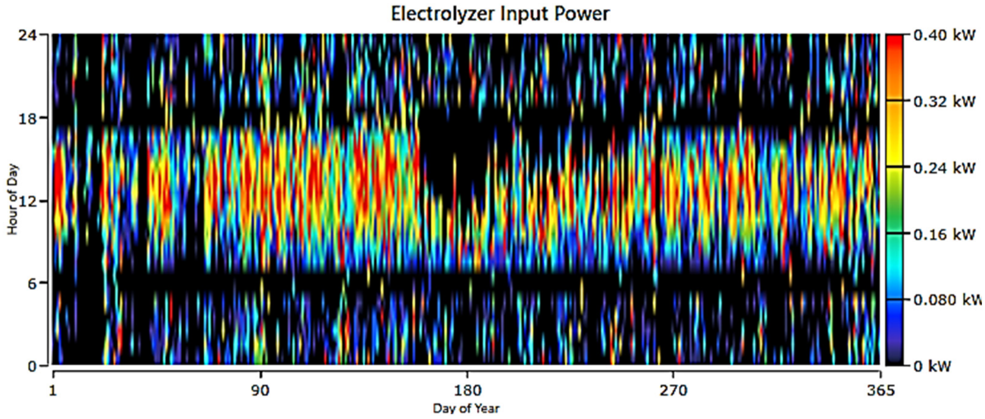

Figure 6. Simulate the Electrolyzer Input power operation in one year.

Table 3. Generator power output.

Quantity	Value	Units
Hours of operation	2307	hrs./year
Number of starts	958	Starts/year
Operation life	17.3	Year
Capacity factor	6.47	%
Fixed generation cost	0.008	$/hr.
Electrical production	227	kWh/year
Mean electrical output	0.0983	kW
Minimum electrical output	0.0208	kW
Maximum electrical output	0.307	kW
Fuel consumption	13.6	kg
Specific fuel consumption	0.06	kg/kWh
Fuel energy input	454	kWh/year
Mean electrical efficiency	50	%

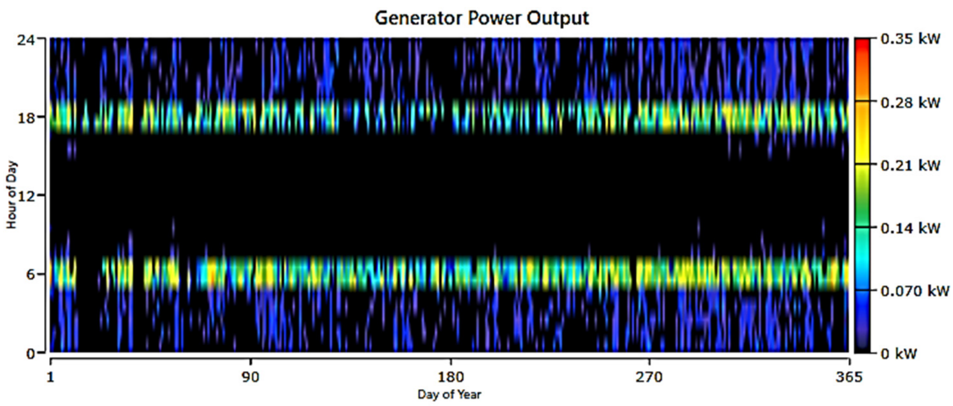

Figure 7. Simulation of generator power output.

The graphs in Figure 8 show the consumption of fuel consumed for energy production. The amount of fuel is measured per hour. We have a maximum consumption in March of approximately 0.18 kg/hr.

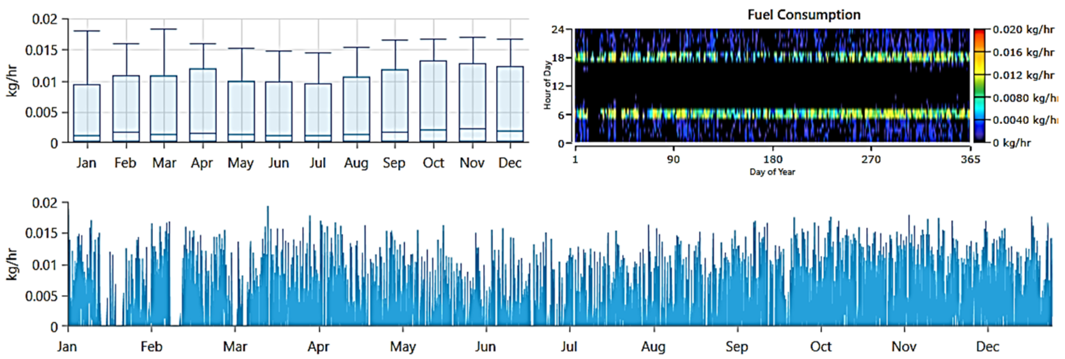

Figure 8. Fuel consumption per year in the system in 2021.

