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Towards net-zero wastewater treatment: Integrating wind, solar, and hydrogen storage in arid regions

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Abstract: The increasing energy demand and environmental pressures faced by wastewater treatment plants (WWTPs) necessitate the development of sustainable, cost-effective, and flexible energy solutions, especially in arid regions. Addressing a critical research gap in the literature, namely, the limited exploration of long-term hydrogen-based energy storage in real-world wastewater applications, this study proposes an innovative hybrid energy management framework integrating solar, wind, and hydrogen technologies for a WWTP in Lusail, Qatar. Unlike previous studies that relied on solar–wind systems with batteries or theoretical models, this work uniquely employs real operational data and detailed HOMER simulations to validate the techno-economic and environmental benefits of hydrogen integration. Simulation results show that the proposed solar–wind–hydrogen configuration achieves a significant annual CO_2 reduction of 1,534,388 kg, outperforming battery-based systems without storage. The hydrogen-powered system ensures superior long-term energy flexibility, strong economic viability, and notable environmental advantages, offering a scalable model for future sustainable wastewater treatment infrastructure in harsh climates. Overall, the findings provide a practical framework for optimizing energy consumption and advancing energy sustainability in industrial wastewater treatment plants operating in arid and high-demand regions.

Keywords: *Carbon reduction strategies, Combined solar-wind systems, Energy solutions for sewage treatment plant, Energy sustainability, Hydrogen storage, Renewable energy.*

1. Introduction

Today, due to the global expansion of industrialization and urbanization, increasing demands for energy production have emerged [1]. Global energy demand is increasing by 1.6% annually, with nearly 65% of this increase coming from developing countries [2]. In order to ensure a sustainable future and address the growing impacts of climate change, particularly global warming, developing countries are striving to replace traditional energy sources with renewable energy [3]. Among renewable energy sources, wind energy has been historically used for applications such as sailing ships, grain mills, and water pumping, and can be considered one of the most suitable alternatives to fossil fuels [4]. Hydrogen is currently experiencing unprecedented momentum, and the world should not miss the opportunity to make hydrogen a key component of the future of clean energy [5]. Hydrogen can be produced from various sources, such as coal, natural gas, biomass, and through the process of water electrolysis [6]. It is projected that global hydrogen demand will increase from 70 million tons in 2019 to 120 million tons by 2024 [7]. Wind power generation accounts for a significant portion of renewable energy production. The coupling of hydrogen energy with wind power generation can effectively address the issue of surplus energy [8]. One of the weaknesses of wind power plants is the potential for unpredictable fluctuations in output power, which depend on short-term variations in wind speed. To mitigate these negative impacts, a system comprising an electrolyzer, hydrogen fuel cell, and hydrogen storage system can be considered as an energy storage solution, where hydrogen produced

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from wind energy is stored through water electrolysis [9]. It is possible to inject hydrogen into the biogas produced from anaerobic digestion to generate electricity, which can then be used to power a wastewater treatment plant [10]. Hydrogen Sulfide (H_2S) is a colorless gas produced under anaerobic conditions through the decomposition of organic materials. It arises both from natural sources (such as oil and volcanoes) and anthropogenic sources (such as pulp production and oil refining). Anaerobic wastewater treatment plants and decomposition processes in landfills are significant sources of this gas [11]. Proper wastewater treatment and purification are crucial for public health and environmental protection. In the United States, it is estimated that nearly 4% of electricity demand is used for the production and distribution of water, as well as for wastewater collection and treatment. With the increase of wastewater treatment plants (WWTPs) globally and the growing quality requirements for effluent, the issue of energy efficiency from both environmental and economic perspectives has gained significant attention [12]. Wastewater treatment plants are designed to collect and treat waste that includes microplastics (MP), synthetic polymer materials smaller than 5 millimeters, and other small human waste such as particles, fibers, and micro-particles [13]. Renewable energy sources are intermittent and may cause system overload. To address these intermittencies and ensure a balance between energy production and demand, Energy Storage Systems (ESS) are considered an effective option for optimizing energy management and controlling energy spillage [14].

The project aims to improve efficiency, increase security, and reduce the plant's energy load on the power grid and the economic sustainability of renewable energy-based hydrogen production systems in Qatari wastewater treatment plants. This research introduces a pioneering concept of combining hydrogen with renewable energy in real time for wastewater treatment plants (WWTPs) designed in harsh environments such as Lusail, Qatar. As major energy consumers, wastewater treatment plants require innovative solutions to reduce energy costs and increase environmental sustainability. Using real-world operational data from Lusail, Qatar, and comprehensive HOMER simulations, our innovation fills an important gap in this field: it provides a scalable, techno-economically optimized, and environmentally sustainable energy model for wastewater treatment infrastructure in arid and high-demand regions.

2. Literature Review

Nadal et al.[15] in their research, it was concluded that surplus energy from Brazil's hydroelectric and wind power plants, which exceeds the network's demand during certain seasons, could be used for hydrogen production. The results indicate that daily usage of this energy for one hour could generate 6.5 billion cubic meters of hydrogen annually. With an increase in usage time to two or three hours, the production would rise to 13 and 20 billion cubic meters per year, respectively. Nagasawa et al. [16] in their study, it was concluded that hydrogen production from wind energy over time was analyzed using a linear programming model. This model aims to maximize revenue by making decisions between hydrogen production and electricity sales to the grid. The hydrogen demand in the United States is estimated to be 53.3, 5.3, and 3.9 billion kilograms per year, respectively. Bernardo et al. [17] in their study introduced four types of membranes for hydrogen separation were introduced. Carbon molecular sieve membranes are produced by carbonizing polymer materials and allow hydrogen to pass through. Ionic liquid-based membranes possess properties such as no vapor pressure and the ability to adjust chemical characteristics for gas separation. Palladium membranes and their alloys are used for hydrogen purification due to their high selectivity. Additionally, electrochemical hydrogen pumps separate hydrogen from gas streams and exhibit high efficiency in producing pure hydrogen. Aasadnia et al. [18] in their research a new module for hydrogen separation from gas mixtures containing nitrogen and hydrocarbons in their research. In this method, the gases are first converted into hydrogen-rich and hydrogen-poor streams using a heat exchanger and phase separators. Subsequently, the purification process is carried out using cryogenic technology, enabling the production of high-purity hydrogen. Mohsin et al. [19] the study examined hydrogen production from wind energy, which is economically feasible. The cost of electricity generation from wind is estimated to be between 0.0862 and 0.0868 USD per kilowatt-hour, while the cost of renewable hydrogen production is estimated to range from 5.30 to 5.80 USD per kilogram of energy. Hdidouan and Staffell [20] in their research, they examined wind speed and its impact on wind energy production. Wind speed was modeled using the Weibull distribution. The capacity for wind energy production in UK farms was calculated with an average capacity factor of 29%, or 2540 full load hours per year. This is equivalent to producing approximately 100 gigawatt-hours of electricity annually for a 40-megawatt wind farm, with wind speed fluctuations affecting the economic revenues. Xu et al. [21]'s life cycle assessments of onshore wind power plants in China have shown that these plants have lower environmental impacts compared to coal and natural gas power plants. For example, the Saihan wind farm consumes only 0.8% of carbon dioxide and 0.6% of fossil energy per kilowatt-hour of electricity produced. However, there is room for improvement in areas such as ozone layer depletion and the reduction of mineral resources. Mendecka and Lombardi [22], according to the research conducted using the Life Cycle Assessment (LCA) method, all stages from raw material extraction to production, transportation, usage, and end-of-life of turbines were examined. This assessment was performed for onshore wind turbines (ranging from 1 to 5000 kW) and offshore turbines (ranging from 500 to 8000 kW). The results indicate that wind conditions (speed and wind class), particularly for smaller turbines, have a greater impact on environmental effects. However, in larger systems, this impact diminishes. Qandil et al. [23] showed that by combining EEOs (11%), CHP (42%), solar PV (29%), and water turbines (15%), a 1.5 MGD wastewater treatment plant can fully meet its energy needs and achieve net-zero energy status. Erdal et al. [24] found in their study that the use of a microgrid led to a 1883.8% reduction in emission rates and prevented the emission of 770,039 kg of hazardous gases. Additionally, battery costs were identified as the most expensive component of the system, with expected future reductions in battery prices contributing to a decrease in the overall project cost.

Gu et al. [25] conducted research, two main methods for energy self-sufficiency in wastewater treatment plants have been introduced: energy recovery from the wastewater treatment process and the use of energy-saving technologies. Chemical energy recovery from sludge and biogas production for electricity and heat generation in combined heat and power (CHP) systems is among these methods, which can reduce costs and generate surplus energy. Additionally, the use of anaerobic ammonium oxidation technology contributes to energy savings. Li et al. [26] this study designed a wind-solar hybrid system and a biological reactor without batteries using a step-feed method, effectively providing energy for rural wastewater treatment. With an average energy efficiency of 80%, the system has improved the removal efficiencies of chemical pollutants, including Chemical Oxygen Demand (COD) (90.2%), ammonia (94.3%), nitrogen (61.4%), and phosphorus (63.1%), contributing to the reduction of groundwater and surface water pollution. Subedi et al. [27] this study investigated the presence and removal of pharmaceuticals and personal care products (PPCPs) in two wastewater treatment plants in southern India. A total of 29 drugs and 6 metabolites were identified and quantified. The Mangalore treatment plant, utilizing the Upflow Anaerobic Sludge Blanket Reactor (UASBR) system, was able to remove up to 95% of PPCPs, whereas the Udupi treatment plant was unable to fully remove certain drugs, such as carbamazepine and diazepam. Woods et al. [6] in their study, it was concluded that the wastewater treatment plant in Sydney generates 37.6 million liters of non-reusable effluent daily, which has the potential to produce 420,000 tons of hydrogen per day or 0.88 million tons of hydrogen per year. Meng et al. [8] in their study, they concluded that the wind-hydrogen system can store excess electricity and compensate for electricity consumption during shortages. The excess electricity difference between standalone and coupled systems was reduced by a factor of 19.5, and the electricity shortage difference was reduced by a factor of 1.54. Bonacina et al. [28] they conducted a techno-economic evaluation of a hydrogen production plant using offshore wind energy for fueling ships. The wind power plant capacity needs to be above 150 MW for the payback period to decrease to under 11 years, and the fixed price of hydrogen is approximately 6 euros. Ayodele et al. [29] they conducted a techno-economic evaluation of hydrogen stations powered by wind energy in South Africa, where the cost of hydrogen production ranges from 6.34 to 8.97 dollars per kilogram. These stations could reduce

73.95 tons of C_2O and 0.133 tons of CO annually. van der Roest et al. [30] studied a neighborhood where solar energy is stored as both heat and hydrogen, and rainwater is collected and treated. As a result, an 8.7 MW solar park could meet the heating needs of 900 homes and provide half of their water consumption, while also supplying the hydrogen needed for 540 hydrogen vehicles. Tazi et al. [31] used the Material Flow Analysis (MFA) model to examine and quantify the material and waste flows of wind turbines at the end of their life in the Champagne-Ardenne region of France between 2002 and 2020. They highlighted the production of over one million tons of waste and the recycling challenges and logistics costs due to the lack of recycling facilities in France. According to Heng et al. [32], it is predicted that by 2050, Canada will face the disposal of 275,299 tons of wind turbine blade waste. To manage this waste, five methods were considered: landfill disposal, incineration with municipal waste, incineration in cement kilns, mechanical recycling with disposal or incineration of the remaining waste. While mechanical recycling requires additional support and investment, incineration in cement kilns, as a more economical option, could also contribute to reducing net greenhouse gas emissions.

