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Research Article

Smart Design and Deployment of Standalone PV System in Mountain Area in Romania

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Renewable energy sources are a promising method of generating clean electricity in remote areas. Solar energy is especially useful for isolated communities without access to electricity. Off-grid photovoltaic (PV) systems' performance depends on the operating conditions and is strongly affected by the environmental conditions. In this research, a standalone PV system is designed and installed in a mountain area in Romania. A family of four is using the system for their daily needs. During the design phase of the system, the electrical needs of the household were evaluated, leading to the conclusion that 18 solar panels of 265 W each and a 58 V lithium-ion (Li-ion) battery with a capacity of 14.7 kWh are sufficient to provide the necessary electrical energy. The performance of the system has been analyzed by collecting data remotely, and the results showed that the system is well designed because the consumers do not remain without electricity, especially in critical weather conditions when the energy production is lower. The system produces less electricity, and the battery is not fully charged on all days in November and December because the solar radiation in these months is low. In the event of battery depletion, the system may experience a power interruption of up to 9 days/month in the month of December.

Keywords: LCOE; LCOS; Li-ion battery; off-grid PV system; renewable energy

1. Introduction

The continued growth of the world's population and rapid industrial development are causing problems for the global energy industry. To meet the world's energy needs, various energy resources are used. Producing energy from conventional fuels has become the main reason for emitting CO_2, depleting fossil fuels, and causing global warming. To mitigate these issues, the usage of renewable energy systems based on sunlight, wind, and biomass is the best option, especially in isolated areas, where it is not feasible to install a system [1]. Researchers worldwide have been working to improve photovoltaic (PV) systems, one of the most used renewable energy sources. Ideally, a PV system should always work under normal conditions, but in practice, faults are inevitable and can appear at any time [2].

The intermittent nature of renewable energy impacts the energy production of PV systems. Therefore, forecasting techniques are essential to reduce the mismatch between expected and actual power generation and to support power system operation [3]. A solution to this issue is the usage of a battery storage system (BSS) [4]. In standalone PV systems, the battery plays a crucial role in storing the energy produced, so that the energy is available to consumers during sunless periods when the energy production is stopped. To serve energy needs, the battery of the standalone PV system should be efficiently designed [5]. One of the most popular types of battery used in PV systems is the lithium-ion (Li-ion) battery. Li-ion batteries are characterized by high energy densities and low self-discharge. The life of a Li-ion battery is defined as the number of full charge and discharge cycles. The battery management system (BMS) is an important component of any Li-ion battery. The state of charge (SOC), voltage, current, and temperature of the cells in the battery pack are monitored and controlled by BMS [6].

PV module performance in real outdoor conditions is often different from the performance observed in controlled laboratory conditions. The difference is due to a dynamic combination of factors in outdoor conditions such as solar radiation, temperature, humidity, wind, and PV soiling as dust and grime [7]. These parameter's values cannot be exactly replicated in the predefined procedures used during certification or qualification tests [8]. The evaluation of PV system performance in real outdoor environments is important for the optimization of energy efficiency, the maintenance of grid stability, and the safety of the power system [9]. To ensure the stability and reliability of the power system, accurate prediction of PV power generation is critical, especially in adverse weather conditions [10]. Several scientists have used different parameters to evaluate the efficiency of PV systems. Malvoni et al. [11] have studied the performance and degradation of a 1 MW PV system in India's tropical semiarid climate, based on monitoring data over 4 years. The monthly average was 6.23 h/day, with a final yield of 4.64 h. System efficiency was 11.02%, and capacity factor was 19.30%. The PV system performance ratio was 74.73%.

The influence of insolation, wind speed, and module temperature on the performance of PV systems has been studied by Abdul-Ganiyu et al. [12]. The performance of the proposed PV system was annual total energy output for the PV module was 194.79 kWh/m^2, annual daily mean electrical energy yield for the PV was 3.21 kWh/kWp/day, and the annual performance ratios based on only electrical energy for the PV was 79.2%. The effects of weather and energy consumption on the performance of a domestic off-grid PV system have been investigated by Mcingani et al. [13]. Monitoring has been carried out over the winter and summer to assess production and consumption. Results have revealed significant seasonal variations in solar irradiance, with an average of 337.27 W/m^2 in winter and 560.65 W/m^2 in summer.

