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Energy management strategies for on-grid renewable energy sources

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Abstract: This study proposes an advanced approach to demand-side management (DSM) within smart grids by presenting an integrated building energy management system (BEMS) driven by a fuzzy logic controller (FLC). Faced with the limitations of traditional DSM strategies, the objective is to minimize operational costs and carbon emissions of a residence equipped with a hybrid renewable energy system (HRES). The proposed BEMS dynamically selects energy sources (grid, solar, battery) based on the grid energy cost and the state of charge (SoC) of the HRES. The methodology involved implementing the system in the MATLAB/Simulink environment to validate its control logic and evaluating its technical and economic feasibility by comparing the results with those of a reference model under HOMER Pro. The results of the 48 fuzzy logic rules executed demonstrate intelligent load management, resulting in significant savings. The system reduced grid energy consumption by 80% during the day and 35% at night, prioritizing the use of solar and wind resources, followed by batteries. These findings confirm the effectiveness of BEMS in reshaping the load profile, thus contributing to grid sustainability and the optimization of energy resources.

Keywords: *Building energy management system, Demand side management, Fuzzy logic controller, Hybrid renewable energy system, Load planning, Techno-economic optimization.*

1. Introduction

The continued growth of the world's population is therefore leading to an increase in global demand for electrical energy. Conventional power grids are no longer sufficient to meet global energy demands, as required by the economic growth observed in the manufacturing and telecommunications sectors in recent years. The challenge of meeting electricity demand with available resources often leads to different problems between users and the utility, including increasing electricity rates, different time-of-use rates, a maximum demand rate, and a high average peak load ratio (PAR). Energy management is often used as a means of improving energy efficiency to meet the growing energy demand at a reduced cost through optimal energy utilization and a smart grid. Energy management techniques play an important role in energy utilization, thus positively affecting the efficiency and reliability of the power system. More generally, energy management in a power grid is broadly classified into two categories: supply-side management (SSM) and demand-side management (DSM). SSM efficiently generates and delivers reliable energy to users. On the other hand, DSM efficiently manages and reduces energy consumption by continuously monitoring electricity consumption and device scheduling through advanced communication and control infrastructure [1].

The key element of the DSM is the Demand Response program (Demand Response: DR) that encourages users to actively participate in load shedding strategies in response to electricity supply fluctuations or dynamic synchronization of electricity prices through supply and demand balancing for improved system reliability. Demand response is generally defined as changes in customers' electricity consumption from their normal consumption patterns in response to changes in the price of electricity

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over time or incentive payments designed to incentivize lower electricity consumption during peak hours or when system reliability is threatened [2]. With demand response, consumers would benefit from reducing tariff costs by making minimal wait times to operate high-demand loads during off-peak periods or by choosing to pay a higher price during peak periods [3].

In the Togolese energy context, Demand-Side Management (DSM) is an essential strategy for optimizing consumption and ensuring the reliability of the electricity supply, beyond consumption tariffs alone. Rather than limiting itself to differentiated tariffs (TOU), the main objective is to mitigate the impacts of supply constraints and recurring outages of the national grid.

In this context, this Building Energy Management System (BEMS) integrates a dynamic Demand Side Management (DSM) approach. It uses a fuzzy logic controller to adjust consumption in real time according to the state of the electricity network and the availability of local resources (solar PV, wind, battery). This device not only shifts loads according to costs but also ensures intelligent prioritization of loads, maintaining the power supply of critical (base) loads and shedding heavy loads during periods of energy deficit. This method not only reduces dependence on the network and energy costs but also guarantees continuity of service for essential building activities, demonstrating an adaptation of DSM to the energy specificities of Lomé.

Conventional energy management approaches for demand response rely mostly on load shifting and load shedding during peak periods [4]. However, technological advances and the decentralization of energy production have introduced a more efficient alternative: the integration of distributed generation (DG) sources to supplement the power grid supply. This approach reduces energy costs and improves system reliability without imposing operational delays on consumers [5, 6]. Shifting part of the loads to alternative sources such as solar photovoltaic, wind, and battery storage thus becomes a viable solution, especially during periods of grid supply constraints.

Moreover, recent analyses demonstrate that the levelized cost of energy (LCOE) for photovoltaic systems has become more advantageous than conventional grid energy for commercial and industrial applications, justifying the extension of this hybridization to residential applications [3, 7-11]. A study by Benson and Magee [12] has also established the superiority of solar photovoltaic in terms of long-term cost reduction.

However, the intermittent nature and high unpredictability of renewable resources and load demand require smart building energy management systems (BEMS) [13-15]. Existing literature reveals that many BEMS often focus on partial aspects, such as microgrid topologies or optimization algorithms, without integrating a multi-objective approach that considers the nonlinear characteristics of PD sources and detailed parameters of energy storage, such as the state of charge (SoC) of batteries [16, 17].

To overcome these limitations, this work proposes a fuzzy logic control (FLC) BEMS, specifically designed for demand-side management. This system is developed for a PV/wind/battery hybrid application, and its originality lies in its ability to perform intelligent selection of energy sources. Based on the grid energy cost and the state of charge (SoC) of the hybrid system, the BEMS ensures optimal management of classified loads. This methodology, which prioritizes the SoC of the battery to supply critical loads, allows for minimizing energy costs without degrading operational performance.

The unique contributions of this study are summarized as follows:

a) Introducing an innovative FLC BEMS that uses real-time data on network costs and hybrid system SoC for efficient demand management.
b) Implemented a system that dynamically balances power between the hybrid system and the grid, improving overall reliability.
c) The use of load classification that allows reducing the installation costs of the decentralized production system compared to conventional approaches.
d) The proposed scheme overcomes the problems related to data sparsity, a major challenge in developing efficient DSM systems.

The remainder of this paper is structured as follows. The Materials and Methods section details the proposed energy management scheme, including the hybrid source modeling and load classification. It also describes the implementation methodology in MATLAB/Simulink and the associated techno-economic analysis. The Results and Discussion section presents the findings from the daily energy mix management and provides a cost comparison with the HOMER Pro reference model. Finally, the Conclusion summarizes the effectiveness of the proposed system in terms of energy savings, grid load smoothing, and system reliability improvement.

2. Materials and Methods

2.1. System Description

The studied architecture is a grid-connected residential system with a hybrid renewable energy system (HRES), a home load, and an energy storage system (ESS), as shown in Fig. 1. The HRES includes a 6 kW photovoltaic (PV) generator and a 6 kW small wind turbine (WT). The home AC load comprises typical electrical loads (e.g., electrical appliances, lighting, etc.) with a nominal power of 7 kW. The ESS involves a lead-acid battery bank with a nominal capacity of 72 kWh [18].

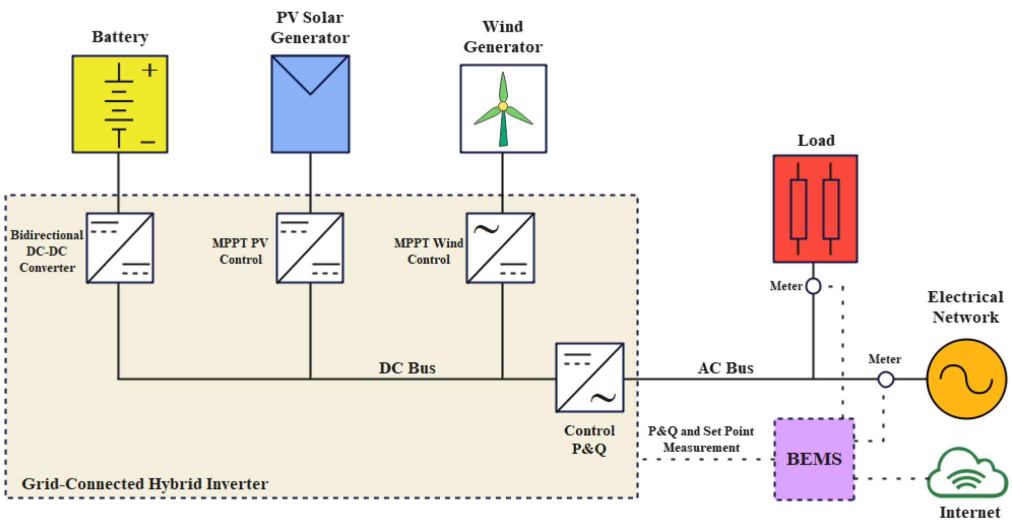

Figure 1.
Architectural design of a grid-connected residential microgrid.

From Figure 1, on the supply side, P_{PV} and P_{WT} represent the photovoltaic and wind power generation, respectively; P_{Bat} represents the power delivered or absorbed by the battery; and P_{Grid} represents the power delivered or injected by or to the grid. On the demand side, P_{Load} represents the charging power demand required by the electrical loads. Moreover, the power variables shown in Fig. 1 are considered positive when the power flows along the direction of the corresponding arrows. Therefore, P_{PV}, P_{WT}, and P_{Load} are always positive, while P_{Bat} and P_{Grid} are considered positive when the battery and the electrical grid inject energy into the HRES. Conversely, P_{Bat} and P_{Grid} are considered negative when they absorb energy from the microgrid.