Brandoni and Bošnjaković [33] in their study concluded that integrating renewable energy technologies could meet up to 74% of the energy needs of wastewater treatment facilities, thereby reducing energy costs. Regarding water reuse, the solutions only cover up to 13% of the energy needs of the facilities. The main gap identified is the high investment costs and limitations of local renewable energy sources, such as biogas, which result in lower efficiency in wastewater treatment for reuse. Halaby et al. [34] in their research, they conducted a sensitivity analysis of a standalone micro-power system designed to supply energy to a wastewater treatment plant, comparing it with conventional power systems. Previous research on powering wastewater treatment plants (WWTPs) has largely focused on integrating solar and wind power with battery storage systems or on theoretical modeling of renewable energy without real-world validation. However, the potential for long-term hydrogen-based energy storage, especially in harsh, arid environments like Qatar, has been largely overlooked, particularly for real-world industrial wastewater applications.

Implementation and evaluation of a real-site hybrid system combining solar, wind, and hydrogen storage technologies, specifically designed for a wastewater treatment plant in Lusail, Qatar. Using real-world operational data (not just theoretical models) to conduct a rigorous techno-economic and environmental assessment through HOMER simulations. Demonstrating the superiority of hydrogen storage over traditional battery systems for long-term reliability, cost reduction, and carbon emission reduction in wastewater treatment plants under extreme weather conditions. By innovatively combining hydrogen storage and renewable energy in a real-world operational context, this paper bridges the gap between clean energy theory studies and industrial applications in challenging environments. This ultimately enables techno-economic optimization, providing a model for achieving Net Zero Water-Energy in the industrial sector.

3. Mathematical Representation

In Mathematical Expression (1) k The parameter is a shape that measures the extent of the distribution. c The scale parameter is close to the mean wind speed. $\boldsymbol{u}$ It is the wind speed, measured in meters per second, and is used to estimate wind characteristics and predict energy production potential. This equation represents the probability density function of the Weibull distribution, which is used to analyze wind speed patterns and estimate wind energy production potential [19].

$$f(u)=\frac{k}{c}\left(\frac{u}{c}\right)^{k-1}\times\exp\left(\frac{-u}{c}\right)^{k} \quad (1)$$

In Mathematical Expression (2), Capex represents the capital expenditure (investment cost), CFR refers to the fixed cost rate, Opex stands for operating costs, and AEP indicates the annual net energy production. This equation calculates the Levelized Cost of Energy (LCOE), which represents the average cost per unit of electricity generated over the lifetime of an energy project [19].

$$LCOE=\frac{(\text{Capex}\times\text{CFR})+\text{Opex}}{\text{AEP}} \quad (2)$$

In Mathematical Expression (3), EI is the environmental impact, PC is the rated capacity of the wind turbine (in kilowatts), and C_2 and $C_1$are model coefficients fitted using the nonlinear regression method [22].

$$EL=C_1\times P^{C_2} \quad (3)$$

In Mathematical Expression (4), t represents the value of the investment in years or the time period. Revenue: The amount of money the project generates in each time period (e.g., electricity sales). Costs: Operating expenses, taxes, interest, and other related costs [35].

$$CF=\sum_{t=0}^{n}(\text{ earinings-costs})_t \quad (4)$$

In Mathematical Expression (5), CF represents the cash flow in year t, and r is the discount rate or the expected rate of return. represents the total initial investment costs, and n is the number of time periods or analysis years [35].

$$NPV=\sum_{t=0}^{n}\frac{CF_t}{(1+r)^t}-I_0 \quad (5)$$

In Mathematical Expression (6), CF represents the cash flow in year t, and r is the discount rate or the expected rate of return. I_0represents the total initial investment costs [35].

$$\sum_{t=0}^{n}\frac{CF_t}{(1+r)^t}-I_0=0 \quad (6)$$

In Mathematical Expression (7), U_{EL}represents the total output voltage, and the number of electrolyzers in series, denoted byN_{el}indicates the number of electrolytes connected in series within a circuit [8].

$$U_{EL}=N_{el}U_{el} \quad (7)$$

In Mathematical Expression (8), the amount of electrical energy consumption in the wastewater treatment process is typically measured in kilowatt-hours (kWh) per volume of treated wastewater, usually expressed in cubic meters (m^3), which is used to calculate the energy efficiency of the process [36].

$$KPI=\frac{\text{electric energy consumption}}{\text{volume of traeted wstewater}} \quad (8)$$

In Mathematical Expression (9), BOD is a measure of the amount of oxygen consumed by microorganisms to degrade organic matter in wastewater [37].

BOD=Sewage discharge*the B.O.D. concentration of raw sewage (9)

In Mathematical Expression (10), η_{el}represents the efficiency of the system in hydrogen production. HHV It is the higher heating value of hydrogen, measured in kilojoules per mole (kJ/mol). W_{el}It is the amount of electrical energy consumed by the electrolyzer, with its unit being kilowatt-hours (kWh). This formula is employed in the process of water electrolysis for hydrogen production [8].

$$\eta_{el}=\frac{HHV.M_{h2.el}}{W_{el}} \quad (10)$$

In Mathematical Expression (11), it refers to the efficiency or effectiveness of the system in producing products such as treated water, biogas, or even by-products derived from treatment processes [38].

$$\text{Product Performance}=\frac{\text{producing product}}{\text{area under cultivation}} \quad (11)$$

In Mathematical Expression (12), M_{h2el}The mass of hydrogen produced in the process is measured in kilograms (kg). μ_{el}It is the electrical efficiency of the system. I_{el} It is the electric current used by the electrolyzer, with its unit being amperes (A). F is an electromagnetic constant in electrochemical equations, with its unit being coulombs per mole (C/mol) [8].

$$M_{h2el}=\frac{\mu_{el}I_{el}}{2F} \quad (12)$$

In Mathematical Expression (13), to determine the hydrogen pressure in the hydrogen reservoir [29].

$$Q=(\frac{R\times T}{V_{ht}})\times n_{ht} \quad (13)$$

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In Mathematical Expression (14), to evaluate the removal efficiency of microplastics (RE%) in wastewater treatment plants (WWTP), the concentration of microplastics in both the influent and effluent is calculated to assess the reduction in pollution and the effectiveness of the treatment system [13].

$$RE=C\left[\frac{C_{MP,infl}-C_{MP,effl}}{C_{MP,infl}}\right]\times 100\% \quad (14)$$

In Mathematical Expression (15), in this study, the concentration of suspended solids in the wastewater is weighted over time, taking into account varying flow rates [39].

TSS=Sewage discharge*the T.S.S concentration of raw sewage (15)

In Mathematical Expression (16), to assess the flow rate in microliters through the treatment plant, the flow rate in microliters (Q) for each treatment stage is calculated by multiplying the average concentration in microliters (C) by the average flow rate (Q)[40].

$$ML=C\times Q \quad (16)$$

4. Methodology

Figure 1presents a clear, step-by-step methodology for simulating hybrid renewable energy systems.

The flowchart begins with the collection of environmental data, followed by the definition of system components (PV, wind turbine, hydrogen, and battery), configuration of the HOMER software with technical and economic parameters, simulation of multiple scenarios, and finally, analysis and comparison of results based on cost, emissions, and energy balance.

