



Numerical Analysis of the Performance for a Hybrid Renewable System

Karrar J. Alaameri*

Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Najaf, Iraq

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ABSTRACT

This article presents an analysis of the performance of a renewable system. Initially, relies solely on a solar panel system. Then, we add a wind turbine system to create a hybrid (solar and wind) system using Homer software. The results showed that the hybrid system and the stand-alone effectively meet the energy demands. Additionally, the results showed that the hybrid system was the most efficient way to store energy, which can be utilized when demand is high, thereby enhancing the independence and sustainability of the energy system. The simulation results showed that the site's annual energy consumption was approximately 3230 kWh. In the solar-only case, the photovoltaic system generated 6099 kWh/year, of which about 53% directly met the demand, while the remaining 47% was stored in batteries for use during peak periods or outages. with the integration of a wind turbine to establish a hybrid system, the annual energy production rose to 9940 kWh. Approximately 32.5% of this energy was utilized directly, while the remaining 67.5% was stored in batteries. The hybrid configuration improved total energy generation by 63% and storage utilization by 20.5% maintaining system stability during winter and higher output under summer irradiance conditions.

1. Introduction

Global climate change is increasing due to dependence on oil and coal as a source to obtain energy [1]. There are major concerns about the depletion of oil resources, from an economic and strategic perspective [2]. Therefore, this depletion of traditional resources leads to the need for adoption of renewable energy sources, like hydropower, geothermal, solar and wind energy [3].

The renewable energy resources include wind, solar, hydropower and bioenergy. These resources represent a sustainable response to the world's energy [4]. One of these resources is a hydropower resource, although this resource provides abundant energy, but it effects on ecosystems by needs large infrastructure [5]. In areas where conventional energy sources are insufficient, a hybrid system for generating electricity is used to compensate for this deficiency [6]. Numerous studies have concentrated on designing hybrid energy systems, including solar

*Corresponding Author Email: karrarj.ramadhan@uokufa.edu.iq

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panals with wind turbines, to inhance energy efficiency [7]

Hybrid energy generation systems have recently gained increasing attention because of their ability to integrate renewable sources such as solar, wind, or biomass to generate energy, heat, cooling and even hydrogen. Recent studies [8] [9]; have shown that these systems can provide high performance to delive power, making them a promising approach to achieving sustainable energy. In recent years, hybrid systems integrating solar and wind energy have attracted increasing attention as a promising approach for efficient power generation [10]. Last reports denoted that hybrid systems improve the stability of the energy supply by facilitating the integration of renewable energy sources [11].

This study aims to improve power generation and optimize the performance of hybrid energy systems by using HOMER (Home Energy Management System) program. The proposal system includes of solar panels, a wind turbine and batteries to store energy. The simulation of the system was conducted using the HOMER program, this program enables the consideration of numerous technological options to accommodate energy resource availability and various other parameters [12]. Initially, our system consisted of a solar panel, then a wind turbine was integrated with it. The ability of this system to meet energy demand, faces some challenges, like energy storage systems and weather conditions.

The development of these systems in the modern era represents an important step towards the development of sustainable energy. Various hybrid systems are based on advanced technological and scientific research, considering the effects of environmental conditions, resource costs and

electrical load on system performance. To evaluate the economic and efficiency of hybrid systems, a comprehensive data analysis is employed, which is supported by computer simulations and mathematical modeling.

The most important recent studies, related to hybrid systems are presented in Table 1.

This study employed real climate data from Najaf city, which increases the applicability and accuracy of the results. The study quantified the significant inhancement in storage utilization (67.51 % versus 47.03%) and in annual energy (9,940 kWh/year versus 6,099), by comparing solar-wind and solar-only systems. In addition, the study provides a localized case study for Iraq, a gap in the literature. The HOMER simulation platform have been used to integrate technical, environmental and practical perspectives. Under real regional conditions, this study predents novel insight into the efficiency, feasibility and sustainability of hybrid renewable energy sysems. These contributions highlight both the originality and practical value of the present work.