The hybrid power converter used in this work includes a wind turbine power conversion module, a battery charger, and a photovoltaic power conversion module, as well as a bidirectional inverter-rectifier module to control the power exchanged with the grid. The battery charger has internal active power control, while the power inverter includes active and reactive power control within it. As shown in Figure 1, the energy management strategy simultaneously provides the reference values of the active power for both converters (i.e., the battery charger and the inverter) and the reactive power of the inverter. In this regard, since reactive power has no associated energy, the bidirectional inverter-rectifier can provide all the reactive power of the load as long as the apparent power does not exceed its reference value. To achieve this, the energy management strategy measures the reactive power of the load and provides it as a reference value to the inverter-rectifier.

According to the configuration illustrated in Fig. 1, the power exchanged with the network is expressed as follows:

$$P_{Grid} = P_{LGen} - P_{Bat} \tag{1}$$

Where P_{LGen} is the net power HRES, which is defined as the difference between the load power demand, P_{Load} and the renewable energy generation, P_{Res}, as follows:

$$P_{LGen} = P_{Load} - P_{Gen} \tag{2}$$

$$P_{Gen} = P_{Pv} + P_{Wt} \tag{3}$$

Being $P_{Gen,}$ the production of renewable energy (PV + wind) from the HRES.

It should be noted that the studied case assumes that both PV and WT operate at maximum power point (MPP), and the load power consumption is controllable (i.e., P_{Load}, P_{Gen}, and P_{LGen} can be controlled). The grid power profile, P_{Grid}, will be controlled by a bidirectional inverter-rectifier, while the battery charger-generator, if capable, will control the resulting battery power, P_{Bat}, according to (1) [19].

2.2. Proposed Energy Management System

Conventional building management relies on the electrical grid for energy supply, an approach vulnerable to outages and fluctuating energy costs, particularly high during peak periods. To overcome these challenges, this work proposes a Building Energy Management System (BEMS) that integrates a Hybrid Renewable Energy System (HRES) comprising photovoltaic, wind, and battery storage sources. This system aims to optimize energy supply while ensuring reliability and reducing costs.

As shown in Figure 1, the BEMS plays a central role in dynamically selecting the most appropriate energy source and controlling the loads. To achieve this, it uses a fuzzy logic controller (FLC), which is at the heart of the methodology and has been evaluated in the MATLAB/Simulink environment. The FLC makes real-time decisions by monitoring key parameters such as the battery state of charge (SoC) and load demand to ensure a continuous power supply without compromising user comfort.

The system prioritizes the use of HRES, particularly for classified loads. Loads are categorized into base loads and heavy loads, and their supply is managed by the FLC based on time, energy cost, and the battery SoC. Thus, the grid is used mainly when HRES production is insufficient, and in a strategic manner: it supplies most loads during off-peak hours but is limited to base loads during peak periods to minimize costs. When the battery SoC reaches a predefined threshold, the BEMS increases the use of heavy loads on HRES, thereby optimizing self-consumption.

The detailed methodology, illustrated in Figure 2, began with the collection of essential data: meteorological data (solar irradiance, wind speed), network tariffs, and technical specifications of the HRES components (batteries, PV, wind turbines). In parallel, an analysis of the building loads was carried out to enable an accurate classification, necessary for the proper functioning of the FLC.

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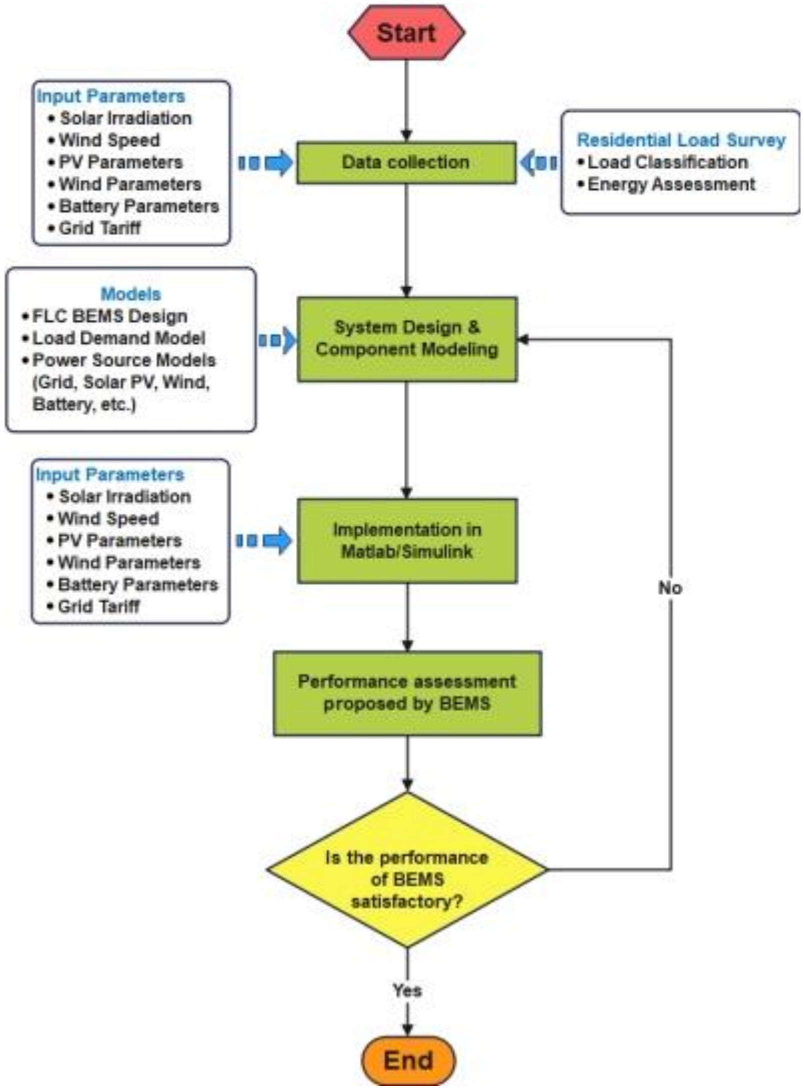

Figure 2.
Proposed BEMS FLC flowchart.

After collecting all the necessary data and component parameters, the system design and component modeling were carried out. In addition, the proposed energy management system was designed, and the load energy demand in the system, as well as the energy sources, were modeled. The implementation of the modeled system was carried out in MATLAB/Simulink, and then the evaluation of the constructed system was carried out using HOMER. In addition, at the evaluation stage, a techno-economic evaluation was also conducted.

2.3. Proposed Energy Management System

In this study, the building's electrical loads were classified according to their nominal power and operating hours to optimize their management. This classification is a fundamental step in enabling the system to manage the different energy sources efficiently and minimize costs.

To do this, we have defined two categories of charges:

- Basic Appliance (A_B): These loads correspond to devices with a nominal power of less than 300

W, such as televisions, lighting, home cinema systems, and laptops. Their operation is considered essential for everyday use.

- Heavy Appliance (A_H): This category includes appliances with a rated power greater than 300 W, such as air conditioners, pumps, ovens, and electric kettles. These devices have higher energy consumption and are given priority in energy management.

A field survey and manual observations were conducted during the summer period to identify the number of appliances in each category and determine their nominal power, as detailed in Table 1. This period was chosen due to its high energy consumption, particularly because of the intensive use of heavy appliances such as air conditioning. This classification allowed for a better understanding of the building's load profile and the design of an appropriate energy management strategy.

Table 1.
Classification of devices.

Basic devices	**Nominal power (W)**	**Quantity of Devices**	**Heavy appliances**	**Nominal power (W)**	**Quantity of Devices**
Television	85	3	Washing machine	500	2
Decoder	25	2	Electric kettle	1200	1
Home Cinema	95	1	Air conditioner	1500	3
Light bulbs	15	10	Freezer	500	2
Fan	100	4	Microwave	750	1
Laptop	50	3	Oven	2250	1

2.4. Modeling of System Components

The components of the energy management system are modeled in this section. The system units are essentially classified as loads and energy sources, which are briefly introduced in the following subsections:

2.4.1. Charging Energy Demand

Load is an important part of the energy management system; loads are classified into base loads (A_B) and heavy loads (A_H) in such a way that BEMS will be able to distinguish the types of loads to be operated with the particular energy source in a given period. Assuming a set of electrical appliances A = [a_1, a_2, a_3, …, a_n] such that a_1, a_2, a_3, …, a_n represents each appliance over the time horizon $t \in T$ = [1, 2, 3, …, 24]. a_n = [$A_B \cup A_H$] represents a set of devices, where A_B corresponds to basic devices and A_H to heavy devices.