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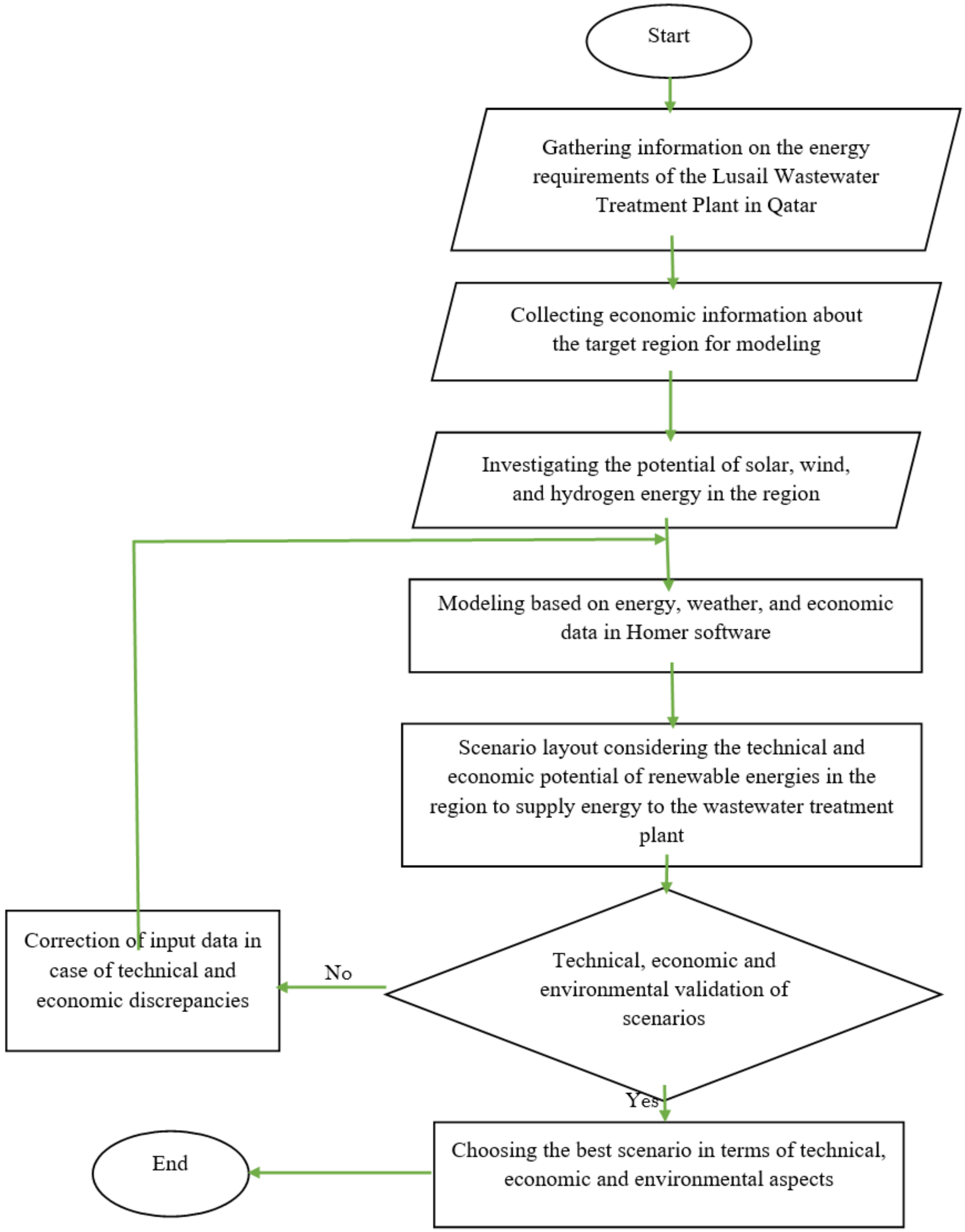

Figure 1.
Structured simulation workflow for evaluating hybrid renewable systems in wastewater treatment.

In this study, the HOMER software is used as the main tool for simulation and analysis. This software was chosen due to its high accuracy in simulation, its ability to conduct economic analysis, and its capacity to evaluate various scenarios. HOMER is a powerful tool for the design and optimization of hybrid energy systems. It helps simulate and evaluate an optimal combination of wind, solar, hydrogen, and battery energy resources to reduce costs and increase system efficiency. It is capable of performing technical, economic, and environmental analyses, including estimating capital costs, operational costs, and financial savings.

In this study, real monthly average data for solar radiation and wind speed were retrieved from the HOMER database, representing the climatic conditions in Lusail, Qatar. Three different energy system configurations (scenarios) were designed and simulated to compare their technical, economic, and environmental performance. The scenarios included:

(1) a base model (Solar+Wind)

(2) (Solar + Wind +Battery storage),

(3) (Solar + Wind + Hydrogen)

The economic parameters listed in Table 1 provide the basic assumptions for the techno-economic assessment of the integration of renewable energy sources (wind, solar, and hydrogen storage) in the wastewater treatment plant in Lusail, Qatar. These parameters directly influence the modeling results, investment feasibility, and long-term sustainability of the proposed system.

The discount rate reflects the project's cost of capital and the required rate of return for stakeholders, given the investment risk profile. The rate of 6.25% is relatively conservative and is in line with typical values used in the evaluation of renewable energy projects, especially in emerging markets where perceived risks (policy, market, technology) are higher than in more mature markets.

The inflation rate of 2.70% is consistent with recent global trends and regional expectations. Inflation affects both operating costs and revenue streams over the life of the project, making its inclusion essential for realistic financial modeling.

The grid electricity price of $0.036 per kWh is relatively low, reflecting the subsidized or regulated electricity tariffs common in the Gulf region. This pricing structure highlights the importance of on-site energy optimization and storage (such as hydrogen), as external revenue from grid electricity sales will not contribute significantly to the project's economics. The scaled annual average energy demand of 30,000 kWh per day reflects the significant and ongoing energy needs of an industrial wastewater treatment plant. This high demand level justifies the need for robust, reliable, and flexible energy solutions, such as integrating renewable generation with long-term hydrogen storage, to ensure operational stability and cost control.

Table 1.
Economic parameters of this study.

Economic indicators specific to this study area	**Quantity**
Discount rate	6.25%
Inflation rate	2.70%
Grid Power Price($/kWh)	0.036
Inflation rate Grid Sellback Price($/kWh)	0.035
Project life time (years)	20
Scaled annual average (kWh/days)	30000

As shown in *Figure 2*, Lusail is a new and advanced city in Qatar that is currently under development. This area faces hot and dry climatic conditions. Qatar, due to the scarcity of natural water resources and its heavy reliance on seawater and water treatment processes, requires advanced technologies, as it faces challenges in providing potable water and managing wastewater. Therefore, to meet the energy needs of the treatment plant and reduce dependence on fossil energy, the use of renewable energy sources such as solar, wind, and hydrogen could be considered, since in Lusail, the solar radiation is constant, and wind speeds are suitably high, making it possible to effectively generate energy from these sources.

Figure 2.
A view of the Lusail wastewater treatment plant, Qatar.

The PLC board acts as the central controller in this project, responsible for monitoring and coordinating the various components of the system. A Programmable Logic Controller (PLC) is an industrial digital computer specifically designed to control and automate complex processes, such as those found in wastewater treatment plants and renewable energy systems. This system includes solar panels and wind turbines for electricity generation, water treatment processes for pollutant removal, and hydrogen production from water. The PLC board intelligently manages the energy produced from renewable sources, directing surplus energy to batteries for storage or for reuse in various processes when needed. Given the region's limited water resources and the necessity of utilizing clean energy, this hybrid system can serve as a sustainable solution for managing both water and energy resources.

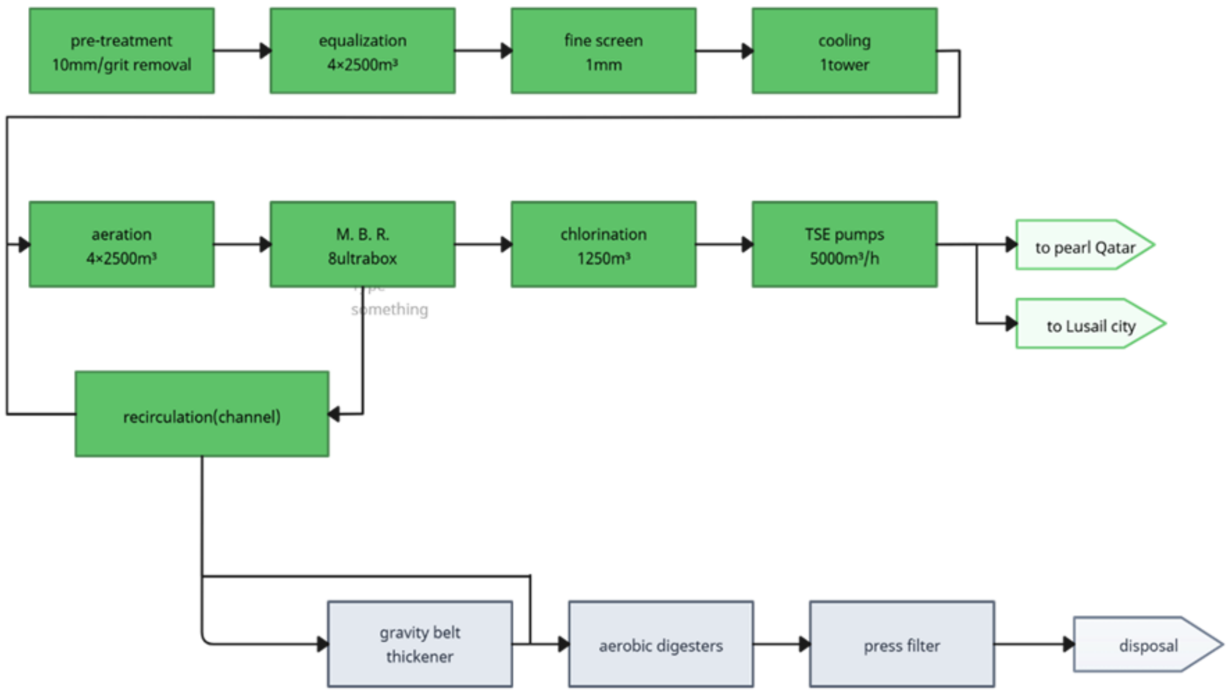

Figure 3.
Process flow diagram of the treatment plant.

Figure 3 illustrates the step-by-step process of wastewater treatment at the Lusail Treatment Plant in Qatar.
This process is divided into two main components: wastewater treatment and sludge management.

5. Results

The treatment plant has been in operation since 2013 under challenging climatic conditions, operating with high quality and focusing on the removal of microbial pollutants. This plant uses Membrane Bioreactor (MBR) technology to combine biological treatment and filtration, providing recycled water for the irrigation of green spaces and Pearl Island in Qatar. The project is designed with the aim of environmental protection, reducing environmental impacts, and ensuring sustainable resource management.

In line with ensuring sustainable energy and reducing environmental impacts, three different scenarios for the utilization of renewable energy in wastewater treatment plants have been evaluated. These scenarios have been designed considering climatic conditions, access to renewable resources, economic costs, and environmental benefits. Each scenario has its own specific advantages and limitations.

5.1. Scenario 1: Solar and Wind Energy

This system, combining solar and wind energy, is designed to meet electrical load demands. Excess energy is sold to the grid, while energy is purchased from the grid during periods of low production, enhancing system stability and efficiency.

Fig. 4 shows the performance of the solar system over the course of one year. The nominal capacity of the solar panels is 500 kW. This reduction in production is due to fluctuations in solar radiation intensity during the day and seasonal changes. Fig. 4 displays the distribution of the solar panel output power across different hours of the day and throughout the year. Lighter colors represent higher power production, while darker colors indicate lower or no power generation. This pattern shows that the highest power production occurs during midday hours and in seasons with greater solar radiation. Conversely, at night or on cloudy days, power production approaches its minimum or zero.

