Design and Optimization of Hydrogen Refueling Station Powered by Hybrid Energy System

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Abstract- Replacement of fossil fuel-based transport systems can be possible by investing in fuel cell vehicles. This can be achieved through the establishment of a hydrogen refueling station that supplies hydrogen fuel to vehicles. This study explores the techno-economic feasibility analysis of setting up a hydrogen refueling station at Makkah city in Saudi Arabia powered by hybrid energy system using HOMER software. The obtained results showed that the lowest net present cost (NPC), levelized cost of energy (LCOE), and levelized cost of hydrogen (LCOH) which amount to $17,521.79, $0.012 per unit, and $0.352 per kilogram, respectively, belong to the wind-battery hybrid energy system. A 330-kW wind turbine, a 700 kW electrolyzer, a 100 kg/L hydrogen tank, a 110 1kW h battery, and a 450-kW converter were all parts of the suggested system. In comparison, the photovoltaic-wind-battery hybrid energy systems exhibit higher NPC, LCOE, and LCOH values of $17,849.58, $0.014 per unit, and $0.369 per kilogram, respectively. The outcome of the study judged the wind-battery hybrid energy systems to be the most viable option for the refueling station project in Makkah, as supported by the return-on-investment analysis. The author proposed that the refueling station should be implemented in the city of Mekkah using wind-battery hybrid energy system by leveraging on the available renewable resources in Makkah for electricity generation and hydrogen production, thereby alleviating the problem caused by pollution from using fossil fuel in transportation.

Keywords: Hydrogen refueling station, HOMER software, photovoltaic, wind turbine, hybrid energy system.

1. Introduction

The correlation between environmental pollution, climate change, and the consumption of fossil fuels has spurred the demand for a more sustainable environment, pushing for a transition to renewable energy sources [1]. The reduction of greenhouse gas emissions and environmental effects associated with hydrogen production can be accomplished by a decrease in reliance on fossil fuels for the creation of hydrogen. Furthermore, the continuous drop in the cost of renewable energy and ongoing innovations indicate an impending shift towards renewable dominance. Photovoltaic (PV) and wind turbines (WT) are commonly utilized renewable energy alternatives in diverse applications and the integration of these two sources can be implemented in hybrid or standalone configurations. Several researchers have undertaken extensive investigations to assess the viability of incorporating renewable energy sources to fulfill the energy requirements of different applications [2, 3]. In a study conducted by Siddaiah et al. [4], the authors investigated the application of hybrid energy systems in delivering dependable electricity to remote areas. The findings of the study indicated that energy systems predominantly reliant on renewable sources exhibited reduced Levelized Costs of Electricity (LCOE) and net present costs (NPC) in comparison to systems that integrated both renewable and non-renewable sources. Furthermore, integrating renewable energy sources in smart grids energy systems have been studied by other researchers to create smart grids and electrical power systems used in different applications [5]. The sustainability and stability of renewable energy sources are contingent upon various elements, such as the geographical placement and prevailing meteorological conditions surrounding the energy sources [6]. Researchers have shown that increased temperatures and wind speeds have a positive impact on the generation of electrical energy in a wide range of applications [7]. The research conducted by El Khashab et al. [8] underscored the significance of ambient temperature and sun irradiation in relation to the efficient and dependable production of electricity in Yanbu, Saudi Arabia. The outcome of the study indicates that the

strategic geographic location of Makkah is expected to enhance hydrogen production.

Various methods have been employed by research groups for efficient and dependable hydrogen production, with water electrolysis proving to be a dependable technique [9]. The Hybrid Optimization Model for Electric Renewable (HOMER) software has found wide application in numerous energy feasibility and optimization studies [10]. This software has been instrumental in conducting feasibility studies for various energy systems, consistently yielding positive results. The Makkah region is endowed with substantial wind and solar energy resources; yet, there is a dearth of comprehensive evaluation of the primary renewable energy sources in this particular region of Saudi Arabia [11].

In recent years, Saudi Arabia has achieved notable progress in the pursuit of sustainability goals, with a specific focus on the production and utilization of green hydrogen. The country now holds the distinction of having the most economically viable solar electricity on a global scale [12]. The primary aim is to produce and disseminate 650 million metric tonnes of hydrogen per day, resulting in an annual decrease of more than 3 million metric tonnes of carbon dioxide emissions by the year 2030 [13]. The Kingdom of Saudi Arabia effectively executed the initial experimental hydrogen filling station in 2019 [14]. The station was purposefully constructed to accommodate a restricted number of fuel cell electric vehicles, situated within the urban area of Dhahran [15]. Saudi Arabia exhibits favorable conditions that render the country very conducive for capitalizing on the generation of green hydrogen. Furthermore, the nation owns a significant amount of land suitable for the implementation of renewable energy infrastructure. Additionally, it enjoys a favorable geographical position that enables a high-capacity factor for renewable energy sources [16].

To cultivate a hydrogen-based economy that is both ecologically sensible and enduring, it is imperative to augment the share of renewable energy sources employed in the production of hydrogen for the city of Makkah in Saudi Arabia. The main objective of this research is to assess the economic viability of a hybrid renewable energy system in Makkah, a location located in Saudi Arabia. The study aims to provide valuable insights for authorities and policymakers, enabling informed decisions on harnessing renewable energy sources for electricity generation and hydrogen production in Makkah. The study's outcomes will serve as a foundation for policymakers to leverage the available renewable resources in Makkah for electricity generation and hydrogen production.

The city of Makkah, situated in Saudi Arabia, is geographically positioned at coordinates 21°'23.3"N, 39°51.5'E as shown in Fig. 1. Located in a small valley, 277 metres above sea level, is positioned 70 km inland from Jeddah on the Red Sea. It holds the distinction of being the third-most populous city in Saudi Arabia. The city of Makkah derives advantages from ample sunlight and regular wind speed, rendering it a favorable site for energy production [18]. Given the prevailing warmth and high wind speed in the area, it is worthwhile to investigate the potential for constructing a cleaner and more sustainable environment by establishing a hydrogen refueling station in the city.

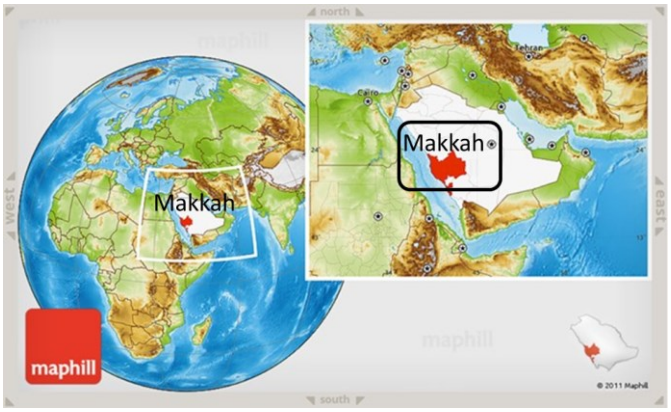


Fig. 1. The geographical location of Makkah, Saudi Arabia (Red portion) [17].

