Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Assessment of Using an Off-Grid Hybrid Solar-Wind Renewable System for Power Generation in the South of Iraq

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ARTICLE INFO

Article Type:

Research Article

Received:2025.12.02
Accepted in revised form:2026.01.31

Keywords:
Off-Grid;
Solar Energy;
South of Iraq;
rural area;
Homer Software;
Wind Energy

ABSTRACT

It is crucial to supply electricity to unconnected rural areas. Typically, diesel generator used to supply electricity in these regions. This article involved examination of the same off-grid hybrid PV/WT system in four locations in the Thi-Qar province, Iraq. The data of weather is collected from NASAPOWER for the year 2024, and utilizing HOMER software, a constant load of 40 kW for each site is applied. The maximum yearly mean value of wind speed and temperature is 4.690 m/s and 27.290°C, respectively, both in the 2nd site positioned in east-north of AL-Jebaish district. The greatest yearly mean value of solar radiation is 5.60 kW/m², noticed at the 1st site located east-south of AL-Jebaish district. The result indicated that the 1st scenario, which represents the modelling of the hybrid system in 1st site, is more reliable and with effectiveness of cost because it has potential, as indicated by annual solar irradiation, with a configuration of photovoltaic panels of 148 kW, wind turbines of 170 kW, a converter of 50 kW, and 530 units of battery. Economically, the levelized cost of energy is $0.3603/kWh, the net present value of the project is $2143028, operation cost is $54899.84, and initial capital is $1.21M.

1. Introduction

Energy is a key factor that catalyst the economy in all countries; therefore, any enhancement or development of technologies related to renewable energy will lead to an improvement in the energy supply that is demanded by all different activities, and the price will match with that produced by traditional fossil fuel. In the following eighty years, renewable energy will meet about 60% of the overall demand for energy at the worldwide level. This orientation is to sustain clean energy resources,

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Cite this article: Mohammad, M. Salman and Hannun, R. M. (2026). Assessment of Using an Off-Grid Hybrid Solar/Wind Renewable System for Power Generation in the South of Iraq. Journal of Solar Energy Research, 11(1), 2802-2819. doi: 10.22059/jser.2026.407179.1675

DOI: 10.22059/jser.2026.407179.1675

contributing to the improvement of the environment, and is expected to minimize the greenhouse emissions in 2050 to three-fourths compared to 1985. On the other hand, it is expected that the continuous reduction in the price of renewable technologies will not result in any additional costs associated with their expanded usage [1]. In the current century, most countries are facing development issues, with the primary challenge being the provision of electrical power. The critical difficulties hindering the expansion of renewable energy utilization are reliability and high costs [2]. The increase in transmission distance leads to an increasing amount of lost energy-related electrical power [3]. These losses formed an additional challenge for rural electrification, which is the primary justification researchers use to pursue off-grid renewable solutions.

The importance of the hybrid system based on wind and photovoltaic solar energy is a promising alternative to the traditional technology of electric power production; therefore, a lot of researchers are involved in a worldwide, implemented experimental and analytical research to develop this technology [4].

Q. Hassan et al. [5] Hasan performed the simulation, by HOMER Pro, of the PV/WT system integrated with a diesel generator to meet the load in Al-Muqdadiiya city; he confirmed that the combination is unfeasible because the LCOE of the proposed system is $0.321/kWh, while that of the grid electricity in Iraq is about $0.2/kWh. In addition to that, the power generated by a wind turbine isn't valuable due to the minimal wind speed.

Saadon A. Hafedh [6] investigated the feasibility of implementing the hybrid system to meet the average daily load of 48.5 kW/day of a small village in Medely city. The optimization results showed the LCOE and NPV of the best option are $0.117/kWh and 14.8 M$, respectively. While increasing the wind turbines by one only leads to changing the value of the LCOE and NPV to be $0.118 /kWh and $14.988 M, respectively.

Zaidoon Waleed AL-Shammari et al. [7] implemented the investigation of the optimal sizing of the hybrid PV/WT system to carry out the average annual load of 35.96 kWh/day of a rural school in Zerbattiya region. They found that the LCOE and reliability of the optimal system sizing are $0.536/kWh and 99.909%, respectively. In addition, the share of PV production is 59%.

Zaidoon W.J AL-Shammari et al. [8] carried out an analytical study to determine the valuable option of the hybrid by using renewable resources such as solar photovoltaic (1 kW PV) and wind turbine (10 kW WT) in addition to traditional resources, such as diesel generator (100 kW DG), for the electrification of Zerbattiya city. The results of the analysis emphasized that the (WT-DG) is a viable scenario with 58% wind energy penetration. The LCOE and NPV are $0.123/kWh and $2.92 M, respectively.

Ammar Issa Ismael [9] Examined two cases to address the gap between the demand load and supply by the grid of a tiny settlement in Bald Ruz region, Iraq. The findings show that the first case with a combination of PV/WT/Grid is the optimum choice, with a LCOE of $0.2/kWh, 57.19%, and 8.31% being the shares of PV and WT, respectively. While the LCOE for the second case (PV/WT/DG) is $0.998/kWh.

Sarah Ali Al-shammari et al. [10] studied experimentally conducted to modify the vane angle of the Savonius vertical axis wind turbine (SWT) based on adjusting its vane shape. The SWT was combined with a solar PV system to provide lighting for a specific house (0.4 kW) in Baghdad. The tilt angle varied seasonally from 18° to 65°. It found the SWT provided 10%-25% of the demand load in case of a cloudy day.

Ahmed Al-Sarraj et al. [11] evaluated the feasibility of the PV/WT/DG hybrid system connected to the grid to satisfy an average load of 145.5 kWh/day in Baghdad. With and without a sellback are the two options that were evaluated. The findings indicated that the total cost for the option with sellback is less than the option without sellback by 15621.95$.

Othman J. Alhyali et al. [12] modelled the hybrid system with its main resources, which are solar PV and a diesel generator, to assess the feasibility of feeding vehicle charging stations (EVCS) in three selected Iraqi cities. The findings illustrated that the best option is located in Mosul city with $0.025/kWh of the LCOE and $1.02M of the NPV; the worst is in Baghdad city with $0.027/kWh of the LCOE and $1.03M of the NPV. The renewable energy fractions at the Mosul and Baghdad sites are 53% and 52.7%, respectively.

Hussein Al-bayaty et al. [13] examined more than one scenario to identify the optimal scenario of the hybrid system to meet the shortage in electrical supply of a certain region in Kirkuk city. The combination of PV/DG is the optimal scenario with a LCOE of $0.254/kWh, as mentioned in their research.

Ali Hadi Kother et al. [14] assessed the proposal for a hybrid PV/WT system that provides electricity to the rural clinic in Al-Faw city based on the PSM approach. The optimization results illustrate that the LCOE and reliability are $0.518/kWh and 99.927%, respectively. The FR is 34% and 66% for solar PV and WT, respectively.

W.J. AL-Sammari Zaidoon et al. [15] evaluated three scenarios that proposed to mitigate the shortfall of grid electricity in Al-Faw city by producing at least 50% of the daily required load, that is, 489268 kWh/day. Solar PV and WT are the renewable resources adopted in those scenarios. The PV/WT scenario is the most effective, with an NPV of $78.8 M, a LCOE of $0.0381/kWh, and an FR of 59.1% of the demand load.

Aysar Yasin and Mohammed Alsayed [16] used PV, DG, battery (BT), and converter (CONV) are the components that are utilized to examine four scenarios, which are PV/DG/BT/CONV, PV/BT/CONV, PV/DG/CONV, and DG only. 300 kWh/day is the daily demand load of a small agricultural society in Palestine. It found that the PV/DG/BT/CONV configuration is optimal scenario with $636150.0 of the NPV and $0.4380/kWh of the LCOE; the article proved the maximum annual capacity shortages (MACS) have no influence; the way of energy control caused by declining the excess of electricity from 10.60% to 6.240% and from $0.480/kwh to $0.4160/kwh of the LCOE.