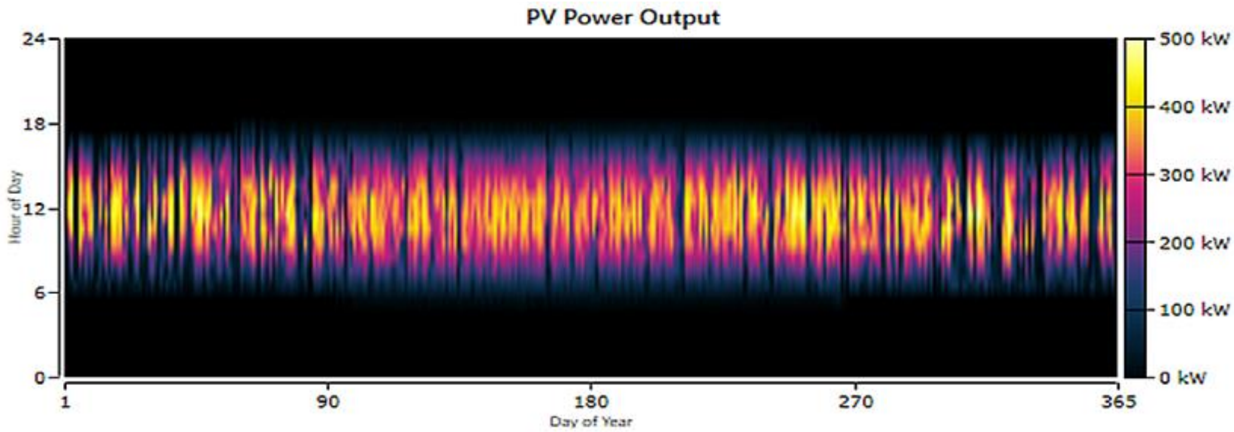

Figure 4.
Solar PV power generation at different hours of the day and days of the year

Figure 5 shows the horizontal axis representing the days of the year and the vertical axis representing the hours of the day. Power production variations are indicated based on a color scheme, where lighter colors such as yellow and red represent higher power generation, while darker colors such as blue and green signify lower output. In conditions where the wind completely stops or is very weak, sections of the chart turn entirely black, indicating zero power output. The average power is shown to be 947 kW, which indicates a relatively stable performance of the turbines throughout the year. The distribution of colors along both the horizontal and vertical axes illustrates the dependence of power generation on factors such as seasonal changes, weather conditions, and time of day. During certain time periods, power generation significantly increased, especially during midday hours or in seasons with higher wind speeds.

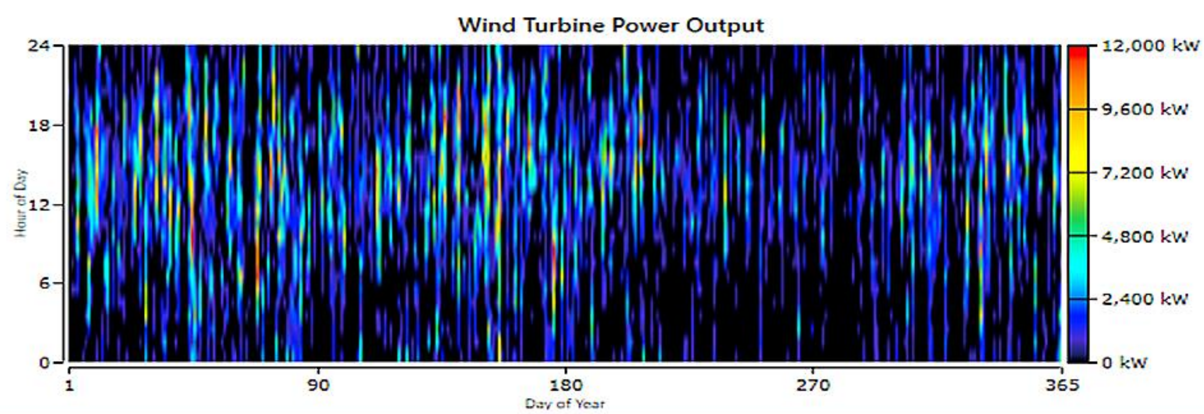

Figure 5.
Wind turbine output power at different hours of the day.

Figure 6 illustrates the variations of the primary electrical load (AC Primary Load), the supplied load (AC Primary Load Served), and the unmet electrical load over the course of a year. The primary electrical load fluctuates within a certain range as the overall system demand, and its value is influenced

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by various factors such as seasonal changes and environmental conditions. The supplied load effectively matches the primary load, indicating the system's optimal performance in meeting consumer demands. The light blue area in the chart represents the primary demand load, which appears constant and stable throughout the year. The average load typically varies between 500 and 2500 kW.

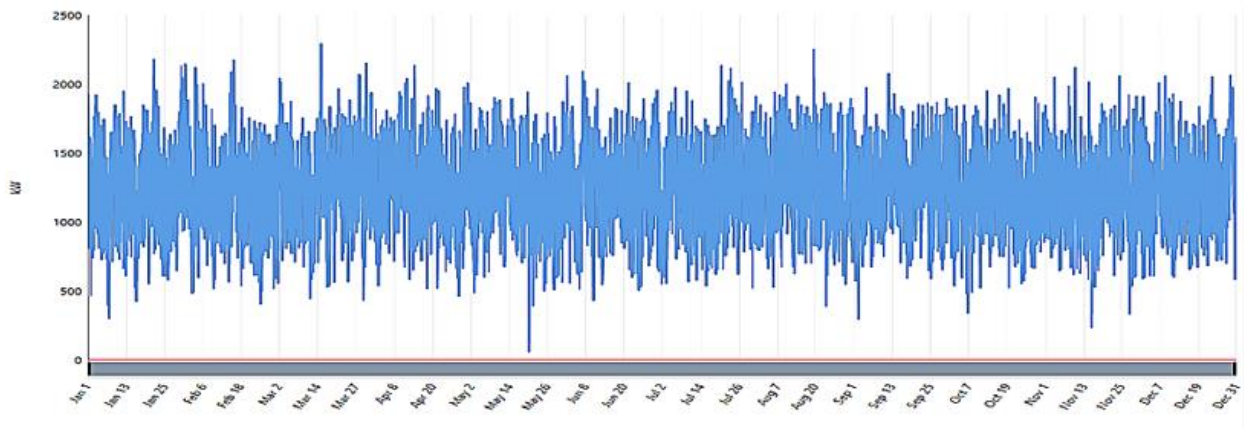

Figure 6.
Analysis of the initial electrical load and its supply in the primary electrical system.

Table 2 shows that the annual carbon dioxide emissions amount to 3,980,983 kilograms per year. This figure represents the primary pollutant generated from the use of non-renewable resources in the system. This amount can be reduced by increasing the share of renewable energy in the system. Furthermore, the absence of carbon monoxide emissions indicates that the system does not use production sources that generate incomplete combustion. The lack of particulate emissions signifies the system's cleanliness in terms of pollutants, suggesting that the system either has complete combustion or limited use of fossil fuels. The annual sulfur dioxide emissions amount to 17,259 kilograms, primarily produced from the use of grid electricity. Additionally, 8,441 kilograms of nitrogen oxides are emitted annually as secondary pollutants from the combustion of fossil fuels in grid electricity generation. These gases have significant environmental impacts.

Table 2.
Annual analysis of carbon dioxide emissions.

Quantity	Value	Units
Carbon Dioxide	3,980,983	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	17.259	kg/yr
Nitrogen Oxides	8.441	kg/yr

5.2. Scenario 2: Solar, Wind, and Battery Energy

Figure 7 shows the monthly average global solar radiation. Solar radiation peaks during the summer months and reaches its lowest value in the winter months. This decrease is due to the lower angle of solar radiation, shorter daylight hours, and the increased likelihood of cloud cover during these seasons. This pattern clearly demonstrates the impact of seasonal changes on solar radiation levels. The increase in solar radiation during the summer may be attributed to the higher angle of solar radiation and longer daylight hours.

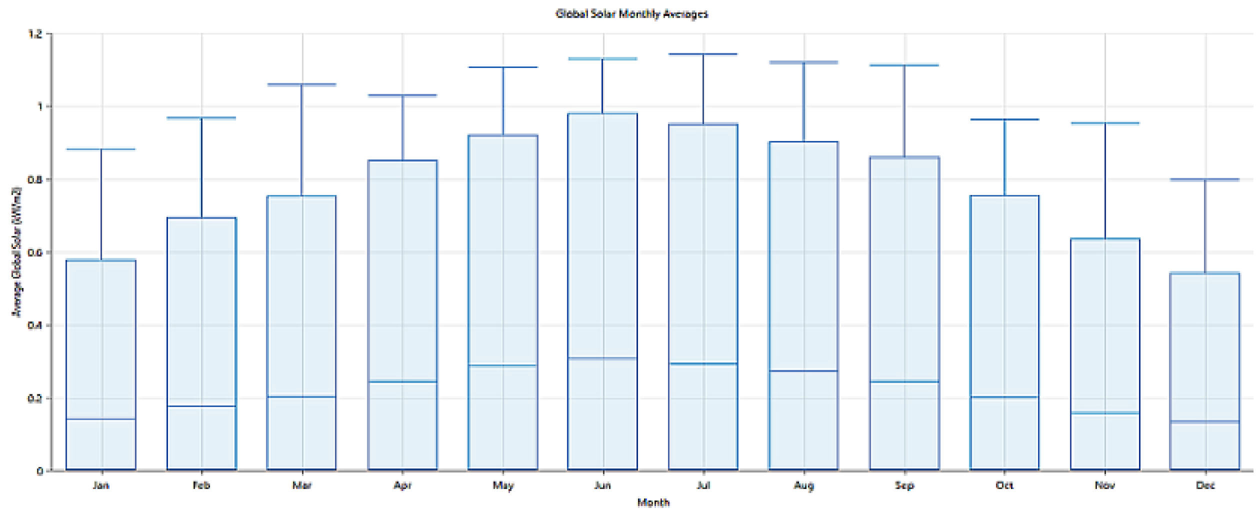

Figure 7.
Monthly average of global solar radiation and seasonal variations.

According to Figure 8, the system is designed to handle an electrical load of 30,000 kWh per day. The rated power of the wind turbine is 1500 kW (G1500), while the battery storage has a capacity of 1 kWh. This configuration represents a modern approach to energy management that prioritizes the integration of renewable resources while maintaining grid connectivity for reliability. Such hybrid systems are increasingly important in the transition to more sustainable energy infrastructures while ensuring a continuous supply of electricity to meet demand needs.