Soyturk et al. [14] have proposed an integrated system that utilizes solar-H2 energy in order to meet the energy needs for a house. The proposed system has been composed of: PV/T panels, batteries, PEM electrolyzers, H2 storage tank, PEM H2 storage tank, PEM FCs, and AC/DC converters. The study showed that the energy obtained from the PV/T panels was higher between May and September, when solar radiation was high, and less energy was obtained between October and April, when solar radiation was low. The PV/T panels produced 5.57 MWh/year, and the house's annual electrical energy demand was 4.10 MWh.

Adesina et al. [15] proposed a versatile method for the design and implementation of a 3.5 kVA off-grid solar system for a typical Nigerian bungalow dwelling. The results have shown that the PV system produces the required energy per day, confirming the PV system design's ability to solve the power supply problem in a residence in Ilorin. The block battery selected after the design can support the load for about 24 h with a specific load. Daily yield between 1400 Wp and 1900 Wp/day made this possible, thanks to the selected panel arrangement.

Salau et al. [16] presented a novel approach to design, model, and simulate an off-grid system by integrating renewable and nonrenewable energy sources to meet the energy needs of a health center in Ethiopia. The proposed PV system produces 154,028 kWh of electricity per year. This is possible with 4484 operating hours per year, which translates to over 10 h of daily use.

Dare et al. [17] designed an off-grid PV power system to reliably supply a daily energy consumption of 9.16 kWh using only PV energy. The proposed PV system contains nine solar PV arrays, an inverter, two charge controllers, and four batteries of 220 Ah at 12 V, which were connected to achieve a total battery size of 11,450 kWh. The PV system design has included various components whose capacities depend on a daily energy consumption of 9.16 kWh. After implementation, the system was tested for 2 days. The design was verified and shown to support the daily load requirements for 24 h without failure.

Fara and Craciunescu [18] proposed a design and implementation for a standalone PV system, which can be used in an isolated mountain area in Romania. The MATLAB/Simulink program was used to analyze the models for the elements of a standalone PV system: PV generator, battery, controller, and load. The article shows that the overall performance of a standalone PV system depends on the level of solar irradiance and on the charge status of the battery. The results for the two types of days (clear sky day and partly cloudy sky day) and the spring and autumn conditions cover the consumer load, regardless of the level of solar irradiation. The proposed system ensures energy independence (electricity for lighting and supply of power to electrical appliances with low consumption during a period of 70% from a year) of a house/chalet in an area where connection to the local grid is impossible or would require very high costs to develop an electricity grid.

The research [19] presents the hardware architecture of a monitoring device and a virtual instrument developed for remote monitoring of a standalone PV system. The PV system is located on a mooring pontoon in the Danube Delta in Romania. It is connected to the Internet via a Venus GX unit from Victron Energy for remote monitoring. The Internet is provided by an LTE router at the location of the pontoon.

This article presents the following:

- An implementation of a residential PV system used by a family with four members in a mountain area in Romania. The system has been operational for ~2.5 years without requiring major equipment replacements.
- A remote monitoring and control system for the PV system is proposed.
- Efficient analysis has been done to identify discrepancies between expected and actual PV system performance by analyzing performance metrics such as energy output and efficiency.
- A thorough performance analysis was performed for financial evaluation, including payback periods and overall cost/benefit analysis.

The article is structured as follows: Section 2 represents the PV system description, Section 3 represents the results and discussions, and Section 4 represents the conclusions and future work.

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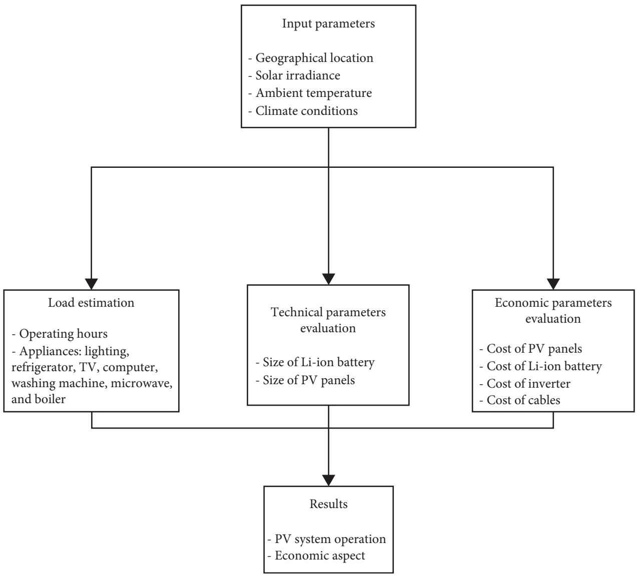

Figure 1: Measures taken while conducting the techno-economic evaluation of PV system [20].