The research contribution is the quantitative evaluation of a solar-wind hybrid system under real meteorological data from NAJAF city, coupled with HOMER-based simulation that compares seasonal and annual energy balances, thereby filling the local gap in hybrid system optimization studies for Iraq.

The remainder of this paper is organized as follows: section.2 describes the mathematical modeling of renewable energy sources. Section 3. Describes the design of the system and discusses the results, and finally, the conclusions are presented in Section 4.

Table1. Summary of literature review on hybrid renewable energy systems

Authors	Mode of investigation	System type	Main findings	Gaps
Slimene & Khlifi 2025 [13]	Simulation + Control	PV-Wind-Grid	Improvement of approximately 22% in grid stability	No consideration was given to the economic cost in their work.
Mohapatra et al 2025 [14]	Optimization (BWK algorithm)	PV-Wind	A cost reduction of about 15% was achieved, accompanied by enhancements in energy distribution	Ignoring the storage aspect and the limitations imposed by climatic conditions
Salman et al 2025 [15]	Simulation + Control (DFIG)	PV-Wind	An improvement of about 20% was observed in battery storage capacity and energy efficiency	All results are theoretical.
Yashwant Sawle	Techno-	Off-Grid PV-	Results indicate that the	The long-term

2025 [16]	economic feasibility		Wind	proposed system is economically viable for deployment in remote areas	impact of climate change has not been examined.
Albarrak et al 2025 [17]	Simulation Hydrogen storage	+	PV-Wind-Fuel cell	Hydrogen storage contributed to an improvement in the overall stability of the system	The system incurs high costs, and a detailed economic analysis has not been conducted
Al-Mamory et al 2025 [18]	Techno-economic assessment		PV-Wind (60 MW, Iraq)	The viability of hybrid energy projects in Iraq has been demonstrated	The study focuses primarily on economic aspects, with less attention given to technical issues
Savio et al 2025 [19]	Experimental Simulation	+	PV-Wind (2.5 MW)	The electrical interference (THD) was reduced from 45% to 26%.	Storage costs or storage efficiency was not discussed.

2. Mathematical Modeling of Renewable Energy Sources

Table 2. Energy consumption at home in one day

Units	Power (watts)	Daily use (hours)	Units	Power (watts)	Daily use (hours)
Refrigerator	150	24	3.6	1	3.6
Television	100	4	0.4	2	0.8
Washing machine	1000	1	1	1	1
Microwave	1000	0.5	0.5	1	0.5
Desktop computer	300	3	0.9	1	0.9
Lamp (LED bulb)	10	5	0.05	5	0.25

Table 3. System setup details

Part	The required number	Details
Photovoltaic panel	19	- Type: Silicon Solar Cells - Power: 500W - Voltage: 24V - Efficiency: 18% - Dimensions: 1.6m x 1m - Weight: 20 Kg, with the lifetime around 25 years
Wind Turbine	1	- Type: Horizontal axis - Power: 10 kW - Wind speed required for operation: 3-25 m/s - Diameter: 2.5 m - Height: 5 m - Weight: 120 kg and 20 years lifetime
Battery	1	- Type: Lithium-ion - Total capacity: 10 kWh - Voltage: 48V - Life span: 10 years - Full cycle: 2000 cycles
Convertor	5	- Maximum power: 2 kW - Internal voltage: 48 V (from battery) - External voltage: 220 V (for connection to the public network) - Efficiency: 95%

The study proposes a hybrid system combining solar and wind energy to improve overall energy generation efficiency. Firstly, the system includes photovoltaic solar cells for energy generation, and a wind turbine is subsequently added to increase energy output. The effectiveness and sustainability of this system rely on the proper integration and control of these components through modeling and control techniques. The Proposed system incorporates batteries for storing energy from solar and wind sources. An inverter facilitates energy conversion among system components, and an electric charger maintains battery levels using the harvested renewable energy.