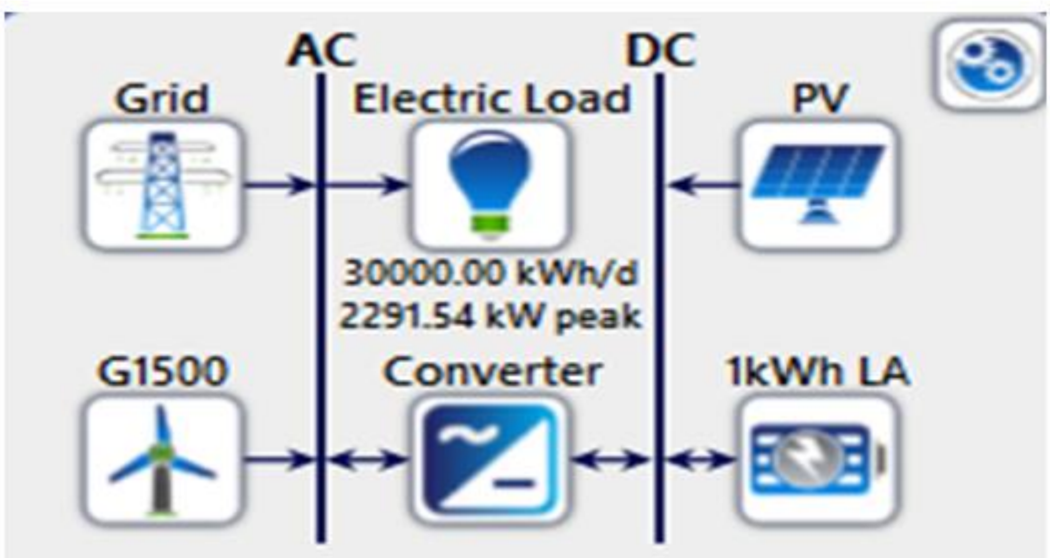

Figure 8.
Analysis of the performance of the combined solar and wind system for electrical load supply.

Figure 9 illustrates the amount of energy sold to the grid throughout the year. The highest sales occur during the day, particularly around midday, when solar energy production peaks. The colors represent the amount of energy sold, varying from 0 kW (blue) to 12,000 kW (red). The highest amount

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of energy sold to the grid typically occurs when local energy production exceeds consumption, and the surplus energy is fed back into the grid.

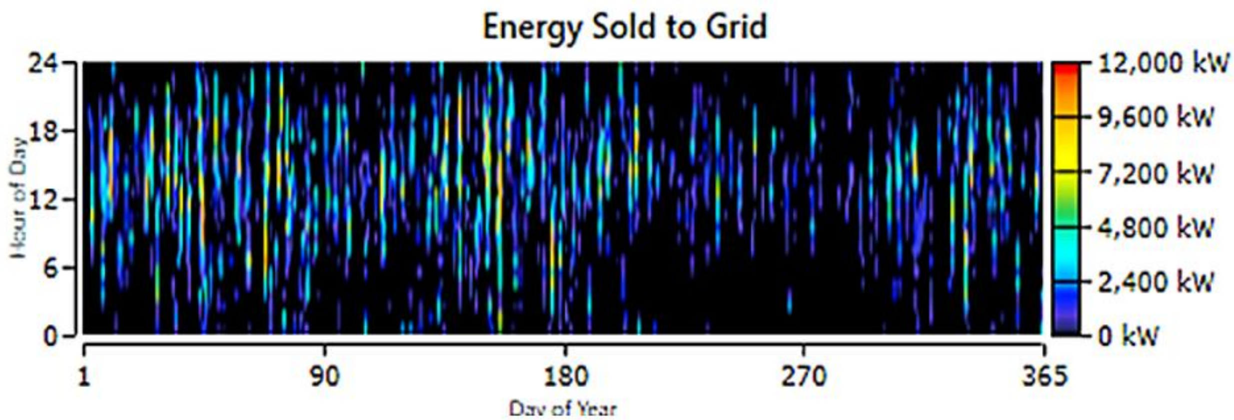

Figure 9.
Energy sales to the grid.

Figure 10 examines the electrical load and its interactions with the power grid throughout the year. The total electrical load is shown in black. The light blue section represents the amount of electricity that the system purchases to meet the electrical load; these values indicate the need for grid support during periods of reduced renewable energy production or increased demand. The sales to the grid are depicted in green. The total electrical load varies throughout the year, increasing in the colder months and decreasing in the warmer months. This increase in winter is due to the higher demand for heating and the use of heating devices.

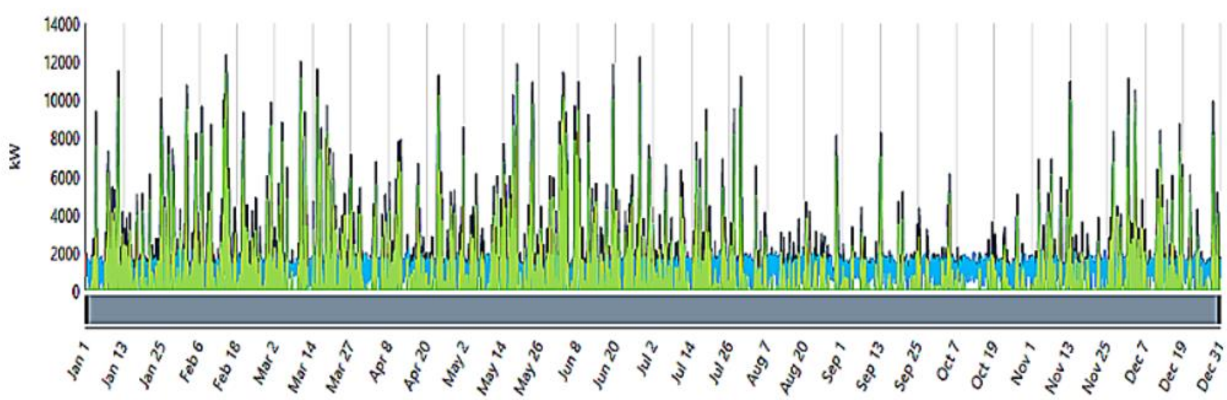

Figure 10.
Electrical load supply from the grid and electricity sales to the grid.

Figure 11 shows a time series analysis that presents data on AC primary load, grid purchases, PV panel output, battery input power (1 kWh), and battery state of charge (1 kWh). The AC primary load values, shown in dark blue, reflect the primary load provided by the system and indicate the relative stability of the primary load over time. Grid purchases, shown in light blue, represent energy supplied to cover shortfalls during periods of insufficient generation from renewable sources. PV power output is shown in yellow, and battery input is shown in brown. This chart allows us to analyze the variations in electrical load and interactions with the power grid throughout the year.

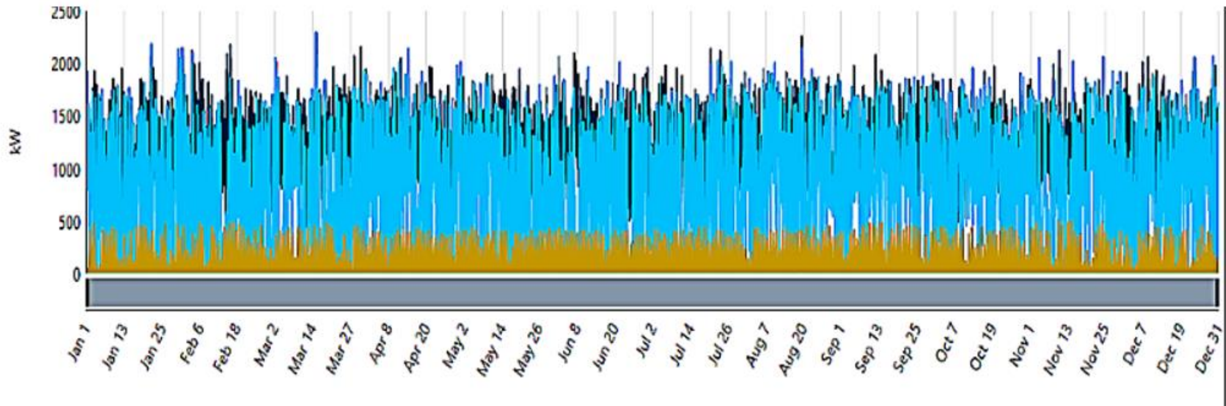

Figure 11.
Analysis of the initial load supply time and electricity purchase from the grid.

Figure 12 shows the amount of energy purchased from the grid throughout the year. The amount of energy purchased ranges from 0 kW (blue) to 2,500 kW (red). The highest purchases from the grid occur during months when local energy production is insufficient, and there is a need to supplement energy from the external grid. Energy purchases from the grid are irregular and intermittent throughout the year, but the frequency and intensity of purchases increase during times when renewable energy production decreases. This behavior results from reduced solar system efficiency at night or on cloudy days and from decreased wind speed in certain seasons.

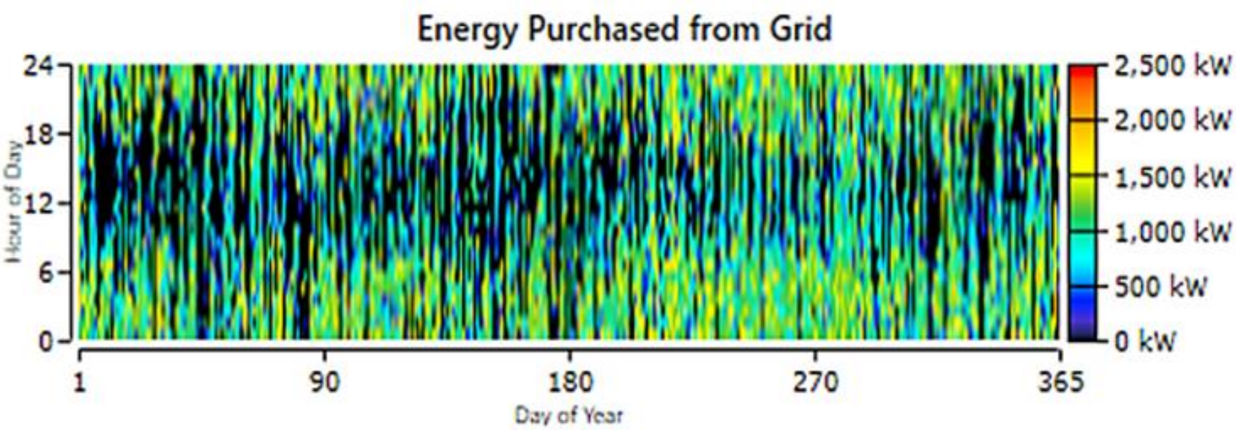

Figure 12.
Power consumption is purchased from the electrical grid.

