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An Optimization-Based Model for A Hybrid Photovoltaic-Hydrogen Storage System for Agricultural Operations in Saudi Arabia

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Abstract: Renewable energy technologies and resources, particularly solar photovoltaic systems, provide cost-effective and environmentally friendly solutions for meeting the demand for electricity. The design of such systems is a critical task, as it has a significant impact on the overall cost of the system. In this paper, a mixed-integer linear programming-based model is proposed for designing an integrated photovoltaic-hydrogen renewable energy system to minimize total life costs for one of Saudi Arabia's most important fields, a greenhouse farm. The aim of the proposed system is to determine the number of photovoltaic (PV) modules, the amount of hydrogen accumulated over time, and the number of hydrogen tanks. In addition, binary decision variables are used to describe either-or decisions on hydrogen tank charging and discharging. To solve the developed model, an exact approach embedded in the general algebraic modeling System (GAMS) software was utilized. The model was validated using a farm consisting of 20 greenhouses, a worker-housing area, and a water desalination station with hourly energy demand. The findings revealed that 1094 PV panels and 1554 hydrogen storage tanks are required to meet the farm's load demand. In addition, the results indicated that the annual energy cost is $228,234, with a levelized cost of energy (LCOE) of 0.12 $/kWh. On the other hand, the proposed model reduced the carbon dioxide emissions to 882 tons per year. These findings demonstrated the viability of integrating an electrolyzer, fuel cell, and hydrogen tank storage with a renewable energy system; nevertheless, the cost of energy produced remains high due to the high capital cost. Moreover, the findings indicated that hydrogen technology can be used as an energy storage solution when the production of renewable energy systems is variable, as well as in other applications, such as the industrial, residential, and transportation sectors. Furthermore, the results revealed the feasibility of employing renewable energy as a source of energy for agricultural operations.

Keywords: mixed-integer linear programming; optimization; photovoltaic system; hydrogen storage

Citation: Mohammed, A. An Optimization-Based Model for A Hybrid Photovoltaic-Hydrogen Storage System for Agricultural Operations in Saudi Arabia. *Processes* **2023**, *11*, 1371. https://doi.org/10.3390/pr11051371

Academic Editor: Xiao Feng

Received: 8 April 2023
Revised: 25 April 2023
Accepted: 27 April 2023
Published: 30 April 2023

1. Introduction

The rapid development of renewable energy sources over the past two decades has led to the installation of numerous power systems. Renewable energy sources include hydroelectricity, geothermal energy, solar energy, and wind energy. In Saudi Arabia, the growing economy and population caused CO_2 emissions to rise gradually from 208,500 Gg to 661,190 Gg in 1990 and 2020, respectively [1]. Water desalination, and electricity production, are the highest sources of CO_2 emission, with 11–15% and 26–33%, respectively. The country recently announced its national environmental program, with the goal of reaching zero emissions by 2060. Saudi Arabia gains from specific geographic and climatic characteristics that enable it to depend on sources of renewable energy and consider them financially desirable, thus supporting initiatives aimed at diversifying their energy sources. Saudi Arabia recently began constructing 1.2 million solar panels in the Sakaka region, as well as 99 wind turbines in Dumat-Al-Jundal. Saudi Arabia receives an average of 2200 W/m^2 of radiation per year [2].

Farmers are confronted with the challenges of meeting the rise in food demand whilst also reducing greenhouse gas emissions and energy costs. Renewable energy appears to be a viable solution to these problems. Farms recently started taking advantage of these never-ending clean power sources to achieve more profitable and environmentally friendly solutions to their power needs. Saudi Arabia has shifted its focus towards renewable energy as part of its ambitious 2030 vision of producing 50% of its energy needs from renewables [3]. To accomplish this objective, private sectors, both large and small, will be involved and encouraged to switch to renewable energy sources whenever possible. In addition, the overall cost and performance effectiveness of the hydrogen storage modules are well-known, as well as their use in green storage systems [4].

The appropriate design of photovoltaic systems is currently the primary concern of both academics and professionals. Ghaithan et al. [5] used mixed-integer linear programming (MILP) to optimize power demand for a small-scale reverse osmosis desalination plant, using power from the national grid, hybrid power from renewable sources utilizing wind through wind turbines, and solar power through PV cells. The desalination plant is located in a remote area of Saudi Arabia's eastern province. Supplying fresh water with varying energy requirements depends on the feed water conditions. The findings indicated that the cost of energy was between 1.72 and 1.84 \$/m^3. Marocco et al. [6] presented a MILP to optimize the design of a hydrogen-battery storage system for an off-grid insular village on the italian island of Stromboli. The aim was to reduce the system cost while increasing demand response efficiency. The LCOE of the optimal solution was 0.455 €/kWh. Garca-Trivio et al. [7] utilized a particle swarm optimization approach to solve the multi-objective, hybrid renewable energy grid connected to a hydrogen-battery storage system. The system had three objective functions: operating costs, efficiency, and equipment lifetime. Anarbaev et al. [8] investigated the effects of renewable energy implementation on CO_2 emissions and potential energy generated from renewable energy sources in Uzbekistan farms for the period of 2014–2018. The findings indicated that using renewable energy in farming saved approximately 1,338,840.5 tons of CO_2. Luta et al. [9] conducted a comparison of expanding the grid and the installation of renewable off-grid hybrid power systems in South Africa. Economic analysis was used to determine the best option. Rezk et al. [10] conducted a techno-economic analysis for a hybrid PV, hydrogen fuel, cell battery system in Neom, Saudi Arabia. Using the cost of energy and net present cost, as the selection criteria, the optimization for a daily 500 kWh demand resulted in the need for a 200 kW PV array, 40 kW fuel cells, and a 110 kW electrolyzer. The system was compared to the other option including the grid and a diesel generator for viability verification. The findings indicated that the developed system was more efficient. Rezk et al. [11] also investigated various renewable options and their feasibility for agricultural purposes in the Minya governorate, Egypt. The hybrid systems under consideration included PV/FC/battery storage (BS), wind turbine generator (WTG)/Fuel Cell (FC), WTG/BS, PV/WTG, PV/FC, and PV/BS. The findings showed that the PV/FC hybrid system had the lowest energy cost. Rezk et al. [12] investigated the effectiveness of self-charging fuel cells powered by a solar PV system in powering the remote brackish water pumping and the reverse osmosis desalination systems for irrigation. The optimization was based on optimizing the cost of energy and the net present cost. The cost of energy for the PV/FC was 0.062 \$/kWh and the net cost was \$115,649. These results indicated that the PV/FC is an excellent and sustainable alternative for remote area energy demands.

