Real Time Design and Analysis of a Hybrid Renewable Energy System (PV/Wind/Battery) for Self-Consumption Residential Building

A. Aqila, Y. Nassar, H. J. El-Khozondar, M. Elmnifi, M. Khaleel, S. Rekik, E. Belal, M. Al-Maghalseh, Rifa J. El-Khozondar

Abstract— **The increasing research interest in Hybrid Renewable Energy Systems (HRESs) reflects a global desire for development and sustainability. Hybrid renewable energy systems aim to meet the energy demand loads, including residential loads, which constitute the largest electricity-consuming sector in Libya, accounting for approximately 56% of the total electric energy consumed in the country in 2022. Consequently, this paper presents a novel approach by designing and analyzing a hybrid renewable energy system to cover the electrical load based on the power capacity of the devices and the actual operational time. The study relied on real-time measured data at 10-minute intervals for climatic conditions (solar radiation intensity, wind speed, and ambient air temperature) as well as the electrical loads consumed in a household located in Samno, Sabha, Libya. A dynamic simulation of the proposed system's performance was conducted using the SAM simulation software, and the results were processed using Microsoft Excel. The results showed that the proposed hybrid renewable energy system is capable of meeting the required electrical load, especially during peak times, and supplying power to the electrical grid. The economic results show that the levelized cost of energy (LCOE) is US$0.0107/kWh.**

Keywords—**Solar energy, Wind energy, Hybrid renewable energy, Electrical load, Real time analysis**

I. Introduction

Driven by environmental pressures, the world is witnessing a shift towards alternative and environmentally friendly energies. The installed capacity of renewable energy at the end of 2024 reached approximately 3,372 GW, with the contribution of solar photovoltaic energy reaching approximately 1,600 GW, the share of wind energy was approximately 1,021 GW, while the contribution of biomass energy reached approximately 150,260 GW, and the share of geothermal energy was approximately 16,335 GW. Despite this, the contribution of renewable energy did not exceed 29% of the total electrical energy produced in the world [1]. The energy industry is considered one of the most polluting sectors, accounting for 75% of the total pollution in the world [2]. This has prompted a comprehensive reassessment of available energy resources to identify sustainable and clean alternatives that can meet the rapid growth in energy demand. Renewable energy is expected to play a significant role in mitigating environmental damage by reducing carbon dioxide emissions in the global energy system by 3.6 Gton by 2035 [3]. In light of the challenges associated with rising energy consumption, the residential sector accounts for approximately 30% of the world's total energy consumption and contributes approximately 27% of the total carbon emissions resulting from the energy sector [4]. The situation differs significantly in developing countries, where residential sector consumption is estimated to be between 40% and 60% of total energy consumption.

In Libya, the residential sector accounts for approximately 65% of the country's electricity consumption. It is considered one of the largest electricity-consuming sectors in 2023 [5]. Libya's electricity production is estimated at approximately 31 TWh, primarily from gas and oil. However, energy demand will increase significantly in the near future as a result of the economic development and political stability the country has witnessed in recent years. This will lead to increased consumption of oil and gas in electricity production, leading to more carbon emissions [6]. Given that Libya is a signatory to all climate change treaties and agreements, and is the largest oil producer in North Africa, and relies primarily on gas and oil for most of the country's revenues and electricity production, the urgent need to use hybrid renewable energy systems to generate power and reduce the carbon footprint is highlighted. Libya has proven potential for diverse renewable energy resources that can play a vital role in the national energy mix [7-17]. Therefore, Libya must leverage its natural resources, such as solar energy, wind energy, biomass energy, and geothermal energy, to meet the growing demand for energy, reduce dependence on fossil fuels, and exploit them in petrochemical industries instead of burning them for energy production. The importance of this study is highlighted by its alignment with Libya's aspirations to increase the contribution of renewable energy to the electricity mix by 30% by 2030, and more than 50% by 2050 [18].These systems can also play an important role in supplying the residential sector with the energy needed to cover all electrical and thermal loads.

A. Aqila and Y. Nassar are with Wadi Alshatti University, Libya (email; a.aqila@wau.edu.ly, and y.nassar@wau.edu.ly)

H. El-Khozondar (corresponding author) is with Islamic University of Gaza, Gaza, (corresponding author to provide phone: 970 599 603 535; email: hkozondar@iugaza.edu,ps).

M. Elmnifi is with Belgorod State Technological University, Belgorod, Russia, (email: monm.hamad@yahoo.co.uk).

M. Khaleel is with Karabuk University, Karabuk 78050, Türkiye, (email: lykhaleel@yahoo.co.uk).

S. Rekik is with National Engineeriisng School of Monastir, University Monastir, Tunisia, (email: sassi.rekik@gmail.com).

E. Belal is with Libyan Center for Solar Energy Research and Studies, Triploi, Libya, (email: is_bilal@csers.ly).

M. Al-Maghalseh is with Palestine Polytechnic University, Hebron, Palestine, (email: maherm@ppu.edu.ps).

R. J. El-Khozondar is with Al-Aqsa University, Gaza, Palestine,(email: rifa20012002@yahoo.com)

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Hybrid energy systems have achieved remarkable successes on a large scale, both locally and internationally, by all scientific and practical standards, through a large number of scientific researches Published in this field [19-40]. The review of previous research included in this study provides an overview of the major developments in this field, highlighting the significance of current research and identifying gaps in previous studies in this area.