Figure 9 shows the simulation of the hydrogen storage tank. The hydrogen storage tank has a capacity of 2 kg and an energy storage capacity of 66.7 kWh. The tank autonomy, which refers to the duration the tank can provide hydrogen at a given rate, is 800 h.

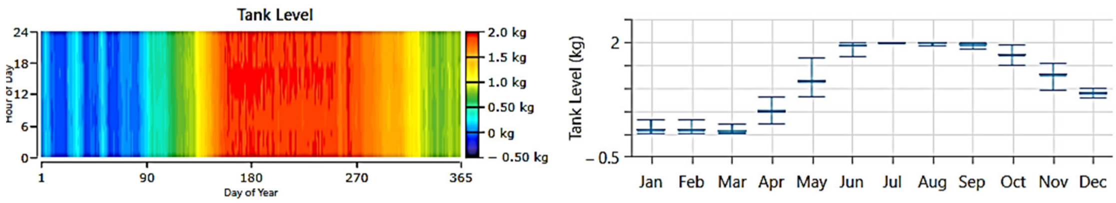

Figure 9. Simulation of hydrogen storage tank.

At the beginning of the year, the hydrogen storage tank has a content of 0.2 kg. This represents the amount of hydrogen gas stored in the tank.

By the end of the year, the content of the hydrogen storage tank increases to 0.889 kg. This indicates that additional hydrogen has been generated and stored in the tank throughout the year.

The storage and accumulation of hydrogen in the tank allow for the utilization of surplus renewable power generated during peak production periods. This stored hydrogen can then be utilized as needed by a fuel cell or other hydrogen-powered devices to produce electricity or provide energy for various applications [42].

The photovoltaic (PV) system has a rated capacity of 0.4 kW, meaning it is designed to produce a maximum power output of 0.4 kW under optimal conditions. The mean output of the PV system is 0.0652 kW, representing the average power output over a given period. The mean daily output of the PV system is 1.57 kWh, indicating the average energy output per day. This value represents the electricity generated by the PV system on an average day.

The capacity factor of the PV system is 16.3%. This percentage reflects the ratio of the actual energy output of the system to its maximum possible output over a specified time. A capacity factor of 16.3% suggests that the PV system operates at a relatively low fraction of its maximum capacity on average.

Figure 10 shows the total power at the output of the system with photovoltaic panels. This power is rendered in hours per day over the course of a year. This time we have a maximum output power of approximately 0.40 kW.

The total production of the PV system over the year is 571 kWh, indicating the total amount of energy generated by the system over the course of a year.

The maximum output of the PV system is 0.383 kW, representing the highest power output it can achieve under optimal conditions.

The levelized cost of electricity (LCOE) for the PV system is $0.201 per kilowatt-hour (kWh). This value represents the average cost of producing each unit of electricity by the PV system, considering the total costs over its lifespan.

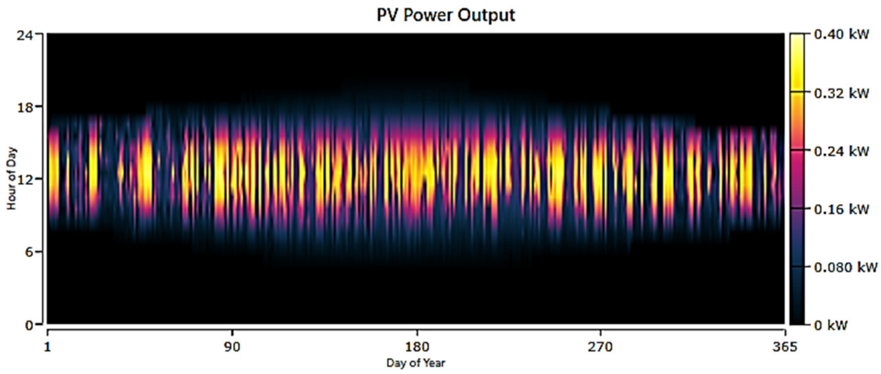

Figure 10. PV power output.