Laila A. Artemi et al. [17] studied the influence of varying values of the maximum annual capacity shortage (MACS) on surplus energy of the off-grid hybrid PV/WT that serves certain buildings in Libya. They examined four scenarios of the hybrid system with different values of MACS: 0.1%, 1%, 2%, and 5%. The findings indicated that a 5% MACS is the optimal scenario with $168173 of NPV and 58.3% of the surplus, while the 0.1% MACS scenario is the worst with 65.5% as surplus electricity.

Amin Jahed et al. [18] investigated the optimal choice of a battery that combined with a PV/WT hybrid system by using HOMER software under conditions of Shiraz, Iran. The demand load is 3000 kWh and 300 kWh for industrial and residential, respectively. Four types of batteries modelled with a combination of the hybrid system are lead-acid, lithium-ion, vanadium redox, and zinc-bromine. The findings highlighted that the lead-acid battery is the optimal choice with $0.47 of LCOE, $6.02 M of initial cost, and the reduction of the GHG is about 1060133 kg/year. They noticed that the Li-ion battery will be optimal if its cost decreases by at least five years.

Karrar J. Alaameri [19] conducted the simulation for enhancing the storage capacity from 47% to 67.55% by upgrading the system from PV/Battery to PV/WT/Battery. The annual demand load was 3230 kWh for a house in Najaf City, Iraq. Additionally, the upgrade led to a 63% increase in electric power generation.

Table 1 provides a summary of the literature review presented above.

Table (1) Summary of literature review

Aurther, year	**Research type**	**Main findings**
Q. Hassan et al. [5], 2016	Simulation by HOMER	The installation of the hybrid PV/WT/DG in Al-Muqdadiiya city is feasible for $0.321/kWh of LCOE, with 36% of PV and 64%, despite the minimal wind speed.
Saadon A. Hafedh [6], 2021	Simulation by HOMER	Optimization of the PV/WT/DG system of a small village in Medley City found an increase in LCOE and NPV from $0.117/kWh and $1.48M to $0.118/kWh and $14.989M when increasing the number of wind turbines by one.
Zaidoon Waleed AL-Shammari et al.[7], 2022	Simulation by HOMER	The reliability and LCOE of the PV/WT hybrid system modelled to serve a rural school in Zerbattiya region are 99.909% and $0.536/kWh. The share of PV is 59%.
Zaidoon W.J AL-Shammari et al.[8] , 2021	Simulation by HOMER	Examination of numerous scenarios of energy resources (PV, WT, DG) for the electrification of Zerbattiya city. WT/DG is a viable scenario with LCOE and NPV at $0.123/kWh and $2.92M, respectively. This model has a 58% share of WT.
Ammar Issa Ismael [9], 2015	Simulation by HOMER	PV/WT/DG and PV/WT/grid, the two are tested to provide a tiny settlement in Bald Ruz region. The first scenario is the optimum, with a LCOE of $0.2/kWh, and PV and WT share 57.19% and 8.31%, respectively.
Sarah Ali Al-shammari et al. [10], 2022	Experimental	A modification of the angle of the vertical-axis wind turbine, integrated with a PV panel installed in Baghdad, enabled the wind turbine to supply 10%–20% of the demand load on a cloudy day.
Ahmed Al-Sarraj et al.	Simulation by	Sellback and without sellback are two options of PV/WT/DG examined

[11], 2020	HOMER	under Baghdad conditions, and it was found that the cost for the option with sellback is less than the option without sellback by 15621.95$.
Othman J. Alhyali et al.[12] , 2025	Simulation by HOMER	The assessment of the PV/DG hybrid system for supplying vehicle charging stations under the climate conditions of three Iraqi cities found that the cost of energy (LCOE) and net present value (NPV) are minimal in Mosul City.
Hussein Al-bayaty et al.[13] ,2025	Simulation by HOMER	By utilizing multiple sources of energy (PV, WT, DG) to optimize the hybrid system for meeting a specific load in Kirkuk city, the PV/DG scenario is found to be the optimal one, with a LCOE of 0.254 $/kWh and a minimum NPV.
Ali Hadi Kother et al.[14] , 2022	Simulation by MATLAB	Under Al-Faw weather conditions, optimization of the off-grid PV/WT system. If found the optimum configuration is achieved, the percentage of renewable energy is 34% PV and 66% WT, with a LCOE of $0.518/kWh and reliability of 99.972%.
W.J. AL-Sammari Zaidoon et al. , [15] 2021	Simulation by HOMER	Under Al-Faw weather conditions, optimization of the connected-grid PV/WT system to meet 50% of the demand load. The optimum configuration is achieved with a cost of $0.0381/kWh, $78.8 million, and a renewable energy penetration of 59.1% of the demand load.
Aysar Yasin and Mohammed Alsayed [16] , 2020	Simulation by HOMER	PV/DG/CONV./BT is the best scenario, with $ 636,150 of NPV and $ 0.438/kWh of examination; MACS doesn't have any impact. This analysis examines four scenarios of PV, DG, CONV., and BT under the conditions of Palestinian weather.
Laila A. Artemi et al.[17] , 2023	Simulation by HOMER	Under the weather conditions of Libya, test the influence of varying MACS levels (0.1%, 1%, 2%, and 5%) on excess energy. The results indicate that the optimal MACS level is 5%, which corresponds to 58.3% excess energy, while the worst level is 0.1%, with 65.5% excess energy.
Amin Jahed et al.[18] ,2024	Simulation by HOMER	The lead-acid battery represented the optimal type, with a LCOE of $0.47/kWh. This conclusion is based on an investigation of the best among four types of batteries examined in combination with PV/WT under the conditions of Shiraz city.
Karrar J. Alaameri [19] ,2025	Simulation by HOMER	Upgrading from PV/BT to PV/WT/BT enhances the storage capacity from 47% to 67.55% and increases electrical generation by 63% under the climate conditions of Najaf City.

The aim of this work is to assess the feasibility of employing the combined configuration of renewable energy in one package as a hybrid system, as an off-grid mode, to produce the AC electric power which is required to electrically power a constant load at a remote cultivatable area in Thi-Qar province. The proposed system consists of a photovoltaic panel module, a wind turbine, a storage unit (battery), and a converter as major elements, modelled and installed at four distinct sites. The outcomes have to specify the more reliable, more cost-effective site among the four.

The area of Thi-Qar governorate is approximately 13,000 km², characterized by diverse geographical terrains, including desert, cultivable areas, saline lands, and wetlands such as marshlands. In addition, it is 121 km from the Persian Gulf, so there are some noticeable tolerances in climate between these sites. Therefore, this study distinguishes itself by modeling the PV/WT hybrid off-grid system at four different sites with varying territories in the Thi-Qar governorate. The simulation conducted at these sites revealed several variations in weather data while maintaining the same electrical load demand, which helped identify the most feasible site for the future installation of the proposed system. The study involved many novelties, as follows:

- The study represents the first step in creating an assessment map for specialists in electrical power production by adopting a hybrid system under constant load, specifically for Thi-Qar lands.
- The results provide clear and promising insights into candidate sites for the installation of hybrid systems in Thi-Qar lands.
- The technique employed by the proposed system is capable of minimizing the unmet load and reducing excess electricity by at least 30%.
- The study introduced a comparison and evaluation of the performance of hybrid systems at four different far sites in Thi-Qar lands, operating in off-grid mode, under a constant load that another researcher had not previously investigated.
- The study contributes to solving the issue of providing the rural remote regions that lie so

far from the main grid of electricity in the country.
- The results encourage considering the combination of more than one renewable resource to achieve reliability in addition to reducing GHG.