Locally, a study was conducted to design an energy system for a house isolated from the public electricity grid in the city of Al-Maqroun, Benghazi (eastern Libya). The system consists of 6 kW wind turbines and 3 kWh batteries, with the aim of meeting the electrical energy demand for this house, estimated at approximately 35 kWh/day. The annual energy produced by the wind energy system was estimated at approximately 23,894 kWh/year, with a capacity factor of approximately 19% [41].

A feasibility study was conducted to evaluate the technical and economic feasibility of an off-grid hybrid power system for the rural village of Al-Baidan, near the city of Ajdabiya in eastern Libya. Due to the lack of electricity in this remote area, the installation of off-grid hybrid power systems has become unavoidable. A hybrid combination of renewable energy technologies has proven to be a viable alternative in remote and off-grid areas worldwide. The HOMER software was used to model, specify components, and size the hybrid system based on the lowest unit cost of energy (LCOE) and the lowest emissions. The results showed that a hybrid system consisting of PV panels and a wind turbine is the viable system for this project. Design, optimization, and sensitivity results also revealed that renewable energy technologies are the viable option for generating electricity for Al-Baidan, with an LCOE of approximately 0.1801 LD/kWh [42].

A study was presented to determine and analyze the size of an independent energy system that operates using photovoltaic panels and batteries for a house in Benghazi, Libya, to meet the electrical energy needs of the house. The size of the proposed system was determined using the HOMER program, and it was found that the system consists of 28 solar panels with a capacity of (330 W/panel) and 32 lead-acid batteries (219 Ah_12V). The dynamic model of the system was implemented using MATLAB/Simulink. The results showed that the proposed system is capable of meeting the electrical energy demand at a constant direct current and a voltage of 48 V. The study also recommended its use to meet the needs of homes in rural communities with low loads or basic electricity needs. The net cost of the proposed system was estimated at $42,892 and the levelized cost at $0.365/kWh [43].

A study was conducted in Palestine to design an off-grid hybrid energy system for the Jenin Governorate in the northern West Bank. The study was based on two years of hourly data for solar, wind, biomass, and electrical load. The SAM renewable energy potential estimation software and the HOMER software were used to determine the components and size of the hybrid renewable energy system. The proposed hybrid renewable energy system consists of an 80MW solar photovoltaic (PV) field, a 66MW wind farm, and a 50MW biogas-fired electric turbine. The investment value was approximately $323 million. The proposed system generates 389GWh/year, which is sufficient to meet the electricity demand 100% of the electricity demand in Jenin Governorate, with a surplus in electricity generation of approximately 4.57%. The cost of energy was estimated at approximately $0.131/kWh, which is slightly higher than the price supplied by the Israeli company to citizens ($0.128/kWh) [44].

In Nigeria, a methodology was proposed to design a standalone hybrid system using photovoltaic (PV), a diesel generator, and batteries for a residence at Marcus Poli Estate Gwarinpa in Abuja, central Nigeria. The system was modeled and optimized using HOMER software. The analysis results showed that, among five hybrid system configurations for covering the electrical load, the hybrid system consisting of PV, a diesel generator, and batteries was the most optimal for that area, with a net present cost of $118,771 and a cost of energy production of $0.34/kWh [45].

In Iran, a comparative study was conducted on the performance of single-source and hybrid renewable energy systems in Zahedan, a city in southeastern Iran with significant renewable energy potential: solar and wind. Eight options were simulated and analyzed using TRNSYS software. The first option consisted of two sources (PV and a wind turbine), while the other configurations included six hybrid systems that included combinations of PV, wind turbines, fuel cells, and diesel generators. The analysis revealed that hybrid systems, particularly those combining PV and wind turbines, outperformed single-source configurations. For example, a hybrid system with 800 kW of PV and 50 kW of wind power reduced diesel consumption by 35% and carbon dioxide emissions by 45% compared to a system relying solely on a diesel generator. Although the performance of hybrid renewable energy systems depends largely on the mix of renewable energy sources, However, they generally provide high reliability and environmental benefits [46].

In China, a technical and economic feasibility study was conducted for an off-grid hybrid renewable energy system for several remote rural areas in western China. Different combinations of PV panels, wind turbines, and biogas generators were modeled and optimized using HOMER software, based on the daily and seasonal characteristics of energy supply, as well as the quantities and patterns of demand in remote rural areas. The goal was to determine the most cost-competitive configuration while ensuring reliable energy supply to meet the needs of the residential, commercial, and agricultural sectors in these areas. The results showed that the most cost-effective and reliable system configuration consisted of 104 kW PV solar panels, three 10 kW wind turbines, a 5 kW gas-fired generator, 331 kWh storage batteries, and a 109 kW frequency converter. The system had an estimated annual production capacity of 322,156 kWh/year, achieving village independence from the main grid. It could also provide electricity to consumers at a cost of $0.201/kWh. The hybrid energy system, which combines solar, wind, and biomass, is a reliable and cost-effective option for electrifying remote rural areas sustainably while achieving environmental benefits [47].

This paper aims to design and analyze a hybrid energy system to cover the electrical and thermal energy loads of a house located in the southern region of Libya, based on energy consumption, location, and available renewable resource capacities. To achieve this goal, the electrical loads of the target house were measured every 10 minutes for an entire year. Climatic data were obtained from the Solargis platform, which provides 10-minute information on the intensity of the total oblique solar radiation, wind speed and direction, and temperature. The dynamic performance of the proposed system was simulated using the SAM simulation program, and the data was processed using Excel. To obtain the optimal size for the system components, the results were subjected to several objective functions and constraints, which were formulated to match the case study; these functions included the economic aspect (LCOE), the environmental aspect (CO_2), the technical aspect, and the probability of power supply interruption (LPSP).