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2. Methodology

The purpose of this study is to assess the feasibility and effectiveness of a hybrid renewable energy system to produce hydrogen in an off-grid setting, specifically for a refueling station located in Makkah, Saudi Arabia. The procedure involves the gathering of data related to several aspects, such as the energy consumption of the refueling station, different arrangements of renewable energy systems, levels of radiation, wind velocity, and ambient temperature. Furthermore, the present study evaluates the economic efficacy of the system by analyzing the levelized cost of hydrogen (LCOH), levelized cost of electricity (LCOE), and net present cost (NPC) associated with each configuration. The subsequent sections offer a comprehensive elucidation of the constituent elements of the system. Fig. 2 presents the flowchart that illustrates the methods employed in the current investigation.

The meteorological data pertaining to Makkah and the characteristics associated with the hybrid energy components are configured within the HOMER software and the best energy system is selected for the refueling station.

2.1. Description of the System Components

This study presents a proposal for the implementation of two hybrid renewable energy systems with the objective of generating green hydrogen for the purpose of refueling stations. The concept incorporates the integration of photovoltaic (PV) technology, a battery, a wind turbine (WT), an Electrolyzer (EL), hydrogen tank (HT), and a converter.

2.1.1. Photovoltaic

Solar PV panels are a widely recognized and established technology utilized for the purpose of generating electricity through the conversion of sunlight [20]. The key consideration of selecting suitable PV arrays stems from the significant impact of solar radiation on the performance of PV cells [21]. In this study, the flat plate mono-crystalline refers to a type of solar panel that is characterized by a single crystal structure and is utilized in the present investigation. The technical and economic parameters of the PV system are presented in Table 1.

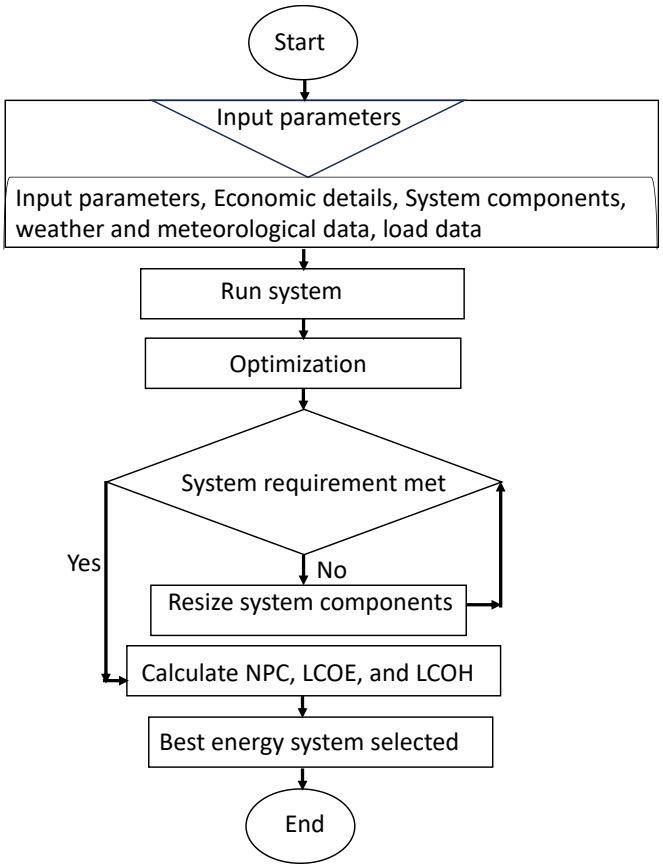


Fig. 2. Methodology and feasibility study summary [19].

2.1.2. Wind turbine

The geographical positioning of Makkah and its favorable conditions for wind energy have prompted investigations into the viability of WT technology as a potential means of generating power and facilitating hydrogen generation. The utilization of WT has become a well-established and mature technology for the purpose of generating power from renewable sources [28, 29]. The functionality of a WT is contingent upon the power output derived from the velocity of the wind, which is influenced by the height of the hub [30]. The determination of wind power output is achieved by HOMER software using interpolation techniques to generate the power curve shown in Fig. 3.

Table 1. Specifications of the PV panel

Parameter	Value	Ref.
PV type	Flat plate mono-crystalline	[22]
Tracking system	No tracking	[23]
Derating factor	80%	[24]
Capital cost	$1200	[25]
Replacement cost	$1200	[25]
Operation & Maintenance	$80	[26]
Lifetime	30 years	[27]

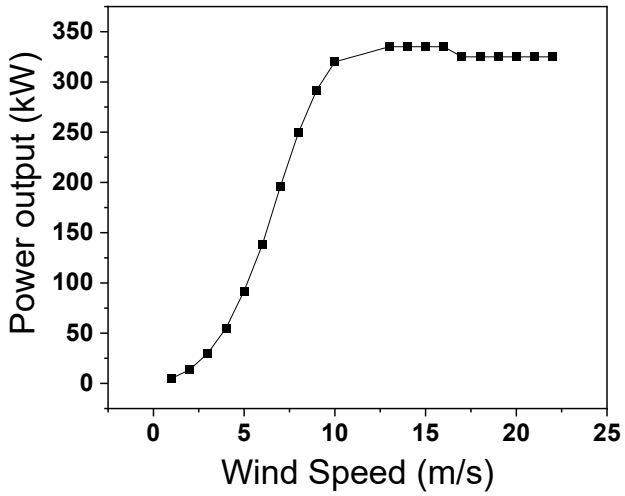


Fig. 3. Wind power curve generated at Makkah location [31].

Table 2 displays the technical parameters of the WT. The HOMER software employs linear interpolation as a method for calculating the WT yield [32].

Table 2. Specifications of the PV panel

Parameter	Value	Ref.
Wind turbine type	XANT330	[33]
Capacity	330 kW	[33]
Hub Height	50 m	[34]
Capital cost	$2,000	[35]
Replacement cost	$2,000	[36]
Operation & Maintenance	$100 per year	[36]

2.1.3. Electrolyzer

The electrolyzer (EL) is an essential constituent in the process of hydrogen production, wherein electrical energy is employed to facilitate the separation of water into its

constituent elements, namely hydrogen and oxygen [37]. The efficiency of electrolysis is often quite low, often ranging from 70% to 80%, primarily due to losses incurred during the electrolysis process [38]. Researchers have indicated that the optimal level of efficiency can be attained through the utilization of water electrolysis, particularly when employed in conjunction with a PV array [39]. Table 3 presents the technical parameters of the EL employed in this investigation.