Moreover, a hybrid big bang-big crunch-based algorithm for selecting the most suitable sizing options for integrated PV-wind-battery systems is presented in [13]. The objective was to minimize the total cost of the systems and meet the demand. The proposed systems were applied to a residential building in Qazvin, Iran. Zhang et al. [14] addressed the effects of the unpredictable availability of wind and solar energy on a large-scale renewable energy plant. The authors integrated PV-wind-hydrogen storage in order to optimize the operation of the system. The objective of the proposed model was to maximize the profit. Moreover, an integrated algorithm based on the particle swarm and genetic algorithms was used to determine the renewable energy system [15]. The monthly wind speed, annual solar irradiance, and annual load demand were simulated using the HOMER software. Mehrjerdi [16] discussed a stand-alone photovoltaic plant for a supplying station for electric and hydrogen automobiles. The model considered the inconsistency of solar energy, and the energy consumed by hydrogen and electric vehicles. As a backup power supply, a diesel generator was also installed. The model was built as a probabilistic model and a good solution was achieved. Moghaddam et al. [17] developed a hybrid PV-wind system with hydrogen storage. The model employed the flower pollination approach to reduce the overall net present cost. Additionally, predicted energy and losses were used to indicate the system's reliability. The findings indicated that a PV system is more feasible than wind turbines in the economical term. Ma and Javed [18] developed a mathematical model to evaluate the impact of various saturations, i.e., growing the saturation of one asset while reducing the ratio of another asset, on battery bank size, payback time, levelized cost of energy, net present cost, excess energy, loss of power supply, and the state of charge. Three systems were addressed with various wind turbine scales. The cases of stand-alone PV, wind, and a combination of PV and wind were also assessed. Hemmati et al. [19] optimized a PV plant with a combination of hydrogen-battery storage to reduce the leveling uncertainty and store electrical power in the form of hydrogen. Both battery storage and hydrogen storage assist in preventing power fluctuations.

Several studies have examined the techno-economic viability of employing integrated systems for supplying energy in remote locations in Saudi Arabia, such as wind-battery-diesel, PV-diesel, and PV-battery-diesel [20–23]. Gutierrez-Martn et al. [20] developed PV-H_2 hybrid systems to perform energy balancing, and analyze the system's performance in terms of load needs, energy storage levels, and related costs. The authors conceded two energy systems to obtain the optimal size and voltage of electrolyzers. Alturki et al. [21] addressed the optimal size of a hybrid renewable energy system including wind turbines, PV, diesel generators, and battery banks. The authors used a metaheuristic algorithm for solving the proposed model. Moreover, Alturki et al. [22] considered the optimal size of an autonomous integrated renewable energy system. The authors used a supply-demand-based approach for finding the optimal size of the proposed system. Al-Shamma'a et al. [23] investigated the techno-economic viability of several hybrid systems to power a remote place located in the north of Saudi Arabia under various fuel cost scenarios. The optimal size was based on long-term energy analysis. The probability of shutdowns and the percentage of energy generated from renewable sources were the crucial issues, while energy prices dictated economic considerations. The results indicated that PV-based systems were more economical. Zhang et al. [24] addressed the designing and sizing of a solar/hydrogen system without a grid. By combining the geographic information systems with a harmony search-based method, the best location was determined. In addition, system design was optimized by reducing the lifecycle costs whilst taking the system's reliability into account. The power supply interruption was used to measure reliability. Lambert et al. [25] developed a PV plant in order to provide cooling and electricity in remote tropical areas. As according to the application analysis, the absorbed cooling system can reduce the working times for the fuel cell and electrolyzer while reducing the cooling requirements. Bidi et al. [26] developed a microgrid including photovoltaic panels, an alkaline electrolyzer, a proton exchange membrane fuel cell, and Li-ion batteries. Xiang et al. [27] developed a mixed-integer linear programming model for an integrated renewable energy system with the grid to minimize environmental airport operations.

Coppitters et al. [28] employed batteries and hydrogen storage to compensate for the PV power supply's inconsistency. A sophisticated design methodology was developed to account for the multiple scenarios of replacement cost caused by altering the market conditions and the uncertainty of electricity prices. Okundamiya [29] designed an optimal design structure to calculate the size of an integrated PV-hydrogen storage system.

A review study on various optimization methods utilized in solar-wind systems incorporating or excluding batteries is provided in [30]. The findings indicated that different optimization strategies have varying levels of reliability and convergence speeds. As a result, effective methods may vary based on factors such as energy demands and application type. The aim, however, is to find the precise optimal solution to the proposed systems. Current techniques in optimization motivate us towards accomplishing the optimal solution without the use of metaheuristics, or break the problems into subproblems in many circumstances. Zhang et al. [31] addressed the viability of integrating a grid with hydrogen storage for a family house in Finland. The results indicated that hydrogen storage is more expensive than the grid. Nonetheless, considering the current technology advancements and large-scale component manufacture, as well as the increasing fossil fuel prices and their distribution, this may be a financially feasible alternative in the future. The ability to store excess power in an electrolyzer, which transforms electrical energy into hydrogen for use in fuel-cell components, is the primary benefit of a hybrid PV-hydrogen system over a standalone PV plant.

Based on the above literature review, the majority of previous studies utilized heuristic and simulation approaches for sizing the hybrid renewable energy systems. However, heuristics have the major disadvantage of obtaining suboptimal solutions [32,33]. In addition, the aforementioned studies indicated that only a few studies have provided precise models for system design, but these models were solved using heuristic algorithms. For instance, the authors in [7,13–15,17] used heuristic algorithms for solving their model. Moreover, it revealed that hydrogen storage systems need to be investigated further as an energy source in the renewable energy system. Consequently, the main purpose of this paper is to design and optimize a hybrid PV-Hydrogen storage renewable energy system using a mixed-integer linear programming model. The decision variables of the proposed model are to find the optimal number of PV panels, hydrogen tanks number, and the energy produced by the hybrid renewable energy system, in order to minimize the total cost of the system. A real case study for a farm located in Saudi Arabia was utilized to assess the performance of the proposed model.

The rest of the paper is organized as follows: the materials and methods are presented in detail in Section 2. The formulation of the optimization models is provided in Section 3, along with the decision variables, objectives, and constraints. Section 4 describes the case study. Section 5 discusses the findings of this study. Finally, Section 6 summarizes the study, and suggests future research works.

2. Materials and Methods

The developed mixed-integer linear programming model was implemented as follows. The first step was to develop a mathematical model that included all the equations required to compute the output energy from the components of a hybrid renewable energy system. Then, the input parameters such as temperature and solar radiation were collected. After that, the total cost of the systems and the constraints were formulated. The developed model was validated using a real case study in Saudi Arabia. The developed hybrid renewable energy system consists of PV panels, a hydrogen storage system (electrolyzer, hydrogen tanks, and fuel cells), and a direct current (DC)/alternating current (AC) inverter. The PV modules absorb solar energy and convert it into DC power. The PV electricity will first meet the load, i.e., demand, and any excess power will be delivered into the electrolyzer. When there is an excess of solar power, the electrolyzer utilizes this power to generate hydrogen to be stored in tanks. The hydrogen then is converted into electricity through the fuel cells to satisfy the power loads, specifically at night.

2.1. Mathematical Model

The optimization of a hybrid energy system requires the mathematical modeling of each system component. In the following subsections, the modeling of the elements and the framework for optimization are covered in detail.

2.1.1. PV Array Electrical Power

Power generated from PV arrays (P_{pv}) is a function of PV optimal voltage (V_{pv}), PV optimal current (i_{pv}), and the PV panel efficiency (η_{pv}), as given in Equation (1) [5]:

$$P_{pv} = V_{pv} \; i_{pv} \, \eta_{pv} \tag{1}$$

The optimum PV voltage (V_{pv}) is calculated as follows:

$$V_{pv}\,(t) = V_{mp}\left[1 + 0.0539 \log\left(\frac{I_t}{I_{st}}\right)\right] + \beta_o\,\Delta T \tag{2}$$

$$\Delta T = T_A + 0.02\, I_t - T_{st} \tag{3}$$

where V_{mp} represents the PV panel's maximum power voltage, I_t is the total irradiation on the tilted panel calculated in Watt(W)/m^2, I_{st} represents standard solar radiation which is 1000 W/m^2, β_o is the cell efficiency voltage temperature coefficient which is generally between 0.004–0.005 V/°C, T_A is the ambient temperature at experimental conditions, and T_{st} represents the temperature at standard conditions 25 °C.