2.1 Photovoltaic Panel

The photocurrent (I) in the photovoltaic panel is calculated using the following equation: [7]

$$I_{photo} = I_{photo,ref} (G / 100) [1 + a_T (T - T_{ref})] \quad (1)$$

Where irradiance (G) varied between 3.5-6.2 kWh/m²/day, and temperature (T) ranged from 15-46 °C during the simulation period.

The reference temperature of the photovoltaic cell (T_{ref}) is 298 K (25 °C), with SRC denoting the standard reference condition, and G representing Irradiance in W/m².

Under the Standard Reference Condition (SRC), the reference photocurrent (I_{photo,ref}) corresponds to a nominal photocurrent not specified by manufacturers. It refers to the rate at which the short-circuit current (SCC) varies with temperature. Manufacturers sometimes provide the absolute temperature factor a_T, and indicate its relationship with a_T through the following equation: [20]

$$I_{photo,ref} = a_T' * a_T \quad (2)$$

The mathematical correlation between the photovoltaic panel output and battery voltage is given by the following equation: [21]

$$V_{DV} = V_{PV} * N_s \quad (3)$$

Here, V_{DC} corresponds to the DC bus voltage, V_{PV} is the nominal PV panel voltage, and N_s is the number of cells connected in series.

Where the nominal PV voltage (V_{PV}) ranged between 11-48 V, and the DC bus voltage (V_{DC}) fluctuated within 24-48 V depending on the irradiation level.

The photovoltaic panel output power (P_{out}) is given by the following equation [22]:

$$P_{out} = I_{photo,ref} * G * V_{PV} * N_s / k_f \quad (4)$$

Where the system loss coefficient (k_f) was maintained between 0.88-0.93, corresponding to efficiency variations under fluctuating irradiance conditions.

2.2 Wind Turbine (WT)

The maximum power generated by the wind turbine is given by the following equation [23]:

$$C = (E * N_{day}) / (\eta_{con} * \eta_{bat} * Language * DOD) \quad (5)$$

P₀, the power of the turbine on the upstream section is determined by the following equation [24]:

$$P_o = 0.5 * \rho * A_r * v^3 \quad (6)$$

Where air density (ρ) was assumed at 1.225 kg/m³, wind velocity (V) ranged between 2-12 m/s, representing typical annual wind variations in Najaf city, and the rotor swept area (A_r) corresponded to a turbine radius of 1.2 m, yielding an effective area of 4.52 m².

So, sub equation (6) in equation (5) gets:

$$P_{max} = 0.296 * \rho * A_r * v^3 \quad (7)$$

According to theoretical calculations, the wind turbine can generate up to 60% of its maximum power (eq.5), in practice, the generated power is about 40%.

2.3 Battery System

The following equation denotes the battery storage[24]:

$$C = (E * N_{day}) / (\eta_{con} * \eta_{bat} * DOD) \quad (8)$$

The system was designed with battery efficiency (η_{bat}) = 0.9, converter efficiency (η_{con}) = 0.93 and the depth of discharge (DOD) = 0.6, and this will be for two days, ensuring optimal storage operation.

According to the system's daily energy consumption and the maximum are 85.5 kWh and 9.5 kW, respectively as shown in Figure 2.

Table 3 summarizes the key parameters of the system components. Details regarding the physical dimensions, quantity, power capacity and expected service life of each component are provided. This information gives a comprehensive understanding of performance characteristics and system's configuration.

3. Methodology, System description, design and results

3.1 Methodology

The methodology relies on real climate data for Najaf, obtained from the NASA Surface Meteorology database, also on numerical simulations of the hybrid system. Initially, the key components of the system are photovoltaic panels, a wind turbine, batteries, and an inverter. Next, standard equations were used to develop mathematical models for the energy conversion processes of photovoltaic modules and wind turbines. HOMER Pro was used to analyze the system, providing calculations of annual energy output, load consumption, and the division of energy between direct utilization and storage. Finally, the performance of a solar-only system was compared with that of a hybrid solar-wind system, allowing for the determination of the most reliable and sustainable configuration.