The energy consumption by (A_B) is represented as:

$$E_{A_B}^{T} = \sum_{t=1}^{T}\left(\sum_{j=1}^{A_B} P_{A_{B\,j}} \times S(t)\right) \tag{4}$$

Furthermore, the total energy cost per day for the (A_B) is given by:

$$C_{A_B} = \sum_{t=1}^{T}\left(\sum_{j=1}^{A_B} P_{A_{B\,j}} \times S(t) \times C(t)\right) \tag{5}$$

Where P_{Ab} and P_{Al} are the nominal powers of the base and heavy loads, respectively, S(t) is the operating state of the devices, and C(t) is the dynamic energy tariff. Similarly, the energy consumption of a heavy load (A_H) is represented by:

$$E_{A_H}^{T} = \sum_{t=1}^{T}\left(\sum_{j=1}^{A_H} P_{A_{H\,j}} \times S(t)\right) \tag{6}$$

The total cost for (A_H) in one day is calculated from:

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$$C_{A_H} = \sum_{t=1}^{T} \left(\sum_{j=1}^{A_H} P_{A_{H_j}} \times S(t) \times C(t) \right) \quad (7)$$

If the total energy consumed by the devices in the total time interval is E_T, then

$$E_T = E_{A_B}^{T} + E_{A_H}^{T} \quad (8)$$

Similarly, the total cost C_T per day of the devices is calculated by:

$$C_T = C_{A_B} + C_{A_H} \quad (9)$$

2.4.2. Energy Sources

In this section, we present the model of the different energy sources used in our study, namely the conventional electricity grid and the Hybrid Renewable Energy System (HRES) composed of a photovoltaic system, a wind system, and a battery storage system. The HRES is considered the main energy source, promoting better energy efficiency and greater autonomy.

To model these sources, we proceeded as follows:

- Electricity grid: The hourly energy demand from the grid was modeled based on the building's daily demand, with a consumption range set between 1 kWh and 7 kWh. The total daily energy consumed by the grid was calculated using Equation (10) [20]:

$$E_{grid} = \sum_{i=1}^{24} E_i(t) \quad (10)$$

To estimate the cost of energy used, the hourly grid energy is multiplied by the dynamic energy pricing from off-peak to peak periods, and the total cost is calculated as follows:

$$C_{grid} = \sum_{i=1}^{24} E_i(t) \times R_p(t) \quad (11)$$

Where: Rp(t) is the dynamic real-time energy price of the network over a given period, and Ei(t) is the hourly energy used.

- Photovoltaic and wind power systems: The energy production of these sources was modeled taking into account local meteorological data, such as solar irradiation and wind speed. The calculation of the generated power incorporated the technical specifications of each component (panel surface area, efficiency, etc.).

The photovoltaic system is another energy source incorporated as part of the hybrid source to power the loads. To install a solar photovoltaic system, certain factors must be considered for efficient operation, including the energy produced by the photovoltaic cells, the cost of the photovoltaic cells, and the sizing of the solar photovoltaic system. The output energy generated by a solar photovoltaic system is given by Hocaoğlu et al. [21]:

$$E_{pv} = A_{pv} \times \rho \times I_{rr}(t) \times P_F \quad (12)$$

Where: A_{pv} is the surface area of the photovoltaic module [m^2], ρ is the overall efficiency or yield of the PV module taken, I_{rr} is the solar irradiation at time t [kWh/m^2], and P_F is the fill factor taken at 0.9.

The cost C_{Pv} used is calculated as follows:

$$C_{Pv} = M_{Pv} \times S_{Pv} \quad (13)$$

Where M_{PV} is the maintenance cost of each unit area of solar power generation equipment per day; S_{PV} is the total area of solar power generation equipment. Note that since wind and photovoltaic power

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generation do not require additional energy, only their maintenance costs are considered.

The wind system is another energy source incorporated within the hybrid source framework to supply the loads. With a global approach, the electrical energy generated by the wind turbine can be formulated proportionally to the swept area of its rotor (A_{wt}) by equation (14) [22]:

$$E_{Wt} = \frac{1}{2}\eta_t \times \rho \times A_{Wt} \times V^3 \times \xi(t) \quad (14)$$

Where η_t is the overall efficiency assumed to be equal to 30% for three-bladed horizontal-axis wind turbines; ρ is the density of the air available in the atmosphere [kg/m³]; A_{wt} is the surface swept by the rotor of the wind turbine [m²]; V is the wind speed [m/s]; ξ(t) is the operating time of the wind turbine [23].

The cost C_{Wt} in equation (15) is calculated as follows:

$$C_{Wt} = M_{Wt} \times N \quad (15)$$

Where M_{Wt} is the maintenance cost of one wind generator per day, N is the total number of wind generators.

The constraint for calculating the load of all end users for their generated renewable energy C_{Gen} is as follows:

$$C_{Gen} = C_{Pv} + C_{Wt} \quad (16)$$

- Battery storage system: The battery bank was modeled to store excess energy from the HRES and to supply power to the loads when production is insufficient. The state of charge and discharge equations were used to monitor the battery capacity, ensuring its durability and efficiency. The battery capacity (C_b) is represented as follows:

$$C_b = \frac{E_t \times D_a}{I_b \times DoD \times V_b} \quad (17)$$

In order to improve the battery life, the states of charge and discharge were adequately considered. The battery states of charge and discharge ($E_b(t)$) were obtained from equations (18) and (19), respectively [24]:

$$E_b(t) = E_b(t-1) \times (1 - DoD) + \left[E_R(t) - \frac{E_D(t)}{\eta^{inv}}\right] \quad (18)$$

$$E_b(t) = E_b(t-1) \times (1 - DoD) + \left[\frac{E_D(t)}{\eta^{inv}} - E_R(t)\right] \quad (19)$$

Where: D_a is the autonomy in days, DoD is the depth of discharge, l_b is the battery loss, V_b is the battery voltage, $E_D(t)$ is the energy demand, η^B and η^{inv} are the battery and inverter efficiencies, respectively.

2.4.3. Energy Management Diagram

The fuzzy logic-based energy management controller aims to intelligently control the engagement of energy sources and ensure smooth operation between energy sources and load to minimize operating costs. The control strategy uses grid cost, solar irradiation level, battery parameters, and other constants to optimize energy source matching with load demand at specific times of the day. Grid energy is readily available to operate the base load and heavy load throughout the day. However, once the battery reaches a certain charge threshold, heavy loads are protected from the grid and supplied with solar PV, wind, or battery energy, especially during peak hours. The selection of energy sources to operate the loads is performed by a fuzzy logic charge controller, as illustrated in the diagram of Figure

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3, where $E_{Grid}(t)$, $E_{Pv}(t)$, $E_{Wt}(t)$, and $E_{Bat}(t)$ represent the energy from the grid, solar PV, wind, and battery, respectively. The fuzzy logic energy management system aims to achieve the objectives of satisfying load demand at specific times, managing energy sources based on energy costs, and maintaining the battery state of charge within the defined thresholds.

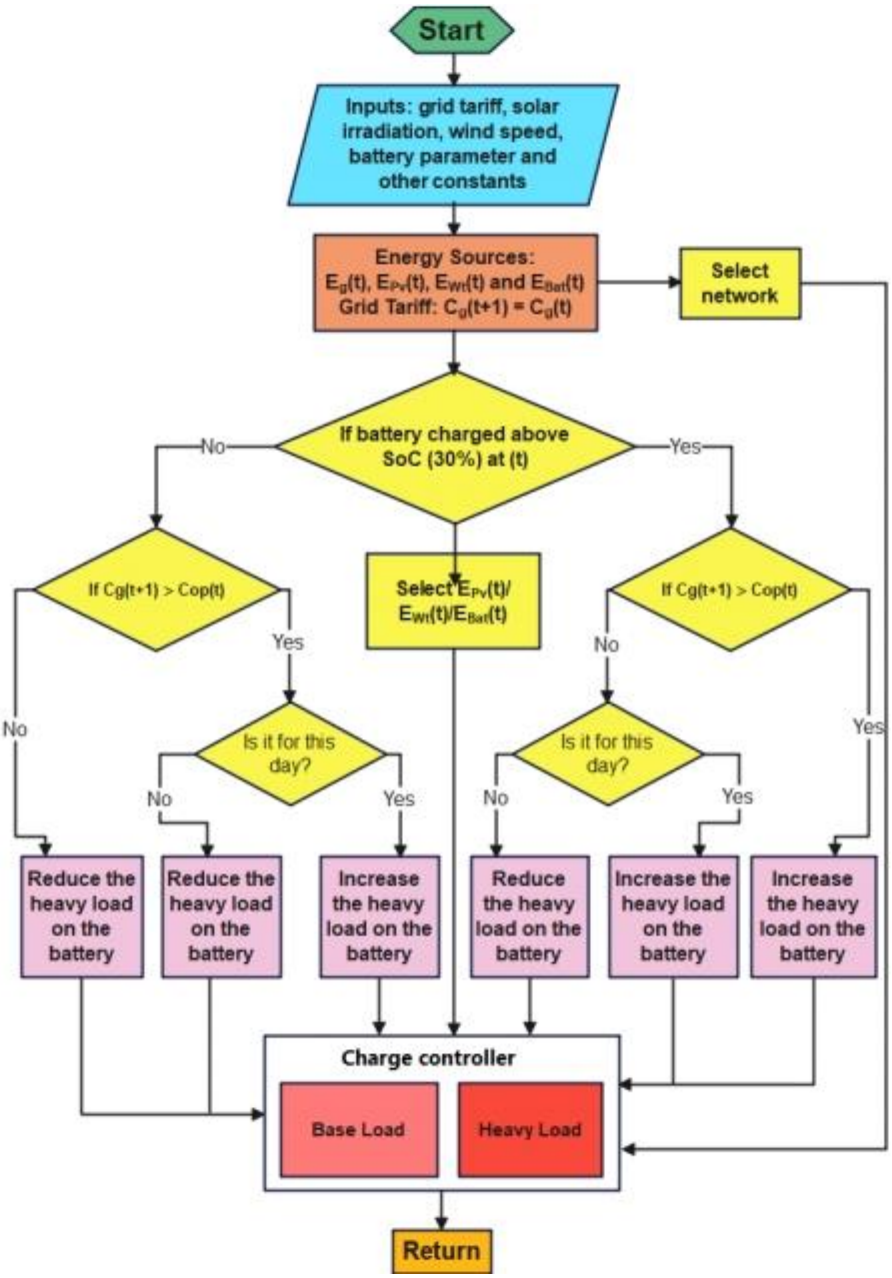

Figure 3.
Energy management diagram.