The second part of the power equation is the current i_{pv} , which can be found by the below formula:

$$i_{pv}(t) = i_{SC}\left(1 - \left[\left(1 - \frac{i_{mp}}{i_{SC}}\right)Exp\left(-\frac{V_{mp}}{C\,V_{OC}}\right)\right]\left[Exp\left(\frac{V_{mp}}{C\,V_{OC}}\right) - 1\right]\right) + \left[\propto_o \left(\frac{I_t}{I_{st}}\right)\Delta T + \left(\frac{I_t}{I_{st}} - 1\right)i_{SC}\right] \tag{4}$$

$$C = \frac{V_{mp}/V_{OC} - 1}{ln\left(1 - \frac{i_{mp}}{i_{SC}}\right)} \tag{5}$$

where i_{mp} indicates the maximum current of the PV panel power, i_{SC} is the short circuit current of the PV panel, V_{OC} represents the open circuit voltage of the PV panel, and $\propto_o$ is the cell efficiency current temperature coefficient A/°C.

The third part is the efficiency of the PV module, which varies depending on the operating temperature. It is provided by the following equation:

$$\eta_{pv} = \eta_r \eta_{pc}\,(1 - \beta(T_C - NOCT)) \tag{6}$$

where η_r is the rated efficiency of the PV panel, η_{pc} represents the power conditioning efficiency, β indicates the generator efficiency temperature factor, T_C is the PV cell's temperature, and $NOCT$ represents the normal cell operating temperature taken as 45 °C.

The power equation can be represented as a function of time (t). The above equations will be incorporated in the mathematical model to represent the power generated from the PV arrays. The total amount of power produced is given as $P_{PV}(t) = N_{PV} P_{PV}(t)$, and the energy generated at time t is provided by $E_{PV}(t) = P_{PV}(t)dt$, where N_{PV} represents the PV and dt represents the step of time.

2.1.2. Hydrogen Storage

The electrolyzer charging and fuel cell (FC) discharging efficiency are utilized to evaluate the overall storage system's effectiveness. The electrolyzer will charge the hydrogen tanks if $P_{PV}(t) \times N_{pv} \times \eta_{inv} \geq \; E_L(t)$, where $E_L(t)$ represents the load demand and η_{inv} represents the inverter efficiency. In this state, the tanks would start charging as according to the following formula:

$$SOC_{HT}(t) = SOC_{HT}(t-1) + \left[N_{pv} P_{PV}(t) - \frac{E_L(t)}{\eta_{inv}}\right].\; \eta_{Elect} \tag{7}$$

where $SOC_{HT}(t)$ is state of charge at time t, $SOC_{HT}(t-1)$ is state of charge at time $t-1$, and η_{Elect} represents electrolyzer efficiency.

On the other hand, the following formula will be applied at a charging state:

$$N_{pv}P_{PV}(t) \times \eta_{inv} \leq \ E_L(t) \tag{8}$$

In this state, the tanks would start discharging according to the following equation:

$$SOC_{HT}(t) = SOC_{HT}(t-1) + \left[\frac{E_L(t)}{\eta_{inv}} - P_{PV}(t)N_{pv}\right].\ \eta_{Elect} \tag{9}$$

In this study, the hydrogen tanks have a restriction where they cannot be lower than 30% of its capacity, and cannot exceed 100% [6].

3. Model Description

The aim of the proposed mathematical model was to specify the number of PV panels and hydrogen tanks, and the energy produced by the renewable energy system. The optimal sizing of the renewable energy system will satisfy the energy load required to meet the demand at the lowest cost. This section describes the procedures for designing the developed model.

3.1. Objective Function

The main objective of this model is to minimize the total cost of the proposed system, which includes all the costs associated with the power of this system. The total annual cost of energy (TC) is made up of the capital cost of the hydrogen storage system and its operational cost, and the capital cost of the *PV* modules and their operational cost. The total cost of the proposed renewable energy systems is given by the following formula:

$$TC = N_{PV}C_{PV}CRF + N_{PV}C_{PV-MNT} + N_{H_2}C_{H_2}CRF + N_{H_2}C_{H_2-MNT} \tag{10}$$

where C_{PV} *and* C_{H_2} are the capital cost of the *PV* modules and hydrogen storage components, respectively. C_{PV-MNT} and C_{H_2-MNT} are the operational and maintenance cost of *PV* and hydrogen storage system, respectively. N_{PV} and N_{H_2} represent the number of *PV* panels and hydrogen tanks, respectively.

To annualize the capital cost, the inflation rate, f, and the interest rate, i_r, were taken into consideration. The following factor was calculated to annualize the initial investment over the 25 years (N).

$$CRF = \frac{\left(1 + \frac{i_r - f}{1+f}\right)^N - 1}{\frac{i_r - f}{1+f}\left(1 + \frac{i_r - f}{1+f}\right)^N} \tag{11}$$

3.2. Constraints

The system's reliability was assessed by including all power inputs to the load at any time t in an hourly interval, and comparing them to the load's power demand. The loss of power probability (LPSP) function, is the ratio of the sum of the power provided over the power demanded.

$$\text{LPSP} = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} E_L(t)} \tag{12}$$

$$LPS(t) = \frac{E_L(t)}{\eta_{inv}} - P_{PV}(t)\ N_{pv} - N_{H2}[\ SOC_{HT}(t-1) - SOC_{HT-min}]\eta_{elec} \tag{13}$$

The number of PV modules and hydrogen tanks that can be installed is limited by the size of the farm. The maximum and minimum number of PV panels that can be installed are as follows:

$$0 \leq N_{pv} \leq N_{max} \tag{14}$$

$$N_{max} = \frac{A_p}{A_{pv}} \tag{15}$$

where Ap is the area allocated for PV modules, and Apv is the area taken by one PV module.

Similarly, the hydrogen tanks number is limited as follows:

$$0 \leq N_{H2} \leq N_{H2-max} \tag{16}$$

$$N_{H2-max} = \frac{A_{P-H2}}{A_{H2}} \tag{17}$$

where A_{P-H2} is the area allocated for hydrogen storage, and A_{H2} represents the area taken by one hydrogen storage tank.

Moreover, the following constraint restricts the amount of hydrogen stored at time t during optimization:

$$SOC_{HT-min} \leq SOC_{HT}(t) \leq SOC_{HT-max} \tag{18}$$

The hydrogen tanks maximum and minimal charge states are denoted by SOC_{HT-max} and SOC_{HT-min}, respectively. When $SOC_{HT}(t) < SOC_{HT-min}$, a portion of the load is not carried by the storage system. Consequently,

During the optimization phase, the proposed model determines to either start charging or discharging based on the amount of solar power generated, as well as the demand requirements. The constraints are introduced, and use a large number M in order to implement the either-or formulation. Due to this, in the case that the hybrid renewable energy plant generates more power than needed, the extra energy can be utilized to electrolyze water in order to generate hydrogen. In this setting, the amount of hydrogen that can be stored at time t is represented by a new variable called $U(t)$. Restrictions on this variable include:

$$U(t) \geq \left[E_{PV}(t) - \frac{E_L(t)}{\eta_{inv}}\right]\eta_{Elect} \tag{19}$$

$$U(t) \leq \left[E_{PV}(t) - \frac{E_L(t)}{\eta_{inv}}\right]\eta_{Elect} + Mz(t) \tag{20}$$

$$U(t) \leq M(1 - z(t)) \tag{21}$$

Energy shortages can be filled by the hydrogen storage system if the hybrid renewable energy plant output is below the amount of energy needed to meet the load. The power supplied by converting the hydrogen quantities using fuel cells at hour t is represented by another new variable, $V(t)$, which is adopted for this task.