2. Methodology

Figure 1 illustrates the logical steps of the optimisation technique that was carried out in this study to determine the optimal site. that is conducted by HOMER software with input data represented by data of weather, demand load, and economical and technical data for each element of the system. The next subtopics will demonstrate the input data.

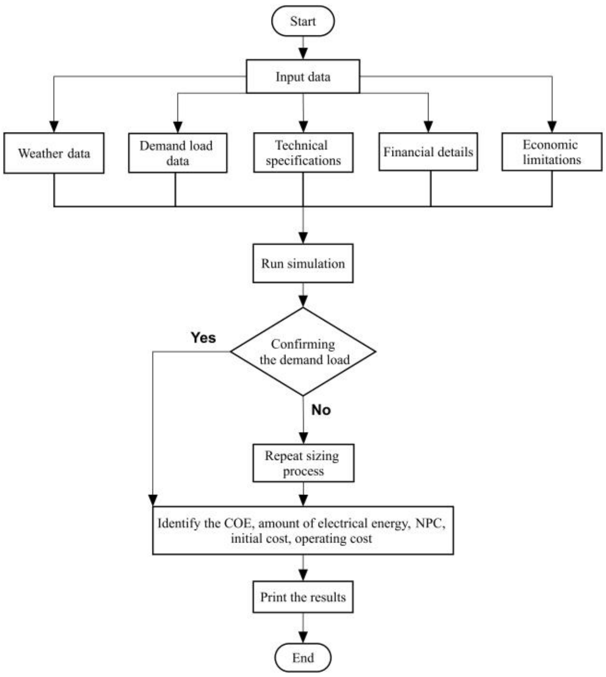

Figure 1. The schematic of a flowchart for optimizing process

2.1 The selected locations

Iraq lies in the Middle East, west of Asia, and has a common international border with many countries. Saudi Arabia in the south and west, Kuwait in the south, Iran in the east, Turkey in the north, and finally Jordan and Syria in the east [20]**.** The study covered four sites that lay in scattered locations in the Thi-Qar province, south of Iraq. There are several criteria based on identifying and candidating each of them, such as a site must be a long distance from the grid of electrical power that is owned by the Iraqi Ministry of Electricity, it is located in a farming settlement, and it enjoys variation in weather conditions and geographical nature. Figure 2 explains the position of each one of the sites studied in this article. The central aspect is employing renewable resources that are available, especially solar photovoltaic and wind energy, as clean, sustainable sources. The locations of the concerned sites are 30.63467°N 46.700302°E of the 1st east-south Al-Jebaish city, 31.136843°N 47.179865°E of the 2nd north Al-Jebaish city, 31.875154°N 45.733695°E of the 3rd west Al-Fajer city, and 31.012964°N 46.101388°E of the 4th south Al-Nasseriyha city.

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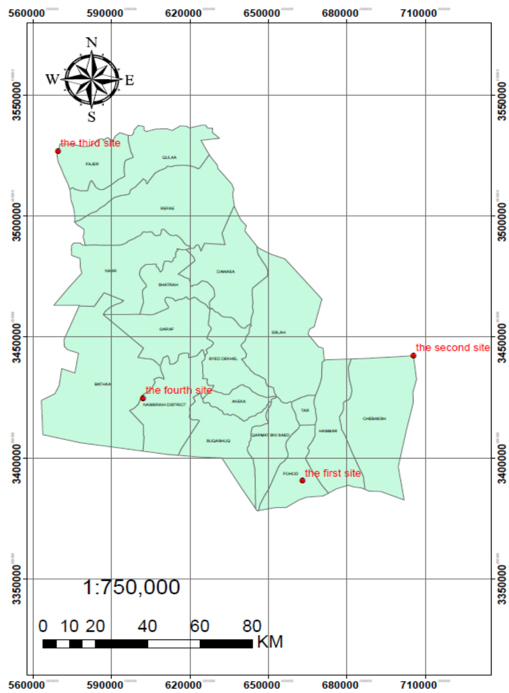

Figure 2. The locations of the sites are studied in Thi-Qar province

Figures 3 and 4 display the potential of wind and photovoltaic energies as promising renewable resources in Thi-Qar.

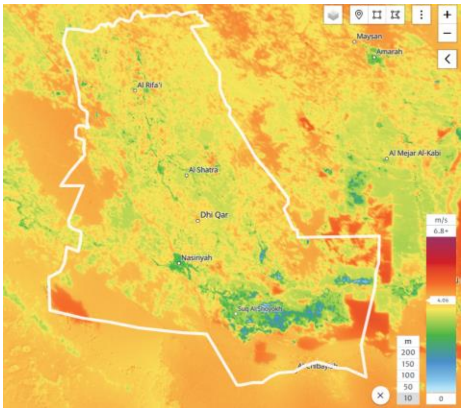

Figure 3. Mean value of wind speed of Thi-Qar province [21]

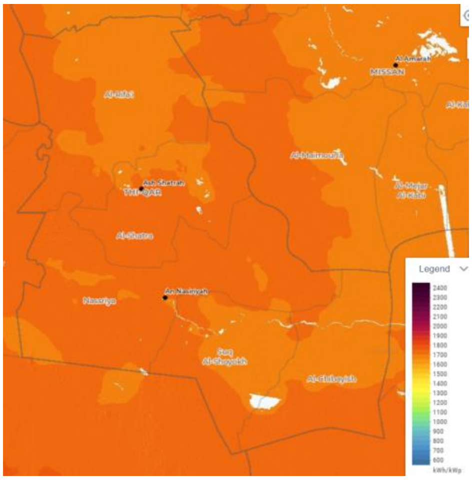

Figure 4. Mean value of solar radiation of Thi-Qar province [22]

2.2 The demand load

The idea of this study is to establish a sustainable source of electrical power that can be utilized by members of the Water Users Association (WUA) for crop cultivation and agricultural purposes in remote rural areas, which are typically not connected to the primary grid. The WUA is a local organization established in accordance with Iraqi laws to manage the common water source. The WUA board meeting prepared a timetable for all farmers who joined the WUA, known as the rotational irrigation approach. However, it is necessary to have a source of electricity active for all hours of the year to ensure the operation of all pumps owned by the farmer under the authority of the WUA in a just manner. In other words, the demand load must be constant. Therefore, the electric power with AC which is demanded at each site is considered as 40 kW that is constant along the hours of the year to operate the central pumping unit that supplies irrigation water to each field owned by a member of the WUA in the site. The daily and annual energy consumed by one pumping unit are 960 kWh and 350400 kWh, respectively, as shown in figures 5, 6, and 7.