The fuzzy logic model was used to implement the energy management operation to obtain the best hybrid energy mix at a reduced cost. The fuzzy logic system intelligently makes control decisions using linguistic variables at the inference engine level based on the provided ensemble rules.

The implementation steps start with the input data, which is fuzzy into the membership function, then the inference engine with the rules, and finally the defuzzification step [25, 26]. The fuzzy logic operation uses four input parameters, including time of day, daily dynamic energy cost, PV/wind/battery status, and grid power as input for decision-making. The minimum and maximum range of these sample input data is fuzzy by mapping the sharp values into fuzzy sets of membership functions (MFs). The triangular membership function was used due to its high level of precision and good computational accuracy, and all the input data used have two membership functions, as presented in the table.

Table 2.
Fuzzy input data sets.

Input data	Membership number	Blurry set	Value range
Time of day (hours)	1	Day	6:00 a.m. – 6:00 p.m.
	2	Night	6:00 p.m. – 6:00 a.m.
Cost of network energy (Fcfa)	1	Off-peak	0 – 120
	2	Culminate	120 – 150
Battery SoC status (%)	1	Low battery SoC	0 – 35
	2	High-capacity battery SoC	35 – 100
PV/wind system power (kW)	1	Weak	0 – 1
	2	High	1 – 10
Network power (kW)	1	Disabled	0 – 1
	2	Activated	0 – 7

The engine Fuzzy Logic inference system interacts between inputs and output using IF-THEN statement rules, as the detail of rules is shown in Table 3. The accuracy of the system depends on the number of prepared rules built for the energy management system, considering different operating conditions based on the time of day (day and night), the state of charge of solar PV/battery (low, high), the type of load demand (base load, heavy), and grid energy cost (peak and off-peak).

Table 3.
Base of 48 fuzzy rules for load/power source management.

Time of Day	Load Type	Grid Availability	Energy Tariff	Renewable Power Level	Battery State of Charge (SoC)		Fuzzy Output
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	High	High	High	1	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	High	Low	2	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	High	Low	High	3	Connection to Battery
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	4	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	High	High	5	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	6	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	Low	High	7	Connection to Grid
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	8	Connection to Grid
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	No	High	High	High	9	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	No	Low	Low	Low	10	Connection to PV/Wind
Daytime: 6:00	Fixed Loads	No	Low	Low	High	11	Connection to

a.m. – 6:00 p.m.	(Low Power)						Battery
Daytime: 6:00 a.m. – 6:00 p.m.	Fixed Loads (Low Power)	No	Low	Low	Low	12	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	High	High	High	13	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	14	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	High	15	Connection to Battery
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	16	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	High	17	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	18	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	High	19	Connection to Grid
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	20	Connection to Grid
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	High	High	High	21	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	22	Connection to PV/Wind
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	High	23	Connection to Battery
Daytime: 6:00 a.m. – 6:00 p.m.	Shiftable loads (High power)	No	Low	Low	Low	24	Connection to PV/Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	High	High	High	25	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	High	Low	Low	26	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	High	27	Connection to Battery
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	28	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	High	29	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	30	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	High	31	Connection to Grid
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	Yes	Low	Low	Low	32	Connection to Grid
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	No	High	Low	High	33	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	No	Low	Low	Low	34	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	No	Low	Low	High	35	Connection to Battery
Nighttime: 6:00 p.m. – 6:00 a.m.	Fixed Loads (Low Power)	No	Low	Low	Low	36	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	High	Low	High	37	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	38	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	High	39	Connection to Battery
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	40	Connection to Wind

Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	High	41	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	42	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	High	43	Connection to Grid
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	44	Connection to Grid
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	High	Low	High	45	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	46	Connection to Wind
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	High	47	Connection to Battery
Nighttime: 6:00 p.m. – 6:00 a.m.	Shiftable loads (High power)	No	Low	Low	Low	48	Connection to Wind

The last step of the fuzzy logic system is the defuzzification step, where all the processed fuzzy data are converted back into values and visualized in the output graph displayed by the system as the energy mix consumed from different sources with different load types as a function of time and energy cost. The details of some commonly used defuzzification methods, such as mean of maximum (MOM), centroid of area (COA), bisector of area (BOA), least of maximum (SOM), and greatest of maximum (LOM), are presented in [27]. Centroid of area (COA) is used in this work due to its simplicity, which takes the output of the distribution found in the previous step and finds the center of the area to get an accurate number.

2.5. Implementation of an Energy Management System for a Building in Lomé

In the context of the energy transition and the optimization of electricity consumption in university infrastructures, the implementation of an energy management system (Building Energy Management System – BEMS) constitutes a strategic solution. This system aims to coordinate and optimize the local production of renewable energy, storage, as well as distribution to the various building loads, taking into account the climatic and socio-economic specificities of Lomé.

The BEMS, illustrated in Figure 4, was designed as a hybrid system, integrating energy sources (photovoltaic panels, battery storage system, and the national electricity grid) and an intelligent controller based on fuzzy logic. The objective is to optimally manage the distribution of energy to the campus electrical loads, classified into two categories: base loads (<300 W) and heavy loads (>300 W). The system was sized based on actual consumption data collected over a representative week. The photovoltaic production was sized using NASA solar irradiance data for Lomé. The battery storage, with a nominal capacity of 40 kWh, was sized to ensure an autonomy of at least 24 hours for heavy loads, with a minimum state of charge (SoC) of 30%.

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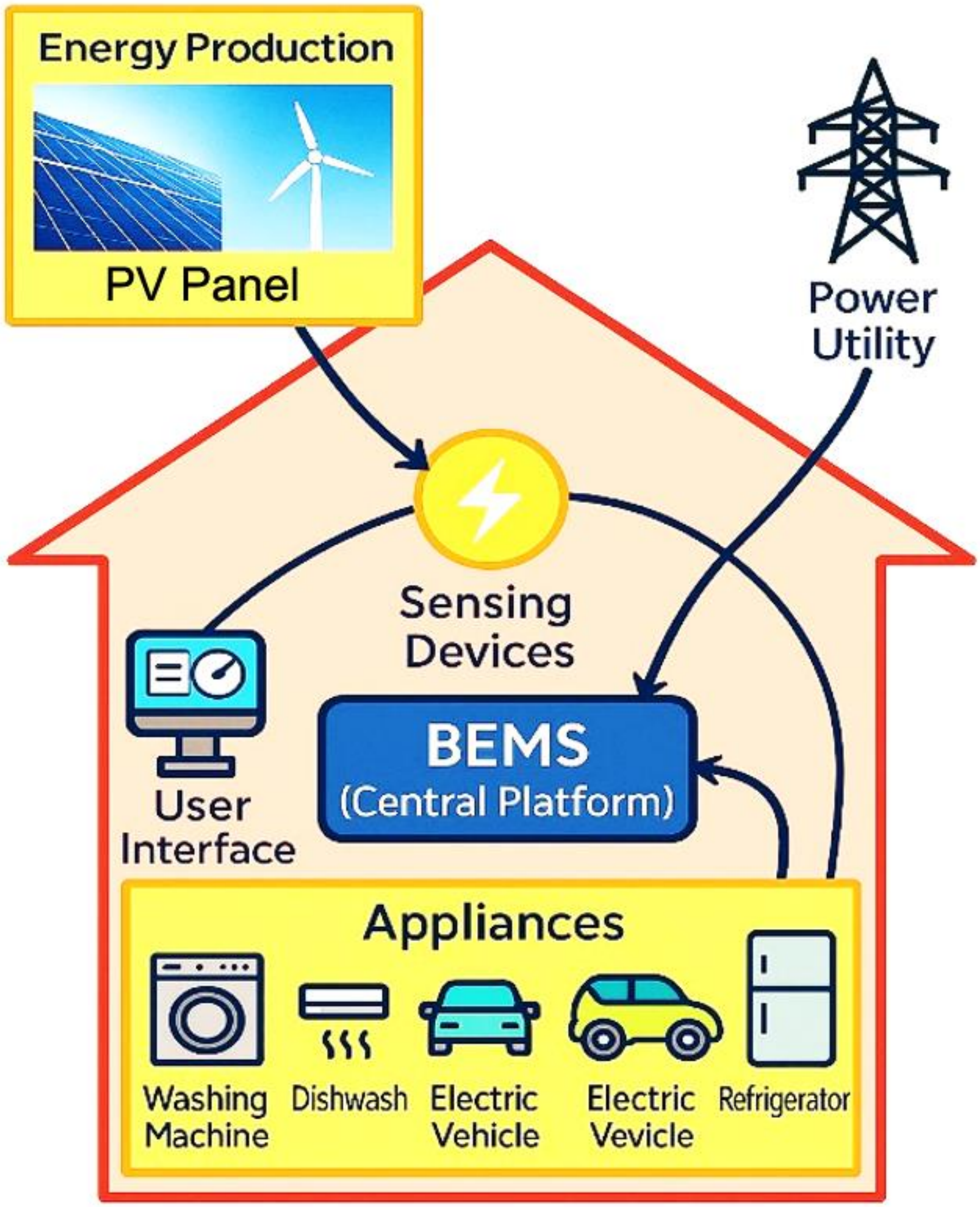

Figure 4.
Architecture of the energy management system (HEMS), integrating renewable generation (solar and wind), the electrical grid, a central control platform, and optimized priority loads.

