Optimizing Grid-Connected Hybrid Renewable Energy Systems: A Case Study of Yanbu, Saudi Arabia

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Abstract

This study presents an analysis of a grid-connected hybrid renewable energy system tailored for Yanbu, Saudi Arabia, combining photovoltaic (PV) arrays and a 20-kW wind turbine. Using the HOMER software, the research aims to optimize renewable energy integration into the grid while minimizing the total net present cost. Two scenarios are investigated: one without a minimum renewable fraction and another imposing a 50% renewable fraction limit. The unique environmental conditions of Yanbu, characterized by ample solar irradiance and wind resources, are leveraged to design a sustainable energy mix. Through detailed simulation modeling, the performance, cost-effectiveness, and environmental impact of the proposed system are evaluated. The objective function prioritizes maximizing renewable energy usage and cost efficiency, considering factors such as solar irradiance, wind speed patterns, and energy demand fluctuations. This research contributes valuable insights into optimal system configurations and trade-offs between renewable energy integration and cost effectiveness, thus facilitating the advancement of renewable energy technologies in real-world applications.

Keywords: Grid-Connected Energy Solutions; HOMER; Renewable Energy Fraction; Saudi Arabia.

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1. Introduction

Renewable energy has seen a significant uptick in adoption, with a marked increase in the use of solar photovoltaic (PV) and wind energy sources. In 2020, despite the global pandemic, renewable energy use increased by 3%, with electricity generation from renewable sources growing by almost 7%. This growth was supported by long-term contracts, priority access to the grid, and the continuous installation of new plants [1]. In 2021, renewable electricity generation was expected to expand by more than 8%, reaching 8,300 TWh, which would be the fastest year-on-year growth since the 1970s. Solar PV and wind were projected to contribute two-thirds of this growth, with significant contributions from China, the United States, the European Union, and India [1]. The International Energy Agency (IEA) reported that the share of renewables in global electricity generation jumped to 29% in 2020, up from 27% in 2019. Wind energy was set for the largest increase in renewable generation, growing by 275 TWh or almost 17%, which is significantly greater than 2020 levels [1].

Looking ahead, the Global Energy Perspective 2023 suggests that the energy transition has gathered pace, but the path ahead is full of uncertainty, ranging from technology trends to geopolitical risks and consumer behavior. Fossil fuel demand is projected to peak soon, but the outlook remains uncertain, with natural gas and oil expected to remain a core part of the world's energy mix for decades to come [2]. Hybrid photovoltaic (PV) and wind systems are pivotal for sustainable development in Saudi Arabia, a country with an abundance of solar and wind resources. The integration of these two renewable energy sources can lead to significant benefits:

- **Reliability and Efficiency:** Hybrid systems ensure a more reliable and efficient energy supply by harnessing the complementary nature of solar and wind energy. This is crucial for Saudi Arabia's goal to diversify its energy mix and reduce reliance on fossil fuels [3]–[9].
- **Economic Advantages:** The adoption of hybrid systems can stimulate local industries, create jobs, and contribute to economic diversification, aligning with Saudi Arabia's Vision 2030 [10]–[17].
- **Environmental Benefits:** By reducing greenhouse gas emissions and other pollutants, hybrid systems support Saudi Arabia's environmental commitments and contribute to global efforts against climate change [10]–[20].
- **Energy Security:** Diversifying energy sources enhances Saudi Arabia's energy security and resilience against oil market volatility [21]–[23].
- **Technological Innovation:** The development of hybrid systems encourages technological innovation

and positions Saudi Arabia as a leader in renewable energy technologies [24], [25].

The primary objective of this research is to design and optimize an integrated PV and wind turbine system for renewable energy generation in Yanbu, Saudi Arabia. This study aims to maximize the integration of renewable energy sources while simultaneously minimizing the total net present cost of the proposed system. By utilizing Homer software for system modeling and analysis, the research investigates the feasibility and effectiveness of the integrated system architecture. A 20 kW Eocycle wind turbine is incorporated alongside PV panels, with variations in system design to accommodate different constraints on the minimum renewable fraction. Through a comprehensive sensitivity analysis, the impact of various parameters on system performance and cost is evaluated. The scope of this research is limited to the design and optimization of the integrated PV and wind turbine system, focusing on the case study of Yanbu to leverage its renewable energy potential and geographic characteristics. By providing insights into optimal configurations and trade-offs between renewable energy integration and cost, this study contributes to the advancement of renewable energy technologies in real-world applications.