Figure 13 shows the percentage of renewable energy penetration as well as the renewable energy output in kilowatts. The renewable energy penetration, highlighted in green, is typically above 50% for most periods, and in some instances, it reaches 100%. This indicates the renewable system's ability to fully supply the load at certain times. The fluctuations in penetration are likely linked to variations in the production of renewable resources such as wind or solar. The renewable energy output, shown in yellow, follows a variable production pattern and generally matches the total load. When renewable energy output decreases, the system is likely to rely on other sources to meet the load demand.

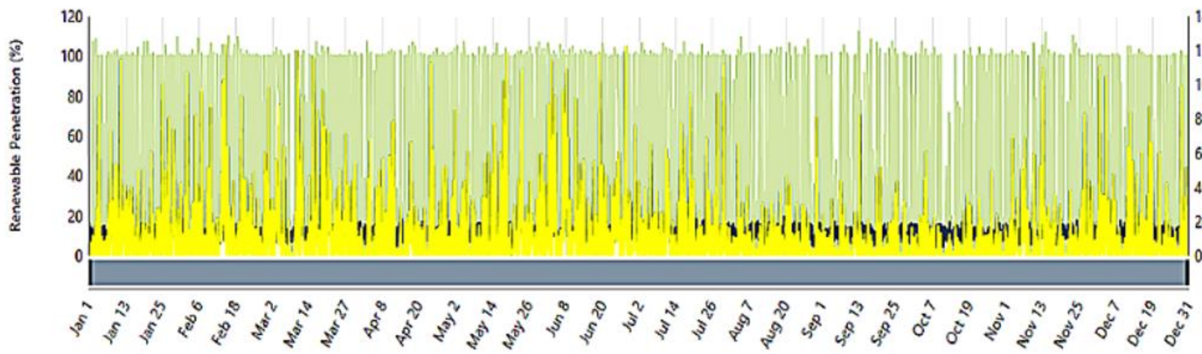

Figure 13.
Time variation analysis of renewable energy generation in the energy system.

5.3. Scenario 3: Solar, Wind, and Hydrogen Energy

This section analyzes the operation of a hydrogen production system utilizing solar and wind energy. Excess energy generated by these renewable sources is employed for hydrogen production through an electrolyzer. The produced hydrogen is then stored in a reservoir to be used for electricity supply or battery charging during periods of demand.

At this stage, as shown in Fig. 14, an electrolyzer with a capacity of 6000 kW is used to convert the excess energy from solar or wind sources into hydrogen. The hydrogen storage tank is considered to have a capacity of 700 kg to store the produced hydrogen for use during times of low or no energy production (such as periods without generation). This is because the tank must be large enough to store the necessary energy during periods of production shortfall. Eventually, the hydrogen fuel cell converts the stored hydrogen into electricity, which is used to supply the consumption load or charge the batteries. The addition of the hydrogen system increases both the initial costs and operational and maintenance costs.

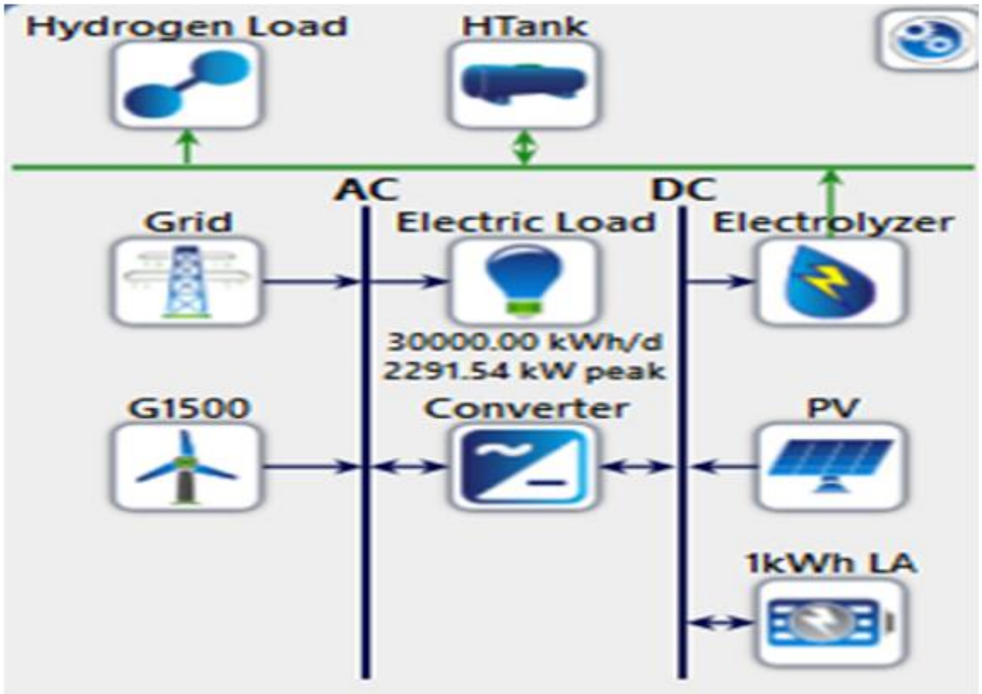

Figure 14.
Operational layout of the hydrogen production system using solar and wind energy.

Figure 15 illustrates the hydrogen production and consumption by the electrolyzer in a hybrid energy system. Hydrogen production is nearly uniform throughout the months of the year, which is due to the proper design of the electrolyzer's capacity, energy sources, and hydrogen storage. The designed hybrid system has achieved stable performance with a high penetration of renewable resources (92.6%) and grid participation, resulting in system alignment with carbon reduction and environmental sustainability goals. The hydrogen production by the electrolyzer amounts to 208,527 kg per year, which exactly matches its consumption of 207,945 kg per year, with zero excess hydrogen, indicating a precise balance between production and consumption.

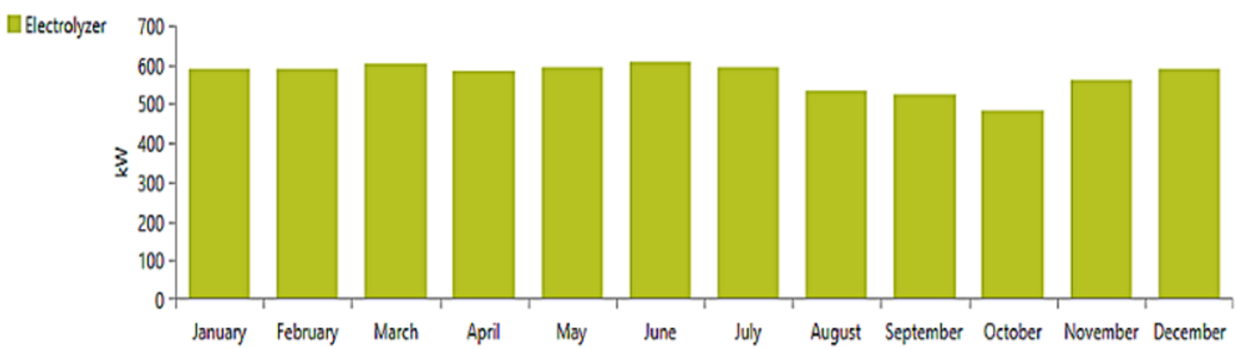

Figure 15.
Analysis of hydrogen production and consumption in the hybrid energy system.

Figure 16: Unlike the inverter, the rectifier operates nearly continuously throughout the day and night. The maximum output power of the rectifier is 2,364 kW, indicating that, during certain periods,

the full capacity of the rectifier is being utilized. Its output power remains high during nighttime, likely due to energy being supplied by the grid. The lighter colors indicate that the rectifier often operates close to its maximum capacity. In this chart, dark colors represent low power (0-500 kW), while the bright yellow and orange colors represent high power (up to 2,500 kW).

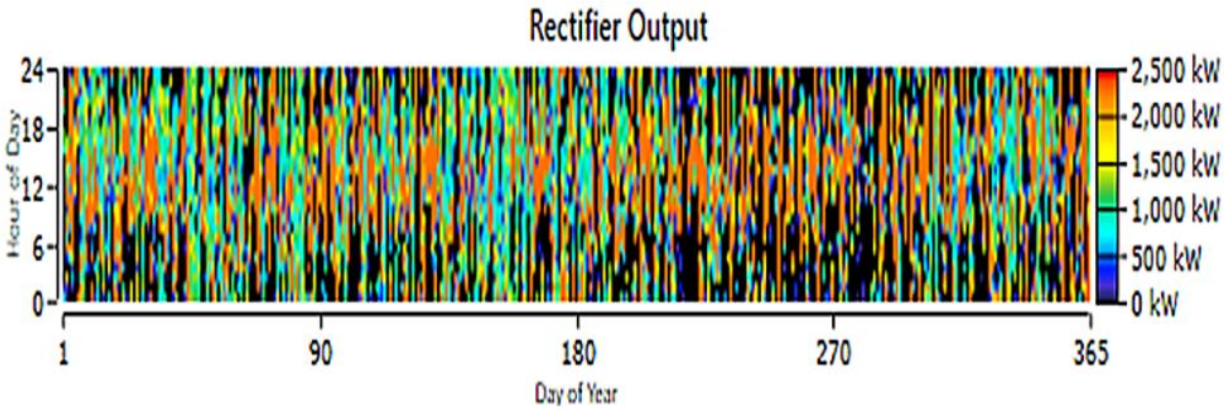

Figure 16.
Rectifier output in the hybrid energy system for hydrogen production.

In Figure 17, these colors represent different amounts of energy purchased from the grid. Black or dark colors indicate energy purchases close to zero, while yellow and red colors represent high energy purchases (2,500 kW). The blue section indicates low or no dependence on the grid, likely related to energy production from renewable sources or energy storage during these periods. More energy is typically purchased at night, which may be due to the reduction in solar energy production at night and the system's reliance on the grid to meet electricity needs.