The current study differs from previous studies in its design and analysis of a hybrid renewable energy system to cover the electrical load based on the capacity of appliances and the actual operating time of household electrical appliances, which is a minimum of 10 minutes for each appliance, tool, or electrical equipment. This approach differs from the traditional method of calculating electrical loads based on energy consumption as the product of the capacity multiplied by the number of hours electrical appliances are operated (Wh). This does not indicate the actual capacity of the power generation system, representing a new approach—to the best of the researchers' knowledge—for designing power generation systems. The remainder of the study is divided into the following sections: the "research methodology" is outlined in Section Two; the "results" are presented graphically in figures and numerically in tables and discussed in Section Three; the "conclusions and recommendations" are formulated in Section Four; and the study concludes with a list of references.

II. RESEARCH METHODOLOGY

This section discusses the methodology used to achieve the desired research objective. The approach begins by importing data from the international information network, including: climate data, economic data, technical data, environmental data, and electrical loads. Renewable energy potential is then analyzed on a real-time basis, every 10 minutes for an entire year, using the SAM program. The capacities of renewable sources are then determined to cover the electrical load, store excess energy in batteries, and export the surplus from the system to the national electricity grid. Finally, an economic and environmental analysis of the system is conducted to determine the ideal size for the system components. The flowchart in Fig. 1 illustrates the methodology used in the research.

A. Study Assumptions, Limitations, and Sources of Uncertainty in Results

To facilitate analysis, the following assumptions were adopted:

1. Neglecting the decline in device performance over time.
2. Neglecting the cost of equipment and devices after their end-of-life (rubbish).
3. Neglecting energy losses through extension cords and connection points.
4. Considering the efficiencies of supporting devices (frequency converter, controllers, transformers, battery) as constant.

The lack of a sensitivity study of the results to differences in some parameters (prices of renewable energy devices and equipment, differences in the load curve pattern) is one of the limitations The study also failed to conduct several scenarios for system components (such as adding a generator and connecting to the public electricity grid), which will be studied in the future. Data, such as climate data and loads, are the largest source of uncertainty. The prices of renewable energy equipment and devices are also a source of uncertainty, with solar cell prices varying by up to 360% in the international solar energy market.

B. Schematic diagram of the proposed system components

The components of a hybrid energy system may vary depending on the design, geographical location, and application intended to achieve the desired goal. The components utilized in this study are renewable energy sources (PV and wind energy), along with a storage system (batteries). Fig. 2 also indicates the components of the system proposed in this study.

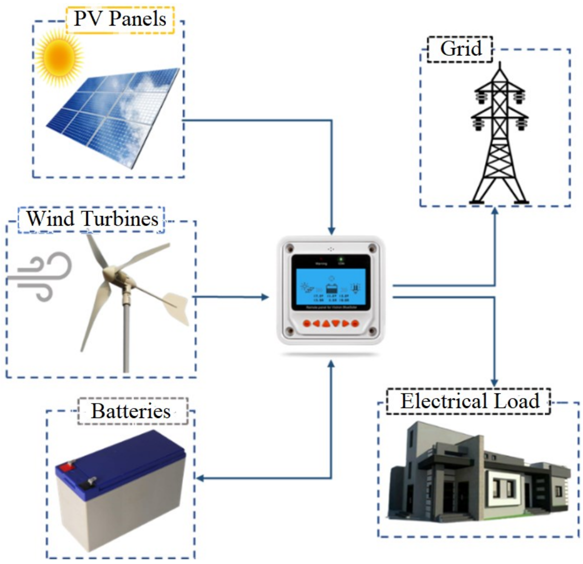

Figure 1. Components of the system proposed in this study.

C. Geographical, climatic and Load data of the study site

The house under study is located in Wadi Al-Buwanis Municipality, a municipality in the southern regions of Libya, and consists of a series of districts, including Samnu District. Samnu District is the largest of these districts in Wadi Al-Buwanis. Samnu District is located in southwestern Libya at longitude 14.889 east and latitude 27.221 north, as shown in the map in Fig. 3, and is approximately 781 km from the city of Tripoli and 60 km from the city of Sebha. The population of the district is estimated, according to the Civil Status Department report for the year 2024, at approximately 16,453 people.

Samnu village has a desert climate, with temperatures rising during the hot seasons from May to September, with an average temperature of 32°C. July is the hottest month, with temperatures reaching 40°C. Temperatures drop significantly during the cold seasons from November to February, with an average temperature of 13°C. The lowest temperatures are in January, with an average of 3°C. The average sunshine hour is with more than 4,300 hours of sunshine per year, the average solar radiation also experiences significant seasonal fluctuations throughout the year. The average daily solar radiation reaches 6.1 kWh/m^2/day. Wind speeds vary significantly. May is the windiest month, with an average wind speed of 4.7 m/s. In contrast, December is the calmest month, with an average wind speed of 3.4 m/s. Fig. 4 represents the main climate data on which the research was based, which were obtained from the SolarGis database.

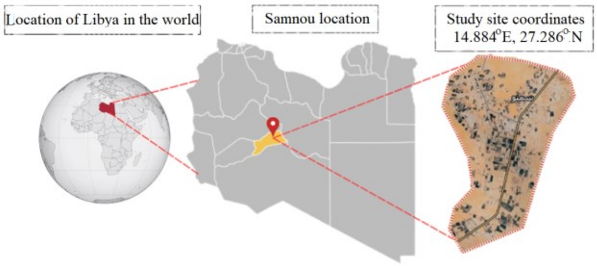

Figure 3. Study site map.