2. Literature Review

In the realm of renewable energy systems, the integration of photovoltaic (PV) and wind turbines has garnered considerable attention due to their complementary nature and potential to enhance system reliability and efficiency. Current literature highlights various approaches and configurations for PV/wind hybrid systems, emphasizing the importance of system optimization to maximize energy production and minimize costs. Studies have explored different control strategies, sizing methodologies, and grid integration techniques to improve the performance and reliability of these hybrid systems.

The latest advancements and trends in the design and optimization of PV/wind hybrid systems for renewable energy generation can be summarized as follows: Researchers have been focusing on identifying promising techniques for the optimization of solar PV-wind-based hybrid systems. Over the last decade, new-generation artificial intelligence algorithms have been predominantly used due to their lower computation time and better accuracy compared to traditional methods [26]. Hybridization of two or more algorithms has been suggested to overcome the limitations of a single algorithm, indicating a trend towards more sophisticated optimization approaches [26]. The key areas of research in the design and optimization of PV/wind hybrid systems include optimization studies, system sizing methodology, and the use of hybrid algorithms for improved accuracy and convergence [27]. Additionally, the review of literature and statistical analysis has highlighted the prevalent use of stand-alone hybrid systems, simulations through software like HOMER and MATLAB, and the widespread use of optimization algorithms such as particle swarm optimization (PSO) and genetic algorithm (GA) [2].

The current trends in the design and optimization of PV/wind hybrid systems involve a growing interest in hybrid wind photovoltaic (PV) systems, particularly for residential uses, and a focus on testing systems in warm or temperate localities [28]. The prevalent tested system configuration mode is the stand-alone hybrid systems, and the most frequently used optimization algorithms are PSO and GA [28]. To make the hybrid system economically viable and environmentally friendly, research has been focused on the modeling and cost analysis of PV–wind hybrid energy systems using software like HOMER, which can be used for optimization, control strategy, sizing, and structure [29]. The review of available literature indicates that hybrid systems significantly mitigate energy intermittency issues, enhance grid stability, and can be more cost-effective due to shared infrastructure. The study also identifies key challenges such as system optimization, energy storage, and seamless power management, and discusses technological innovations like machine learning algorithms and advanced inverters that hold the potential for overcoming these hurdles. The role of policy in accelerating the adoption of hybrid renewable energy systems has been highlighted, with successful case studies of government incentives, public-private partnerships, and regulatory frameworks that have fostered investments in hybrid renewable energy systems [29].

HOMER software, an acronym for Hybrid Optimization Model for Electric Renewables, serves as a pivotal tool in optimizing hybrid renewable energy systems, significantly influencing system design, performance assessment, and economic analysis. This software, widely utilized in the field, facilitates the design of various power plant configurations, incorporating essential components such as PV panels, wind turbines, utility loads, generators, converters, and battery backup [30]. Through its simulation capabilities, HOMER software explores diverse power plant schematics to ascertain the most optimized configuration concerning operating cost, net present cost (NPC), emissions, and economic comparisons [30]. In terms of system design, HOMER software offers the means to optimize hybrid systems comprising solar panels, wind turbines, and batteries for supplying electricity to off-grid areas. This optimization process leads to the determination of the optimal number and characteristics for each component, thereby enhancing the technical-economic profitability of hybrid energy systems and reducing costs, energy dependence, maintenance expenses, and lifespan concerns [31], [32].

Regarding performance assessment, HOMER software yields real results by considering cost constraints and variations in off-grid weather data. It facilitates assessments encompassing the cost of energy, optimal number and characteristics of components, and costs associated with different time periods and seasons. Through technical, economic, and environmental assessments, the software aids in determining the most feasible off-grid system and enables comparisons with grid extension and diesel generator options [31], [33]. In economic analysis, HOMER software emerges as a robust tool, conducting assessments considering factors like net present cost, cost of energy, electricity cost, and operational & maintenance cost. It enables comparative economic and modeling analyses on distributed generation power systems, aiming to derive the optimal solution in terms of cost, performance, size, and structure [34], [35].