In order to validate the management logic and evaluate the system performance under varied operational conditions, a dynamic model was developed in MATLAB/Simulink [28]. This model allowed for the simulation of the behavior of the BEMS by integrating hourly production and consumption profiles, local climatic data (solar irradiation), and technical specifications of the components. The simulation tested the robustness of the fuzzy logic-based controller against fluctuations in sunlight and variations in building occupancy, thus ensuring the reliability of the solution.

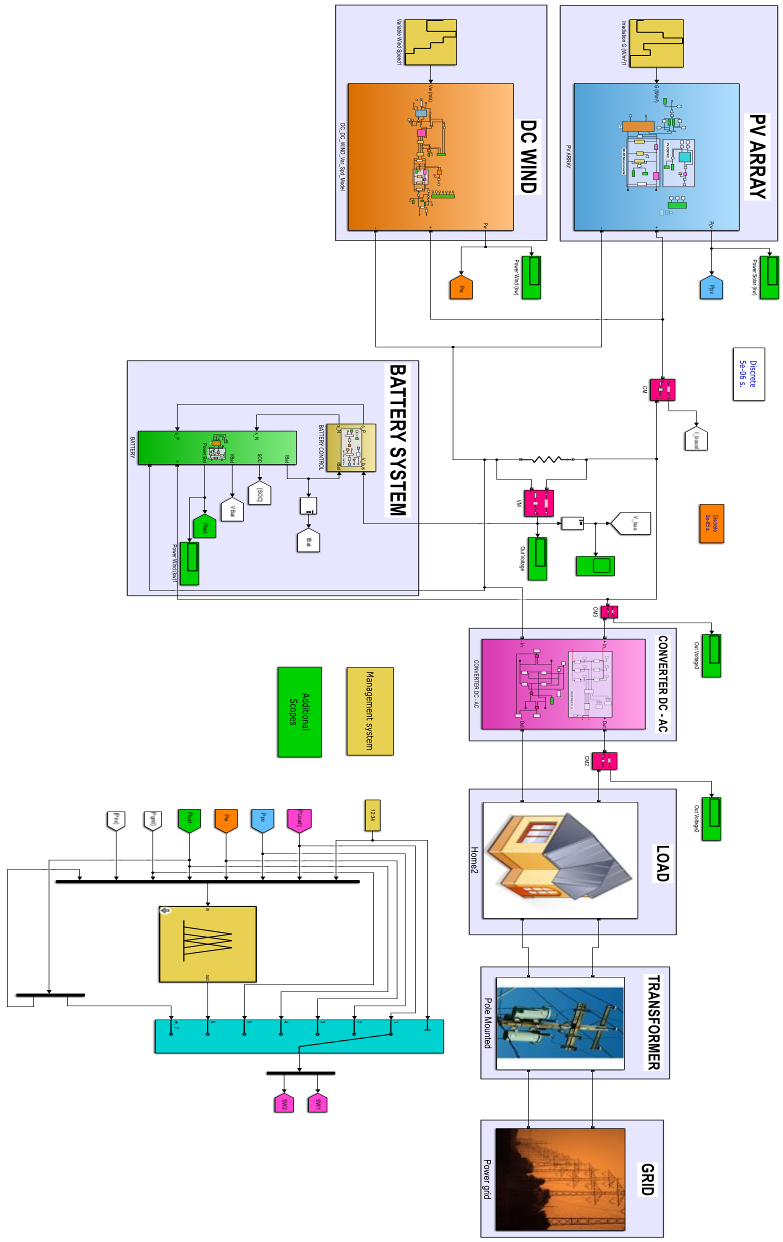

Figure 5.
Simulink energy management model.

In parallel, HOMER Pro software was used for a technical and economic analysis of the PV/battery hybrid system. This model validated the component sizing and compared possible configurations based on key performance criteria. The indicators evaluated included Total Net Value (TNV), Levelized Cost of Energy (LCOE), renewable fraction, and CO_2 emissions. This analysis quantified the project's benefits in terms of reduced energy costs, improved power supply reliability, and reduced carbon footprint, thus providing a robust framework for decision-making.

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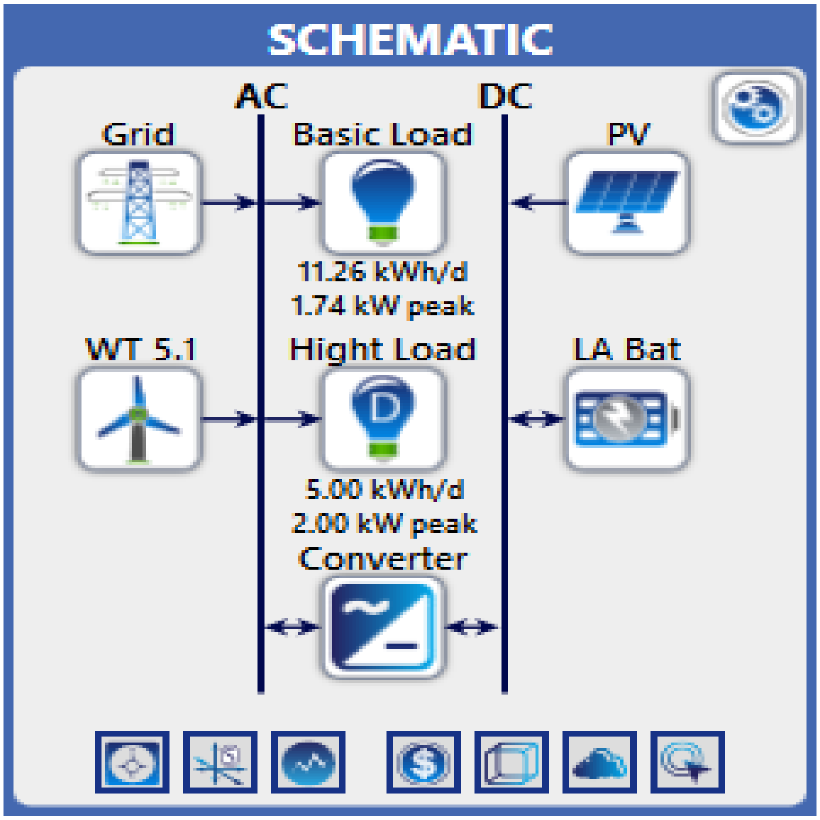

Figure 6.
Homer model of a grid-connected solar PV/battery hybrid system.

The integration of architectural modeling, dynamic simulation using MATLAB/Simulink, and technical-economic optimization using HOMER established a rigorous methodology. This methodological framework not only validated the technical feasibility of the energy management system (BEMS) but also quantified the potential benefits. The results of this approach demonstrate its ability to reduce energy costs, improve power supply reliability, and promote the integration of renewable energy on Lomé's university campuses.

2.6. Techno-Economic Analysis

Techno-economic analysis plays an important role in determining the lifetime cost of energy sources. It allows the cost, emissions, and performance of an energy source to be assessed before it is put into service [21].

Among the tools available for techno-economic analysis is the levelized cost of energy (LCOE), which is a measure of the lifetime cost of an energy source that allows for consistent comparison with other energy production methods. LCOE is calculated from the total cost of energy production divided by the total energy produced over its useful life. LCOE is represented by the relationship (20) [29]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (20)$$

Where M_t is the capital expenditure in year t, M_t is the operating and maintenance expenditure in year t, F_t is the fuel expenditure in year t, and tr is the electrical energy produced in year t. r is the discount rate, and n is the expected lifetime of the power system or plant.

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The life cycle cost (LCC) of a hybrid electric system is generally evaluated using the net present value (NPV) method. The total net present value (TNPV) of a system is the sum of the investment cost (IC), recovery cost (SC), replacement cost (RC), and operation and maintenance (OM) costs as expressed in (21) [30].

$$TNPV_{sys} = \sum_{i=1}^{n} (IC_i + OM_i + RC_i - SC_i) \quad (21)$$

To minimize the total energy cost, the objective cost function is based on the net present value presented in equation (22), and the total TNPV values should be minimal for the total usage period of all source energy.

$$minTNPV(E_{grid}, E_{Pv}, E_{Wt}, E_B) = NPV_{grid} + NPV_{Pv} + NPV_{Wt} + NPV_B \quad (22)$$

The network LCOE is calculated based on the dynamic day-to-day pricing for peak and off-peak periods to provide an estimated network cost at a specific time of day, as shown in relation (23):

$$LCOE = \frac{[C_1 \times P_h \times E_1] + [C_2 \times O_h \times E_2] \times d \times y}{[P_h \times E_1 + O_h \times E_2] \times d \times y} \quad (23)$$

Where d is the number of days in a year, C_1 and C_2 are the peak and off-peak costs of dynamic pricing, E_1 and E_2 are the energy used during peak and off-peak periods, P_h and O_h are the peak and off-peak periods of a day.