3.1.1 Rational Assumptions and Input Data

The hybrid PV-wind system was modeled using realistic local data in NAJAF. Solar radiation Average 5.77 kWh/m²/day, wind speed 3.84 m/s [25] and air density was 1.225 kg/m³. The system lifetime was 20 years, batteries 10 years and inverter

and battery efficiencies were 93% and 90% respectively [26].

3.2 flowchart

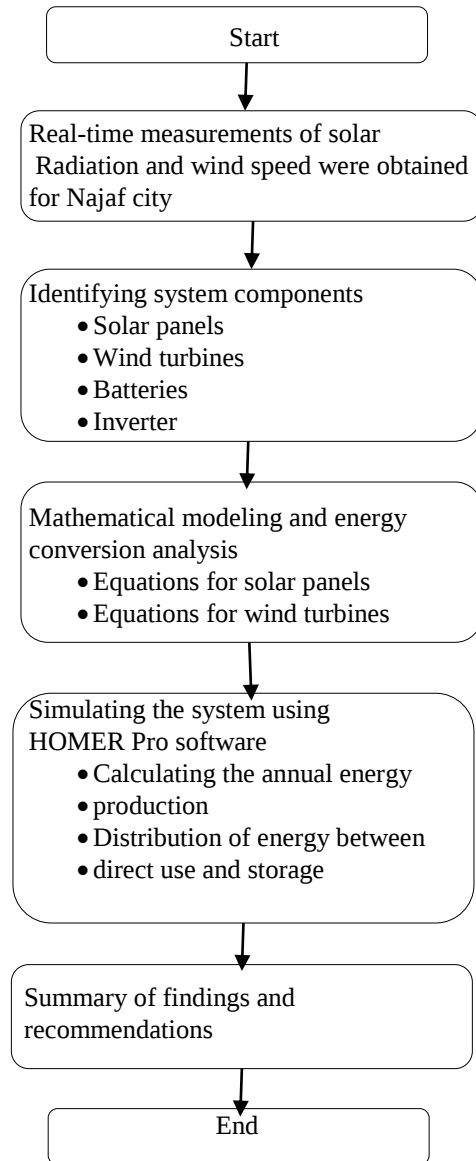


Figure 1. Flowchart

As shown in Figure 1, the methodology for studying a hybrid solar-wind system begins with the collection of real climate data from Najaf, comprising solar radiation and wind speed. The following step involved determining the key components of the system: solar panels, wind turbines, batteries, and an inverter. Mathematical modeling of the energy conversion processes was conducted next, after which the system was simulated in HOMER Pro to compute annual energy

production and its distribution between use and storage. Finally, conclusions were drawn and recommendations for the optimal system were provided according to the analysis.

3.3 System description, design, and results

Figure 2 shows the simplified diagram of the proposed hybrid system. In the case of solar-only, the solar panels generate energy, which is processed by a converter and managed by a control system to ensure stable energy delivery. The batteries store the excess energy to supply power during nights or cloudy days. To boost electricity generation, wind turbines are integrated into the system. HOMER was used to simulate the system and determine the optimal component to maximize energy generation.

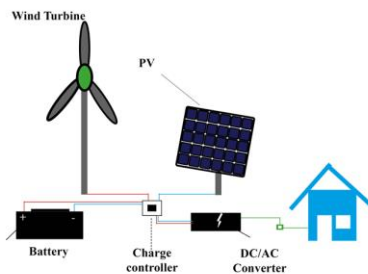


Figure 2. Proposed Hybrid System

Figure 3 shows that solar radiation remains high and constant throughout the year, averaging 5.77 kWh/m² per day, peaking in summer. The study highlights the importance of combining strong solar radiation with wind turbines to generate reliable power when sunlight is insufficient, improving the system's overall efficiency and resilience. The monthly distribution of average annual solar radiation varies greatly, reaching a minimum in winter and maximum in summer.