3. Methodology

3.1 Case Study:

The study area, Yanbu, Saudi Arabia, located at coordinates 24° 8.7' N and 37° 57.8' E, exhibits promising solar and wind potentials conducive to renewable energy generation. With an annual average radiation of 5.85 kWh/m²/day, Yanbu boasts ample solar irradiance levels suitable for PV system deployment. Additionally, the region experiences an annual average temperature of 27.73°C, further indicating favorable conditions for solar energy harnessing. Moreover, Yanbu benefits from an annual average wind speed of 5.48 m/s, presenting opportunities for wind turbine installations. These climatic characteristics align with the renewable energy requirements of the region, facilitating the integration of solar and wind technologies to meet energy demands sustainably.

In the context of energy consumption, Yanbu's small Supermarket, with an average daily load of 4813.33 kWh and a peak demand of 366.38 kW, presents a significant electricity demand profile. The load factor, calculated at 0.55, indicates the ratio of the average demand to the peak demand, offering insights into the load's variability throughout the day. Figures 2 to 4 illustrate the annual solar Global Horizontal Irradiance (GHI), wind speed, and daily load profiles, providing visual representations of the renewable energy resources and energy demand patterns in Yanbu. These figures serve as valuable reference points for assessing the feasibility and optimization of solar and wind energy systems in meeting the region's energy requirements sustainably and economically.

3.2 System design:

The system design comprises a combination of a photovoltaic (PV) array and a 20-kW wind turbine, aimed at maximizing renewable energy generation in Yanbu, Saudi Arabia. The PV array consists of generic flat-plate PV modules, each with a rated capacity of 1 kW and a derating factor of 80%. The capital cost of the PV system is estimated at $2500 per kW, with a replacement cost of $2500 per kW and an annual operation & maintenance cost of $10 per year. On the other hand, the wind turbine has a rated capacity of 20 kW, with a capital cost of $40000 per kW, a replacement cost of $28000 per kW, and an annual operation & maintenance cost of $200 per year.

In this system design, the utility grid serves as a backup power source and a means for selling excess generated electricity. The grid power price is set at $0.069 per kWh, representing the cost of purchasing electricity from the grid when the renewable sources are insufficient to meet demand. Conversely, the grid sell-back price, which accounts for the compensation received for excess electricity fed back into the grid, is established at $0.05 per kWh. These grid parameters play a crucial role in the economic analysis and decision-making process regarding the system's operation and integration with the grid. Through careful consideration of these factors, the design aims to optimize renewable energy utilization while ensuring cost-effectiveness and reliability in meeting the energy demands of Yanbu.

3.3 Objective Function

The objective function for the system design in Yanbu, Saudi Arabia, is defined with two primary goals: to maximize renewable energy integration and to minimize the total net present cost (NPC) of the system.

1. **Maximize Renewable Energy Integration:**

This objective aims to optimize the utilization of renewable energy sources, namely solar and wind power, within the system. By maximizing renewable energy integration, the design seeks to harness the available solar irradiance and wind resources to their fullest extent, thereby reducing reliance on non-renewable sources and minimizing environmental impact. The objective function prioritizes the efficient utilization of renewable energy to meet the energy demands of Yanbu while promoting sustainability and reducing carbon emissions.

2. **Minimize Total Net Present Cost:**

The second objective focuses on minimizing the total net present cost (NPC) associated with the system over its lifetime. This includes the capital costs of installing and replacing PV arrays and wind turbines, as well as the ongoing operation and maintenance expenses. By minimizing NPC, the design aims to achieve cost-effectiveness and financial viability while ensuring the reliability and performance of the renewable energy system. This objective considers both the initial investment and the long-term operational costs, considering factors such as equipment efficiency, reliability, and lifespan to optimize economic efficiency.