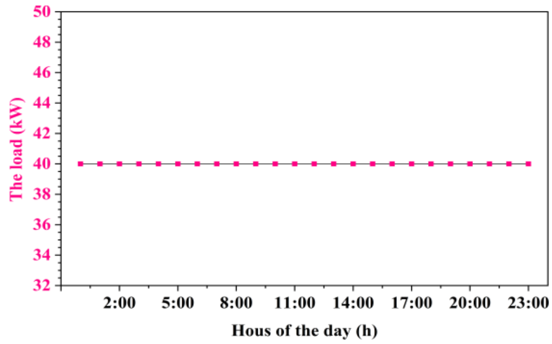

Figure 5. Daily Profile load

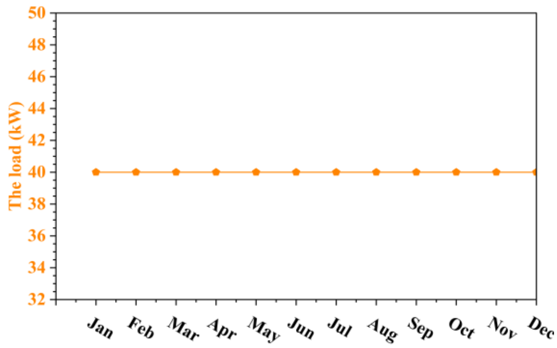

Figure 6. Monthly Profile load

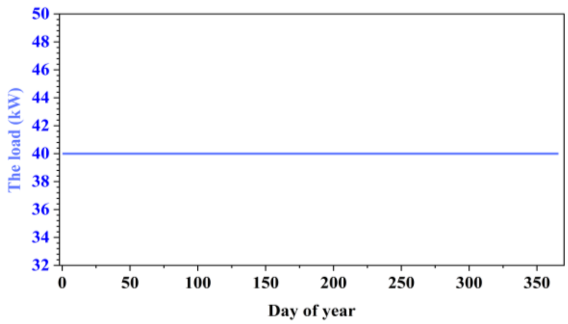

Figure 7. Annually Profile load

2.3 The Weather conditions

The climate of Iraq can be described as warm, dry, and sub-arid in summer and cold with a moderate rainfall rate in winter. Lately, Iraq has been influenced by periodic droughts that are caused by decreasing rainfall rates and global warming [20]. Thi-Qar province's summer weather is characterized by hot, dry, sub-desert conditions and humidity for numerous days. Typically, it is warmer in the northern province of Iraq. Concerning the winter season, it is described as cold with a shortfall of rainfall. Generally, the summer season has a period longer than that of the winter season, in addition to the sharp variation in climate between the two seasons.

In this study, the NASA POWER database was used as the source for the hourly averages of solar radiation, wind speed, and temperature, covering the targeted period from January 1, 2024, to December 31, 2024 [23]. Figure 8. demonstrates the monthly mean value of solar radiation for the four sites; it is noticed that Jan, Feb, Nov, and Dec have the lowest values for all sites. The monthly mean solar radiation values ranged from 3 kWh/m² to 89 kWh/m² across the four sites. The yearly mean values are 5.60 kWh/m², 5.30 kWh/m², 5.380 kWh/m², and 5.430 kWh/m² for the 1st, 2nd, 3rd, and 4th sites, respectively.

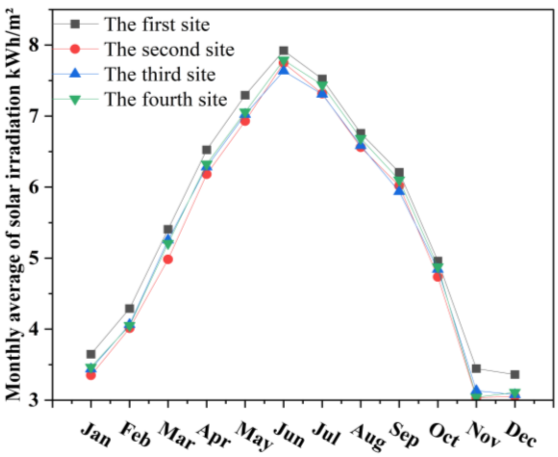

Figure 8. The monthly mean values of solar irradiation for the four sites in the year 2024

Figure 9. depicts the monthly mean value of the ambient temperature for the four sites; it is observed that Jan, Feb, Nov, and Dec have the lowest values for all sites. The monthly mean temperature values ranged from 12.0°C to 40.0°C across the four sites. On the other hand, the yearly mean values are 29.940°C, 27.290°C, 26.550°C, and 27.050°C for the 1st, 2nd, 3rd, and 4th sites, respectively.

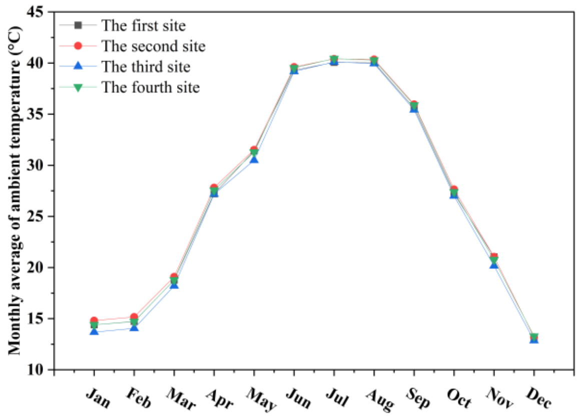

Figure 9. The monthly mean values of the ambient temperature for the four sites in 2024

Figure 10 illustrates the monthly mean value of the wind speed for the four sites; it is observed that Jun, Jul, and Aug have the highest values for all sites. The monthly mean wind speed values fluctuated between 3.0 m/s and 7.0 m/s across the four sites. While, it found the yearly mean values of wind speed are 4.650 m/s, 4.690 m/s, 4.450 m/s, and 4.510 m/s for the 1st, 2nd, 3rd, and 4th sites, respectively.

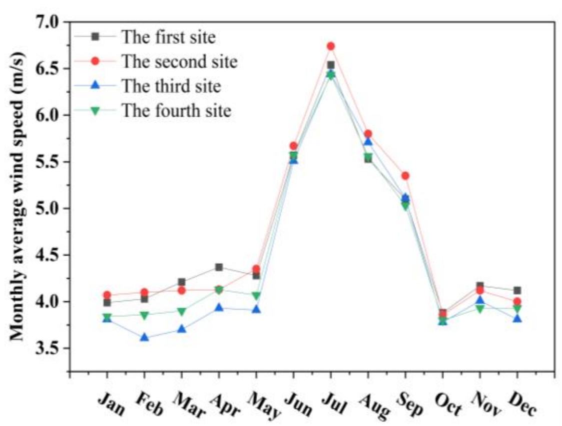

Figure 10. The monthly mean values of wind speed for the four sites in the year 2024

The NASA POWER database can be utilized as a reliable source of Iraqi weather data; however, it had to be validated [24]. Therefore, the weather data taken from NASA POWER for 2024 was validated by comparing it with the available data from the two nearest Ground-based Meteorological Stations (GMSs) to the second and third sites, which are administered by the Ministry of Agriculture; the distance from one GMS to the second site is approximately 23 km, while the distance from the other GMS to the third site is around 8 km. Unfortunately, the GMSs did not record all data for 2024, so the comparison for validation is limited to November and December at the second site and September, October, November, and December at the third site. Regarding the second site, the deviations in temperature, wind speed, and solar radiation are approximately 12.35%, 179%, and -4.6%, respectively. At the third site, the deviations for temperature, wind speed, and solar radiation are approximately 8.9%, 91%, and 15.2%, respectively. Therefore, the deviation associated with temperature and solar radiation is considered reasonable and can be adopted to validate the amount of both. On the other hand, it can be noticed that the deviation of wind speed is very large; this is because the GMSs are measuring at a height of 3 m. In addition, those MGSs were installed in cultivated farming fields

3. The proposed system

Figure 11 depicted the schematic design of the proposed hybrid system, which has two resources of renewable energy. The two resources combined functionally to make the system more reliable and stable. The major characteristic of the equipment is the photovoltaic cell. Monocrystalline (N type), 20.0 m is the height of the hub of the horizontal wind turbine. These resources are integrated with a dual-direction rechargeable storage unit (BAT) of 1.250 as the factor of safety and 0.80 DoD. HOMER Pro software was used to simulate the system with a resolution of one hour.

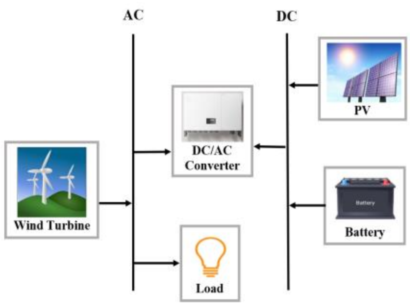

Figure 11. The schematic design of the proposed system is available

To meet the demand load for each site, the optimization is based on the search space mode, ensuring the balanced dispatching of PV and WT, which results in a decrease in the sizing of the storage system (battery). The annual capacity shortage considered no more than 8% of the electricity-generating capacity; this technique This will allow for a controlled shortage by making the system work below its highest demand, which helps manage electricity by providing more flexibility to reduce excess electricity. However, the maximum allowable percentage of excess electricity was set to be less than 30%. The strategy of energy storage in a set of batteries ensures preventing the stored energy from matching zero level, which increases the battery's life and enhances the reliability of the hybrid system. Therefore, the current hybrid system modelled with a 30% state of charge is the minimum state of charge. The design parameters are set based on a conservative approach, which includes a 5% safety margin to cover the expected increase in demand and to compensate for the loss of electrical resistance. On the other hand, to identify the optimal site among the four, the NPV is the main economic output, the value by which it ranks all system configurations in the optimization results.