$$V(t) \geq \left[\frac{E_L(t)}{\eta_{inv}} - E_{PV}(t)\right]/\eta_{Elect} \tag{22}$$

$$V(t) \leq \left[\frac{E_L(t)}{\eta_{inv}} - E_{PV}(t)\right]/\eta_{Elect} + M(1 - z(t)) \tag{23}$$

$$\mathrm{V(t)} \leq Mz(t) \tag{24}$$

As a result, the hydrogen quantity stored $SOC_{HT}(t)$ can be expressed as:

$$SOC_{HT}(t) = SOC_{HT}(t-1) + U(t) - V(t) \tag{25}$$

If $z(t) = 0$, then the values of $U(t)$ equals $\left[E_{PV}(t) - \frac{E_L(t)}{\eta_{inv}}\right].\eta_{Elect}$, based on Equations (22)–(24), which reveal that the energy produced by the proposed system is greater than the demand. In this situation, the hydrogen quantities of $\left[E_{PV}(t) - \frac{E_L(t)}{\eta_{inv}}\right].\eta_{Elect}$ will be stored in the tanks charged by the electrolyzer at time t. In contrast, V(t) will be forced to equal to zero by Equations (19)–(21). On the other hand, if $z(t) = 1$, Equations (22)–(24) forces U(t) to be zero, thereby revealing an energy shortage. In contrast, Equations (19)–(21) force $V(t)$ to equal $\left[\frac{E_L(t)}{\eta_{inv}} - E_{PV}(t)\right] / \eta_{Elect}$, and this sum will be utilized to meet the demand in the situation of a shortage.

The quantity of hydrogen stored is defined as a non-negative variable, and the number of hydrogen tanks and PV modules are also both non-negative integer variables.

$$N_{pv} \in N; \quad N_{H2} \in N; \quad SOC_{HT}(t),\ U(t),\ V\ (t)\ \geq 0 \tag{26}$$

3.3. Decision Variables

The number of hydrogen tanks, the number of PV units, and the amount of hydrogen stored at hour t were chosen as the variables for developing the proposed renewable energy system. If the amount of energy generated by the PV modules is greater than the load, the electrolyzer uses the extra energy to charge the hydrogen tanks. Conversely, the fuel cell fills this shortage load if the power generated by the PV panels is less than the energy required. In this instance, two types of binary variables are combined to generate an either-or option at time t.

3.4. Carbon Dioxide Saving Calculation

Countries are seeking sustainable, clean, and renewable energy sources to reduce the carbon footprint generated by the flaring of fossil fuels. In this paper, the reduction in carbon dioxide CO_2 emissions due to the use of hybrid renewable energy systems was calculated. The following equation can be used to estimate the grid's *GHG* emissions [34]:

$$GHG_{grid} = \alpha_{grid}\ GWP \sum_{t}\ E_{grid}(t) \tag{27}$$

where GWP represents the global warming potential, α_{grid} is the emission factor which is equal to 0.50089 Kg CO_2 per kWh of electric energy generated, and $E_{grid}(t)$ is the hourly energy imported from the grid. In accordance with the Kyoto protocol, the *GWP* for CO_2 was 1 [35]. In this paper, the whole load demand was satisfied from the renewable energy system. Therefore, the total amount of GHG_{grid} is considered as a saving emission.

Figure 1 shows the process flow of the proposed approach, including the economic and technical inputs, model formulation, and model solution.

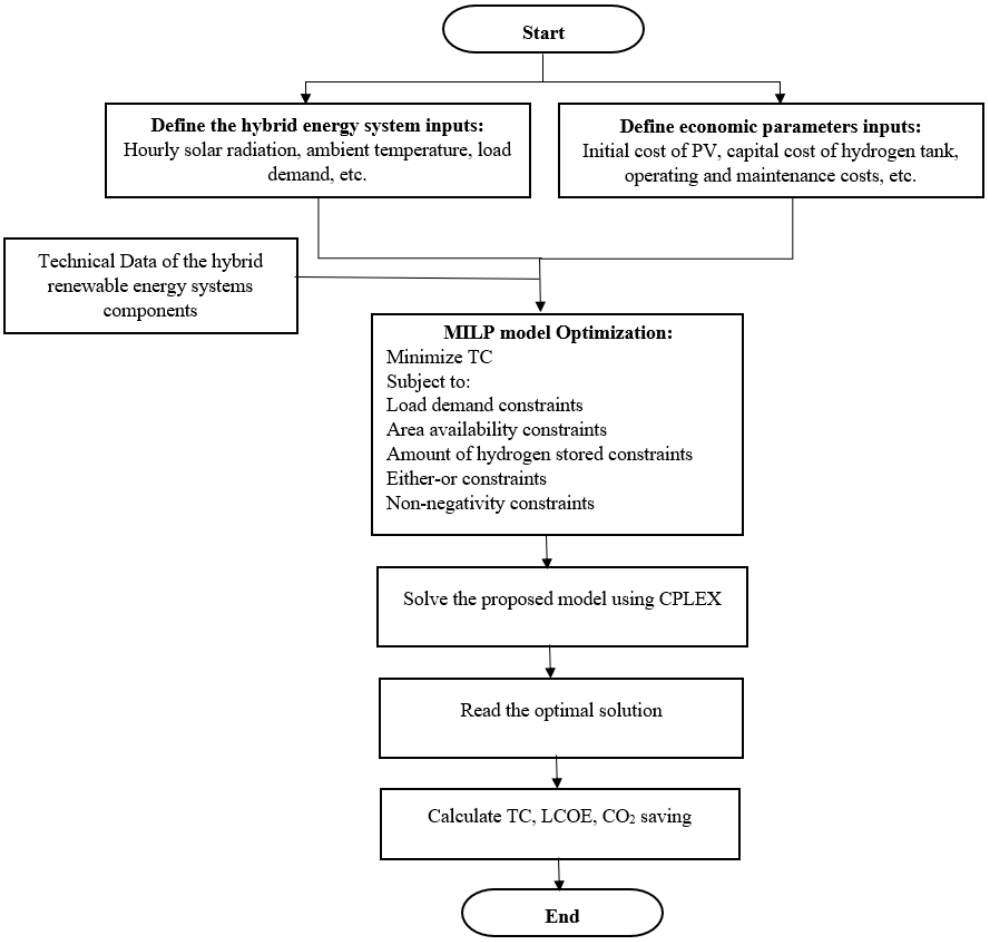


Figure 1. Process flow of the proposed model.

4. Case Study

The aim of this research was to develop a mixed-integer linear programming model for sizing a PV-hydrogen renewable system. The proposed energy system, which is depicted in Figure 2, consists of photovoltaic modules and hydrogen tanks connected to the power load of a farm via a distribution board and an inverter.