Table 1: Consumption profile of the house.

Appliance	Daily use (kWh)	Monthly share (%)
Lighting	0.5–1.0	5–10
Refrigerator	1.0–1.5	10–15
Washing machine	0.3–0.5	5–7
Water heating (electric)	1.5–3.0	15–25
Cooking (electric stove)	1.0–2.0	10–15
Entertainment (TV and PC)	1.0–1.5	10–15
Standby/other loads	0.5–1.0	5–10

2. PV System Description

Before designing the off-grid solar system to produce electricity for the house, the electrical needs of the residence need to be assessed. The authors conducted a thorough investigation of the technical and economic elements of solar PV systems. The technical and economic evaluation begins with data collection and analysis of equipment usage in a five-bedroom, bathroom, and kitchen, four-person house. One phase of the classification process is the consideration of permanent equipment and loads that are adaptable, scheduled, or shiftable based on their duration of operation. The stages involved are outlined below, with an illustration of the process, as shown in Figure 1.

The proposed off-grid PV system has been installed in the center of Romania in a mountain area (45°45′20″N 25°00′46″E). The system has been designed to assure the daily energy needs for a family with four members, without relying on the grid. It was determined that a monthly energy consumption in the range of 200–300 kWh (~6.7–10 kWh/day) would be adequate to satisfy the household's energy requirements. Table 1 illustrates the household energy consumption profile.

The standalone PV system consists of solar panels, which are responsible for power generation, an inverter, a battery pack, and a remote monitoring and control system. To ensure a continuous supply of electricity, a system of batteries has been installed to ensure a continuous supply of electricity to all household appliances. The inverter converts the high-voltage electricity generated by the PV modules into a lower voltage DC that can be used by the batteries [21].

Table 2: The electrical characteristics of PV panels.

Solar panel electrical characteristics	Value
Type of PV panels	Monocrystalline
Maximum power	265 W
Vmp	35.4 V
Imp	7.51 A
V_{OC}	43.83 V
I_{SC}	8.16 A

Figure 2: The configuration of PV panels.

The system design took into account periods with low solar radiation (winter period when the days are the shortest and rainy days) because these periods are critical and the PV system was desired that the household consumers would have electricity permanently.

The PV system has a projected operational lifespan of 10 years with minimal maintenance and no major device replacements anticipated. After this timeframe, key components may require renewal or enhancement in response to wear or technological advancements.

2.1. The Configuration of the PV Panels. The proposed solution consists of 18 PV panels, which are configured in two strings of nine PV panels each. The PV panels within a string are connected in series, and the strings are connected in parallel. The characteristics of the PV panels used are presented in Table 2.

The solar panels are mounted on the roof at 45° tilt angle, and they face south so that solar radiation can be collected from sunrise to sunset, as presented in Figure 2. There are no elevated structures nearby, which ensures the absence of the shades on the PV panels used and that they are exposed to direct sunlight.

2.2. The Battery of the PV System. Figure 3 presents the Li-ion battery configuration for the PV system. Due to the fire hazard associated with Li-ion cells, the Li-ion battery was located outside of the house but protected against animals and extreme weather conditions.

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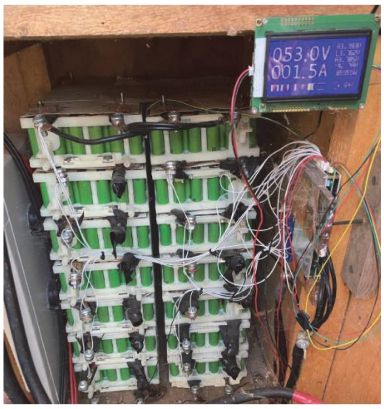

Figure 3: The configuration of the Li-ion battery.

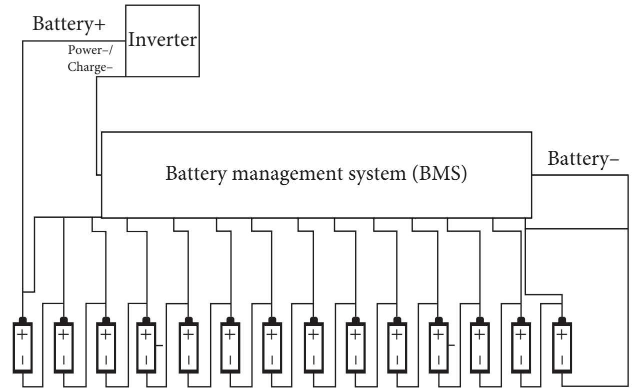

Figure 4: BMS connection to battery.