The important technical details that are required to conduct the modelling of the proposed system components, such as efficiency, capacity, and service life, are depicted in Table 2. Furthermore, financial data for the proposed system elements, such as initial cost, replacement cost, and the cost of maintenance and operation that are unavoidable to achieve reality simulation, are listed in Table (3).

Table 2. Technical details of the proposed system elements

Element	The model	The capacity	The efficiency %	Service life (month)	Ref.
Photovoltaic panels	NEG21C20	0.70 kW	22.50	300	[25]
Wind turbine	Generic10	10 kW	30.0% – 45.0 %	180	[13]
Converter	Leonics	25 kW	96.0%	300	[11]
Battery	Surrette	6.91 kWh	95.0%	96	[12]

Table 3. Financial data of the proposed system elements

Element	IC ($)	RC ($)	O&M ($ per year)	Ref.
Photovoltaic panels	120.0	120.0	1.0	[25]
Wind turbine	50000.0	50000.0	500.0	[13]
Converter	8000.0	8000.0	20.0	[11]
Battery	600.0	500.0	0.00	[12]

Table 4. The economical constrains

parameter	dataset
economic lifetime	300 months
Discounting rate [26]	6.0%
Inflation level [27]	2.70%

Although the hybrid system is proposed as off-grid, the grid source is included in the model as an element to facilitate comparison with the base reference, as required by HOMER. Actually, importing electricity from the main grid involves paying fees to the Ministry of Electricity in Iraq. The Ministry of Electricity's statistical analysis indicates that the cost of producing and distributing one kilowatt-hour is approximately $100 [11, 28].

Compared to PV/WT and diesel-based systems, the reliability of the diesel-based system is higher than that of the PV/WT hybrid system due to the latter's reliance on fluctuating resources (solar irradiation and wind speed). On the other hand, the project life is one parameter that depends on identifying the LCOE; whereas it is a hybrid system ranging from 20 to 30 years, and for diesel-based systems, it is about 5 to 10 years. The available resources have a significant impact on the LCOE; for the hybrid system, abundant renewable resources will reduce the LCOE, while for the diesel-based system, the LCOE is influenced by the price of fuel and the cost of transporting it. Emissions: Diesel-based systems emit CO_2, while hybrids have zero carbon emissions. The capital cost of the hybrid is more than that of a diesel-based system with the same power capacity. The study conducted by [13] presented the economic assessment of PV/WT and diesel-based systems for meeting specific loads in Kirkuk city under annual average weather conditions of 5,756 m/s of wind speed, 4.47 kWh/m² of solar irradiation, 21.7°C of temperature, and 0.03 $/h the cost of diesel operating. The LCOE and NPV of the PV/WT hybrid system were $0.277/kWh and $5.27 million, respectively, and $0.391/kWh and $7.70 million for the diesel-based system. The outlines of the study explored by [8] regarding supplying the electrical load of Zerbattiya city under annual average conditions of 5.36 m/s of wind speed, 5.14 kWh/m², 22.38°C of temperature, 0.25 $/h the cost of diesel operating. The study found that the LCOE and NPV of the hybrid system are $0.485/kWh and $11.50 million, respectively. On the other hand, the LCOE and NPV for the diesel-based system are $0.143/kWh and $3.4 million, respectively. However, the use of the diesel-based system results in emissions of greenhouse gases that are linked to health issues and environmental pollution [29].

4. Governing Equations

This section outlines the mathematical equations used to determine the required calculations for the proposed system components.

4.1 Photovoltaic power

There are many factors that influence the power that is produced by the solar photovoltaic (P_{PV}), such as solar radiation, temperature, and the humidity of the ambient. Mathematically, the equation (1) is used to calculate the P_{PV} that consists of several parameters, such as the reduction factor of *PV cell* (f_{pv}), the nominal power capacity of *PV cell* (α), the temperature coefficient of power (Y_{PV}), the standard test condition temperature ($T_{C,STC}$) is equal to 25°C, the incident solar irradiation (S_T), and the incident solar irradiation at standard test condition ($S_{T,STC}$) is equal 1 kW/m². T_C is the practical temperature of the photovoltaic cell, which is greater than the standard test condition [30].

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

T_C can be identified via equation (2) that contains parameters such as ambient temperature at nominal operating cell condition ($T_{A,NOCT}$), temperature of the PV cell at nominal operating condition ($T_{C,NOCT}$), incident solar irradiation at nominal operating condition ($S_{T,NOCT}$), the efficiency of PV panel (η_C), and the transmittance-absorptance product [30].

$$T_C = T_A + S_T\left(1-\frac{\eta_C}{\tau\alpha}\right)\left(\frac{T_{C,NOCT}-T_{A,NOCT}}{S_{T,NOCT}}\right) \quad (2)$$

4.2 Wind turbine power

To calculate the delivered power from a wind turbine (P_{WT}) , it is identified by multiplying the wind energy by the power coefficient of the turbine (C_P) and the efficiency of the gearbox (η); this is by equation (3) under certain conditions of wind speed (U) and density of air (ρ) [31].

$$P_{WT} = \frac{\eta\rho A C_P U^3}{2} \quad (3)$$

4.3 Converter (CONV.)

The rectifier and inverter are the main classes of the converter systems. The major functional duty of a rectifier is to transform the electrical current that is produced by wind turbine power ($P_{elect., WT}$) into (DC) current, and the inverter's functional duty is to convert the electrical current produced by solar photovoltaics power ($P_{elect., PV}$) into (AC) current. The mathematical equations (4, 5, and 6) listed below are adopted to determine the efficiency of the converter (η_{CONV}), which is considered an important parameter for managing the electrical power passed through the converter [32].

$$\eta_{CONV.} = \frac{P_{oCONV.}}{P_{iCONV.}} \quad (4)$$

$$P_{elect.,PV} = P_{PV}\left(\eta_{CONV.}\right) - P_{COM} \quad (5)$$

$$P_{elect.,WT} = P_{WT}\left(\eta_{CONV.}\right) - P_{COM} \quad (6)$$

In this context, P_{iCONV}, P_{oCONV}, and P_{COM} represent the applied power of the converter, the delivered power of the converter, and the waste power, respectively, in the elements of the PV/WT hybrid system.

4.4 Storage unit (battery)

There are many parameters used to identify the capacity of unit storage (C_{BT}). There are storage periods (autonomy) (Na), daily mean usage (DAL), the depth of discharge (DoD), and system voltage (V_{sys}), using a specific equation (7) [10].

$$C_{BT} = \frac{\left(DAL \times Na\right)}{\left(DoD \times V_{sys} \times \eta_{BT}\right)} \quad (7)$$

5. Results and Discussion

The results of electricity production from renewable energy resources for the four sites are introduced and analyzed, with a focus on the unique characteristics and available potentials at each site. A simulation process was conducted to optimize each component of the proposed hybrid system to achieve the demand load with a sustainable path and cost-effectiveness. Iraq is located in the Northern Hemisphere, so the investigation of the weather situation at the four sites over two days, which are characterized by their unique weather conditions. On 22 June 2024, there is the longest daylight of the year with high solar irradiation, as the solar declination angle (δ) reaches its maximum positive value of +23.45°; conversely, on 22 December 2024, there is the shortest daylight of the year with low solar irradiation because the declination angle is at its minimum negative value of -23.45°.