The total rated capacity of the wind system is 0.55 kW, indicating its maximum power output under optimal conditions. The mean output of the wind system is 0.106 kW, representing the average power output over a given period.

The capacity factor of the wind system is 19.3%, which reflects the ratio of the actual energy output of the system to its maximum possible output over a specified time. A capacity factor of 19.3% suggests that the wind system operates at a relatively low fraction of its maximum capacity on average.

Figure 11 represents the total power at the output of the wind turbine system. As in the case of photovoltaic panels, the power is reproduced in hours per day over the course of a year. The maximum output power this time is around 0.60 kW.

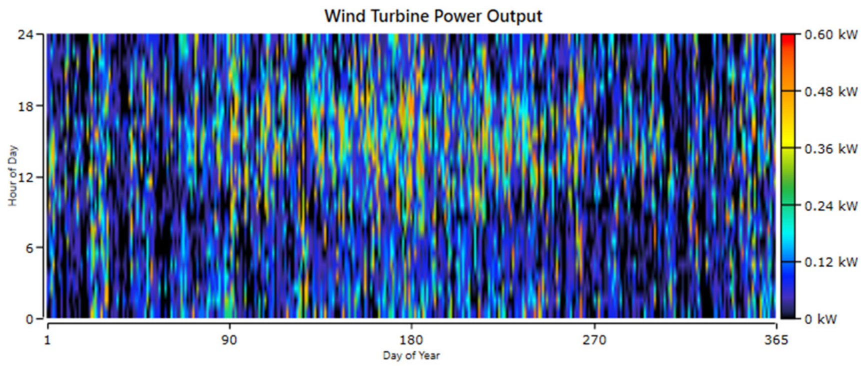

Figure 11. Simulation of Wind turbine power output.

The total production of the wind system over the year is 928 kWh, indicating the total amount of energy generated by the system over the course of a year. The wind system can achieve a maximum output of 0.547 kW, representing the highest power output it can generate under optimal conditions. The wind penetration is 127%, which suggests that the wind system can generate more energy than is needed for the site's power requirements. This implies that the wind system can potentially contribute excess energy to the grid or be used for additional purposes such as energy storage.

The levelized cost of electricity (LCOE) for the wind system is $0.168 per kilowatt-hour (kWh). This value represents the average cost of producing each unit of electricity by the wind system, considering the total costs over its lifespan.

4. Sensitivity Cases

The sensitivity analysis encompassed a range of scenarios involving different components of the renewable energy system, namely PV, wind, hydrogen, diesel, and batteries. By scrutinizing these scenarios, we aimed to discern their effects on the system's performance. Among the key metrics analyzed, the net present cost (NPC) emerged, calculated at $622, which reflects the comprehensive expenses throughout the system's lifespan.

Delving deeper, the levelized cost of electricity (COE) was a focal point, determined to be $1.1/kWh. This metric encapsulates the average cost linked to the production of each unit of electricity. Within the annual operating cost of $356/year, factors such as fuel consumption, production, and operation and maintenance expenditures were meticulously considered. Notably, the total fuel consumption stood at 13.6 kg/year, while electricity production peaked at 227 kWh.

Furthermore, crucial insight was gained into operation and maintenance costs, approximated at $18.5/year. This segment covered the spectrum of routine system maintenance and general upkeep. By scrutinizing the outcomes of these sensitivity scenarios, a comprehensive overview of the renewable energy system's adaptability and financial intricacies emerged, substantiating the significance of this analysis.

5. Conclusions

The analysis conducted on the renewable energy system reveals valuable insights into its components and performance. By considering photovoltaics (PV), fuel cells, and small wind turbines, along with the hydrogen storage system, the study aimed to determine the most efficient and cost-effective approach to supplying power to a remote site.

The PV system proved to be a significant contributor, with a rated capacity of 0.4 kW and a total production of 571 kWh/year, accounting for approximately 33.1% of the total energy production. The fuel cell, on the other hand, provided 227 kWh/year, representing around 13.1% of the total. The SW AIR X small wind turbine demonstrated its potential by generating the highest production of 928 kWh/year, making up approximately 53.8% of the total energy production.

The electrolyzer played a crucial role in the system, converting surplus renewable power into hydrogen through electrolysis. It had a rated capacity of 0.4 kW and a mean input of 0.0847 kW. The electrolyzer total input energy throughout the year amounted to 742 kWh, with a capacity factor of 21.2%. The mean output of the electrolyzer was 0.00163 kg/hr., and the maximum output was 0.00771 kg/hr., resulting in a total production of 14.3 kg/year.