D. *Classification of electrical and thermal loads*

With the goal of maximizing the use of renewable energy, this research categorizes household electrical loads into three main categories for precise analysis and processing. These categories include: Thermal Loads: This category includes appliances that rely on heating, such as water heaters and heating. Electrical Loads: This category includes electrical appliances such as lighting, refrigerators, washing machines, televisions, and others, as well as heating appliances that operate for no more than 10 minutes, such as irons and hair dryers. Chemical Loads: This category includes the use of cooking gas. Fig. 5 shows the percentages of electrical appliances contributing to the load for the home under study. In this section, special emphasis will be placed on addressing electrical loads, given their importance in energy consumption within the home. This will be achieved by analyzing consumption patterns and identifying peak times. As for thermal and chemical loads, future studies have been identified to address them in detail.

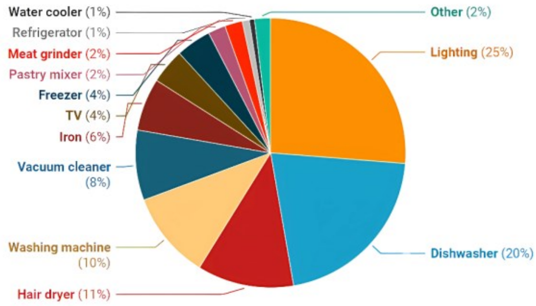

Figure 5. The percentage of electrical appliances participating in the electrical load of the house under study.

E. *Electrical loads of the study site*

The study was conducted on a residential house in the Samnu area. The house has an area of 300 m^2 and consists of three bedrooms, two living rooms, a hall, a kitchen, and three bathrooms. Seven people live there. The frequency of electrical appliance uses and consumption within the house was recorded for a full year, with the actual annual consumption value reaching 51,238 kWh. This was done under real-world conditions with the minimum operating time for household electrical appliances, which is 10 minutes. Fig. 6 also indicates the frequency of electrical appliance use during a single day in the summer and winter, respectively. Fig. 7 shows the box plot of the electrical loads during the year. Thus, the demand for residential loads, which focuses specifically on the demand for electricity in Libyan households, does not vary greatly from one house to another, regardless of the social and economic conditions of its residents and the number of people living in it [48].

It is noted in the previous figures that the consumption of electrical energy depends on different conditions such as the seasons of the year (summer or winter), so that the maximum energy consumption in the summer is about 6000 W, while in the winter it is about 4000 W, and this confirms that the energy consumption in the summer is higher [49]. As a result,

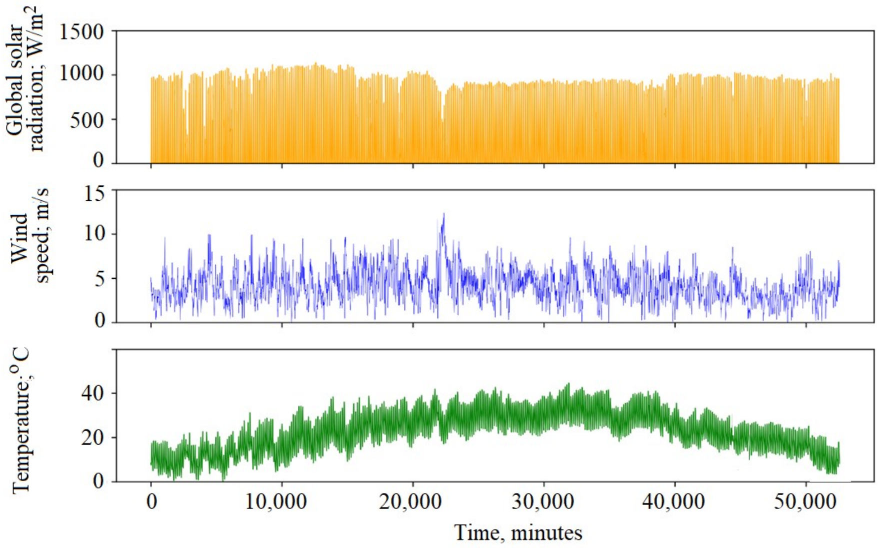

Figure 4. Solar radiation, wind speed and temperature for the area under study.

the electrical load stems from the vast number of modern household electrical applications, most of which are not constant in terms of consumption value, such as lighting, refrigerators, and washing machines. This, in turn, adds complexity to the electrical load curve, making ideal consumption difficult to achieve in practice. In fact, during the morning hours, energy consumption is concentrated on small kitchen appliances and heating devices. Consequently, energy consumption is generally lower during the day, when residents are often out of the home. Energy demand increases as residents return home around 2:00 PM, leading to increased electricity use. Energy consumption gradually decreases during sleeping hours, due to reduced use of lighting, entertainment devices, and major appliances.

F. Mathematical modeling of system components

PV solar panels

The electrical energy produced by solar cells can be estimated from the following equation [50-52]:

$$E_{PV} = P_{STC}\left[1 + \beta_p (T_{cell} - T_{STC})\right] \frac{H_t}{H_{STC}} \quad (1)$$

$$T_{cell} = T_\infty + 7.8 \times 10^{-2} H_t \quad (2)$$

P_{STC} represents the power produced by a solar cell under standard test conditions. β_p represents the temperature coefficient of power, while T_{cell} and T_{STC} represent the cell surface temperature and the cell temperature under standard test conditions. H_t and H_{STC} represent the total solar radiation and the solar irradiance under standard conditions. T_∞ represents the ambient air temperature. A specific type of renewable energy equipment was selected based on local research results to achieve the best performance under the harsh climatic conditions of Sebha city [53-55]. Table (1) shows the specifications of the selected PV panels in the hybrid system.