The study illustrates a clear vision of the nature and potential of traditional weather conditions in each site. For solar irradiation, it was observed that the first site has the highest annual average of 5.6 kWh/m², while the second site has the lowest at 5.3 kWh/m². Figures 12 and 13 illustrate that the first and fourth sites both have the greatest hourly average solar irradiation, while the minimum occurs at the third site on June 22 and December 22, 2024.

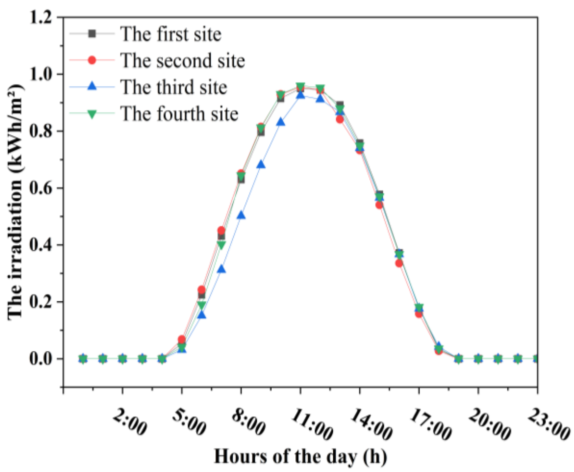

Figure 12. The hourly average solar radiation for the four sites on June 22, 2024

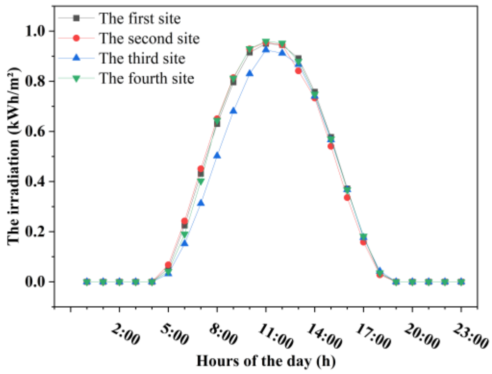

Figure 13. The hourly average solar irradiation for the four sites on Dec 22, 2024

Regarding wind speed, the most significant annual average value is 4.69 m/s at the second site, and the lowest is 4.45 m/s at the third site. On June 22, 2024, the first and fourth sites had the fastest wind speeds, while the second site had the lowest, as shown in Figure 14. For December 22, 2024, Figure 15, which appears in both the first and second, represents the rapidly increasing wind speed, while the minimal wind speed is at the third site.

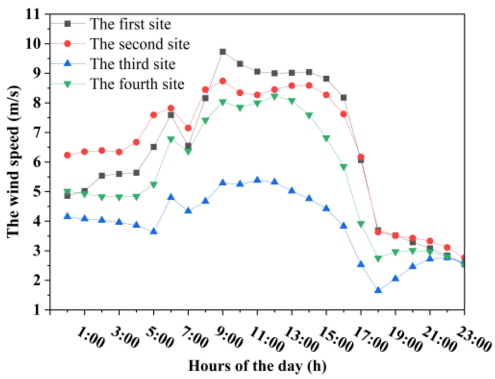

Figure 14. The hourly average wind speed for the four sites on June 22, 2024

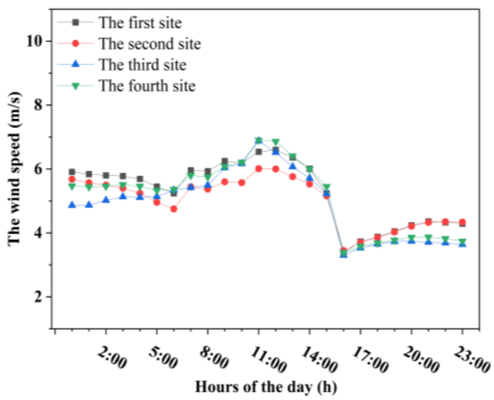

Figure 15. The hourly average wind speed for the four sites on Dec 22, 2024

Analysis of weather data indicated that the annual average of ambient temperature has a peak magnitude of 29.94°C at the first site, and the lowest is 26.55°C at the third site. Figures 16 and 17 display both the third and fourth sites with the most significant hourly average ambient temperature.

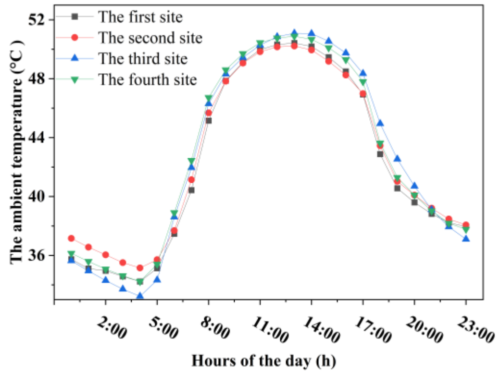

Figure 16. The hourly average temperature for the four sites on June 22, 2024

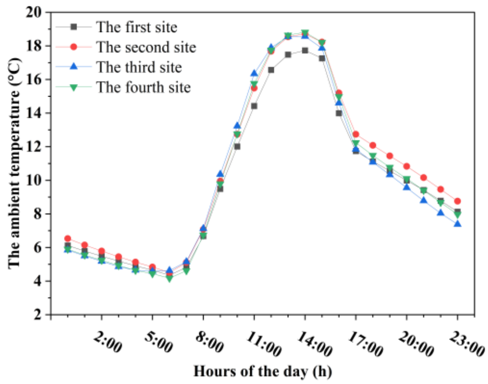

Figure 17. The hourly average temperature for the four sites on Dec 22, 2024

The sizing process achieved by HOMER for the PV/WT hybrid systems in the four sites is illustrated in Table 5.

Table 5. The sizing of hybrid systems

Element	PV	WT	CONV.	BAT
Unit	kW	kW	kW	No. of strings
1st	148	170	50	530
2nd	145	180	50	545
3rd	149	160	50	622
4th	149	170	50	540

The above values represent the essential configuration of the proposed hybrid system to meet the demand load at each site.

Figure 18. displayed the share of renewable energy resources (solar photovoltaic and wind energy) that produced the electric power in all the sites. The analysis showed that the 2nd site has the highest share of wind energy with 43.5% of the overall electricity produced, and the 3rd site has the highest share of solar photovoltaic energy with 65.2% of the overall electricity produced.

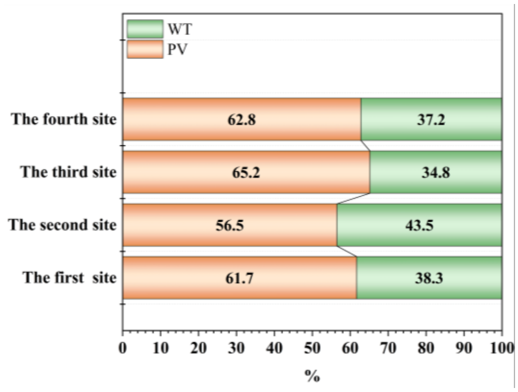

Figure 18. The share of electric power produced by renewable energy at each site

Figure 19 represents the overall summation of renewable energy achieved via the set of photovoltaic panels and wind turbines at each site. The highest amount of energy produced by photovoltaic panels is 294340 kWh/year; that is at the first site. The most significant energy produced by wind turbines is 209000 kWh/year at the second site. On the other hand, the lowest energy achieved by photovoltaic panels and wind turbines is 270995 kWh/year at the second site and 152788 kWh/year at the third site, respectively.