The simulation of the system's operation over the course of a year showcased its efficiency and performance. The electrolyzer operated for 2307 h/year with 958 starts/year and an expected lifespan of 17.3 years. It had a capacity factor of 6.47% and a fixed generation cost of $0.008/hr. The system's electrical production reached 227 kWh/year, with a mean electrical output of 0.0983 kW. The minimum and maximum electrical outputs were 0.0208 kW and 0.307 kW, respectively. The system consumed 13.6 kg of fuel, with a specific fuel consumption of 0.06 kg/kWh. The mean electrical efficiency was recorded at 50%.

The hydrogen storage tank, with a capacity of 2 kg and an energy storage capacity of 66.7 kWh, demonstrated a tank autonomy of 800 h. At the beginning of the year, the tank contained 0.2 kg of hydrogen, which increased to 0.889 kg by the end of the year. This indicates successful storage and accumulation of hydrogen throughout the year, allowing for the utilization of surplus renewable power during low production periods.

The analysis also included insights into the PV system and the small wind turbine. The PV system had a rated capacity of 0.4 kW, with a mean output of 0.0652 kW and a capacity factor of 16.3%. It generated a total production of 571 kWh/year, with a maximum output of 0.383 kW. The levelized cost of electricity (LCOE) for the PV system was calculated to be $0.201/kWh.

The small wind turbine had a total rated capacity of 0.55 kW, with a mean output of 0.106 kW and a capacity factor of 19.3%. Its total production reached 928 kWh/year, with a maximum output of 0.547 kW. The wind penetration was measured at 127%, indicating the potential for excess energy generation beyond the site's power requirements. The levelized cost of electricity (LCOE) for the wind system was determined to be $0.168/kWh.

The analysis of the renewable energy system highlights the significance of utilizing a combination of PV, fuel cells, small wind turbines, and the hydrogen storage system to provide efficient and sustainable power to a remote

The analysis indicates that the battery bank is currently the more viable option for providing power to the remote site. However, as technology advances and costs change over time, it is essential to continue monitoring and evaluating the performance of both systems. A comprehensive analysis, considering various factors such as site location, energy needs, and available resources, can help determine the most suitable option for providing power to the remote site.