Table 3. Specifications of the electrolyzer

Parameter	Value	Ref.
Efficiency	80%	[40]
Capital cost	$1000/kW	[41]
Replacement cost	$1000/kW	[42]
Operation & Maintenance $5 per kW/year	$50 per kW/year	[42]
Lifetime 15 year	Lifetime 30 years	[43]
Efficiency	80%	[40]

2.1.4. Battery

Battery banks serve as storage and backup systems, facilitating the provision of uninterrupted electrical power in situations where other energy sources are not accessible. The present study selects a Lithium-Ion battery with a nominal voltage of 12 V and a nominal capacity of 1 kWh. It possesses a lifetime throughput of 3000 kilowatt-hours (kWh). The roundtrip efficiency of this battery is measured at 90%. Furthermore, the maximum charge and discharge currents for this battery are 167 Amperes (A) and 500 Amperes (A) respectively. The battery's initial state of charge and minimum state of charge are established at 100% and 20%, respectively. The battery has a capital cost of $110/kW, replacement cost of $110 /kW, and operation & and maintenance cost of $10 / kW per year Lifetime of 15 years.

2.1.5. Hydrogen tank and compressor

Hybrid energy systems incorporate a hydrogen tank as one of its parts. When there is no demand for hydrogen and the electrolyzer is producing more hydrogen than is needed, the hydrogen can be stored in the hydrogen tank. The hydrogen tank has a capital cost of $600/kg, a replacement cost of $400/kg, operation & and maintenance cost of $10/kg for a Lifetime of 25 years. Hydrogen refueling stations have been specifically engineered to facilitate the replenishment of fuel cell cars' storage tanks, operating at either 350 or 700 bars [44]. To construct a hydrogen refueling station using a proton exchange membrane electrolyzer, it is imperative to employ a compressor capable of effectively compressing hydrogen to elevated pressures, with a minimum need of 300 bars [45]. The hydrogen compressor is simulated by HOMER using a comparable principal electrical load and a compressor efficiency of 0.75 was used in the study.

2.1.6. Converter

The system employs a generic converter model that is tasked with converting alternating current (AC) to direct current (DC) using an inversion process. This converter model exhibits an input efficiency of 90%. The converter has a capital cost of $300/kW, replacement cost of $300/kW, and operation & and maintenance cost of $5/kW per year for a Lifetime of 15 years.

2.1.7. Comparison between the fuel cell-based vehicle and battery based vehicle

Both the fuel cell-based vehicle and battery-based vehicle provide electrical power to operate electric motors, thereby eliminating the environmental contamination and inefficiencies associated with the traditional internal combustion engine. While fuel cells-based vehicle draws their power from hydrogen stored on the vehicle, and battery-based vehicle often acquire their energy from the electrical grid or other energy sources [46]. In terms of weight, fuel cell-based vehicles are less heavy than battery-based vehicles due to the requirement of additional support to ensure the necessary strength by the battery-based vehicle [47]. When comparing the storage volume, the fuel cell-based vehicles are significantly more compact compared to battery-based vehicles [48]. Consequently, the battery electric vehicle necessitates a greater amount of stored energy per mile compared to the fuel cell electric vehicle due to the increased weight of the batteries and the subsequent heavier components [49]. Although it has been reported that the battery-based vehicles are more efficient than the fuel cell-based vehicles, essentially, the added weight of a long-range battery-based vehicle even with sophisticated lithium-ion battery technology cancels out the enhanced efficiency of the battery pack as compared to a fuel cell system [49].

2.2. Energy Resources at Makkah City

The sun and the wind are the two renewable energy sources commonly being explored for electrical energy generation [50]. There is an abundance of renewable energy sources, each of which is susceptible to the local climate, and will be discussed in the subsequent section.

2.2.1. Solar radiation

The assessment of solar radiation in Makkah was conducted using the HOMER simulation, which utilized data obtained from the NASA Prediction of Worldwide Energy Resource (POWER) database [51]. The output from the study is displayed in Fig. 4.

Based on the data presented in Fig. 4, it can be observed that the maximum recorded daily radiation in the month of June amounted to 7.116 kWh/m2/day, and the minimum recorded daily radiation in December was 4.323 kWh/m2/day. The Clearness Index displays a spectrum of values, with a minimum value of 0.623 recorded in January and a maximum value of 0.661 recorded in October.

2.2.2. Wind speed and temperature

The analysis of the wind and temperature resources also incorporates data acquired from the NASA (POWER) database [52]. The temperature of Makkah is shown in Fig. 5a.

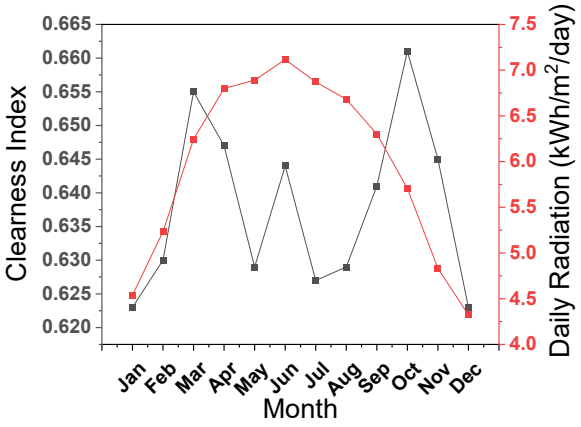


Fig. 4. Daily radiation and clearness index of Makkah [31].

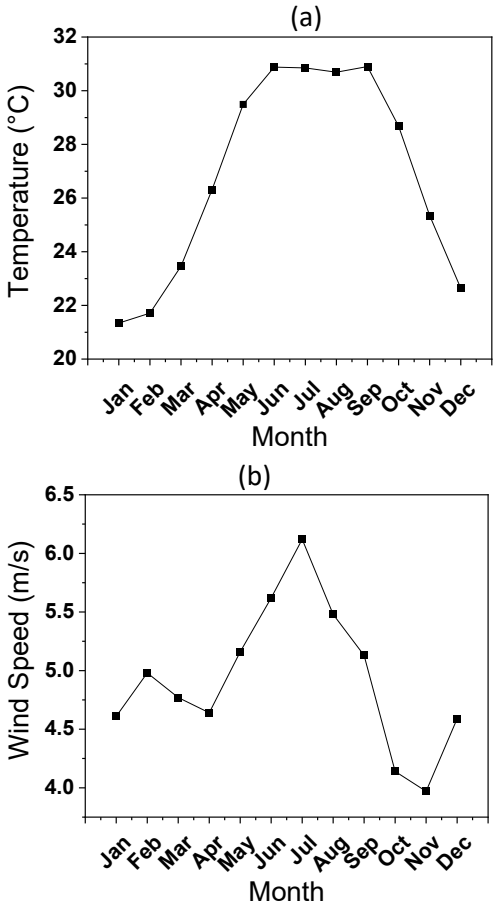


Fig. 5. Recourses of (a) Wind speed and (b) temperature at Makkah [31].