TABLE 1 SPECIFICATIONS OF THE SELECTED PV PANELS

Item	Specifications
Capacity	560W
Efficiency	21.87%
Temperature Coefficient of Power	0.4%/°C
Construction Cost	\$1.5/kWp
Operation and Maintenance Cost	\$0.02/kWp
Solar Cell Lifespan	25 **years**

Wind energy

The amount of electrical energy produced from wind energy can be estimated using the following equation [56,57]:

$$E_{WT}(t) = \begin{cases} 0 & v(t) \le v_{c-in} \ or \ v(t) \ge v_{c-out} \\ P_r \dfrac{v(t) - v_{c-in}}{v_r(t) - v_{c-in}} & v_{c-in} \le v(t) \le v_r \\ P_r & v_r \le v(t) \le v_{c-out} \end{cases} \quad (3)$$

P_r represents the rated power of the wind turbine at the operating wind speed v_r, while v_{c-in} v_{c-out} represent the inlet and outlet wind speeds, respectively. In the same context of the renewable energy equipment selection process, ATO wind turbines were chosen in this study due to their responsiveness to the desert climate. Table (2) shows the specifications of the selected wind turbines.

TABLE 2 SPECIFICATIONS OF THE SELECTED WIND TURBINE

Item	Specifications
Turbine Type	ATO-X5-500
Rated Power	500W
Cut in, Cut off and rated Wind Speed	2, 50, 12 m/s
Capital Cost	\$1.2/kW
Operation and Maintenance Cost	\$0.081/kW
Turbine Lifespan	25years

Batteries

The level of electrical energy stored in a battery pack can be estimated as follows [58]:

$$E_B(t) = E_B{}^{t-1}(1 - \delta) + \left[E_{PV} + E_{WT} - \frac{E_{Load}}{\eta_{inv}}\right] \times \eta_B \quad (4)$$

Where $E_B{}^{t-1}$ represents the state of charge of the battery pack at time $(t-1)$, $E_{PV}\ (t)$ and $E_{WT}\ (t)$ are the power generated by the PV panels and wind turbines, respectively. $E_{Load}\ (t)$ represents the electrical load to be covered. η_{inv} and η_B represent the efficiency of both the inverter and the battery. Table (3) shows the specifications of the batteries selected to support the hybrid system. The proposed system must be safe and reliable in supporting the power supply, so the reliability of the power supply ratio

TABLE 3 TECHNICAL SPECIFICATIONS OF THE SELECTED BATTERY

Item	Specifications
Voltage	12V
Construction Cost	\$1.4/Wh
Maintenance and Operation Cost	\$0.005/Wh
Battery Life	5

(LPSP) was considered as the design constraint. It can be calculated using the following equation [59]:

$$LPSP = \frac{\sum_{i=1}^{52560}[E_{Load}(t_i) - E_{HR}(t_i)]}{\sum_{i=1}^{52560} E_{Load}(t_i)} \quad (5)$$

$E_{HR}(t_i)$ represents the energy produced by the hybrid system, and $E_{Load}(t_i)$ represents the electrical load to be covered.

G. Economic and Environmental Analysis

The levelized cost of energy (LCOE) is considered as an objective function, which is estimated together with the payback time (PBTM), taking into account the cost of environmental C_{CO_2}. This is calculated using the following equations [59]:

$$LCOE = \frac{\left[\begin{array}{l}\left(\frac{i(1+i)^n}{(1+i)^n-1}\right) \times (C_{PV} + C_{Wind}) + \\ \left(\frac{i(1+i)^m}{(1+i)^m-1}\right) \times C_{Batt} + C_{O\&M} - C_{CO_2}\end{array}\right]}{\sum_{t=1}^{52576}(E_{Load}(t) + E_{grid}(t))} \quad (6)$$