Author Contributions: Conceptualization, M.G.O., G.L. and C.-V.S.; Methodology, G.L. and M.G.O.; Data curation, G.L. and M.G.O.; Writing—review and editing, G.L., M.G.O. and C.-V.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a grant of the Ministry of Research, Innovation, and Digitization, CNCS-UEFISCDI, project number PN-III-P4-PCE-2021-0777, within PNCDI III, contract PCE 5/2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Nikos, H.; Asano, H.; Iravani, R.; Marnay, C. Microgrids: An overview of ongoing research, development, and demonstration projects. *IEEE Power Energy* **2007**, *5*, 78–94.
2. Hashimoto, K.; Kumagai, N.; Izumiya, K.; Takano, H.; Żabiński, P.R.; El-Moneim, A.A.; Yamasaki, M.; Kato, Z.; Akiyama, E.; Habazaki, H. The use of renewable energy in the form of methane via electrolytic hydrogen generation. *Arch. Metall. Mater.* **2013**, *58*, 231–239. [CrossRef]
3. Paleta, R.; Pina, A.; Silva, C.A. Remote Autonomous Energy Systems Project: Towards Sustainability in Developing Countries. *Energy* **2012**, *48*, 431–439. [CrossRef]
4. Anuphappharadorn, S.; Sukchai, S.; Sirisamphanwong, C.; Ketjoy, A.N. Comparison the Economic Analysis of The Battery Between Lithium-Ion and Lead-Acid in PV Stand-Alone Application. *Energy Procedia* **2014**, *56*, 352–358. [CrossRef]
5. Blanco, H.; Faaij, A. A Review of The Role of Storage in Energy Systems with A Focus on Power to Gas and Long-Term Storage. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1049–1086. [CrossRef]
6. Wang, B.; Min, H.; Sun, W.; Yu, Y. Research on Optimal Charging of Power Lithium-Ion Batteries in Wide Temperature Range Based on Variable Weighting Factors. *Energies* **2021**, *14*, 1776. [CrossRef]
7. Van Zyl, A. Review of The Zebra Battery System Development. *Solid State Ion* **1996**, *86–88*, 883–889. [CrossRef]
8. Ruetschi, P.; Meli, F.; Desilvestro, J. Nickel-Metal Hydride Batteries. *Prefer. Batter. Future J. Power Sources* **1995**, *57*, 85–91. [CrossRef]
9. Masuda, M.; Shintomi, T. Superconducting Magnetic Energy Storage. *Cryogenics* **1977**, *17*, 607–612. [CrossRef]
10. Weyers, C.; Bocklisch, T. Simulation-Based Investigation of Energy Management Concepts for Fuel Cell–Battery–Hybrid Energy Storage Systems in Mobile Applications. *Energy Procedia* **2018**, *155*, 295–308. [CrossRef]
11. Ren, G.; Liu, J.; Wan, J.; Guo, Y.; Yu, D. Overview of Wind Power Intermittency: Impacts, Measurements, and Mitigation Solutions. *Appl. Energy* **2017**, *204*, 47–65. [CrossRef]
12. Jain, S.; Chen, H.Y.; Schwank, J. Techno-Economic Analysis of Fuel Cell Auxiliary Power Units as Alternative to Idling. *J. Power Sources* **2006**, *160*, 474–484. [CrossRef]
13. Mousavi, G.S.M.; Faraji, F.; Majazi, A.; Al-Haddad, K. A Comprehensive Review of Flywheel Energy Storage System Technology. *Renew. Sustain. Energy Rev.* **2017**, *67*, 477–490. [CrossRef]
14. Li, T.; Yuan, X.-Z.; Zhang, L.; Song, D.; Shi, K.; Bock, C. Degradation Mechanisms and Mitigation Strategies of Nickel-Rich NMC-Based Lithium-Ion Batteries. *Electrochem. Energy Rev.* **2020**, *3*, 43–80. [CrossRef]
15. Chen, W.; Li, G.; Pei, A.; Li, Y.; Liao, L.; Wang, H.; Wan, J.; Liang, Z.; Chen, G.; Zhang, H.; et al. A manganese–hydrogen battery with potential for grid-scale energy storage. *Nat. Energy* **2018**, *3*, 428–435. [CrossRef]
16. Lin, Y.; Eto, J.H.; Johnson, B.B.; Flicker, J.D.; Lasseter, R.H.; Villegas Pico, H.N.; Seo, G.S.; Pierre, B.J.; Ellis, A. *Research Roadmap on Grid-Forming Inverters (No. NREL/TP-5D00-73476)*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2020.
17. Hossain, T.; Adams, M.; Walker, T.R. Role of Sustainability in Global Seaports. *Ocean Coast Manag.* **2021**, *202*, 105435. [CrossRef]