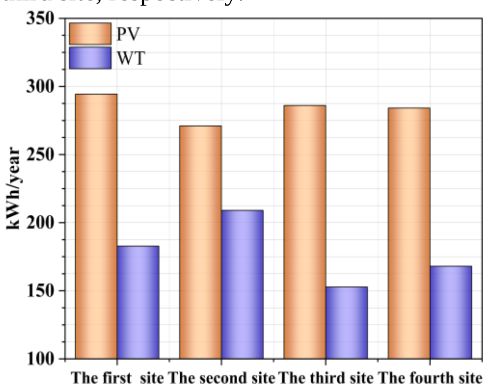

Figure 19. Summation of renewable energy produced in all sites

The financial results of the four sites are tabulated in Table 6. Depicted the economical outcomes related to modelling all studied sites. The LCOE spans from $0.3603 to $0.3641/kWh, the initial capital cost spans from $1.11M to $1.27M, and the operation costs span from $54,999.84 to $57,420.27.

Concerning NPV ($), they are from 2143028 to 2244377. The examination displayed that the 1st site represents the optimal site to conduct the proposed system due to its minimum LCOE and Net Present Value (NPV); the 2nd is the lowest.

Table 6. The economical results

The site	LCOE ($/kWh)	NPV ($)	O&M ($)	ICC (M$)
1st	0.3603	2143028	54899.84	1.21
2nd	0.3772	2244377	57420.27	1.27
3rd	0.3674	2183094	56939.95	1.21
4th	0.3641	2164014	55770.95	1.22

In Figure 20, it is clear that the optimal site is at the peak monthly amount of renewable product produced by the PV/WT hybrid system, with 61115.2 kWh occurring in July, because the monthly average of solar radiation and wind speed is at the maximum value of their monthly average of 7.922 kWh and 5.57 m/s. In contrast, the minimal monthly amount of renewable energy is 28971 kWh and 29802 kWh in February and November because of the smallest monthly amount of solar radiation and wind speed, with values of 4.29 kWh, 3.44 kWh, 4.03 m/s and 4.17 m/s, respectively.

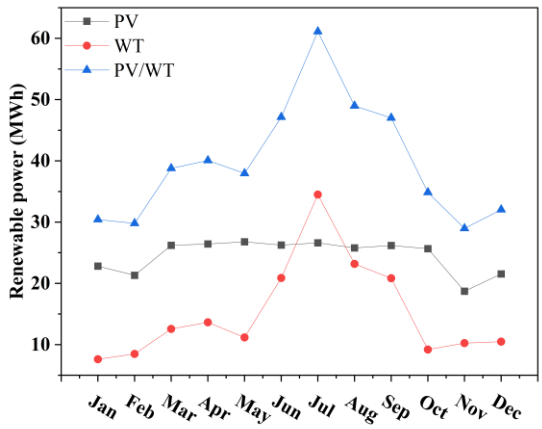

Figure 20. The monthly renewable energy production at the o site

as illustrated in Figure 21, the monthly average of power electricity production by the PV/WT system at the first site. Due to a decline in solar radiation and wind speed, noticeably the highest amount of gap between production and demand is 5121.4 kWh and 2337 kWh in November and February, respectively. Conversely, there was a surplus of power electricity of 1450.0 kWh in March, April, May, June, July, August, and September due to an increase in solar radiation and wind speed.

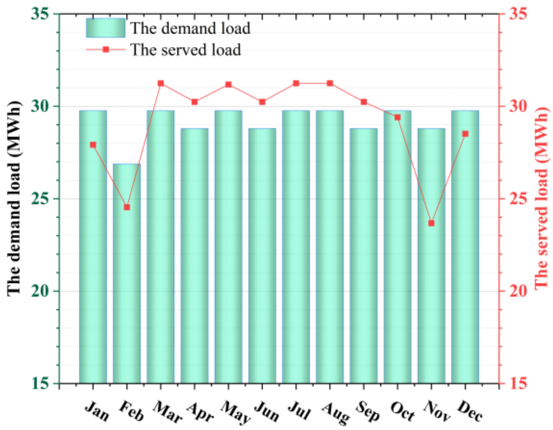

Figure 21. The monthly average of electricity production and demand at the first site

The performance of the battery is closely related to that of the PV solar panel because of the fluctuating nature of the solar energy produced. Figures 22 and 23, dated June 22, 2024, and December 2024, respectively, clarify the integration of PV power, wind turbine power, and battery discharge with a demand load by the proposed hybrid system.

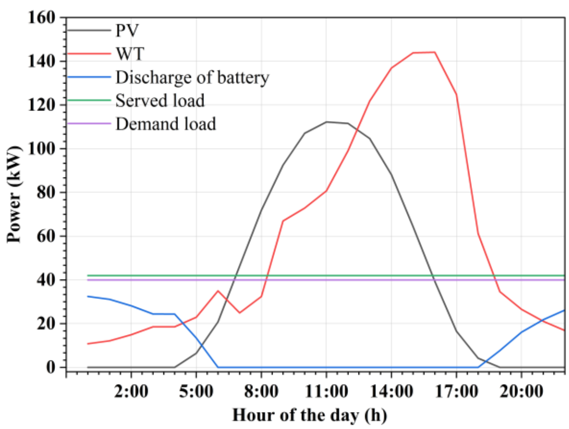

Figure 22. The performance of the proposed system elements at the first site, in June 22, 2024

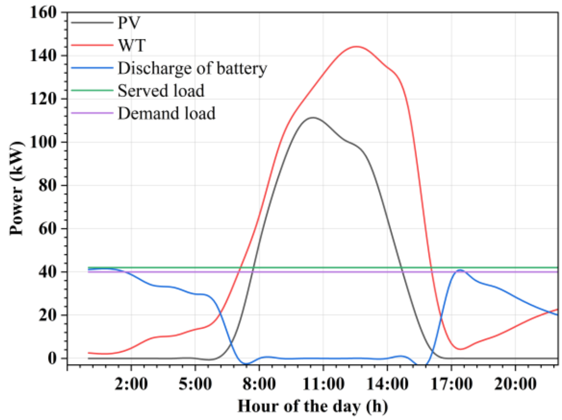

Figure 23. The performance of the proposed system elements at the first site, in Dec 22, 2024

Figure 24. Summarizing the battery's performance along the year 2024, when solar irradiation rises to the highest amount, the battery can store energy until it reaches 100% capacity. Noticeably, the state of charge (SOC) remained above the previously identified minimum limit of 30%.

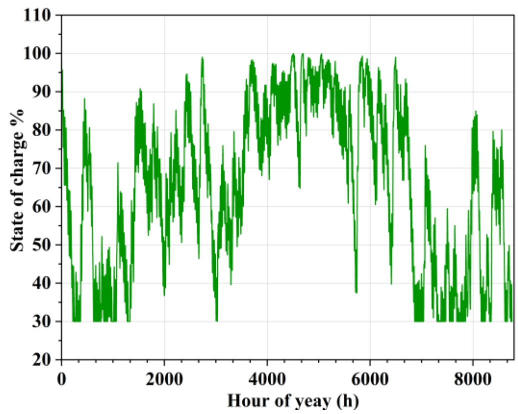

Figure 24. The battery state of charge in the first site, along year 2024

Figure 25 illustrates the crucial role of the battery in regulating and managing the energy produced by the system in February 2024. Low solar irradiation from a cloudy climate resulted in a small amount of energy production, which was insufficient to meet the required load, so the battery filled this gap. For this month, the battery was operated with the average monthly discharge, charge, and PV power being approximately 19.8 kW, 21.4 kW, and 30.6 kW, respectively.