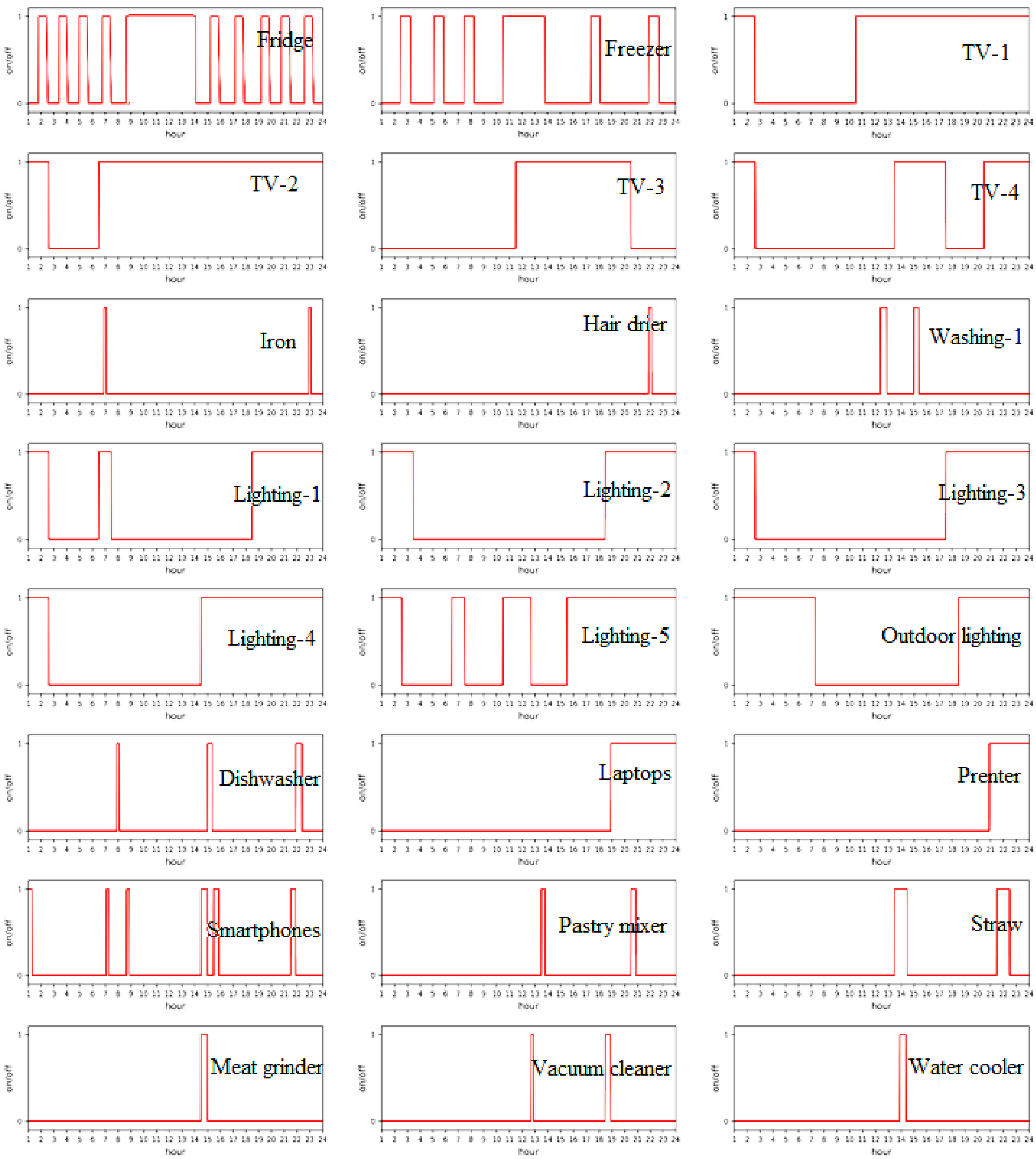

Figure 6. Load curve for electrical appliances during one day in the summer (July 14, 2024).

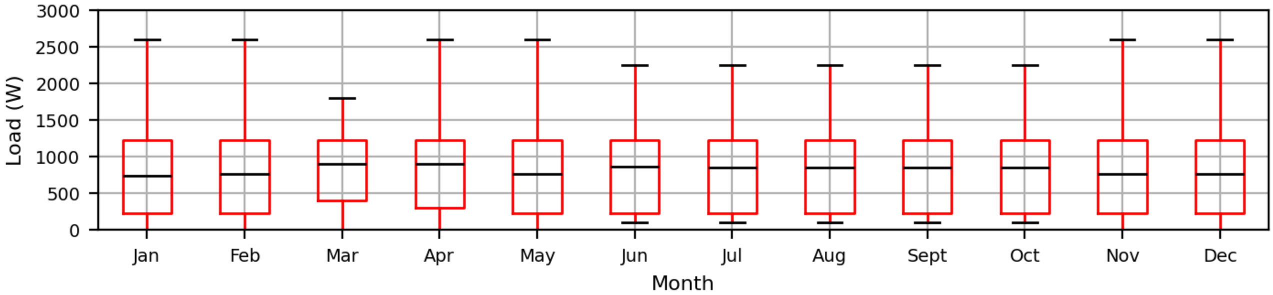

Figure 7. Box plot of electrical loads during the year.

$$PBTM = \frac{C_{PV} + C_{Wind} + 5C_{Batt}}{I_H} \quad (7)$$

$$C_{CO_2} = EF_{CO_2} \times \emptyset_{CO_2} \times \sum_{t=1}^{52576} \left[E_{Load}(t) + E_{grid}(t)\right] \quad (8)$$

Where: n refers to the plant lifetime, which is 25 years for PV systems and wind turbines, while m is the expected lifetime for storage systems, which can be considered 5 years. i represents the real discount rate, and its value is 0.08. C_{PV}, C_{Wind}, and C_{Batt} represent the capital for PV systems, wind turbines, and storage systems (batteries), respectively. $C_{O\&M}$ represents the annual operating and maintenance cost of the proposed system. I_H refers to the annual income of the hybrid system from electricity sales, E_{Load} refers to the electrical load to be covered, and E_{grid} refers to the energy exported to the grid. EF_{CO_2} represents the carbon dioxide emission factor for the power system in Libya (1.037 tonCO_2/MWh).[60] and $\emptyset_{CO_2}$represents the social cost of carbon, which can be considered as \$70/tonCO_2 [60]. While the environmental impact and societal conditions of PV solar fields has been intensive discussed by Al-Maghalseh [61]