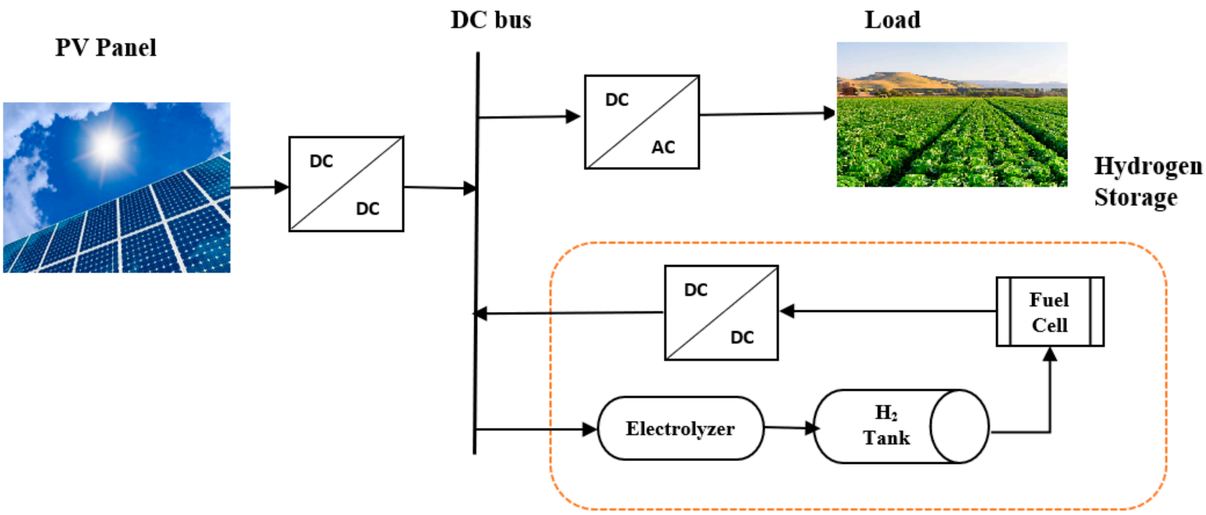


Figure 2. PV-hydrogen storage system diagram.

In this research, the proposed model was assessed utilizing an hourly power demand for a farm in eastern Saudi Arabia. The PV modules first supply energy to the farm in order to satisfy its load. Hydrogen is produced from water using surplus solar energy, and is then kept in the tanks. In the case of an unanticipated weather condition, or a breakdown in the PV plant, the required power can be supplied from the hydrogen tank. The PV panel is also connected to an inverter, which converts the electricity from DC into AC. At present, the farm's electricity demands are met by the grid at a cost of $0.085/kWh. Figure 3 shows the average of farm demand in 2022. The highest use of energy occurs during the summer months of July, August, and September, when the hourly energy demand averages 204.1 kWh. A smart meter that was installed in the farm's power room was used to collect the data. An intelligent system in the farm, which is linked to the smart meter, kept track of the energy imports and exports from the farm. By reducing the prices down and launching the modern era of renewable energy as an option of sustainable energy, this technology will assist the farm in its privatization process.

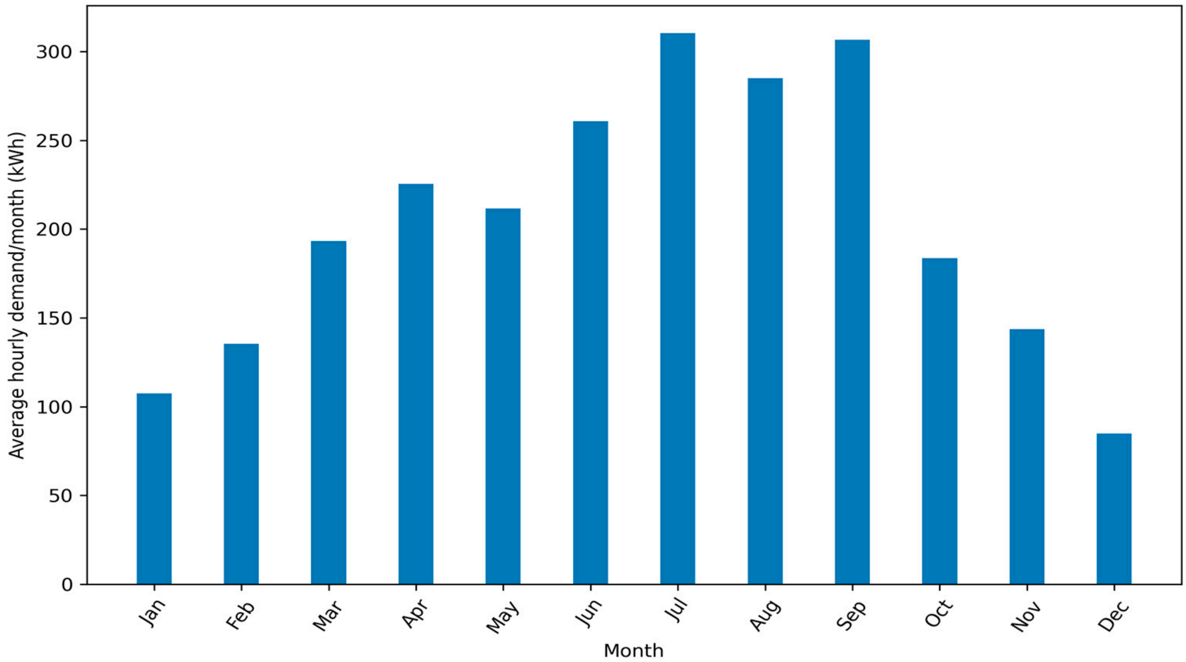


Figure 3. The average hourly demand.

The farm management was motivated by a variety of factors to address switching from the national grid to solar energy as an energy production source. These factors contain Saudi Arabia's abundant sunshine, the carbon dioxide emissions carried through the utilization of fossil fuels to generate the power, and rewards provided to the locals. The proposed system is optimized using the mixed-integer linear programming model. The RRRM system's data on solar irradiation and air temperature were used in this study [36]. Then, a calculation of the global irradiation function, diffuse radiation, geographical factor, and angles was used to determine the incident solar irradiation on the PV plant. The model was performed using hourly meteorological data for solar radiation and temperature an in eastern region of Saudi Arabia for the year 2022. The ambient temperature and hourly variations are shown in Figures 4 and 5, respectively. These figures indicate that the demand is high during the summer months. This is because more energy is consumed during the summer. In addition, solar radiation is at its peak during the summer months. Moreover, the temperature is high in the summer, and low in the winter.

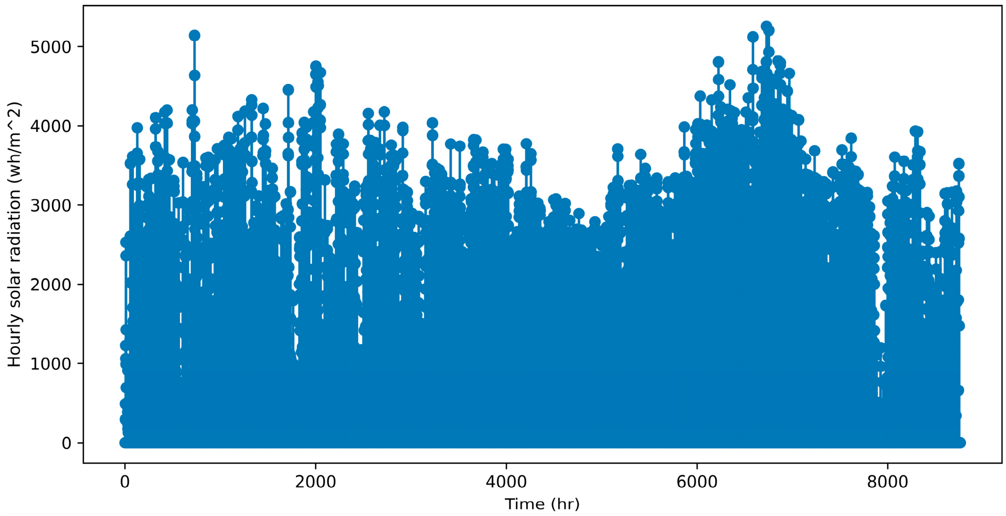


Figure 4. Hourly solar radiation on a horizontal plane.