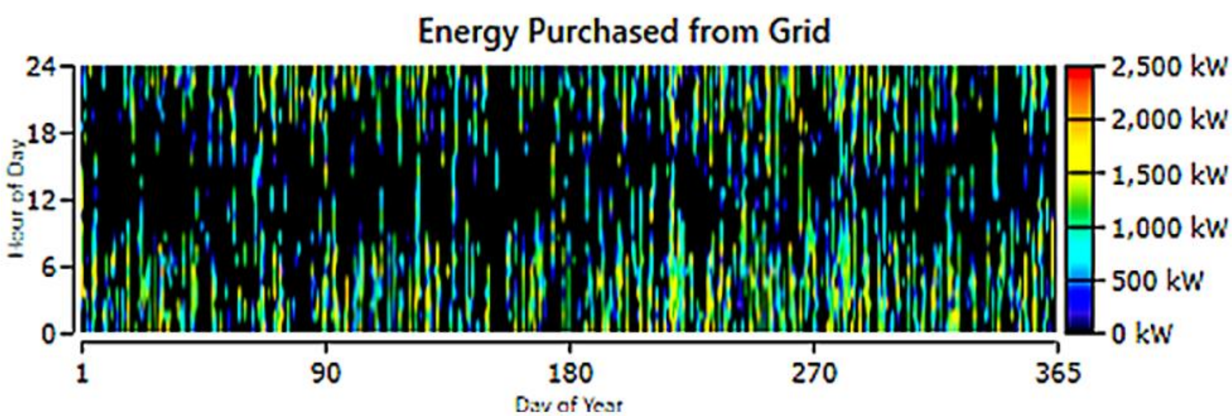

Figure 17.
Energy purchased from the grid.

Figure 18 shows the amounts of energy sold to the grid. The blue colors represent low or negative energy sales, while the yellow and red colors indicate high energy sales (around 12,000 kW) that occur during peak solar production hours. More energy is sold during the day, which results from the high energy production of solar panels and wind turbines, with surplus energy being sold to the grid.

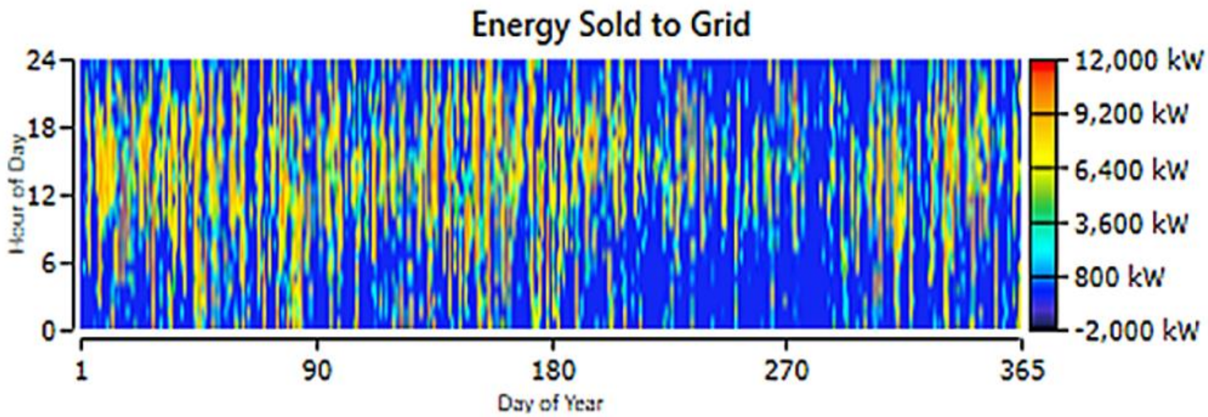

Figure 18.
Energy is sold to the grid.

Figure 19 shows that the nominal power of the electrolyzer is 6,000 kW, but its average input power is 1,105 kW, utilizing only 18.4% of its full capacity. The light yellow and orange areas indicate higher power (up to 3,000 kW), while the darker areas (blue) indicate lower power or no energy consumption. The performance of the electrolyzer is highly dependent on renewable energy production.

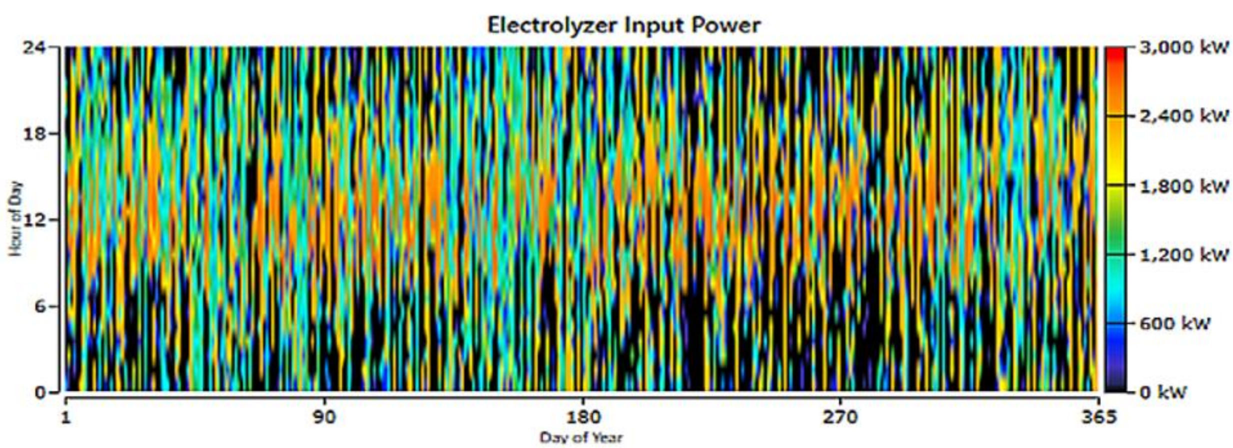

Figure 19.
Changes in the input power of the electrolyzer.

Figure 20 shows the changes in the storage tank level, representing the dynamics of hydrogen energy consumption and production throughout the year. Warmer colors (orange and red) indicate higher hydrogen storage levels, while cooler colors (blue and green) represent a decrease in stored hydrogen. In the summer months, an increase in hydrogen storage is clearly observed, as solar system production reaches its peak.

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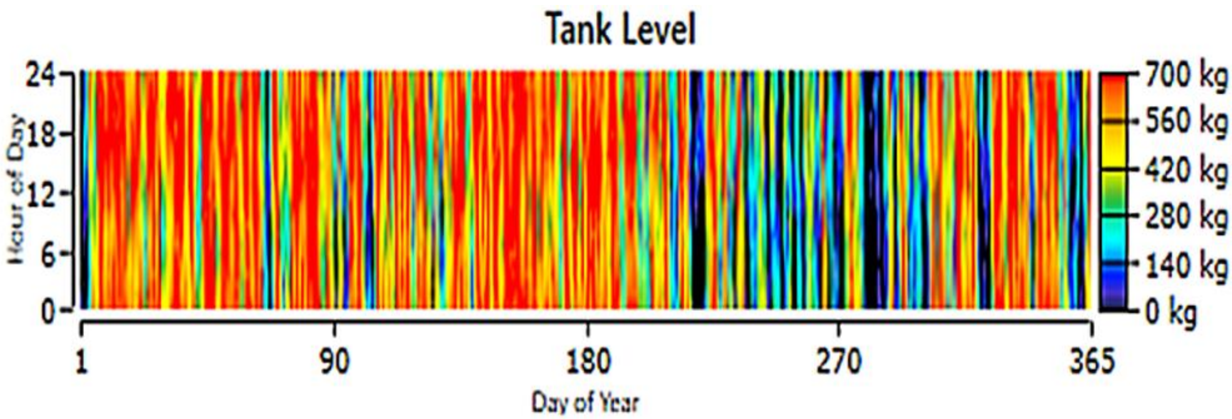

Figure 20.
Variations in hydrogen tank level throughout the year.

Figure 21 presents the statistical variations in hydrogen levels across different months in a boxplot format. The highest stability in hydrogen storage is observed during the summer months, likely due to increased solar energy production. This highlights the direct impact of solar energy production on the stored hydrogen level. In contrast, during months with higher energy consumption, the plot shows values closer to the lower limit, which may be attributed to the tank's discharge in response to energy demands. In certain areas, the range of fluctuations is wider, indicating unpredictable variations in energy consumption or production.

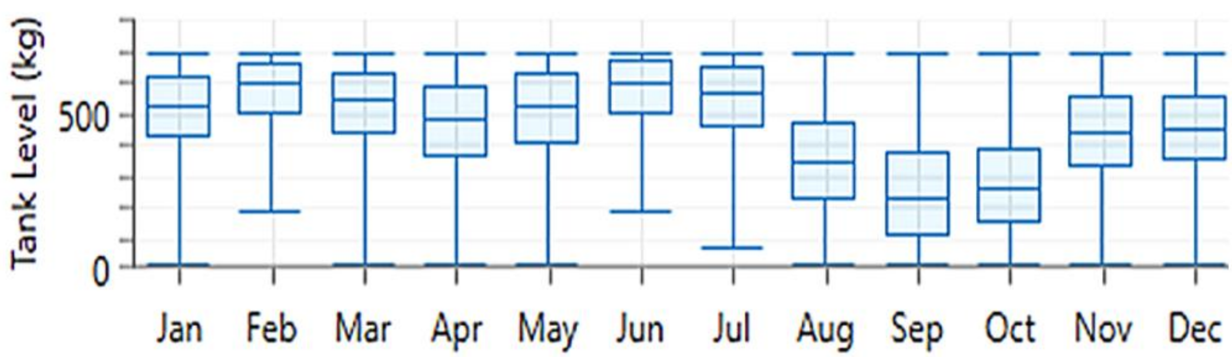

Figure 21.
Box plot of hydrogen tank level distribution based on months of the year.

Figure 22 illustrates a hybrid system integrating renewable energy sources and hydrogen, offering an efficient approach to reducing energy costs and enhancing sustainability in hybrid systems. Cost analysis indicates that utilizing the electricity grid as a backup can significantly lower operating expenses and improve system profitability. The energy production cost with this configuration is considerably more economical compared to conventional systems. Although the high investment cost of electrolysis for hydrogen production increases initial expenses, it reduces dependency on the grid. Wind turbines, despite their high installation and maintenance costs, constitute the largest share of total system costs but are vital for providing sustainable renewable energy. Solar systems, characterized by lower investment and maintenance costs, contribute substantially to cost reduction.