Overall, the objective function aims to strike a balance between maximizing renewable energy integration and minimizing total net present cost, thereby achieving a sustainable and economically viable solution for meeting the energy needs of Yanbu. Through optimization algorithms and modeling techniques, the objective function guides the system design process to achieve an optimal balance between renewable energy utilization and cost efficiency.

$$Maximize: Renewable\ Energy\ Integration = \sum_{t=1}^{T} \left(P_{PV}(t) + P_{wind}(t)\right)$$

Where $P_{PV}(t)$ is the power output from the PV array at time t, and $P_{wind}(t)$ is the power output from the wind turbine at time t.

$$Minimize: NPC = Capex_{PV} + Capex_{wind} + Opex_{PV} + Opex_{wind}$$

Where:

$$Capex_{PV} = Capital\ cost\ of\ PV\ array + Replacement\ cost\ of\ PV\ array$$

$$Capex_{wind} = Capital\ cost\ of\ wind\ turbine + Replacement\ cost\ of\ wind\ turbine$$

$$Opex_{PV} = Annual\ operation\ and\ maintenance\ cost\ of\ PV\ array$$

$$Opex_{wind} = Annual\ operation\ and\ maintenance\ cost\ of\ wind\ turbine$$

These equations represent the optimization objectives of the system design, where the goal is to maximize renewable energy integration while minimizing the total net present cost. Figure 5 presents the system configuration for the grid-connected hybrid renewable energy system in Yanbu, Saudi Arabia. The configuration comprises a combination of PV arrays and a wind turbine, integrated with the utility grid. The PV array consists of generic flat-plate PV modules, each with a rated capacity of 1 kW and a derating factor of 80%. On the other hand, the wind turbine has a rated capacity of 20 kW. The system design incorporates the utility grid as a backup power source and a means for selling excess generated electricity, with defined parameters for grid power price and grid sell-back price. This configuration aims to maximize renewable energy integration while ensuring cost-effectiveness and reliability in meeting the energy demands of Yanbu. Through careful consideration of system components and grid integration, the configuration seeks to leverage Yanbu's abundant solar and wind resources to achieve sustainable energy generation and minimize environmental impact.

4. Results

The simulation results for the grid-connected hybrid renewable energy system are presented under two distinct scenarios: 0% and 50% renewable fraction limits. In the 0% scenario, no photovoltaic (PV) capacity is installed, while in the 50% scenario, the PV array is sized at 253.03 kW. The wind turbine's capacity remains constant at 5 kW for both scenarios. The grid serves as a backup power source and a means for selling excess electricity. The total net present cost (NPC) of the system, which encompasses capital costs, operational expenses, and other associated costs, is computed. Additionally, the cost of energy (COE), representing the cost per unit of energy generated, and the annual operating costs are evaluated. Initial capital investments required for system setup are also examined.

Furthermore, the achieved renewable fraction, indicating the percentage of energy generated from renewable sources compared to total energy consumption, is analyzed. The total fuel consumption, ratios of PV and wind turbine capital costs to total initial capital investment, and ratios of PV and wind turbine energy production to total energy generation are scrutinized. Moreover, the annual operation and maintenance cost of the wind turbine and the average output powers of the converter or rectifier and the converter or inverter are assessed. Total energy purchased from and sold back to the grid over the simulation period are also quantified. These simulation outcomes offer valuable insights into the system's performance, costs, and efficiency under varying renewable fraction limits, aiding in the evaluation of its operational and economic viability. The simulation outcomes for 0% and 50% renewable fraction limits are presented in Table 1.

Sensitivity limit/Renewable Fraction (%)	PV (kW)	WT	NPC ($)	COE ($)	Ren Frac (%)
0	-	5	1,627,559	0.060	25.73
50	253.03	5	1,923,289	0.070	50.03

In Case I with 0% renewable fraction limits, the system architecture consists of 5 wind turbines integrated with the grid. The wind turbines contribute 25.7% (452,565 kWh/yr.) of the total system electrical production, while the grid purchases represent 74.3% (1,306,190 kWh/yr.) with zero excess electricity, resulting in a 25.7% renewable fraction. Figure 6 illustrates the monthly electrical production of the proposed system. The rated capacity of the wind turbines is 100 kW, with a mean output of 51.7% kW and a capacity factor of 51.7%. The wind turbines operate for 7596 hours per year, with a levelized cost of 0.0343 $/kWh. Table 2 provides detailed monthly data on the grid energy purchases and sales. This analysis offers insights into the energy production distribution, cost implications, and operational efficiency of the system under 0% renewable fraction limits.