III. RESULTS AND DISCUSSION

In this section, the results obtained from the design and analysis of a hybrid renewable energy system including PV panels, wind turbines, and batteries are presented and discussed under actual conditions to cover the electrical loads of a house in the Samnu area. Using the SAM program and with the help of Excel and Jupiter programs, the productivity of a 560-watt PV solar panel and a 500-watt wind turbine is estimated for every 10 minutes, as shown in Figs. 8 and 9. Fig. 10 illustrates a model of the concept of energy storage level in one of the batteries in a hybrid energy system for every 10 minutes for a full year. In this cycle, the storage level at the beginning of the cycle is equal to its level at the end, indicating a closed cycle. Therefore, all batteries used in the hybrid energy systems in this study follow this concept in terms of energy storage level. This leads to the concept of energy discharge behavior being repeated periodically, annually. Fig. 11 clearly shows how combining renewable energy sources, such as PV panels and wind turbines, with batteries can improve the efficiency of hybrid energy systems. Using this integrated approach, electrical energy can be provided sustainably and consistently, especially during peak periods. Therefore, 10 diverse configurations were created, varying in the contribution of energy sources to the electrical energy supply. This strategy reflects how hybrid systems benefit from a harmonious balance between energy sources to meet energy needs efficiently and effectively. Fig. 11 also indicates the impact of the contribution of renewable energy sources (PV panels and wind turbines) on battery capacity.

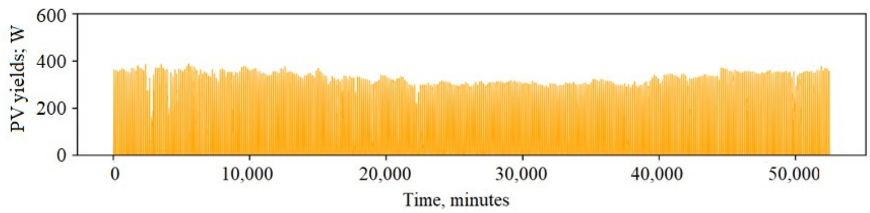

Figure 8. 560W PV solar panel output per 10 minutes.

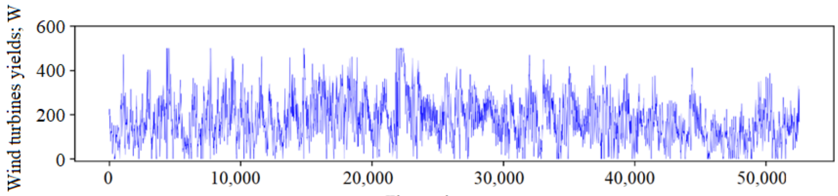

Figure 9. 500W wind turbine output per 10 minutes.

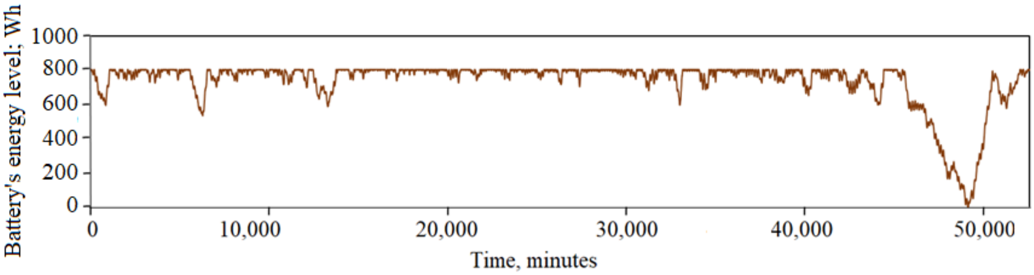

Figure 10. Energy storage level in batteries per 10 minutes.

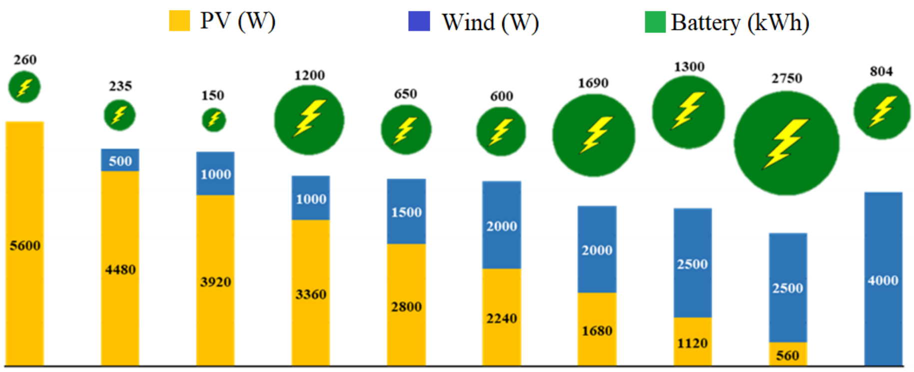

Figure 11. Configurations of renewable energy sources for electricity supply.

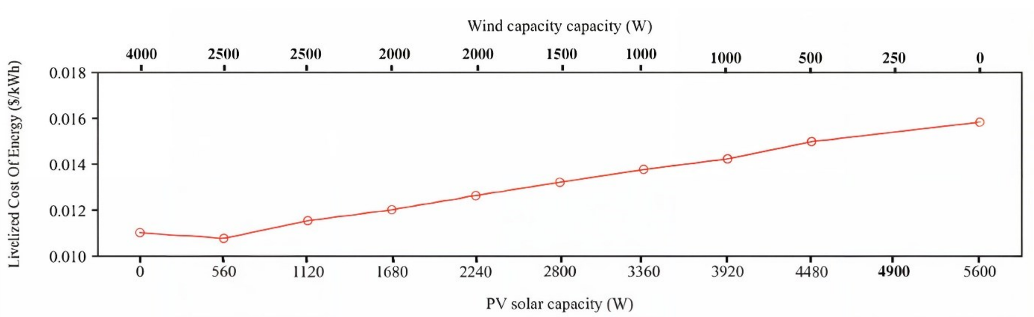

Figure 12. Levelized cost of energy (LCOE) for hybrid renewable energy configurations.