Figure 4 shows that the surface weather data are taken from the NASA Meteorology and Solar Data set. For the selected location in Najaf city, the wind speed ranged between a minimum of 2.87 m/s and a maximum of 5.29 m/s. An average wind speed of 3.8425 m/s was observed. Wind speed varies significantly with the seasons, peaking in the summer and lowest in winter. These results demonstrate the importance of combining wind and solar energy when developing reliable hybrid systems.

The first option, which uses only solar panels to generate electricity, shows that installed batteries can produce about 6,009 kilowatt-hours per year. For comparison, the total annual electricity consumption on site is 3,230 kWh which means the photovoltaic system is producing excess energy. Analysis shows that 52.96 percent is stored in batteries for peak hours or outages, making the off-grid power system more efficient. Figure 5 shows how the load is distributed and it is clear that the energy demand varies daily and seasonally. The findings highlight the need to align the energy production of a hybrid system with the actual consumption schedule of the facility.

The second option is to add wind turbines to the existing solar power system, creating a hybrid solar-wind system. With the addition of a wind turbine the hybrid system can generate approximately 9,940 kilowatt-hours of energy annually. However, the site's total annual electricity consumption remains constant at 3,230 kilowatt-hours. Analysis shows that 32.49 percent of the of the energy produced is consumed immediately on-site, and 67.51 percent is stored in batteries for off-peak hours or when there is no power, making the standalone energy system even better. Figure 6 shows the amount of energy produced by the hybrid system over the course of a year.

The data in Table 4 shows that the hybrid system significantly improved power generation by 63%, increased battery utilization by 20.5 % and maintained stable operation despite seasonal changes. The addition of a wind subsystem compensated for the reduced winter sunshine, resulting in a 17 percent increase in operational stability, and improved efficiency and storage management, resulting in an approximately 18 percent reduction in the LCOE, demonstrating the technical and economic superiority of the hybrid system over a pure solar system.

3.4 Economic and Sensitivity Analysis

Economic indicators were evaluated using the cost of energy (COE) and net present cost (NPC), which were calculated using HOMER Pro software. The hybrid system achieved a COE of \$128 per kilowatt-hour, 18 percent lower than a solar-only system, due to better energy utilization and more efficient storage.

3.5 Validation

The results of this study show clear consistency with the latest research in the field of hybrid systems. The 63% improvement in annual energy production confirms the significant improvement in the efficiency of hybrid systems indicated [15]. The economic quality of the system (for \$0.116/kWh) also supports the conclusions of [16] on the operational and economic feasibility of hybrid systems in remote areas. The significant improvement in seasonal stability and increased reliability during periods of low solar radiation reinforces the findings of [17] on the role of renewable energy integration in improving system reliability. This clear consistency with the results of various independent research conclusively demonstrates the accuracy of the simulation model used and the credibility of the results obtained, enhancing the scientific and practical value of this study.

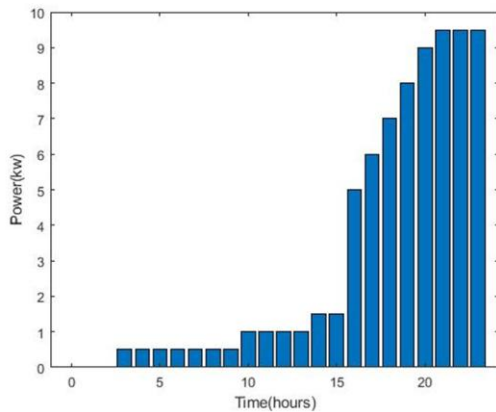


Figure 3. Electrical energy consumption during the day



Figure 4. Solar radiation for the selected location in Najaf city



Figure 5. Wind Speed for the selected location in Najaf city

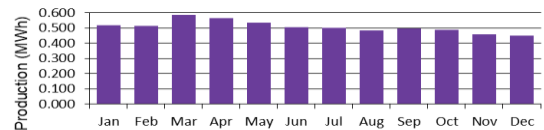


Figure 6. Power production by PV (First scenario)