Table 2: The detailed monthly data on the grid energy purchases and sales in case I

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge
January	87,739	369	87,370	266	$6,036
February	78,776	456	78,320	258	$5,413
March	93,628	349	93,279	289	$6,443
April	104,133	159	103,974	312	$7,177
May	122,362	42.3	122,320	340	$8,441
June	125,790	0	125,790	347	$8,680
July	139,292	0	139,292	367	$9,611
August	132,320	0	132,320	351	$9,130
September	119,060	1.33	119,059	342	$8,215
October	117,607	20.0	117,587	303	$8,114
November	99,203	49.3	99,154	301	$6,843
December	86,278	444	85,834	271	$5,931
Annual	1,306,190	1,890	1,304,300	367	$90,033

In Case II with 50% renewable fraction limits, the system architecture comprises a 253-kW photovoltaic (PV) array, 5 wind turbines, and grid integration. The PV array contributes 25.7% (461,758 kWh/yr.) of the total system electrical production, while the wind turbines contribute 25.1% (452,565 kWh/yr.), and the grid purchases represent 49.2% (885,607 kWh/yr.) with 0.262% excess electricity, achieving a 50% renewable fraction. Figure 7 illustrates the monthly electrical production of the proposed system. The rated capacity of the wind turbines is 100 kW, with a mean output of 51.7 kW and a capacity factor of 51.7%. The wind turbines operate for 7596 hours per year, with a levelized cost of 0.0343 $/kWh. Additionally, the rated capacity of the PV array is 253 kW, with a mean output of 1265 kW/day and a capacity factor of 20.8%. The PV array operates for 4402 hours per year, with a levelized cost of 0.0943 $/kWh. Table 3 provides detailed monthly data on the grid energy purchases and sales. This analysis offers insights into the energy production distribution, cost savings, and operational efficiency of the system under 50% renewable fraction limits.

Table 3: The detailed monthly data on the grid energy purchases and sales in case II.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge
January	56,329	3,038	53,292	259	$3,735
February	48,938	2,990	45,948	250	$3,227
March	55,622	2,538	53,083	251	$3,711
April	66,658	873	65,785	267	$4,556
May	84,752	263	84,490	320	$5,835
June	89,202	10.8	89,191	318	$6,154
July	101,604	0	101,604	324	$7,011
August	95,455	150	95,305	309	$6,579
September	82,648	164	82,483	289	$5,694
October	80,891	640	80,251	285	$5,549
November	67,568	1,235	66,334	255	$4,600
December	55,940	3,592	52,348	236	$3,680
Annual	885,607	15,494	870,114	324	$60,332

5. Discussion and Conclusions

The analysis of the grid-connected hybrid renewable energy system in Yanbu, Saudi Arabia, provides valuable insights into the feasibility, performance, and economic implications of renewable energy integration. Through simulation outcomes for two scenarios - one with no minimum renewable fraction (0%) and the other imposing a 50% renewable fraction limit - key findings were obtained. In Case I, where no renewable fraction limit was imposed, the system predominantly relied on grid energy purchases, resulting in a renewable fraction of 25.73%. Despite minimal reliance on renewable sources, the system demonstrated operational efficiency, with wind turbines contributing 25.7% of the total electrical production. However, the net present cost (NPC) was relatively high at $1,627,559, with a corresponding cost of energy (COE) of $0.060/kWh. This scenario underscores the importance of enhancing renewable energy integration to achieve sustainability goals and reduce dependence on non-renewable sources.

In contrast, Case II, with a 50% renewable fraction limit, showcased a more balanced distribution of energy production from photovoltaic (PV), wind, and grid sources. The system achieved a renewable fraction of 50.03%, with PV contributing 25.7% and wind turbines contributing 25.1% of the total electrical production. Despite increased renewable energy integration, the NPC slightly increased to $1,923,289, with a corresponding COE of $0.070/kWh. However, the higher renewable fraction demonstrates significant progress towards sustainability goals and aligns with global trends in renewable energy adoption. The detailed monthly data on grid energy purchases and sales further elucidated consumption patterns and energy utilization throughout the year. Both scenarios highlighted seasonal variations in energy demand, with peak demand occurring during summer months. Understanding these patterns is crucial for optimizing system operation and energy management strategies.