According to Fig. 5a, the lowest temperature recorded at Makkah was 21.34 degrees Celsius in January, and the highest temperature recorded there was 30.90 degrees Celsius in September. As can be seen in Figure 5b, average temperatures rise from January to August and then fall from September to December. Corresponding to the data presented in Fig. 5 (b), it can be observed that the maximum recorded wind speed of 6.12 m/s was documented in the month of July, whereas the minimum wind speed of 3.970 m/s was observed in November. The wind energy produced can not only generate electrical energy that can power several applications but can significantly generate a substantial amount of electrical energy for the electrolyzer [53].

2.3. Load Demand and Profile

The design of the refueling station (RFS) considered the presence of vehicles, each equipped with a hydrogen tank capable of holding 5kg. The twenty vehicles considered in this study collectively require a daily supply of 100kg of hydrogen. It is anticipated that the hydrogen demand will be satisfied by the utilization of hydrogen generated by the electrolysis process. The electrical energy for the system is generated using either PV or WT technologies. This energy is harnessed to fulfil the system's electrical energy demands and provide the necessary power input to the electrolyzer, facilitating the synthesis of hydrogen. The determination of the required load in HOMER is achieved by the utilization of meteorological data specific to the site. The HOMER software utilizes two distinct methodologies, namely day-to-day or step-to-step randomization, in order to estimate the load profile [54]. Fig. 6 displays the daily electrical and hydrogen loads.

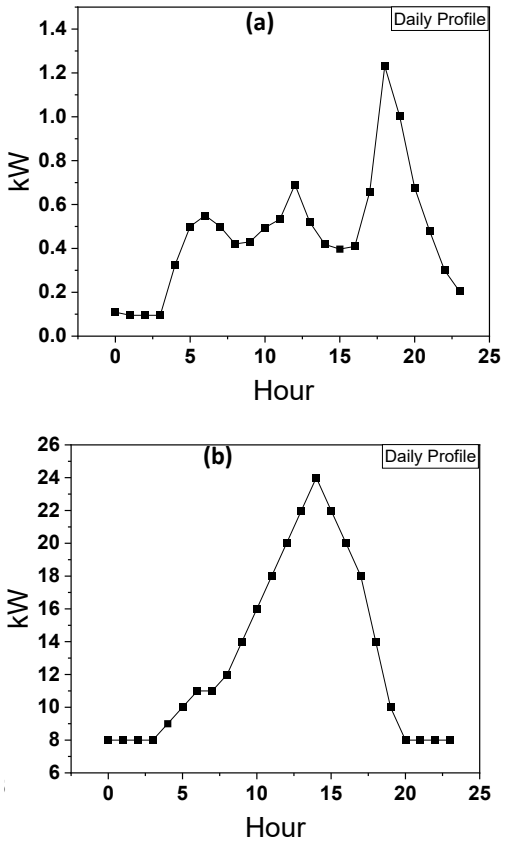


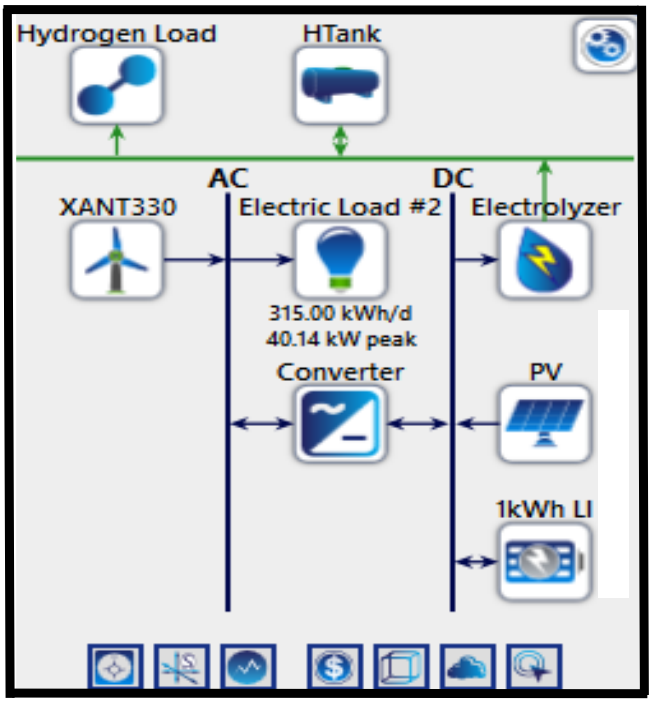
Fig. 6. Daily (a) hydrogen load demand and (b) electrical load demand [19].

3. Analysis and Validation of HOMER for Hybrid Energy System Configuration

As shown in Fig. 6, the load curves are a graphical representation that depicts the fluctuation in electrical and hydrogen loads demands [55]. While there is gradual increase in the hydrogen load demand from 4 am with peak load of 1.23 kW occurring at 6 pm, the electrical load exhibited a peak load of 24 kW at 2 pm as shown in Fig. 6. The electrical load is the load demanded by the electrolyzer and other components in the hybrid energy system. Often, the load profile is subject to variation based on weather and other factors [56]. However, HOMER software assesses the energy demand of the load during each time interval and then computes the energy generation during the corresponding time interval. Upon comparing the results, the HOMER software determines if the battery requires charging due to an excess of electricity or if this surplus electricity should be directed to the electrolyzer for hydrogen production.