Table 3: Li-ion cells characteristics.

Li-ion parameter's name	Value
Nominal voltage	3.6 V
Maximum voltage	4.2 V
Capacity	2.5 Ah
Discharge pick current	35 A
Nominal power	W

Li-ion cells were used for the system's battery. They were chosen due to their characteristics such as energy density, long cycle life, good efficiency, faster charging, scalability, and integration [22]. The cells used in the configuration were Sony Murata VTC5A, and their characteristics are presented in Table 3. The Li-ion battery configuration consists of 14 series and 110 parallel connections. The battery capacity is 14.7 kWh with a round-trip efficiency of 90% [23], and it assures the daily energy needs for a family with four members, which is in a mountain area in Romania. It supports up to 1000 cycles at 70% depth of discharge (DoD).

There were two limits set for the battery pack to protect the battery: the battery discharges to 44 V, and it charges until 58 V. The battery pack is charged during the day when the sunlight is available. During the periods without sunlight (night or cloudy days), the house consumers use the energy stored in the battery pack, and the discharge process starts.

The energy generated can be distributed in-house for users' needs and to charge the battery pack. For better management of energy production, the inverter was set to prioritize the energy consumption for the house's needs and the remaining electrical energy to be stored in the battery pack.

The safety, efficiency, and the reliable operation of the BSS are assured by the BMS, which controls the current and voltage during the charging and discharging processes. During the charging and discharging processes, the BMS has the role to balance the Li-ion cells. The BMS monitors the voltage of each battery series. When the voltage of one or multiple series gets unbalanced, the BMS will stop the battery from charging or discharging. The BMS allows the user to set up different limits for the discharge and charge current, minimum and maximum voltage, cell imbalance, and battery temperature. Figure 4 presents the connection of the BMS to the battery.

The only way to determine which cells are defective is to disconnect the series with issues and check the pack with a thermal vision camera, or disassemble each cell and measure them. When the battery voltage reaches the limit voltage set in the BMS, the inverter will not be powered, and the householders will be without electricity. To regain electricity to householders, the battery needs to be charged from the solar panels.

2.3. Monitoring and Control System. A smart inverter with internet capabilities was utilized to transmit the system's data online. Table 4 presents the inverter specifications. Two scenarios were configured in the inverter: the first prioritizes supplying electricity to consumers, while the remaining energy is stored in the battery, as shown in Figure 5. The inverter incorporates a maximum power point tracking (MPPT) system to optimize the energy harvested from PV panels.

The use of monitoring and control software has become popular to achieve better performance from PV systems and extend the life of the equipment. The software tools are designed for data acquisition, visualization, and storage [24]. The proposed off-grid PV system implementation can be remotely monitored and controlled by using Wi-Fi communication. The logical scheme of the monitoring and control system is presented in Figure 6. The data collected are available in the mobile application, where it can be seen the evolution of the solar energy produced. For data security and data confidentiality, the user must have a username and password to access data from their PV system.

2.4. Economic Aspects. In this study, the economic analysis of the designed system was made. According to Table 5, the initial cost of the PV system is 5790 euros. The battery is the most expensive component of the PV system.

The total annual electricity consumption was taken into account to establish the payback period of the system, which can be calculated with Equation (1) [25].

$$\mathrm{PP} = \frac{C_0}{\sum_{T}^{t=1}\left(\mathrm{CF}_t - \mathrm{Q\&M}\right)}, \tag{1}$$

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Table 4: Inverter specifications.