In conclusion, the analysis underscores the importance of renewable energy integration for sustainable energy development in Yanbu, Saudi Arabia. While Case II demonstrated progress towards higher renewable energy penetration, further optimization and investment in renewable infrastructure are necessary to achieve long-term sustainability goals. Policy initiatives aimed at incentivizing renewable energy investments and promoting regulatory frameworks supportive of renewable energy integration are essential for accelerating the transition towards a more sustainable energy future. Through continued research, innovation, and collaborative efforts, Yanbu can harness its abundant solar and wind resources to drive sustainable development and reduce reliance on fossil fuels.

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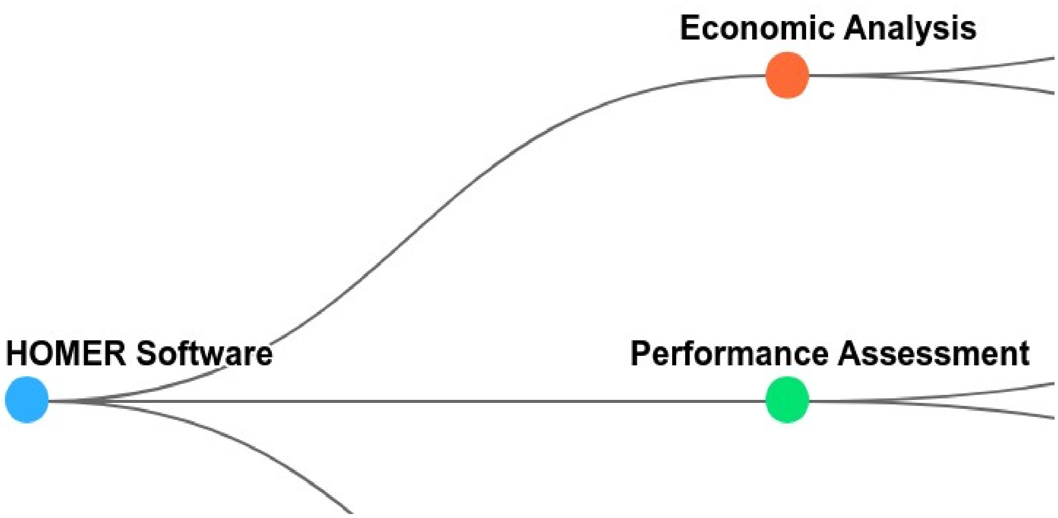

Fig. 1. Overview of HOMER Software's role in hybrid power system

Fig. 2. The annual average solar radiation of the study area.

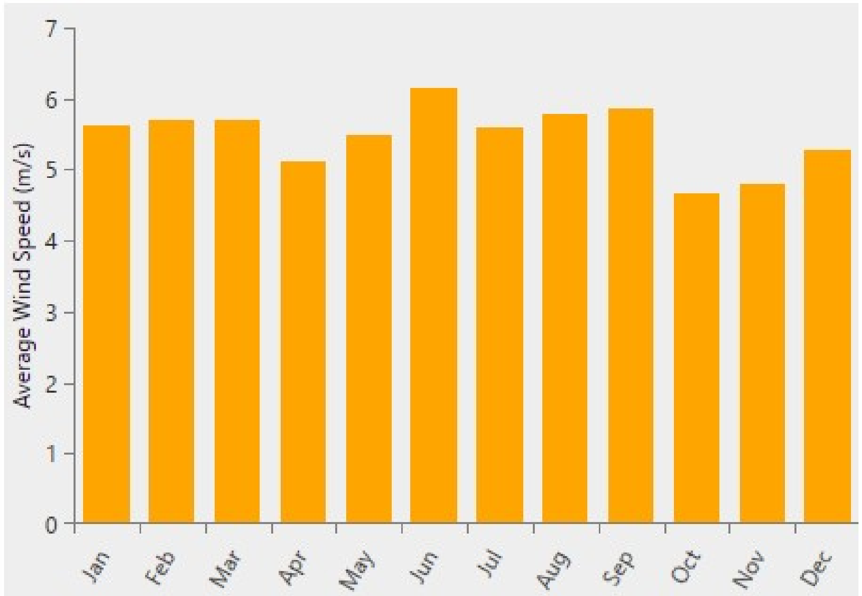

Fig. 3. The annual average wind speed of the study area.