The hybrid energy system design employed in this investigation is depicted in Fig. 7 via the HOMER simulation software. Fig. 7 depicts a variety of components powered by either PV or WT. It has been shown that a hybrid energy arrangement can increase energy production and applications [58]. To optimize the energy system, HOMER simulates the input parameters and local weather data. Consequently, the most cost-effective energy system is selected for implementation. Several researchers have explored the viability of different energy projects using HOMER software and the results presented [59, 60]. The overall agreement is that HOMER software through its techno-economic analytical ability can provide a feasible hybrid energy system for a given project and is used in this hydrogen refueling station study.

a



b

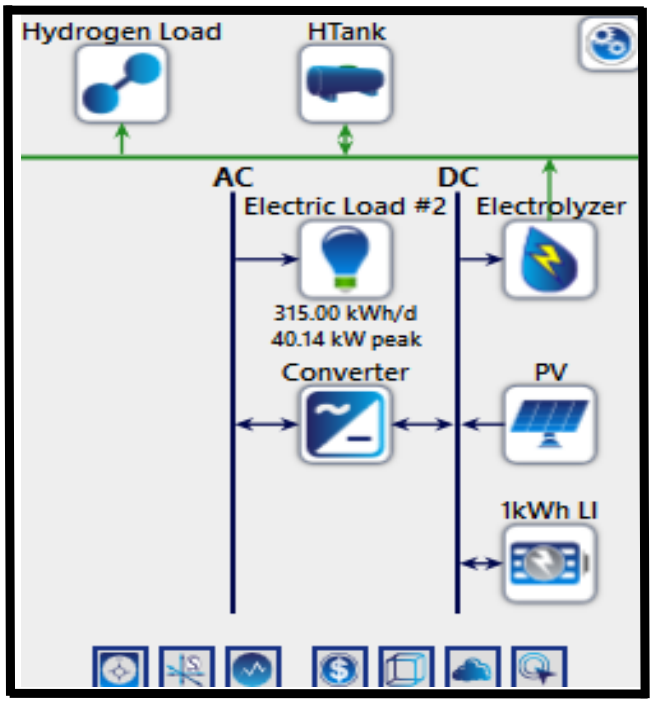


Fig. 7. The hybrid configuration under consideration [57].

3.1. Constrains Considered for Optimization Procedure in HOMER

HOMER actively seeks the most cost-effective and practical system during the optimization process. Several constraints are considered during optimization to provide feasible and efficient energy systems, for instance, restricting fuel usage, pollutants, or battery longevity [61]. The economic efficiency of a renewable energy system can be greatly enhanced by constraining some components used in the system [62]. For instance, the efficiencies of system components can be selected and constrained and the limit to which the battery can be charged be may needs to be constrained. Furthermore, if the system can tolerate occasional downtime or if non-essential loads can be reduced during periods of low battery capacity, substantial savings in capital expenditure can be achieved. HOMER represents this scenario by incorporating a constraint that limits the maximum annual capacity shortfall. In this study, the state of battery charge is set at 100% and minimum state of charge is constrained at 20%. While the efficiency of the electrolyzer was selected to be 80%, the derating factor was also selected to be 80%.

4. Economics and Environmental Analysis

To find the most efficient setup for a hybrid power system, HOMER employs optimization techniques. To minimize net current cost while achieving required performance criteria, like minimizing power supply loss probability and energy cost, HOMER Pro analyses available resources like solar and wind energy and energy storage to find the appropriate sizing of each component. The NPC is a

measure that factors in the purchase price, fuel costs, salvage value, operational lifetime, replacement price, discount rate, and replacement cost. The viability of a hybrid energy system can be assessed using the NPC, LCOE and LCOH. Using the optimized result from highest to lowest cost, the HOMER software determines the NPC and COE.

The present value calculations are used to simulate the lifetime capital cost, replacement cost, maintenance cost, and operating cost. After subtracting the total expenditure from the expected income, the net present value is determined using Equations (1) and (2) [63].

$$NPC = \sum_{n=1}^{i} id\,(C_{com} + C_{rep} + C_{M\&O}) \quad (1)$$

$$id = \frac{1}{(1+i)^n} \quad (2)$$

In this context, the variable "id" represents the discount rate, "n" signifies the number of years, "C_com" defines the capital cost of a system component, "C_rep" represents the replacement cost, "C_(M&O)" signifies the operation and maintenance cost.

The LCOE refers to the comprehensive expense associated with producing one kilowatt-hour of electricity using a hybrid renewable energy system. This cost encompasses the initial capital expenditure, ongoing operational costs, and the annual energy production. The LCOE is determined by the utilization of Equations 3 [63] and 4 [61].

$$LCOE = \frac{CRF\,X\,NPC_{total}}{\sum_{t=1}^{8760} pl\,(t)} \quad (3)$$

$$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1} \quad (4)$$

The expression ∑ Pl (t) represents the total energy production over the course of one year, where t ranges from 1 to 8760. NPC total represents the sum of the net present costs associated with various components of the system, such as wind, PV, converter, battery, hydrogen tank, and electrolyzer. The Capital Recovery Factor (CRF) is utilized to incorporate the annual real interest rate (i) and the duration of the investment (N). Equation 5 [61] establishes a relationship between the annual interest rate and two key factors: the nominal interest rate (i_0) and the inflation rate (f).

$$i = \frac{i_0 - f}{1+f} \quad (5)$$

In the same way, the calculation of LCOH is derived through the use of the subsequent Equation 6 [63].

$$LCOH = \frac{CRF\,X\,NPC_{total}}{\sum_{t=1}^{8760} LH2\,(t)} \quad (6)$$

The denominator in this context (LH2) denotes the total quantity of hydrogen generated throughout the entire year.

4.1. Return on Investment

Alternative economic performance measurements like return on investment (ROI) are explored in system feasibility study [64]. ROI is calculated using Equation 7 [63].

$$ROI = \frac{(Initial\ cost - Final\ cost) - Investment}{Investment} \quad (7)$$

5. Results and Discussions

5.1. System Optimization

To fulfil the necessary load requirements, HOMER software undertakes the simulation and optimization of all systems pertaining to the RFS application, as outlined in Table 4. The HOMER Pro is utilized for the purpose of determining the most suitable renewable energy system to be employed in the generation of hydrogen for refueling stations.

Since NPC, LCOE, and LCOH are the primary economic criteria needed to test the viability of the hybrid energy system, the HOMER reliably determines the system that meets the electrical load demands at the lowest values of these parameters. These factors were used by Roy [5] to determine the viability of renewable energy for remote villages in India. Furthermore, modeling of off-grid, optimization of hybrid energy system, and selection of viable options for different application have been performed using these economic parameters [56, 65]. Based on the optimization result showed in Table 4, it can be seen that Case 4 which comprises of 330 (kW) of WT, 700 kW of EL, 100 kg/L of HT, 110 1kW h of battery, and 450 kW of converter has the lowest NPC, LCOE, AND LCOH of $17520, $/kWh 0.012, and $/kg 0.352 respectively.