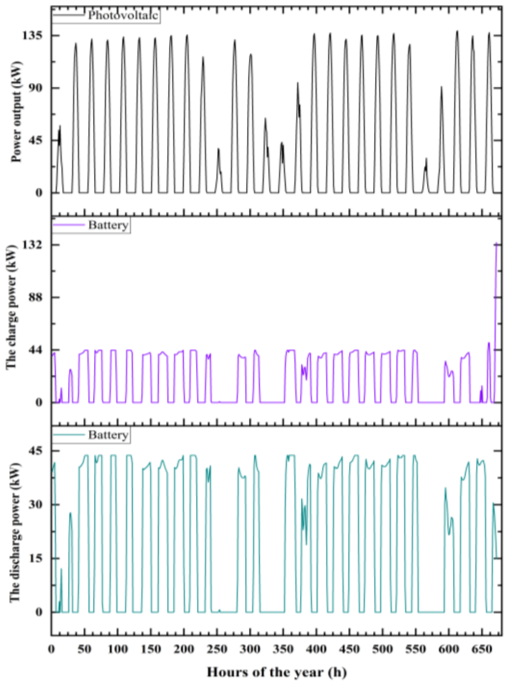

Figure 25. The power discharged by the battery at the first site, in February 2024

Figure 26. illustrates how to address the large amount of PV power in July 2024 by storing and feeding some of the power needed to meet the demand load.

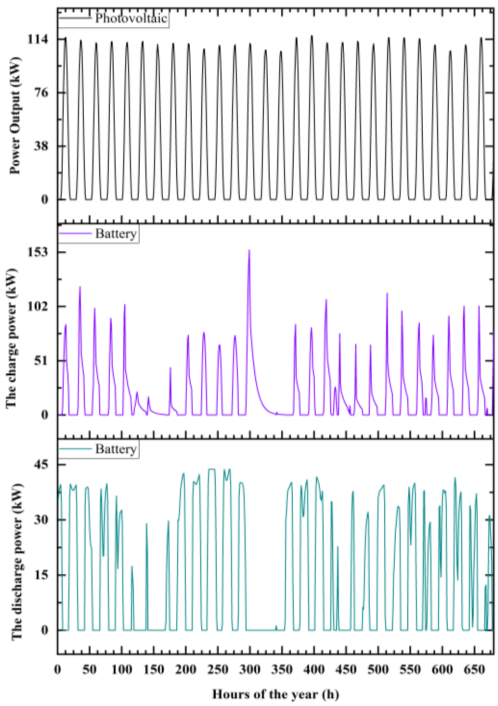

Figure 26. The power discharged by the battery at the first site, in Jul 2024

To examine the accuracy of the optimal site result of this study, it was compared with two cases of an off-grid PV/WT hybrid system and simulated by HOMER software. The LCOE parameter is based on the comparison because it is the clearest indicator of assessing the feasibility of any energy production system.

The 1st case regarded the study conducted by [8] that studied many scenarios in Zerbattiya, Iraq; the result of the off-grid PV/WT hybrid system has a deviation rate of about -25% related to the optimal site of this study. There are numerous causes; the significant differences are that the share of solar photovoltaic sources is 78% in the Zerbattiya case and 62.8% in the optimal site, and the yearly mean value of solar radiation is 5.35 kWh/m² in the Zerbattiya case and 5.6 kWh/m² in the optimal site.

The 2nd case concerned the article performed by [18] under conditions of Shiraz, Iran. A PV/WT hybrid system is one of the studied scenarios. Noticeably, the deviation rate is around -23.3%. The yearly mean value of wind speed is 3.05 m/s in Shiraz and 4.65 m/s in the optimal site. The share of solar photovoltaic is 68.2% in the Shiraz site and 62.8% in the optimal site.

6. Conclusions

Providing electricity to rural areas is one challenge against development in these regions. In Iraq, there are large areas not served by grid electricity; therefore, this research introduces one of the more active techniques to solve this issue. The research proposes the installation of a hybrid PV/WT system as a valuable approach. Thi-Qar province enjoys significant renewable resources such as solar irradiation and wind energy. This proposal for a hybrid system is off-grid and comprises a wind turbine, photovoltaic module, converter, and energy storage system (battery). Four sites were examined, all located in distinct areas within Thi-Qar. HOMER Pro and climate data of 2024 from NASA POWER are integrated into modelling the hybrid system in these sites.

The analysis of the modeling results showed that the system sizing at each site varies according to the renewable energy available at that site.

The results of this research present the researchers, decision-makers, and engineers with a valuable map of renewable energy investment opportunities in the Thi-Qar governorate. The following is a summary of significant conclusions.

- This work addresses the electrification of remote rural areas and includes a comprehensive review of hybrid renewable system projects for electrification.

- In the Thi-Qar region, the climate varies slightly, which has several effects on the performance of both the wind turbine and the photovoltaic system.
- The regions located in the south of Thi-Qar enjoyed high averages of solar irradiation and temperature, while the wind speed in the east-south is faster due to its proximity to the Persian Gulf coastline among the regions within Thi-Qar province.
- Far distance from the main electricity grid, farming settlement, variation in weather conditions, and diverse geographical nature were the criteria for identifying the four sites.
- The integrating of two renewable energy resources in a hybrid system strengthens the ability to handle fluctuations, which increases electricity production throughout the year and makes it more reliable and stable.

This work faces some limitations that should be addressed to make the modelling more realistic and acceptable. There are three major limitations. The weather data collected is not based on ground meteorological stations, and the averaging was performed over a one-year period. The effects of storms and dust aren't addressed enough. Finally, the study focused on the off-grid PV/WT scenario only; that was the hybrid system's lone style, which has been addressed in depth.

Regarding the future works, the weather data should be the average of a long-term period, for instance, 20 or 30 years, based on a ground meteorological station. Storms and dust issues must be addressed because the weather in Iraq has been facing this challenge recently. Another approach is to modify the combination and examine it further, such as by using a vertical-axis wind turbine or movable photovoltaic panels.

Nomenclature		**Abbreviations**	
A	Area (m^2)	*AC*	Alternating current
C_{BT}	The battery storage capacity (kWh)	*BAT*	Battery
C_p	The wind turbine coefficient	*LCOE*	Levelized cost of energy
DAL	The daily average battery usage (kWh/day)	*CONV.*	Converter
DoD	The depth of discharge of the battery	*DC*	Direct current
f_{pv}	The reduction factor of the Photovoltaic module	*DG*	Diesel generator
Na	Number of autonomy days of the battery	*HOMER*	Hybrid optimization of multiple electric renewables
P_{COM}	The useless power of the converter (kW)	*IC*	Initial cost
t	Time (h)	*ICC*	Initial capital cost
$P_{elect,PV}$	AC power of photovoltaic panel (kW)	*MACS*	Maximum annual capacity shortage
$P_{elect,WT}$	DC power of wind turbine (kW)	*MGS*	Ground-based meteorological station
P_{iCONV}	The input power of the converter (kW)	*NOCT*	Nominal operating cell temperature
P_{oCONV}	The output power of the converter (kW)	*NPV*	The net present value
P_{pv}	The photovoltaic panel output power (kW)	*O&M*	Operation and maintenance
P_{WT}	The wind turbine power output (kW)	*PV*	Photovoltaic
		RC	Replacement cost
S_T	The incident solar irradiation (°*C*)	*STC*	Standard test condition
$S_{T,STC}$	The incident solar irradiation at standard test conditions (°*C*)	*WT*	Wind turbine
T_A	Ambient temperature (°*C*)	*WUA*	Water user association
$T_{A,NOCT}$	The ambient temperature at nominal operating cell conditions (°C)	α_p	Temperature effect on the power of photovoltaic (%/°C)
V_{sys}	The voltage of the hybrid system (volts)	**Greek symbols**	
T_C	The practical temperature condition (°*C*)	α	Solar absorptance of photovoltaic (%)
$T_{C,NOCT}$	The ambient temperature at nominal	η_{BT}	The efficiency of the battery

	operating cell condition (°C)		
U	Wind speed (m^2/s)	η_c	The efficiency of the photovoltaic
$T_{C,STC}$	The standard test condition temperature (°*C*)	τ	Transmittance of photovoltaic cover (%)
Y_{pv}	Nominal power capacity of photovoltaic (kW)	$\tau\alpha$	The transmittance-absorptance product

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