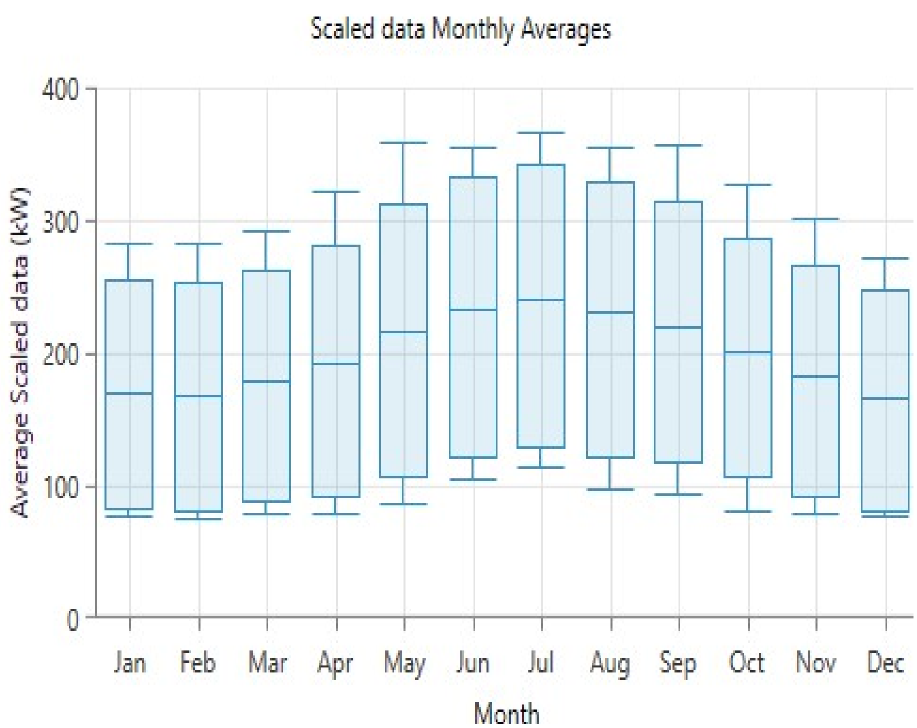

Fig. 4. The annual average load profile of the study area.

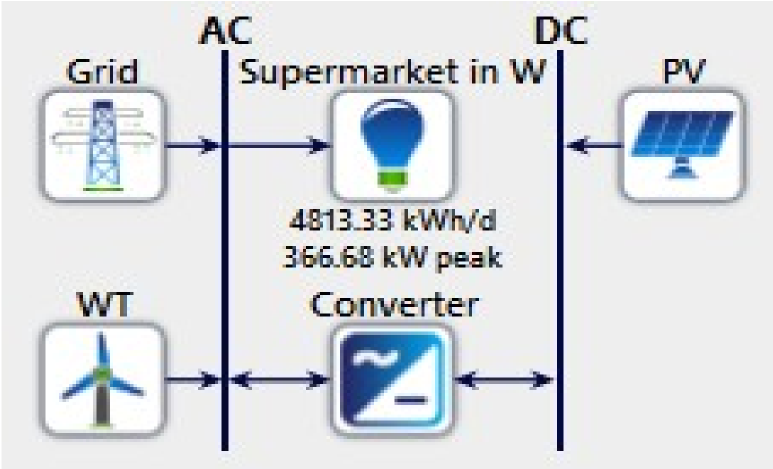

Fig 5. The system configuration for the grid-connected hybrid renewable energy system