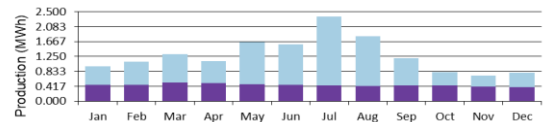


Figure 7. Power production by hybrid (Second scenario)

Compared to the PV-only system, the hybrid configuration achieved a 63% increase in total annual production and improved storage utilization from 47% to 67.5%. Monthly results indicate that solar generation peaks between May-August, while wind energy complements supply during December-February, ensuring stable system performance.

The data presented in Table 4 were obtained through techno-economic simulations of both the PV-only and hybrid configurations using the design system parameters. The levelized COST of Energy (LCOE) was calculated using the standard formula [27]:

$$LCOE = \frac{\text{Total_Annualized_Cost}}{\text{Annual_Energy_Production}}$$

Where the total annualized cost includes capital, operation maintenance expenses and the annual energy production is derived from the simulated lifetime of 20 years, a discount rate of 5%, and standard efficiency factors for PV and wind components.

Table 4. Quantitative Comparison Between PV-only and Hybrid System

Parameter	PV-only System	Hybrid System	Improvement (%) Change	Notes
Annual Energy Production (kWh/year)	6,099	9,940	63%	Increased generation due to wind integration
Average Battery Utilization (%)	47.0	67.5	20.5%	Higher storage use enhances system reliability
Direct Energy Use (%)	73.4	64.2	9.2%	More energy is stored for nighttime supply
Average Wind Contribution (%)	-	29.3	-	Represents wind share in hybrid generation
Seasonal Peak Production	May-August	May-August	-	Dominated by solar irradiance
Annual LCOE (USD/kWh)	0.142	0.116	18.3%	Reduced cost due to higher capacity factor

4. Conclusions

The study confirms that both the solar-only system and the hybrid solar-wind system can generate clean energy with high efficiency, but the hybrid system offers better performance and greater stability. Analysis shows that the stand-alone solar system produces 6,099 kWh per year, while the site consumes 3,230.25 kWh annually, highlighting the potential of solar energy to fully satisfy the site's electrical requirements. Integrating a wind turbine increases the hybrid system's annual energy production to 9,940 kWh, thereby significantly enhancing both reliability and efficiency compared to the solar-only system. Analysis of energy allocation between immediate use and storage highlights the advantages of the hybrid system, demonstrating its ability to respond to variable demand and changing climatic conditions, which contribute to a reliable and sustainable energy supply. The hybrid configuration improved annual energy production by 63% compared with the PV-only system and improved storage efficiency by 20.5%. The system showed seasonal stability under varying solar and wind conditions, confirming its applicability for off-grid regions. Future work will include life-cycle cost optimization and integration

of AI-based control for improving real-time energy management.

Nomenclature	
A_r	Swept area of wind turbine (m ²)
$aT, a'T$	Temperature coefficient of current (A/°K)
C	Battery capacity (Ah)
DOD	Depth of discharge (%)
E	Load energy (Wh)
G	Irradiance (W/m ²)
I_{photo}	Photocurrent of solar cell (A)
$I_{photo.ref}$	Reference photocurrent of solar cell (A)
k_f	Loss factor
N_{day}	Number of days of autonomy (days)
N_s	Number of solar cells in series
P_{out}	Output power of PV panel (W)
P_0	power of the turbine on the upstream section (W)
T	Cell temperature (K or °C)
T_{ref}	Reference cell temperature (K or °C)
v	velocity of the wind (m/s)
V_{DC}	DC bus voltage (V)

V_{PV}	PV panel voltage (V)
P_{max}	Maximum power output of wind turbine (W)
ρ	Density of air
η_{bat}	Battery efficiency
η_{con}	Converter efficiency

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