The LCOE of the solar photovoltaic unit is calculated to determine the life cycle cost for a specified period of use, and this is represented by:

$$LCOE_{pv} = \frac{C_{Pv}}{E_t \times d \times y} \quad (24)$$

Where C_{Pv} is the total cost of solar panels estimated by multiplying the number of solar PV panels by the cost of each solar panel, and E_t is the average energy consumed per day.

The LCOE of the wind unit is calculated to determine the life cycle cost for a specified period of use, as represented by equation (25):

$$LCOE_{Wt} = \frac{C_{Wt}}{E_t \times d \times y} \quad (25)$$

Where C_{Wt} is the total cost of wind turbines, and Et is the average energy consumed per day.

The battery LCOE is the cost of the battery's lifetime over years and is represented as follows:

$$LCOE_B = \frac{C_B}{E_t \times d \times y} \quad (26)$$

Where C_B is the total battery cost estimated by multiplying the number of batteries used by the cost of each battery and the number of times the batteries are replaced during the life of the project.

A solar photovoltaic system includes other installation components such as charge controllers, inverters, cables, and electrical accessories. In most cases, the cost of these additional installation components is usually estimated at 10% of the total cost of the main component, and the Levelized Cost of Energy (LCOE) is estimated as follows [26].

$$LCOE_i = \frac{10\%(C_{Wt} + C_{Wt} + C_B)}{E_t \times d \times y} \quad (27)$$

3. Results and Discussion

This paper analyzes the performance of a grid-connected hybrid renewable energy system (HRES) by integrating a smart energy management controller based on fuzzy logic, aiming to optimize residential energy consumption without compromising user comfort. The current practice of designing energy management systems at the DSM generally focuses on shielding or shifting the load at the expense of user comfort. However, a recent analysis of RES shows that the cost is flattened compared to the cost of grid energy. This competitive advantage was explored in this study to ensure that the load operating pattern is not distorted, as desired in residential buildings. The performance of an energy management system based on fuzzy logic rules was studied for a defined period in the MATLAB/Simulink environment.

The performance was evaluated using a typical load demand of a residential building with an average daily energy consumption of 15 kWh per day. The energy management system manages the hybrid energy system comprising the grid system, PV/wind/battery energy sources, and loads classified into base load and heavy load types. In the system operation, the RESHy is the primary source to operate the base load and heavy loads, with the grid being readily available to ensure system continuity in case of RESHy unavailability to operate the base load and heavy loads throughout the day. However, the heavy loads are protected from the grid and powered by the RESHy through the energy management control action, especially during peak sunshine hours, favorable wind hours, and when the battery SoC level is above the minimum threshold of 30%. This state is maintained until the battery state of charge is reduced to less than 30% or when the cost of grid energy decreases during the off-peak period. The daily energy demand from solar PV/battery has been set at 40 kWh, which is sufficient to operate all heavy loads and represents 60% of the daily energy required to operate all loads.

In order to ensure that the hybrid system (HRES) can efficiently meet the energy demand of heavy loads during periods of high demand, an analysis was carried out to assess the combined production capacity of the photovoltaic modules and the wind turbine to maintain a battery charge level above the critical threshold of 30% (State of Charge, SoC).

Local climatic conditions at the study site located in Lomé (6°7.8'N, 1°13.2'E, Togo) were incorporated into the simulation model using hourly solar irradiance, ambient temperature, and wind speed data obtained from the NASA database, as shown in Figure 7.

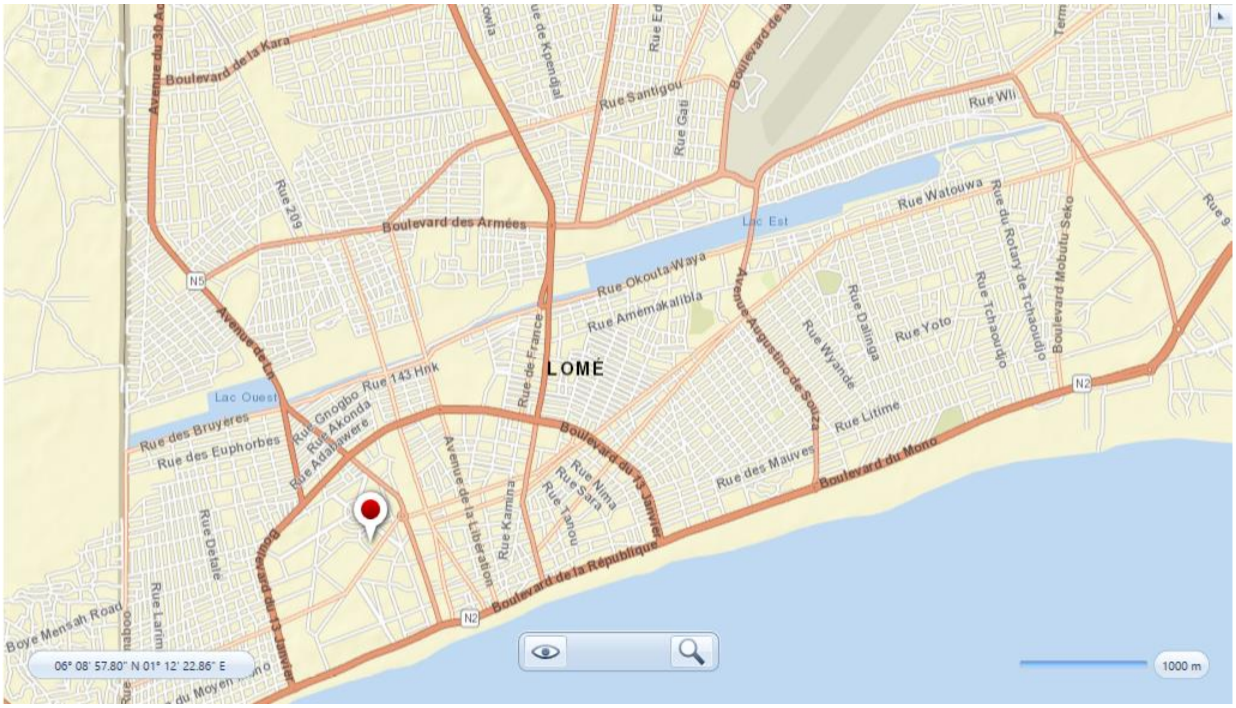

Figure 7.
Geographical site of the building study.

These data were introduced into the MATLAB/Simulink environment to evaluate the hourly energy available for battery charging and powering the loads.

The simulated results, illustrated in Figure 8, indicate that the combined production of the photovoltaic system and the wind turbine is sufficient to meet the daily energy demand of heavy loads. The battery State of Charge (SoC) remains above the minimum required threshold of 30% throughout the analyzed period, with an average minimum observed value of 40%. These results confirm the ability of the grid-connected Hybrid Renewable Energy System (HRES) to ensure a reliable power supply to critical loads, even in the occasional absence of the grid resource, thanks to optimized energy management based on available renewable resources.

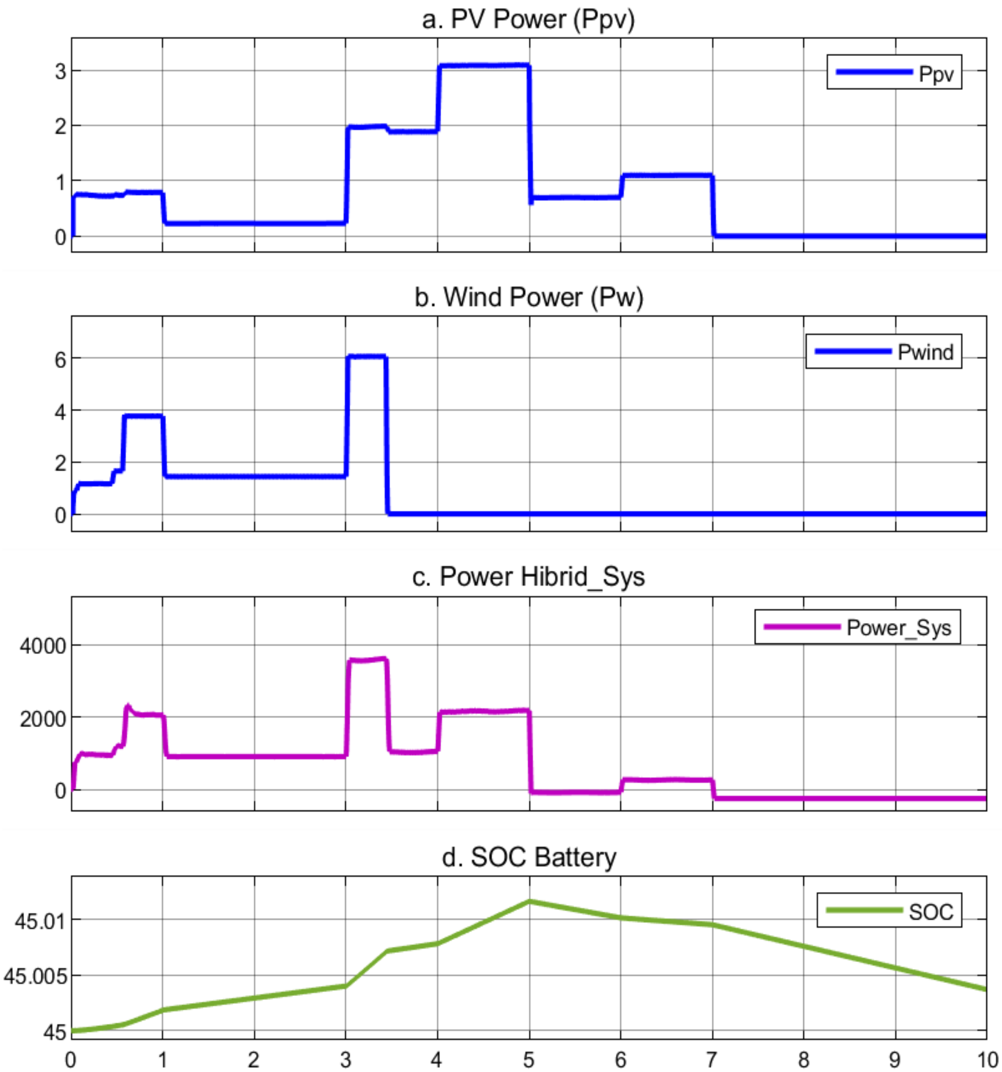

Figure 8.
Power generated by the grid-connected hybrid system.