Table 4. System component criteria considered in the analysis

Cases	System Components								
	WT (kW)	**PV (kW)**	**EL (kW)**	**HT (kg/L)**	**Battery (1kW h LI)**	**Converter (kW)**	**NPC ($) x 10^3**	**LCOE $/kWh**	**LCOH $/kg**
1	-	100	500	100	110	450	17.85	0.014	0.369
2	-	150	500	100	120	492	18.01	0.015	0.376
3	-	200	500	100	110	492	18.24	0.017	0.378

4	330	-	700	100	110	450	17.52	0.012	0.352
5	380	-	700	100	120	492	17.63	0.013	0.354
6	420	-	800	100	110	492	17.80	0.014	0.361

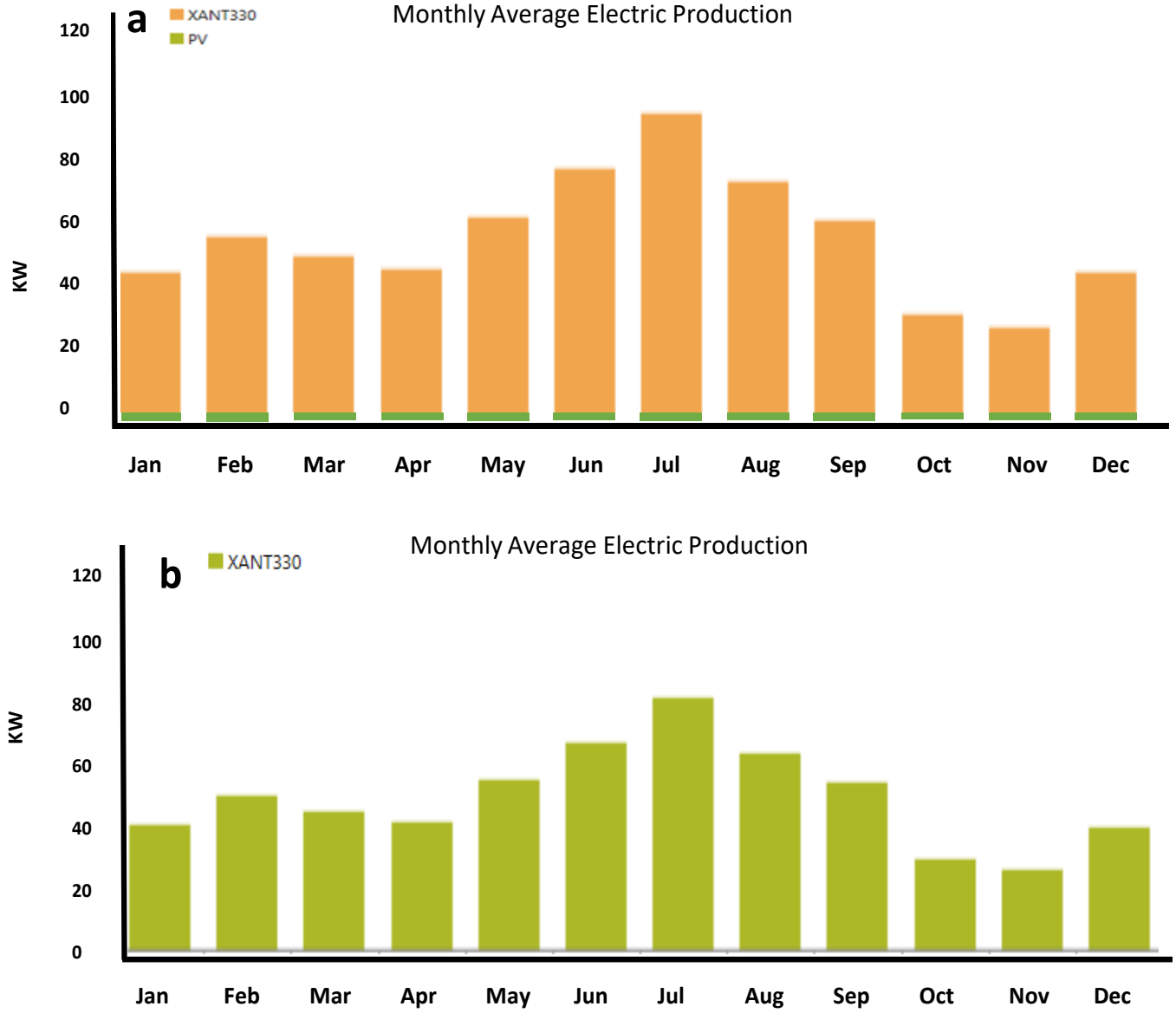


Fig. 8. Electrical energy generation from (a) photovoltaic and (b) wind turbine [58].

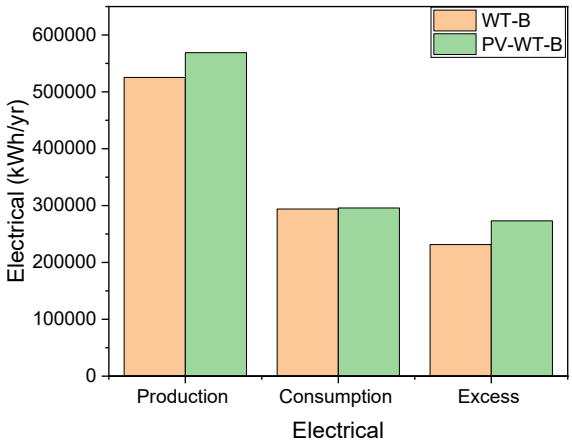
5.2. Electrical Energy Generation

Fig. 8 depicts the monthly fluctuations in electricity generation derived from hybrid renewable power output. The PV-WT-B energy system (Fig. 8a) generates a combined annual electricity output of 527,817 kWh. Of this total, 0.465% (2456 kWh/yr) is created by the PV panels, while the remaining 99.5% (525,361 kWh/yr) is generated by the WT.

Fig. 8b shows the electrical energy generated by the WT-B hybrid energy system. For the WT-B energy system, the substantial electricity output from WT in the Makkah region can be attributed to the prevailing high wind speeds shown in Fig. 5b and reported by other researchers [66]. When the amount of electric power produced by WT exceeds the current demand, the surplus electricity is stored in storage components to be utilized during periods of low supply from alternative electric sources. As stated by Dunn et al. [67], the available or saved energy can be utilized during periods of low supply to fulfil the daily load requirements. Fig. 9 clearly shows the amount of electrical energy produced by the two energy systems and the consumed of energy consumed.

5.3. Hydrogen Production

Fig. Fig. 10a illustrates the annual hydrogen production by the electrolyzer in the two energy systems. It can be seen that WT-B energy system produced 3961 kg/yr of hydrogen while the PV-WT-B produced 3855 kg/yr of hydrogen. The higher hydrogen produced by the WT-B energy system compared to PV-WT-B energy system can be ascribed to the high wind speed prevailing in the Makkah [66].



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Fig. 9. Electrical energy production, consumption, and excess [68].