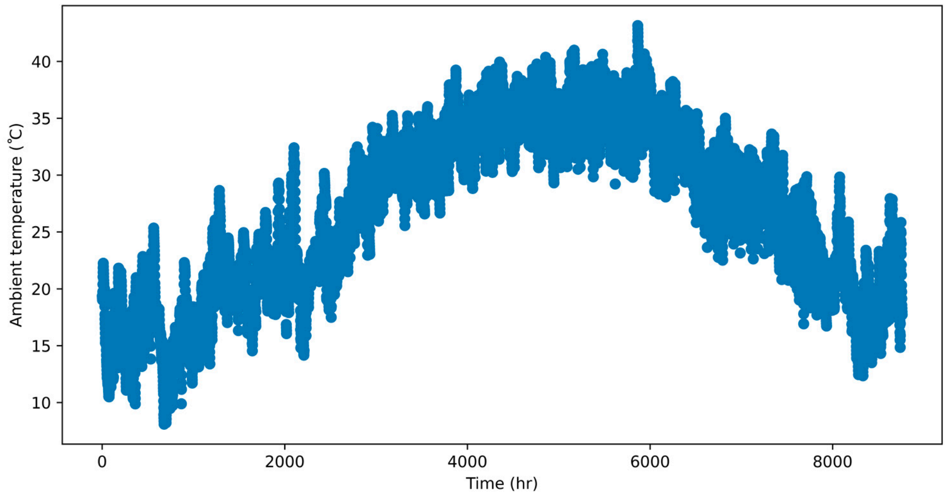


Figure 5. Variation in the hourly ambient temperature in °C.

Table 1 describes the hybrid systems' capital costs, operating and maintenance costs, and component details.

Table 1. Hybrid renewable system specifications [31,37,38].

Parameter	Value
PV	
Installation cost per panel ($)	1500
Maximum Power Current (A)	8.11
Short Circuit Current (A)	8.56
Maximum Power Voltage (V)	18.5
Maximum Power (W)	150
Maintenance cost per panel per year ($)	20
Coefficient of temperature for the cell efficiency	0.004–00.5
Standard radiation from the sun (kW/m^2)	1
Open Circuit Voltage (V)	22.5
Ambient Temperature °C	(8.1–43.15)
PV module lifetime (years), N	25
PV efficiency (%)	15.8
PV module type	Ultra-efficient polycrystalline

Table 1. *Cont.*

Parameter	Value
Hydrogen tank	
Capital cost ($)	600
Maintenance cost ($/year)	5
Nominal capacity of hydrogen tank (kWh)	0.3
Hydrogen tank lifetime (years)	25
Electrolyzer	
Efficiency (%)	75
Lifetime	5
Replacement cost	700
Nominal electrolyzer power (kW)	3
Capital cost ($)	4500
Model name	Bipolar, alkaline type
Fuel cell	
Efficiency (%)	75
Lifetime	5
Replacement cost ($)	700
Nominal fuel cell power (kW)	3
Capital cost ($)	6000

5. Results and Discussion

In this section, the results of the proposed renewable energy system are discussed. First, the levelized cost of energy and the carbon dioxide emission caused by using the grid was computed. The grid case was then used as a baseline to compare the performance of the proposed model. Then, the findings of the developed system are presented and discussed.

5.1. Grid

In this scenario, the energy demand of the farm operations is powered using the electricity imported from the national grid. The total annual energy demand of the farm operations is 1,763,100 kWh. This amount is satisfied by the grid with a cost of energy of $0.085 per kWh. In addition, the amount of CO_2 emissions generated to produce this quantity, according to Equation (27), is 881,550 kg of CO_2. According to the UNEP (United Nations Environment Programme), a typical tree absorbs 167 Kg of CO_2 per year [39,40]. As a result, the number of trees required to absorb the amount of CO_2 produced by the grid is 5279.

5.2. The Proposed System

The proposed hybrid renewable energy system was designed to meet the needs of the farm. When there is radiation, the PV will be used to meet the load demand, whereas the hydrogen tanks will be used to meet the demand at night. The proposed MILP model's purpose is to size the developed PV-hydrogen storage system. In this research, the CPLEX solver embedded in the GAMS software was utilized to solve the proposed model for a one-year time horizon. The time unit is set as an hour, i.e., t = 1,2, . . . , 8760 h. The statistics of the model are provided in Table 2.

Table 2. Statistics of the proposed model.

Single Equations	78,850
Discrete variables	2
Binary Variables	8760
Non-Zero Elements	227,332
Single Variables	35,046

Table 3 highlights the outputs of the proposed model, which include the number of hydrogen tanks and PV modules, total system cost, CO_2 emissions savings, produced energy, and energy cost. To meet the demand and produce 1,763,100 kWh of annual energy, the optimal number of PV modules is 1094, and the optimal number of hydrogen tanks required is 1554. In addition, the annual cost of the energy system is $228,234. With energy costs calculated as $0.12 per kWh, the proposed technologies will reduce carbon dioxide emissions by 881,550 kg per year. The minimization of CO_2 emissions is an important advantage of substituting traditional fuel with clean energy sources. Zhang et al. [38] indicated that for every 1 kWh of energy used, conventional fossil fuels produce 0.50089 kg of CO_2. Consequently, the proposed renewable energy system produces 1,763,100 kWh of power, which indicates that if this quantity of electricity was generated by traditional fossil fuel, about 881,550 kg of CO_2 will be emitted each year. The results showed that integrating PV with a hydrogen storage system offers significant insights regarding the possibilities for a sustainable fuel in Saudi Arabia. In addition, the findings illustrated that it is possible to integrate an electrolyzer, hydrogen tanks storage system, and a fuel cell. In a non-financial perspective, the emissions of carbon dioxide will be decreased, and an efficient energy source will be made attainable. The energy provided by such systems are impacted by a number of variables, including climatic conditions for hydrogen fuel cells, the weather, geomorphological circumstances, interest rates, and energy tariffs. If fossil fuel prices rise as predicted, transferring from the traditional energy sources to renewable energy sources will ultimately be more desirable. Furthermore, the difficulty of managing the frequency of the system due to the variation in the output of renewable energy system power generation—often for a significant deviation in frequency—results in a decline in the performance of the system. However, the intended system can accommodate daily and annual variations in the weather.

Table 3. The results.

Parameter	Value
Annual total cost	228,234
Number of Hydrogen tanks (N_{H2})	1554
Number of PV modules (N_{pv})	1094
LCOE ($/kWh)	0.12
Annual energy Production (kWh)	1,763,100
CO_2 saving (kg of CO_2)	881,550

A specific day was selected to illustrate the ability of the developed model to produce energy with changing the radiation. Figure 6 depicts the energy generated by the hybrid renewable energy systems and radiation during a 24 h period. It is obvious that the hybrid system's peak energy generation arises during the day, from 10:00 AM to 15:00 PM. This is due to the exceptionally high levels of radiation over this time period, as illustrated in Figure 6. The hybrid system produces very little energy when radiation levels are low, and since radiation levels are zero at night, no energy is produced. The hydrogen tank will supply the demand at night, as shown in Figure 7.