A weekly simulation was conducted to evaluate the performance of the smart controller-based energy management system (BEMS – Building Energy Management System) in a hybrid grid-connected environment. This analysis covered the first four days of the week, Monday to Thursday, considered representative of working days.

- The results are illustrated in Figure 8(a–d), which shows the hourly distribution of the building's total energy demand over 24 hours, distinguishing between base loads and heavy loads. Three curves are shown:
- The dotted curve (marked with a star) corresponds to the energy coverage provided by all hybrid sources.
- The cross line indicates the combined contribution of the photovoltaic system and the battery.
- While the diamond line represents the share supplied by the electricity network.

The analysis of these curves highlights a significant reduction in dependence on the electricity grid, thanks to the intervention of the BEMS. Indeed, the remaining demand, not covered by renewable sources, is mainly satisfied by the PV/battery system, whose contribution is modulated according to the state of charge (SoC) of the battery, itself influenced by the available solar irradiance.

Furthermore, the fuzzy control system used for BEMS relies on a set of 48 output combinations, each associated with a specific inference rule. Figure 3 illustrates the membership functions of the input variables, with each column representing an input and each row corresponding to a fuzzy rule. The plots of the output columns show how the rules are applied to generate a control response.

The controller's effectiveness was evaluated through the balance between energy supply and demand. One of the representative configurations observed in the rule viewer shows an energy distribution composed of 35.3 kW supplied by the grid, 17.5 kW by the battery, and 17.5 kW by the photovoltaic generator. This configuration illustrates one of the 33 logical combinations observed, where demand satisfaction is prioritized, forcing each source to participate according to its availability and predefined energy optimization rules.

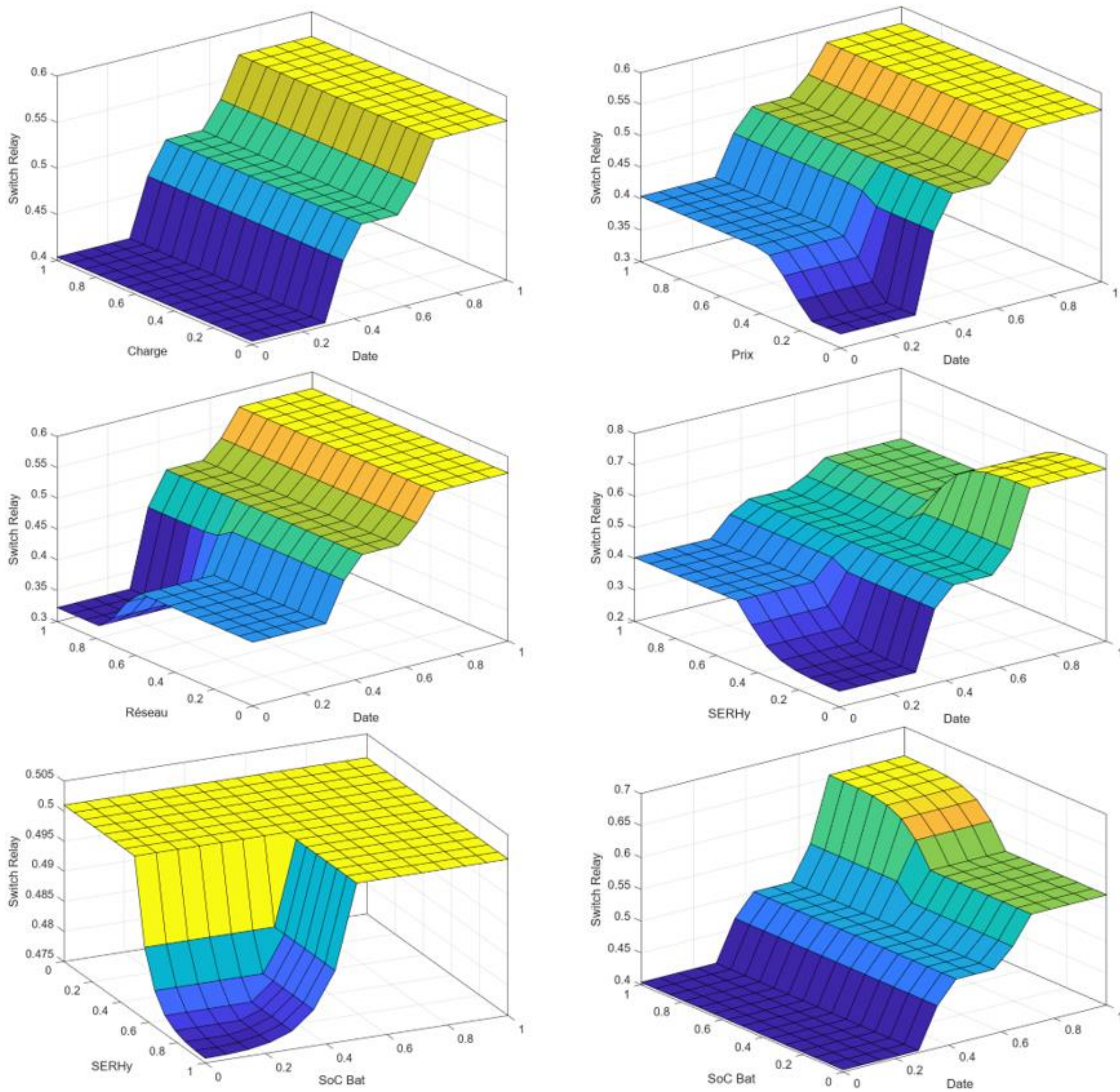

Figure 9.
Surface plot of the input-output relationship of the equilibrium fuzzy system.

Figure 10.
Performance evaluations.

3.1. Behavior of the Energy Management System

The analysis of energy management rules, carried out using the rule viewer, highlighted the effectiveness of a smart controller based on fuzzy logic in dynamically distributing the load between the different available energy sources. The management system demonstrated its ability to automatically switch loads to the most available energy resources, based on the instantaneous production of photovoltaic (PV) generators, the state of charge of the batteries (SoC), as well as the availability of power from the grid.

In accordance with the principles outlined by Vivas et al. [31] and El Zerk and Ouassaid [32], the controller ensures an optimal balance between generation and demand by intelligently distributing power between solar energy, batteries, and the electricity grid. This mechanism guarantees a continuous power supply to the community load, 24 hours a day, without service interruption (see figure 9). During daytime hours, light and medium loads are supplied primarily by PV modules or the battery, while heavy loads are supported by a combination of solar energy and the battery. On the other hand, during the nighttime period, light and medium loads are switched to batteries, while heavy loads are mainly supplied by the grid, depending on the availability and marginal cost of energy.

3.2. Integration of a Grid-Connected Hybrid System

The methodology adopted in this study allowed the design of a hybrid energy system composed of photovoltaic (PV) modules, wind turbines (WT), a diesel generator (DG), and a battery storage system, all coupled to the electricity grid. This architecture aims to meet the energy demand of a residential building while reducing dependence on conventional sources. The approach is inspired by the studies conducted by Jiang and Iqbal [33] and Luna-Rubio et al. [34], which highlight the benefits of a multi-source combination to improve energy reliability and reduce the size of storage devices and thermal generators.

To evaluate the effectiveness of the implemented management strategy, the power output of each source was monitored throughout the day. Figures 11 to 13, respectively, illustrate the variations in production from each source:

- The heat map of electricity production from renewable sources,
- The amount of energy purchased from the network,
- And the amount of excess energy injected into the network.