18. Xavier, L.S.; Amorim, W.; Cupertino, A.F.; Mendes, V.F.; do Boaventura, W.C.; Pereira, H.A. Power converters for battery energy storage systems connected to medium voltage systems: A comprehensive review. *BMC Energy* **2019**, *1*, 1–15. [CrossRef]
19. Inthamoussou, F.A.; Pegueroles-Queralt, J.; Bianchi, F.D. Control of A Supercapacitor Energy Storage System for Microgrid Applications. *IEEE Trans. Energy Convers.* **2013**, *28*, 690–697. [CrossRef]
20. International Renewable Energy Agency. *Electricity Storage and Renewables: Costs and Markets to 2030*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2017.
21. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in Electrical Energy Storage System: A Critical Review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
22. Nielsen, K.E.; Molinas, M. Superconducting Magnetic Energy Storage (SMES) In Power Systems with Renewable Energy Sources. In Proceedings of the IEEE International Symposium on Industrial Electronics, Bari, Italy, 4–7 July 2010; pp. 2487–2492.
23. Mahmoud, M.; Ramadan, M.; Olabi, A.G.; Pullen, K.; Naher, S. A Review of Mechanical Energy Storage Systems Combined with Wind and Solar Applications. *Energy Convers. Manag.* **2020**, *210*, 112670. [CrossRef]
24. Osman, M.G.; Ciupageanu, D.; Stan, A. Analysis of Solar Radiation in Sudan and Optimal Location of Photovoltaic Panels. *U.P.B. Sci. Bull. Series C* **2022**, *84*, 387–401.
25. May, G.J.; Davidson, A.; Monahov, B. Lead Batteries for Utility Energy Storage: A Review. *J. Energy Storage* **2018**, *15*, 145–157. [CrossRef]
26. Das, C.K.; Bass, O.; Kothapalli, G.; Mahmoud, T.S.; Habibi, D. Overview of Energy Storage Systems in Distribution Networks: Placement, Sizing, Operation, and Power Quality. *Renew. Sustain. Energy Rev.* **2018**, *91*, 1205–1230. [CrossRef]
27. Adeagbo, A.P.; Ariyo, F.K.; Makinde, K.A.; Salimon, S.A.; Adewuyi, O.B.; Akinde, O.K. Integration of Solar Photovoltaic Distributed Generators in Distribution Networks Based on Site's Condition. *Solar* **2022**, *2*, 52–63. [CrossRef]
28. Montoya, J.H.; Seitz, L.C.; Chakthranont, P.; Vojvodic, A.; Jaramillo, T.F.; Nørskov, J.K. Materials for Solar Fuels and Chemicals. *Nat. Mater.* **2016**, *16*, 70–81. [CrossRef]
29. Osman, M.G.; Ciupagenau, D.-A.; Lazaroiu, G.; Pisa, I. Increasing Renewable Energy Participation in Sudan. In Proceedings of the 11th International Conference on Renewable Energy Research and Application (ICRERA), Istanbul, Turkey, 18–21 September 2022; pp. 169–173.
30. Arani, A.A.K.; Karami, H.; Gharehpetian, G.B.; Hejazi, M.S.A. Review of Flywheel Energy Storage Systems Structures and Applications in Power Systems and Microgrids. *Renew. Sustain. Energy Rev.* **2017**, *69*, 9–18. [CrossRef]
31. Talaat, M.; Farahat, M.A.; Elkholy, M.H. Renewable Power Integration: Experimental and Simulation Study to Investigate the Ability of Integrating Wave, Solar and Wind Energies. *Energy* **2019**, *170*, 668–682. [CrossRef]
32. Akinyele, D.O.; Rayudu, R.K. Review of Energy Storage Technologies for Sustainable Power Networks. *Sustain. Energy Technol. Assess.* **2014**, *8*, 74–91. [CrossRef]
33. Meah, K.; Fletcher, S.; Ula, S. Solar photovoltaic water pumping for remote locations. *Renew. Sustain. Energy Rev.* **2008**, *12*, 472–487. [CrossRef]
34. Gallo, A.B.; Simões-Moreira, J.R.; Costa, H.K.M.; Santos, M.M.; Santos, M.M.; Dos Santos, E.M. Energy Storage in The Energy Transition Context: A Technology Review. *Renew. Sustain. Energy Rev.* **2016**, *65*, 800–822. [CrossRef]
35. Dowds, J.; Hines, P.; Ryan, T.; Buchanan, W.; Kirby, E.; Apt, J.; Jaramillo, P. A review of large-scale wind integration studies. *Renew. Sustain. Energy Rev.* **2015**, *49*, 768–779. [CrossRef]
36. Jung, W.; Jeong, J.; Kim, J.; Chang, D. Optimization of Hybrid Off-Grid System Consisting of Renewables and Li-Ion Batteries. *J. Power Sources* **2020**, *451*, 227754. [CrossRef]
37. Worku, M.Y.; Hassan, M.A.; Abido, M.A. Real Time Energy Management and Control of Renewable Energy Based Microgrid in Grid Connected and Island Modes. *Energies* **2019**, *12*, 276. [CrossRef]
38. Bortolini, M.; Gamberi, M.; Graziani, A.; Pilati, F. Economic and Environmental BI-Objective Design of an off-Grid Photovoltaic–Battery–Diesel Generator Hybrid Energy System. *Energy Convers. Manag.* **2015**, *106*, 1024–1038. [CrossRef]
39. Chtita, S.; Derouich, A.; El Ghzizal, A.; Motahhir, S. An Improved Control Strategy for Charging Solar Batteries in Off-Grid Photovoltaic Systems. *Sol. Energy* **2021**, *220*, 927–941. [CrossRef]
40. Merei, G.; Berger, C.; Sauer, D.U. Optimization of an off-Grid Hybrid PV–Wind–Diesel System with Different Battery Technologies Using Genetic Algorithm. *Sol. Energy* **2013**, *97*, 460–473. [CrossRef]
41. Triki, Y.; Triki, A.; Bechouche, A.; Abdeslam, D.O.; Porumb, R. An Efficient Battery-Charging algorithm with ANN Based MPPT Method for off-Grid PV Systems. In Proceedings of the 21st International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), Sousse, Tunisia, 19–21 December 2022; pp. 106–111.
42. Perry, M.L.; Fuller, T.F. A historical perspective of fuel cell technology in the 20th century. *J. Electrochem. Soc.* **2002**, *149*, S59. [CrossRef]