Figure 7 displays a hydrogen tank's charge and discharge on a certain day (25th of February). The hydrogen tank is charged throughout the day, reaching its maximum at noon. The tanks of hydrogen begin charging between 7:00 AM and 17:00 PM, when radiation levels are high. Conversely, the discharge of hydrogen tanks begins when the PV module produces insufficient energy and there is no radiation. Consequently, the discharge time is from 18:00 PM to 6:00 AM. During hydrogen tank charging, the PV module immediately meets the energy need. However, the energy needs are fulfilled at night by transforming hydrogen into energy. This finding is confirmed in Figure 8.

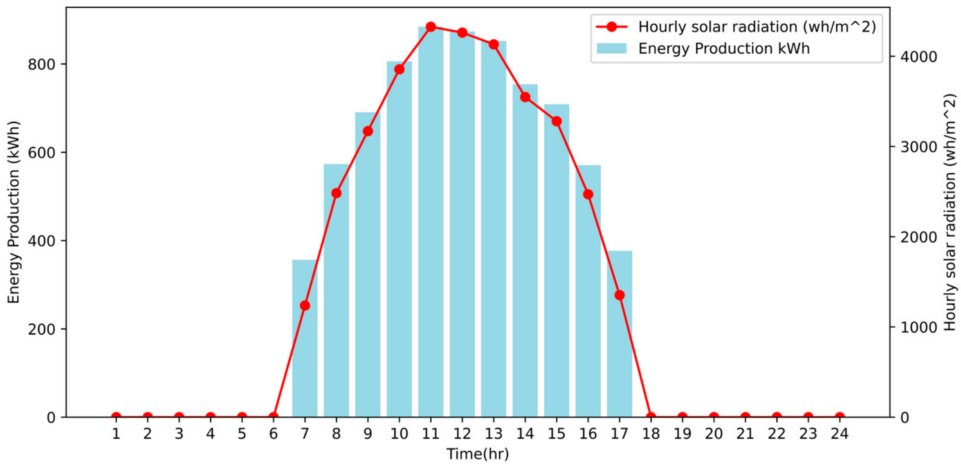


Figure 6. Daily average energy production vs. radiation.

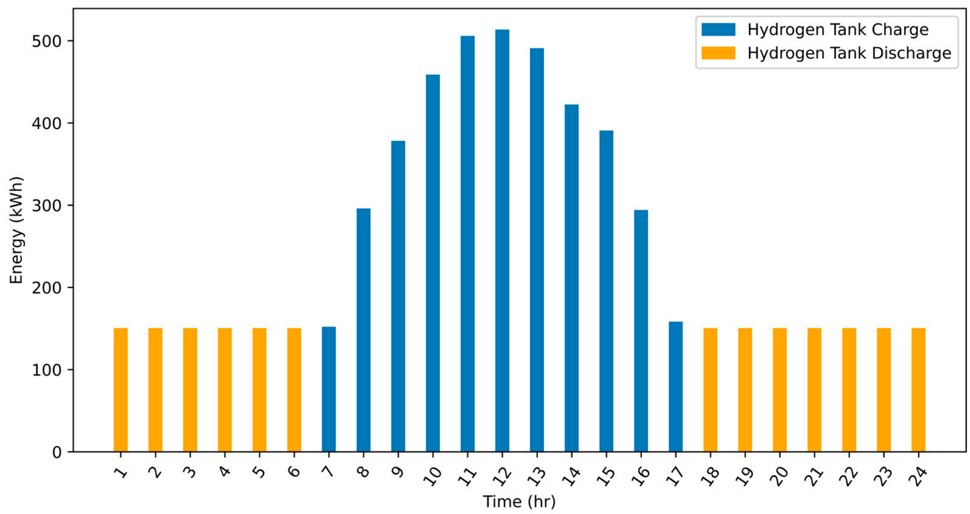


Figure 7. Hydrogen tank charging and discharging.

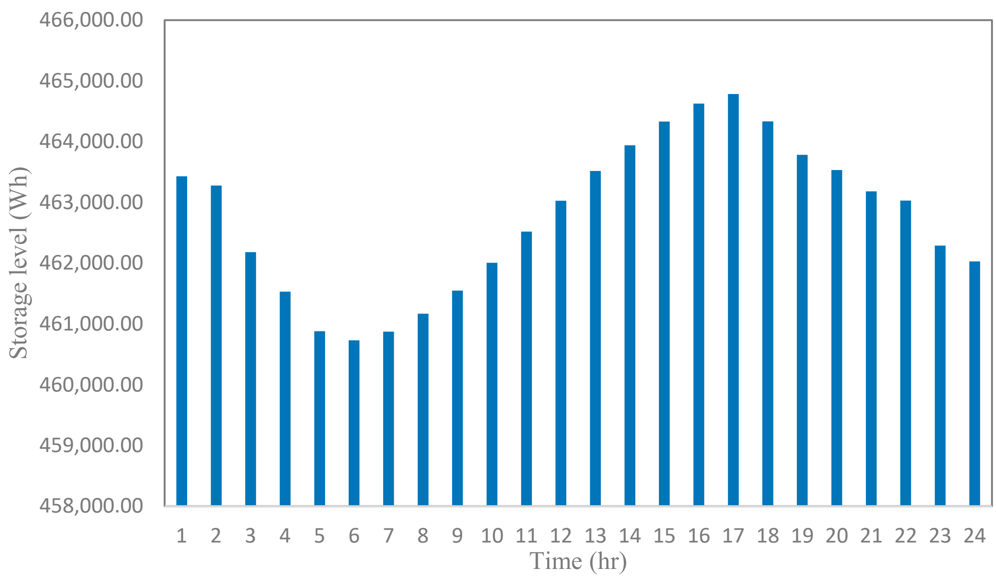


Figure 8. Storage capability of hydrogen tanks during a 24 h period in February.

The status of the hydrogen tanks over the duration of a day is shown in Figure 8. It is obvious that the tanks of hydrogen begin to charge at 7:00 AM, and keep charging until they are fully charged at 17:00 PM. After that, the hydrogen tanks begin to discharge throughout the night at 18:00 PM, and start decreasing until they attain their lowest level at 6:00 AM.

5.3. Discussion

In this paper, a hybrid renewable energy optimization system was developed. The objective was to find the hydrogen tank number, PV panel number, PV panel production energy, and the amount of hydrogen accumulated in the tanks over time. To demonstrate how well the proposed approach performs, an actual life case was used. The devised methodology, and the developed model, however, could be used in other situations across different sectors. It can be applied to residential buildings, the industrial sector, electric vehicles, etc. In addition, the proposed model is flexible to include other renewable energy sources, such as wind turbines and batteries. The proposed solution methodology aids in finding the best solutions for renewable energy plants. In this paper, the task of optimization can be taken as a mechanism to size the integrated renewable energy plants to reduce the overall cost of the plant by addressing the different constraints. In addition, solar energy surplus can be converted into hydrogen through the use of PV panels and a hydrogen storage system. The hydrogen is kept in tanks and transformed into energy to meet the demand when there is no solar radiation.

In this research, the proposed renewable energy system was analyzed. The findings indicated that the developed model was capable of capturing monthly and hourly changes in environmental circumstances. Due to the extremely high solar irradiation levels, the PV system generates more energy in the middle of the day. In addition, hydrogen is generated from water during this period of time, and stored in hydrogen tanks using extra solar energy. Hydrogen is converted to energy to satisfy the demand if the PV systems are unable to supply all of the energy needed during the night. In contrast, while the process for emptying hydrogen tanks starts at night, the procedure for filling hydrogen tanks happens during the daylight hours of the day, when solar radiation is at its highest level.