Inverter specification	Value
Type	DC/AC inverters
Model number	AS-5K-alicosolar
Input voltage	48 V
Voltage	230 VAC
Frequency range	50 Hz/60 Hz
AC voltage regulation (battery mode)	230 VAC ± 5%
Efficiency (peak) PV to INV	97%
Efficiency (peak) battery to INV	94%
MPPT range operating voltage	120–450 VDC
Maximum PV array open circuit	500 VDC
Maximum charging current	100 A

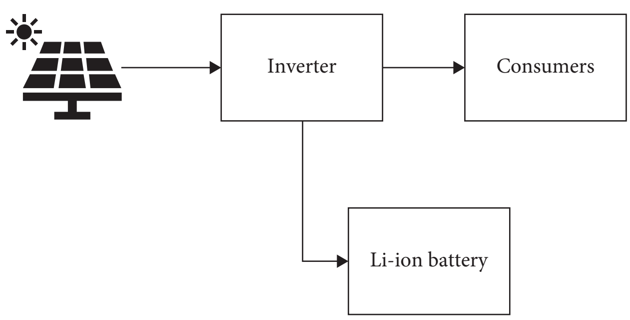

Figure 5: Inverter in off-grid PV system.

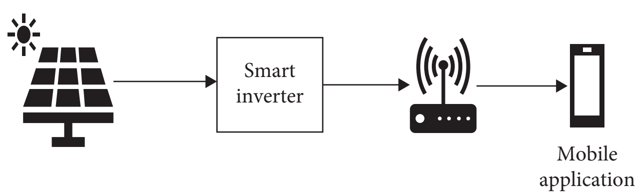

Figure 6: The logical scheme of the monitoring and control system.

Table 5: Cost details of the standalone PV system.

PV system components	Initial investment cost (euro)
PV panels	1286
Battery	3757
AC/DC inverter	502
Cables	245
Total	5790

where C_0 is the initial investment, $O\&M_t$ represents the annual operation and maintenance costs, and CF_t refers to the annual cash flow.

The levelized cost of energy (LCOE) compares different energy production methods by showing the average net present cost of producing energy over its lifetime. LCOE describes the cost of each unit of electricity generated over a project's lifespan, shown as USD/kWh [25]. The LCOE equation is described below:

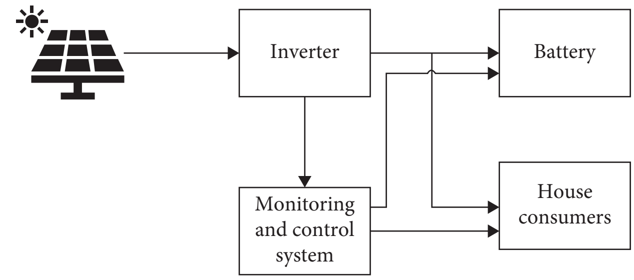

Figure 7: The schematic diagram of a standalone PV system in the mountain area.

$$\mathrm{LCOE} = \frac{C_0 + \sum_{t=1}^{T} \mathrm{Q\&M}_t}{\sum_{t=1}^{T} E_t}, \quad (2)$$

where C_0 is the initial investment, $O\&M_t$ represents the annual operation and maintenance, and E_t is the total energy produced within a single period t.

According to Lai and McCulloch [26], the net levelized cost of storage (LCOS) can be calculated using Equation (3).

$$\mathrm{LCOS} = \mathrm{LCOE} - \frac{\text{price of charging power}}{\text{overall efficiency}}. \quad (3)$$

3. Results and Discussions

This section presents the results of a 1-year analysis of the proposed off-grid PV system, along with a comparison to other PV systems suitable for similar climate conditions. The proposed solution works continuously since installation (no issues occurred during the operation time) in a temperate continental climate, specific to central Europe, with four different seasons. The logical scheme of the PV system is presented in Figure 7.

Daily PV system production varies from a minimum of 0.001 kWh/day (in the month of December 2024, on cloudy days) to a maximum of 23.4 kWh/day (in the month of November 2024 with temperature under 0°C) due to seasonal variations. The system operates entirely independently of the grid; all the electrical energy produced by the PV panels should ideally be used or stored, the excess being a loss because it cannot be introduced into the grid as in on-grid systems. This restriction may result in situations where the system's power generation exceeds its actual power and storage capacity. As a result, during certain periods, the PV modules' design capacity will exceed the system's needs, resulting in periods of underutilization or energy losses.