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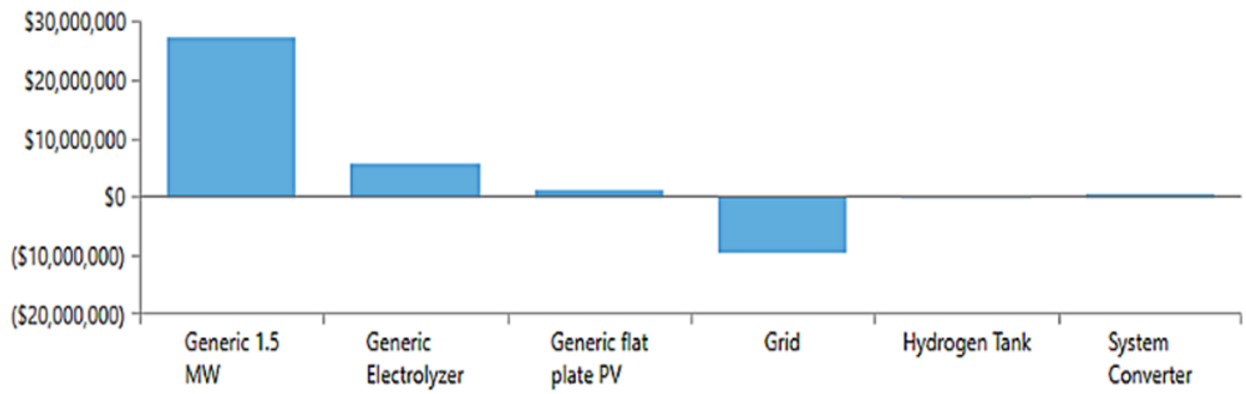

Figure 22.
Economic analysis and cost of the hybrid system, including solar, wind, and hydrogen energy.

Table 3 shows the environmental pollutants produced by the system. The most significant pollutant is carbon dioxide, with 1,534,388 kg per year, which results from the use of non-renewable resources in some parts of the system. Additionally, sulfur dioxide at 6,652 kg per year and nitrogen oxides at 3,253 kg per year are other important pollutants that affect air quality and contribute to acid rain. In contrast, the amounts of carbon monoxide, unburned hydrocarbons, and particulate matter are zero, indicating the use of clean technologies within the system. These results highlight the need to reduce carbon dioxide and other pollutants through an increased share of renewable energy and system optimization.

Table 3.
Analysis of system environmental pollutants in one year.

Quantity	Value	Units
Carbon Dioxide	1,534,388	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	6.652	kg/yr
Nitrogen Oxides	3.253	kg/yr

6. Discussion

This study evaluates and compares three different energy supply scenarios for a wastewater treatment plant in Qatar, focusing on economic, environmental, and energy sustainability aspects. The aim is to simulate various energy supply configurations utilizing renewable resources in a region characterized by its arid climate and limited water resources, and to assess their performance across these dimensions.

6.1. A Revolution in Energy Management of Industrial Wastewater Treatment Plants with a Focus on Hydrogen Storage

The results of this study indicate a fundamental shift in sustainable energy strategies for industrial wastewater treatment plants, especially in hot and dry climates such as Qatar. By introducing energy storage using hydrogen, this research fills a gap in the scientific literature that previously focused mainly on the use of batteries or conventional systems. Unlike conventional methods that mainly focus on short-term energy storage, this new approach provides long-term storage capacity, operational flexibility, and continuity of energy supply in adverse weather conditions.

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6.2. Environmental Analysis and The Role of Hydrogen in Mitigating the Effects of Climate Change

Wastewater treatment plants are one of the major energy consumers in urban industries. Improving the efficiency of these systems has a significant impact on reducing greenhouse gas emissions. The results of this study show that replacing battery storage systems with hydrogen storage can reduce CO_2 emissions compared to baseline systems. This finding highlights the critical importance of developing a hydrogen economy in managing the global climate crisis.

6.3. The Importance of Environmental Conditions in the Design of Hybrid Energy Systems

The arid climate and high temperatures of the Lusail region of Qatar pose additional challenges in providing sustainable energy. This study provides a detailed modeling of energy systems using real operational data and a detailed analysis of climate conditions. In this regard, the use of wind and solar energy combined with hydrogen storage has been the best response to the severe fluctuations in energy production caused by Qatar's specific climate conditions.

6.4. Conceptual Achievement: Moving Towards "Energy Self-Sufficient" Refineries

This study is a step towards "Net Zero Energy" refineries. In other words, with the careful design of a combined solar-wind-hydrogen system, it is possible to make wastewater treatment plants completely self-sufficient from the electricity grid and transform them into energy-generating centers. Such development can play a significant role in energy security in water-scarce regions, improving industrial energy efficiency, and urban sustainability.

6.5. Advantages and Limitations

Scenario 1**:** This scenario offers advantages in terms of simplicity and low initial investment costs. However, its limitations are significant, primarily due to the instability of energy supply and its high dependence on weather conditions, particularly in regions with arid climates and sporadic weather patterns.

Scenario 2**:** The use of batteries improves system stability, reduces dependence on the grid, and enhances overall energy efficiency. However, the high maintenance costs and limited lifespan of batteries pose operational challenges that need to be addressed for long-term viability.

Scenario **3:** The combination of solar, wind, and hydrogen storage offers the best performance both economically and environmentally. However, the higher initial capital costs and technical complexities in implementing advanced hydrogen storage technologies may present challenges during the deployment phase.

The results in Table 4 show that Scenario 3 performs best economically and environmentally, reducing CO_2 emissions to 1,534,388 kg/year. This scenario outperforms the other two scenarios in terms of cost-effectiveness and environmental impact. Scenario 2, with CO_2 emissions of 2,576,000 kg/year, offers a balanced solution between cost and sustainability. In contrast, Scenario 1, with the highest CO_2 emissions (3,980,983 kg/year), is less sustainable due to the lack of an energy storage system. These findings highlight the critical role of energy storage systems, such as hydrogen, in reducing costs, minimizing greenhouse gas emissions, and improving the long-term sustainability of wastewater treatment plants, especially in arid regions such as Qatar, which face challenges of water scarcity and extreme weather conditions.

Table 4.
Comparative summary of the three simulated scenarios in terms of cost, emissions, and system reliability.

Scenario	CO_2 Emissions (kg/year	Energy Storage Type	System Stability & Reliability	Summary
Scenario 1	3,980,983	None	Low (high dependency on weather)	Environmentally weak, low-reliable
Scenario 2	2,576,000	Battery	Medium (buffer during fluctuations)	Balanced cost & emissions
Scenario 3	1,534,388	Battery	Medium (buffer during fluctuations)	Balanced cost & emissions

The comparative results indicate that Scenario 3, which integrates solar, wind, and hydrogen storage, outperforms the other scenarios in terms of cost efficiency and environmental performance. This scenario offers long-term energy resilience, making it suitable for off-grid facilities in regions with variable renewable energy availability. However, the higher capital cost and technical complexity of implementing hydrogen infrastructure may present challenges in real-world deployment, which should be explored further in future studies.

7. Conclusion

This study systematically investigates the techno-economic and environmental feasibility of integrating renewable energy systems, particularly solar and wind, with advanced hydrogen storage technologies to power a wastewater treatment plant (WWTP) in Lusail, Qatar. Using real-world operational data and detailed HOMER-based simulations, it addresses a critical gap in existing research, which has largely ignored the role of hydrogen storage for long-term energy resilience in harsh and arid environments. The findings clearly demonstrate that coupling renewable energy generation with hydrogen production and storage offers significant advantages over conventional battery-based systems or systems without storage.

Among the three modeled scenarios, the solar-wind-hydrogen configuration emerged as the most optimal solution, achieving the largest reduction in CO_2 emissions (1,534,388 kg/year). This configuration not only increases operational independence from the grid but also ensures superior reliability, economic sustainability, and environmental sustainability.

The innovation introduced in this research creates a scalable and realistic framework for future wastewater treatment facilities aiming to achieve net-zero energy targets in extreme climate conditions. Furthermore, it provides strong experimental evidence that hydrogen storage can effectively reduce renewable energy outages, reduce carbon footprints, and reduce long-term operating costs in industrial-scale applications. Overall, this study provides a new and robust model for sustainable wastewater treatment in arid and high-demand regions. By integrating wind and solar energy with hydrogen production and storage technologies, a practical and cost-effective solution is provided to address the economic and environmental challenges posed by energy consumption in wastewater treatment plants. Detailed analysis using HOMER software shows that this approach not only reduces energy costs but also significantly reduces carbon dioxide emissions, thus contributing to energy and environmental sustainability in the region. The results of this research are valuable for policymakers, engineers, and environmental activists who are looking for innovative solutions for the sustainable management of water and energy resources.

7.1. Future Research

1. Investigating the long-term operational reliability and maintenance challenges of hydrogen storage systems in wastewater treatment plants under varying climatic and operational conditions.
2. Exploring the integration of advanced hydrogen separation and purification technologies to improve the efficiency of hydrogen production from renewable sources.

3. Expanding the hybrid system model to include other renewable sources, such as geothermal or biomass to enhance energy resilience and sustainability.

4. Conducting life cycle assessments (LCA) and environmental impact analyses over the entire system lifespan, including end-of-life management of hydrogen storage components.

5. Developing real-time control and optimization algorithms to dynamically manage energy flows between solar, wind, hydrogen storage, and wastewater treatment demands.

6. Assessing socio-economic impacts and scalability potential of hydrogen-integrated renewable energy systems in wastewater treatment plants across different regions and scales.

These directions will deepen understanding and practical implementation of hydrogen-based renewable energy systems in industrial wastewater management, further promoting sustainable and cost-effective energy solutions.

Nomenclature

Abbreviations	
HOMER	Hybrid Optimization of Multiple Energy Resources
COD	Chemical Oxygen Demand
WWTP	Wastewater Treatment Plant
MBR	Membrane Bioreactor
CHP	Combined Heat and Power
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
UASBR	Upflow Anaerobic Sludge Blanket Reactor

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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