The hydrogen level within the HT is depicted in Figs. 10b and 10c for the energy systems. Fig. 10b shows that the storage level of the tank exhibits an upward trend from January to March, followed by a minor decline in April, and subsequently resumes its upward trajectory in May before a gradual reduction from October to November for the WT-B energy system. However, the PV-WT-B energy system displayed in Fig. 10c follows a similar trend but has a lower hydrogen level in April compared to the WT-B energy system. A period of stability in hydrogen levels is observed from June to September, followed by a further fall in October as shown in Fig. 10c.

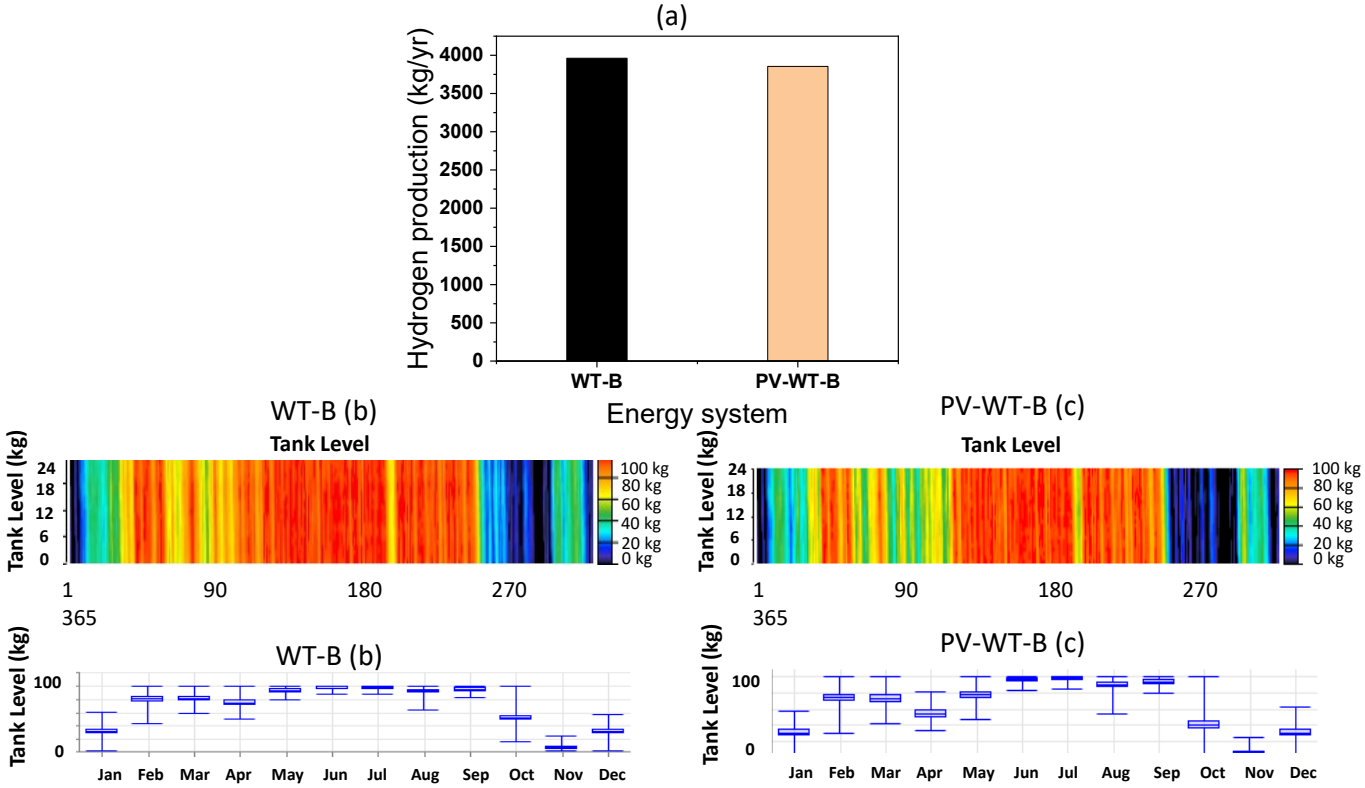


Fig. 10. Hydrogen produced, used, and storage level in the tanks (a) Hydrogen production, (b) WT-B and (c) PV-WT-B energy systems [68].

5.4. System Component Economic Cost Analysis

Fig. 11 provides a comprehensive overview of the capital expenses, operation, and maintenance (O&M) costs,

and replacement costs associated with the two energy system components.

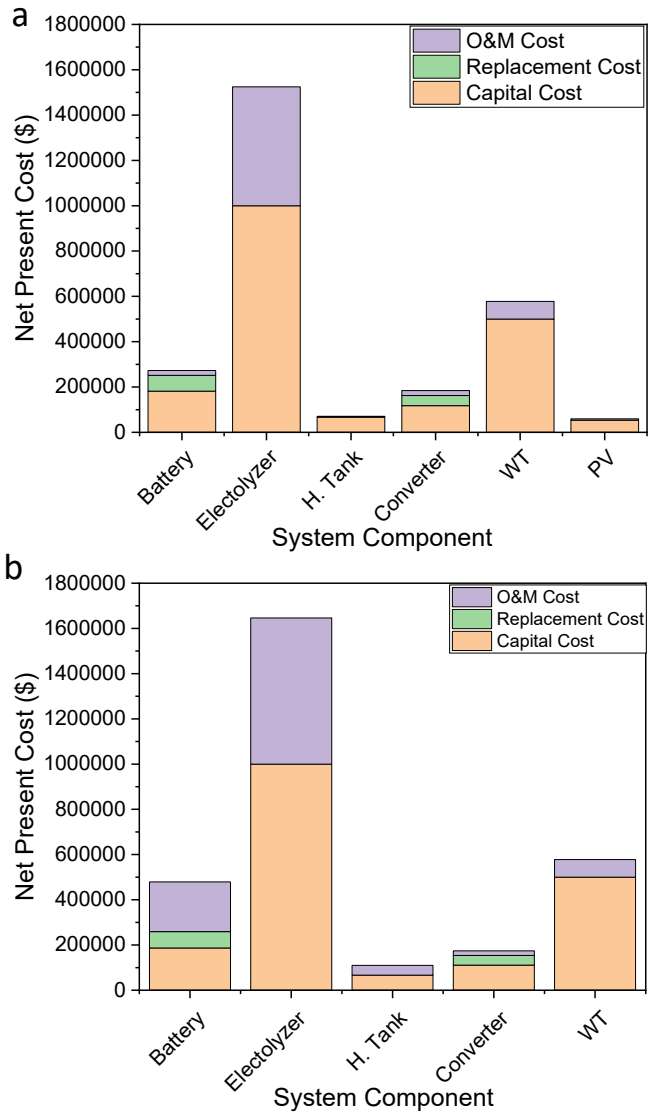


Fig. 11. Optimized (a) WT-B-HT-EL and (b) PV-WT-B-HT-EL renewable energy system component cost analysis [69].