Power generation is affected by various factors such as irradiance, weather fluctuations, temperature values, dust, and the characteristics of the PV modules. Period 10th–17th of March was selected because it marks the completion of the PV system and the first notable performance results. Additionally, March represents a transitional month from winter to spring, characterized by significant fluctuations in solar radiation, temperature, and precipitation, particularly in Romania's mountainous regions. The period analyzed included days with significant variations in solar radiation (consecutive cloudy

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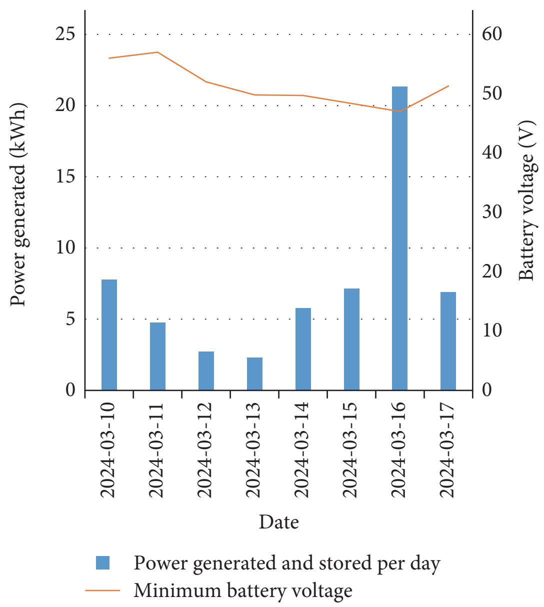

Figure 8: The total power produced during the period March 10–17, 2024.

and sunny days), which allowed the evaluation of the system's performance under different conditions. Thus, it was possible to verify the feasibility of the implemented solution and to identify possible needs for improvement in case the system failed to fully cover the energy needs of the household. Figure 8 shows the evolution of power generation over the period from March 10 to 17, 2024, covering eight consecutive days and analyzing the behavior of power production and consumption. It has been observed that power production varies as follows:

- March 10, 2024, which was a day with thin clouds and sunshine but no raining clouds, the generated power was 7.762 kWh/day.
- March 11–15, 17, 2024—6 rainy days, of which 5 consecutive days with rain, 11th–15th. It can be observed that the power generation was smaller than 7.762 kWh/day on March 10, 2024, which was a sunny day, and it was influenced by the weather conditions (cloudy days), see Figure 8.
- March 16, 2024 was a sunny day, and in the graph below can be seen that the power generation was bigger, 21.336 kWh/day.

Figure 9 displays the daily maximum current and voltage values generated by the PV panels throughout the March 10–17, 2024 period. These values exhibit noticeable fluctuations, which are primarily influenced by variations in solar irradiance due to the daily solar cycle, as well as transient weather conditions such as cloud cover, temperature changes, and atmospheric humidity. These environmental factors directly affect the efficiency and performance of the PV system, resulting in observable variations in the electrical output from 1 day to the next.

Throughout the research, the performance of the off-grid PV system was evaluated across all four seasons: winter, spring,

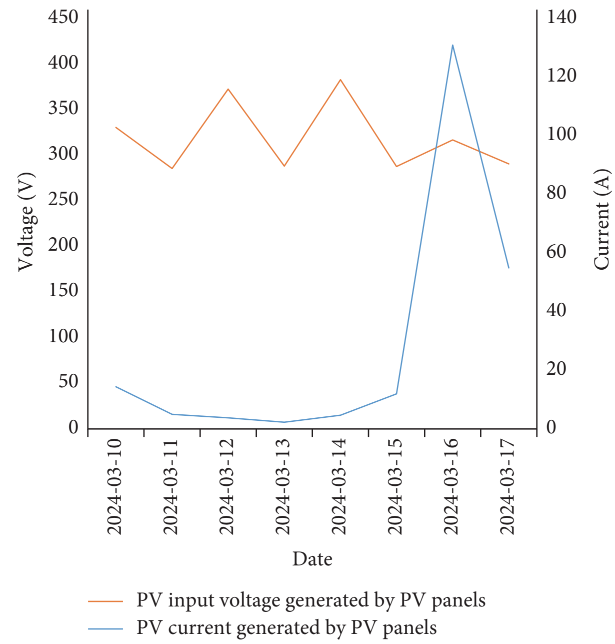

Figure 9: Maximum values per day for current and voltage generated by the PV panels for the period March 10–17, 2024.