In line with the above, the objective function was applied by calculating the levelized cost of energy (LCOE) within the criteria specified in the research framework, which is considered the decisive factor in determining the size of the proposed hybrid energy system. A life cycle analysis of carbon dioxide was integrated for all components of the hybrid energy system, according to Equation (6). Fig. 12 illustrates the levelized cost of energy (LCOE) for all hybrid renewable energy source configurations in this studyrelies on multiple energy sources. These results highlight the importance of investing in renewable energy, both locally and internationally. This reflects our commitment to achieving sustainable development and environmental conservation.

However, the energy balance process between generation and electrical load was represented under actual time conditions, which were every 10 minutes for a full year. Fig. 13 shows the energy balance between electricity generation and electrical load, which is represented by the household electrical load and the load supplied to the grid. The hybrid power generation system includes a 560W PV solar panel, five 500W wind turbines, each with a total capacity of 2500W, and 2750kWh storage batteries to meet the annual electrical energy demand of 51238kWh. In contrast, the total annual energy generated by the system is 51580kWh. Solar energy contributes approximately 5388kWh, while wind energy contributes 45909kWh. This energy is sufficient to meet the required electrical load, and the surplus, estimated at approximately 342kWh, is exported to the public electrical grid.

IV. CONCLUSIONS AND RECOMMENDATIONS

This study designed a hybrid renewable energy system combining solar PV, wind energy, and batteries under real-time conditions to cover electrical loads in the residential sector. The study was conducted on a house located in the Samnou area, one of the southern regions of Libya. The results of the study show that the use of hybrid renewable energy systems in the residential sector is technically, economically, and environmentally feasible. This contributes to generating energy with the highest efficiency, at the lowest cost, and is more environmentally friendly in terms of reducing greenhouse gas emissions. The results showed that the proposed hybrid energy system consists of a 560-watt PV solar panel and five 500-watt wind turbines, with a total capacity of 2,500 watts. Additionally, storage batteries with a capacity of 2,750 kWh are also used. The results also showed that the proposed hybrid renewable energy system is capable of covering the required electrical load, which amounted to 51,238 kWh annually, especially during peak times, and also supplying power to the electricity grid. The economic results of the proposed system show a levelized cost of energy (LCOE) of $0.0107/kWh, which encourages investment in grid-integrated renewable energy sources. The research may convincingly promote the acceptance of renewable energy sources in all environments based on the environmental and economic benefits.

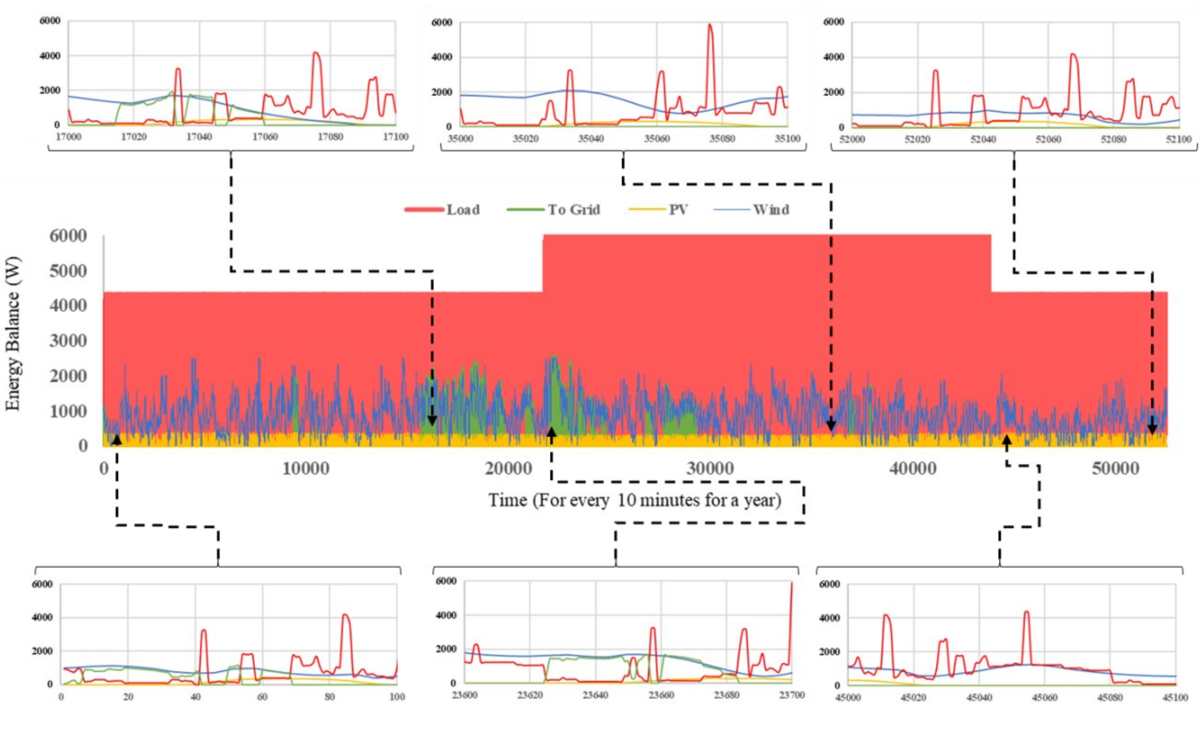

Figure 13. Energy balance of the proposed hybrid renewable energy system.

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