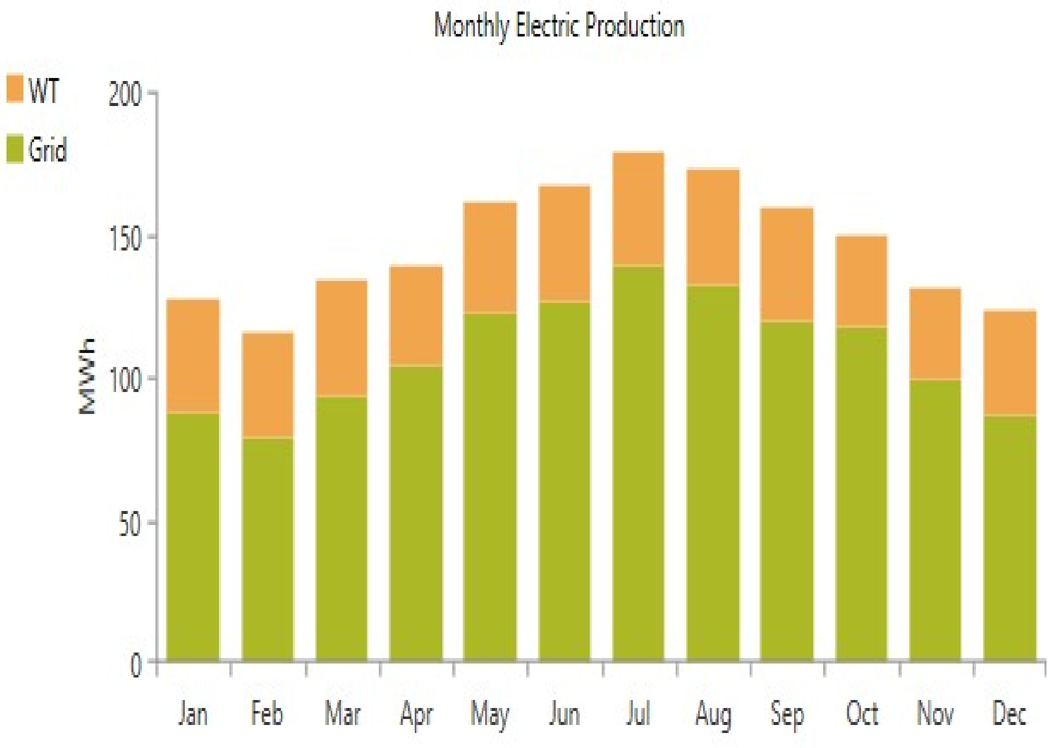

Fig. 6. The monthly electrical production of the proposed system in case I.

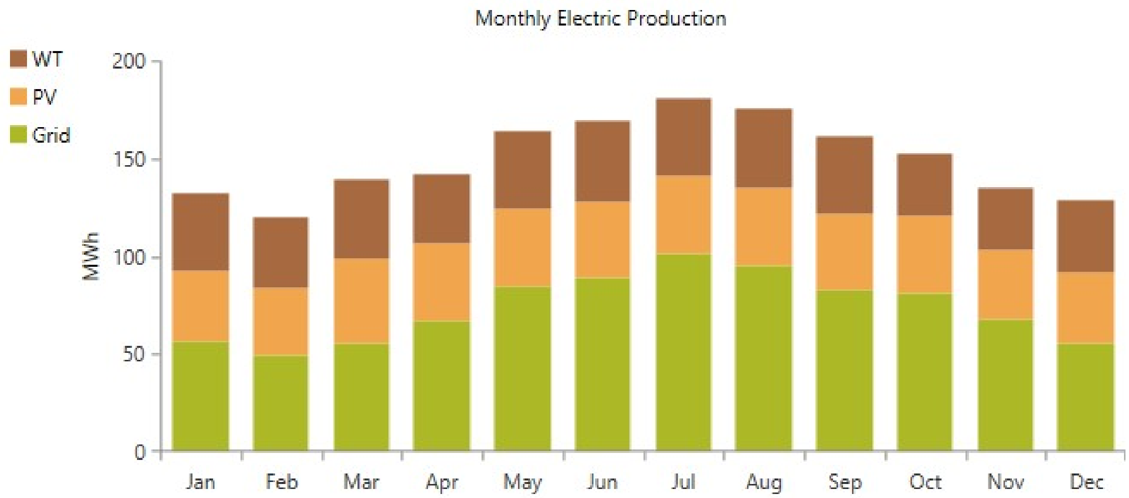

Fig 7. The monthly electrical production of the proposed system in case II.