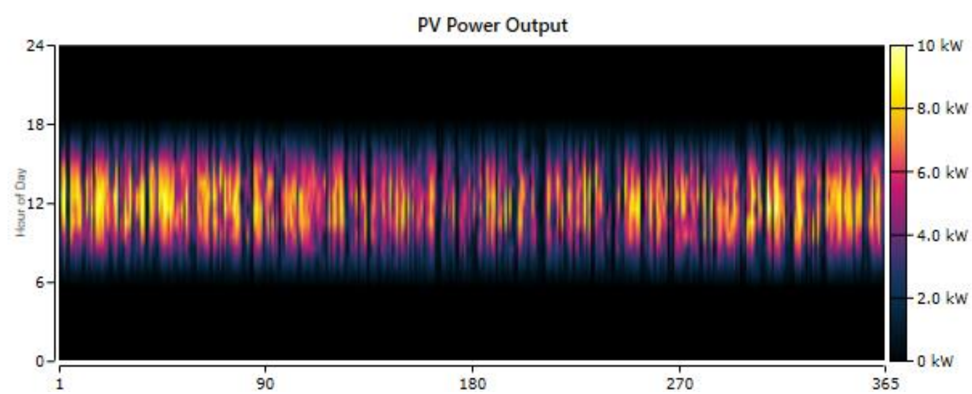

Figure 11.
Heat maps of the panels' electrical production.

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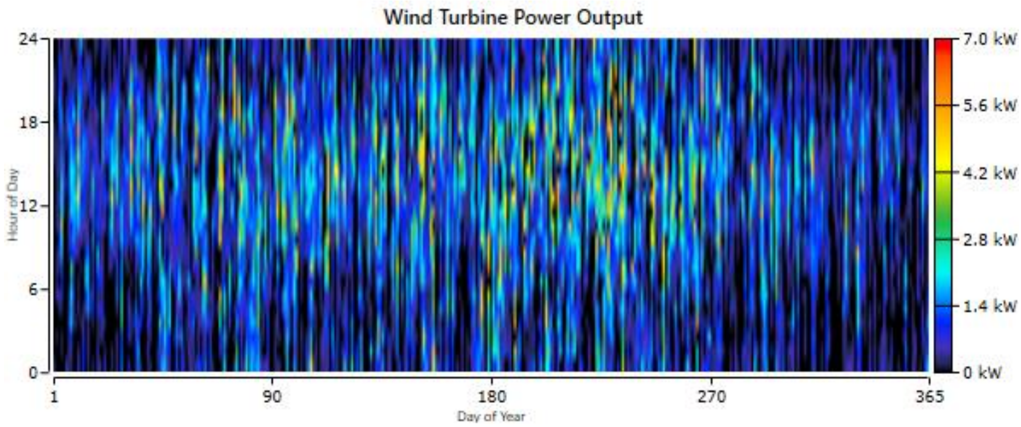

Figure 12.
Heat maps of wind turbine electricity production.

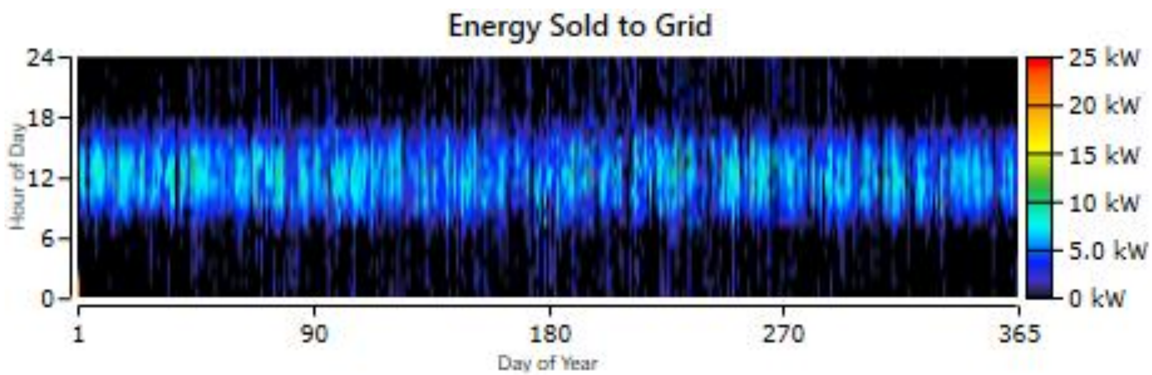

Figure 13.
Heat maps of energy purchased from the grid.

These results allow us to evaluate the overall performance of the system in terms of flexibility, autonomy, and operational cost reduction. The analysis highlights the positive impact of the energy control strategy on optimizing energy flows in a grid-connected residential environment, ensuring reliable and sustainable energy coverage.

3.3. Analysis of the Energy Contribution of Different Sources to the Production Mix

Once the output power profiles of each system component (PV, wind, battery, grid) have been characterized at different times of the day, it is essential to assess their respective contributions to meeting overall energy demand. This assessment provides a better understanding of the functional role of each source within the interconnected hybrid system.

A monthly assessment of energy production was carried out to quantify the contribution of each source (grid, photovoltaic, wind, battery) to meeting overall demand. Figure 14 shows that, although the grid remains the main source of energy, photovoltaic production constitutes a significant share of the total supply.

Figure 14 shows the monthly distribution of energy production from each component of the hybrid system. As shown, energy supplied by the national electricity grid is the main source of supply, reflecting the complementarity between intermittent renewable sources and stable conventional sources. Photovoltaic energy represents the second major contribution, reflecting its increasing role in supporting the load, particularly during hours of high irradiance.

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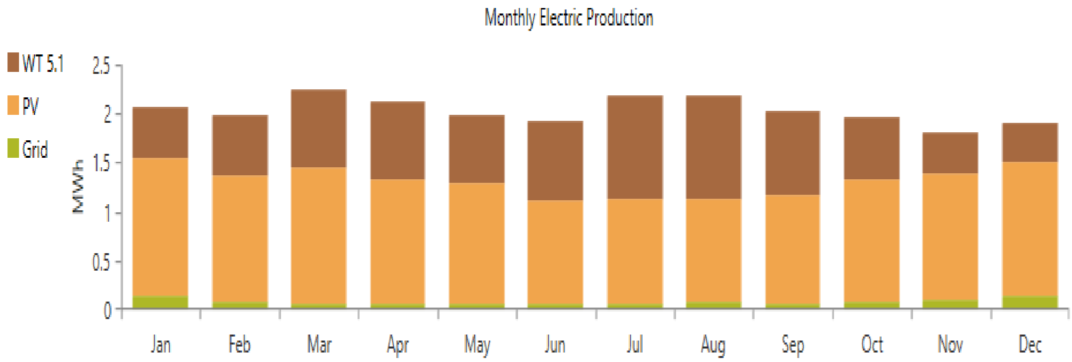

Figure 14.
Electrical components each month.

This sharing dynamic is consistent with the results of Du et al. [35], who demonstrate that a fuzzy controller applied in real time enables efficient energy management in a fuel cell bus by taking into account system durability with notable gains in economics and longevity. This approach is also supported by a study by Xu et al. [36] according to which a two-level fuzzy controller optimizing decision boundaries ensures more reliable, economical, and rapid energy allocation in autonomous hybrid systems. Moreover, Araoye et al. [37] confirm the effectiveness of fuzzy logic-based hybrid strategies in the energy management of smart microgrids, improving stability and performance in the presence of uncertainties.

Similarly, Ahmed et al. [38] showed that a hybrid system optimized by priority rules integrated via SCADA allows a 23% reduction in energy consumption compared to standard models, while ensuring operational resilience. This work highlights the interest of an intelligently managed hierarchy of sources, where the network intervenes in support only when renewable resources are insufficient.

Thus, the results of this study fit into a growing body of evidence demonstrating that the combination of a PV/wind/storage mix, managed via intelligent controllers, allows a reduction in grid dependence and an improvement in energy autonomy, while maintaining a stable and continuous power supply.

A sensitivity analysis was conducted using HOMER Pro to assess the impact of different techno-economic parameters on the optimal configuration of a grid-connected PV/wind/battery hybrid system. Two scenarios were explored: the first one focusing on component costs (PV, wind, battery), and the second one on energy demand and grid tariffs. This approach allows for identifying the conditions influencing the economic and energy performance of the system. The results confirm the findings of Olatomiwa et al. [39] and Mumtaz et al. [40], highlighting the importance of an optimization strategy that integrates cost and load variability.

4. Conclusion

This study developed and validated a rigorous and holistic methodological approach for the energy optimization of buildings in an environment characterized by supply constraints and high solar potential, such as that of Lomé, Togo. The integration of a building energy management system (BEMS) driven by a fuzzy logic controller (FLC) was specifically designed to address these challenges, overcoming the limitations of traditional management methods.

The results of dual modeling and simulation, via MATLAB/Simulink and HOMER Pro, confirm the effectiveness of our solution. Operationally, BEMS-FLC has enabled a substantial 58% reduction in grid consumption by prioritizing self-consumption of renewable energy and battery storage. This intelligent management results in improved system reliability, ensuring continuity of service for critical loads even in the event of a grid failure. Additionally, our approach has demonstrated technical and economic superiority compared to a reference model, with a 6.6% increase in the renewable fraction and a 10.6% reduction in the Levelized Cost of Energy (LCOE).

Beyond energy and financial savings, this work contributes significantly to sustainability. The 5-point reduction in CO_2 emissions demonstrates the positive impact of the smart integration of renewable energy. This methodological framework, based on adaptive control logic, is highly reproducible and can be extended to other infrastructures, particularly in the higher education sector and in regions with similar climatic and socio-economic characteristics.

In conclusion, this research opens new perspectives for energy management in developing countries by proposing a solution that is not only technically viable but also economically advantageous and environmentally responsible. It constitutes a solid basis for the development of energy policies promoting autonomy and infrastructure resilience, marking a crucial step towards Togo's sustainable energy transition.

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Transparency:
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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