For the PV-WT-B energy system (Fig. 11a), the EL incurs the most initial investment of $10,000000.00, constituting around 64.9% of the total system cost. The battery capital cost amounts to $181500, while for WT, the capital cost is $50,0000. The replacement costs associated with batteries are generally inexpensive which incurs a substantial replacement cost of $21,330 annually. Similarly, Fig. 11b shows that the EL has a capital cost of $10,000000.00 and an operation and maintenance cost of $646370.00. Numerous studies have been conducted to examine the techno-economic analysis of hydrogen RFSs, focusing on various energy sources and components [70, 71]. The overall findings suggest that the electrolyzer exhibits the highest cost and needs optimization to attain trustworthy and feasible outcomes.

5.5. Hybrid Energy System Selection

Fig. 12 shows the trends in the NPC, LCOE, and LCOH as economic parameters used for feasibility analysis.

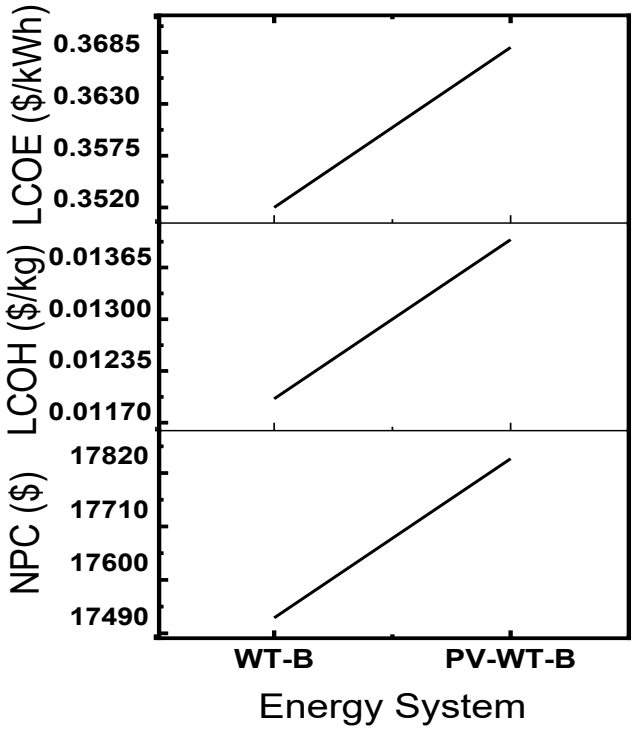


Fig. 12. Optimized energy systems [72].

Fig.12 shows that the WT-B energy system has the lowest NPC, LCOE, and LCOH of $ 17521.79, 0.012 $/ and 0.352 $/kg respectively as compared to the PV-WT-B energy system that has NPC, LCOE and LCOH of $ 17849.58, 0.014 $/ and 0.369 $/kg and the optimized system denoted as "WT-B" energy system is regarded as the most effective method for providing dependable electricity in order to generate hydrogen for the RFS in Makkah. When the wind speed is high in a given location, the energy generation appears predominantly high due to the association between wind speed and the energy generated from the WT [73]. Hence the lowest NPC, LCOE, and LCOH values observed in the WT-B energy system compared to the other hybrid energy system counterpart deemed the WT-B energy system reliable candidate for electrical power generation and hydrogen production for the proposed refueling station in Makkah. Return on Investment (ROI) is a measure used to evaluate the profitability of an investment by comparing the gain or loss generated relative to the initial amount of capital spent. Typically, ROI is stated as a percentage. As previously mentioned, it is imperative to choose the most effective and cost-efficient RFS for the Makkah community. The HOMER software incorporates considerations of prospective community expansions. Fig. 13 shows the ROI results of the two hybrid energy systems under consideration.

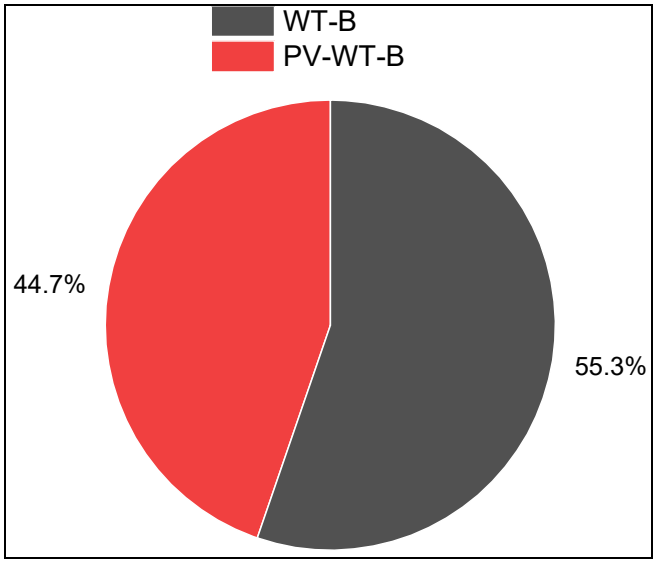


Fig. 13. The return on investment for the two energy systems [74].

The WT-B energy system exhibits a higher return on investment (ROI) of 55.3% in comparison to the PV-WT-B energy system that has 44.7%. Accordingly, the WT-B energy system is considered the most appropriate choice for establishing a hydrogen refueling station.

6. Conclusion

This study investigated the feasibility of establishing a hydrogen refueling station in a city of Makkah. Two off-grid energy systems of photovoltaic-wind-battery and wind-battery were considered to power the electrolyzer for hydrogen production. HOMER software was used to simulate and optimize the systems to ascertain the system with the lowest NPC, LCOE, and LCOH. Based on the results, the wind-battery energy system that comprised of a 330-kW wind turbine, a 700 kW electrolyzer, a hydrogen tank with a capacity of 100 kg/L, a battery with a storage capacity of 110 1kW h, and a converter with a power rating of 450 kW is selected as the cost-effective hybrid energy system to power the hydrogen refueling station. These findings ultimately establish the selected hybrid energy system as the most suitable option for the proposed project. The wind-battery energy system selected exhibits a larger return on investment compared to the photovoltaic-wind-battery energy system, therefore indicating the greater practicality of the wind-battery energy system for the hydrogen refueling station project in the city of Makkah, Saudi Arabia. The results of this research will hopefully inform the establishment of the Makkah area's hydrogen production and refueling station in the city of Makkah.

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