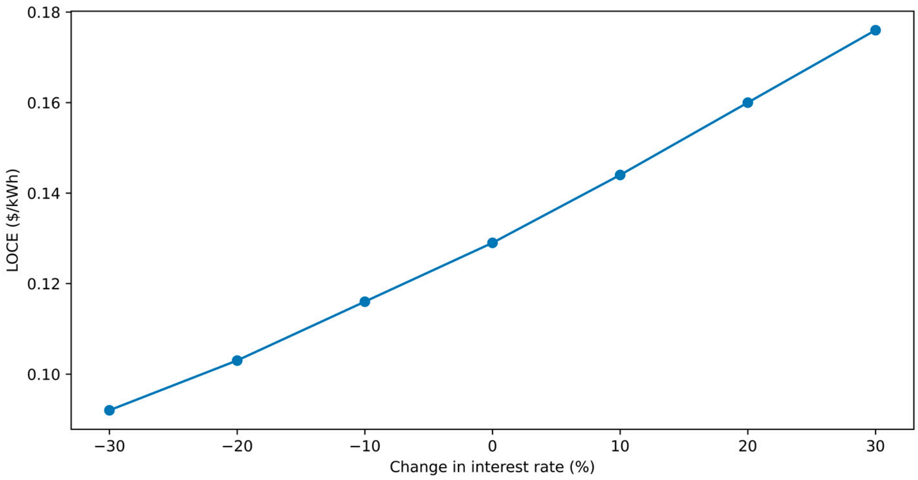
These findings demonstrate that generating hydrogen utilizing renewable energy allows for the generation of clean and sustainable fuel. The findings also revealed that integrating fuel cells, hydrogen tanks, and electrolyzers are technically possible; but the cost is high due to the capital expenditure cost being also high. The capability for seasonal energy storage, and the versatility of using hydrogen as a fuel for transportation applications, make hydrogen technology an attractive energy storage option for inconsistent renewable energy systems [41]. The results provide useful information about Saudi Arabia's potential for renewable energy as well. The proposed methodology can be also be applied to other regions.

Although integrated hydrogen storage with renewable energy systems is appealing, some challenges occur using hydrogen as an energy source. These challenges include designing a suitable hydrogen storage system that is powered by the sources of renewable energy. These systems are typically based on compressed gas and/or metal hydrides. Furthermore, there are no limitations on the volume, area, or output pressure that can be utilized for the intended purpose when producing hydrogen from low pressure storages in fuel cells to improve energy efficiency [42]. The state of hydrogen storage is another challenge with the hydrogen production system. When hydrogen is kept as a compressed gas, the hydrogen may be lost due to changes in pressure or temperature [43]. However, some materials and composites might be useful for hydrogen and energy storage [44,45].

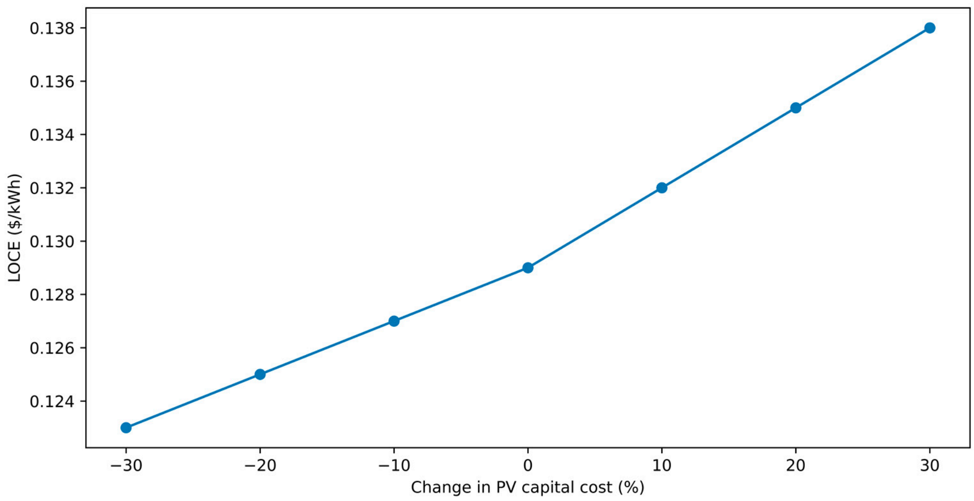
5.4. Sensitivity Analysis

In this study, sensitivity analysis was conducted to figure out the impact of changing the renewable energy system parameters on the proposed system viability. The effects of changing these parameters will be reflected in the final values of the performance metrics.

The sensitivity analysis offers an indication of the feasibility of the system. In addition, it provides the required information to enhance the variability of the systems. In this paper, the sensitivity analysis was conducted by changing the parameters values within the range of -30% to + 30% from the original parameter value. Two input parameters were tested to address their impact on the levelized cost of energy. Figure 9a shows the impact of changing the interest rate on the levelized cost of energy. It is clear that as the interest rate increases, the levelized cost also increases. In addition, Figure 9b illustrates the effect of changing the capital cost of PV panel on the LCOE. From Figure 9b, it is evident that the levelized cost increases as the capital cost increases. This indication confirms that renewable energy systems will be feasible due to the prices of its components dropping. Moreover, Figure 9 shows that the levelized cost of energy is more sensitive with changing the capital cost of PV.



(**a**)



(**b**)

Figure 9. Sensitivity analysis. (**a**) Change in the interest rate against LCOE, and (**b**) change in the capital cost of PV against LCOE.

6. Conclusions

In this research, a mixed-integer linear programming model was proposed for the optimal design of integrated PV-hydrogen storage systems. The proposed renewable energy system was optimized to determine the optimal number of PV panels, hydrogen storage capacity at each tank, and the number of hydrogen tanks required while minimizing the total cost of the system. In this paper, an exact approach was utilized to obtain the optimal solution. Moreover, a real case study was used to validate the proposed model. The findings revealed that 1094 PV panels and 1554 hydrogen storage tanks are required. The annual energy cost was at $228,234, with a LCOE of 0.12 $/kWh, and 882 tons of CO_2 were saved as a result of utilizing renewable energy instead of energy from the grid.

The results further demonstrated that a hybrid renewable energy system that combines solar power and hydrogen storage can provide useful insights about the potential for green fuel and renewable energy. The findings also revealed that it is possible to integrate an electrolyzer, hydrogen tanks, and fuel cells to construct an energy storage system. In addition, the utilization of hydrogen technologies as a form of energy storage for inconsistent renewable energy systems are appealing. Transforming to solar energy is a desirable option if fuel energy costs rise over time as it is currently predicted. Additionally, whenever a substantial deviation in frequency occurs, the system's overall performance is reduced due to the difficulty in controlling the frequency caused by the variation in the electricity generation output from renewable energy systems. The developed system, however, can capture monthly and hourly fluctuations in the weather, according to analysis of the proposed renewable energy system.

Among the factors affecting project viability are interest rates and energy prices. The switch to solar-based energy will be more desirable if, as predicted, fuel energy costs increase over time. Future work could take demand uncertainty and system performance uncertainty into account when designing a reliable energy system that can handle the different types of uncertainties. However, this could involve investigating the integration of various energy storage technologies, as well as developing methods for dealing with the variability and uncertainty of renewable energy systems.

Funding: There is no external fund received in this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to thank the King Fahd University of Petroleum and Minerals, and the deanship of research oversight and coordination for their assistance and support.

Conflicts of Interest: The author has no competing interests relevant to the content of this article to declare.

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