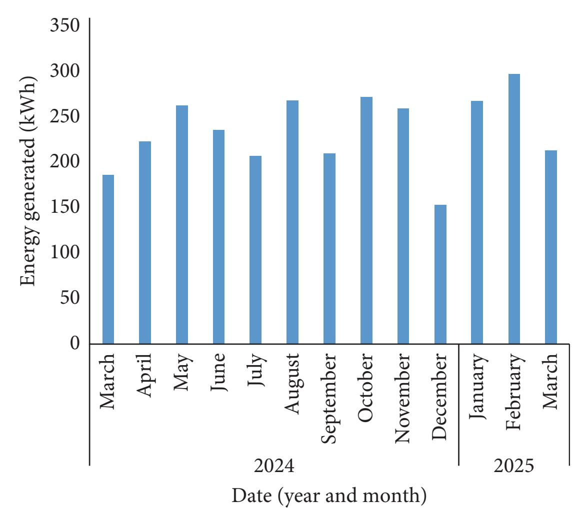

Figure 10: The total produced energy per month.

summer, and autumn. The system operated effectively under all weather conditions.

Figure 10 illustrates the total monthly energy output starting from March 2024 to March 2025. In Romania, December is typically marked by cloudy skies, rain or snow, and shorter daylight hours, with sunrise around 7:30 AM and sunset around 4:40 PM. Consequently, December 2024 recorded the lowest energy production, making it the month with the least amount of electricity generated by the system.

In the above graph, it can be observed that in the month of October was produced and used the highest amount of electricity. During the month of October, the amount of wasted energy produced by the PV panels is minimal because the Li-

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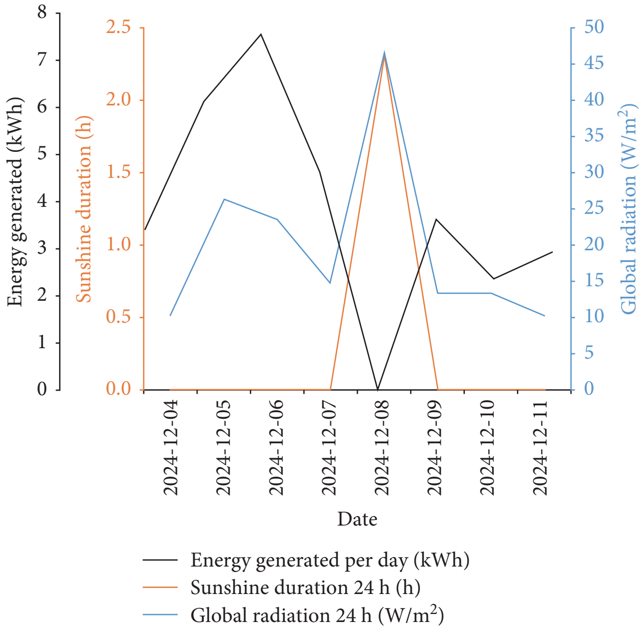

Figure 11: Global radiation, sunshine duration, and energy generated vs. days.

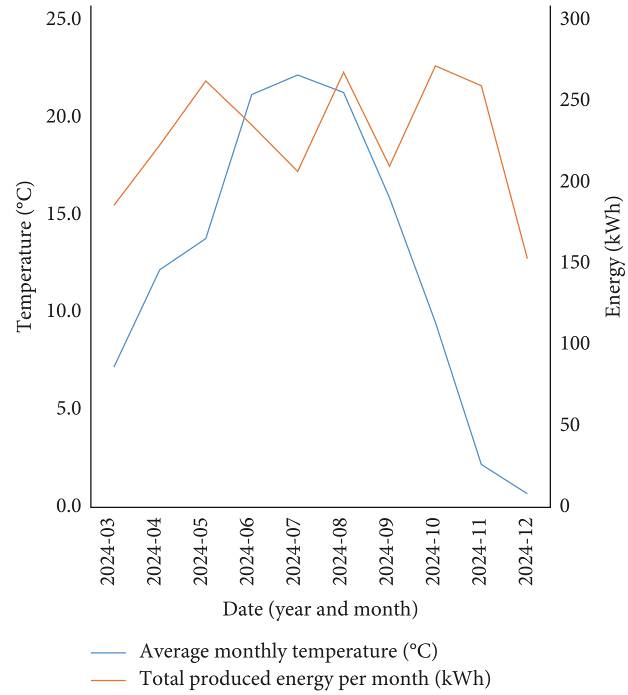

Figure 12: Average monthly temperature vs. total energy produced per month by the PV panels for the period March–December 2024.

ion battery was almost fully discharged at night and almost fully charged during the day.

From March to May 2024, the number of hours of sunshine has increased (around 14 h of light per day in Romania), we have observed an increase in energy production and for September 2024, we observed a decreased in the energy generation as the number of hours of sunshine decreased (light duration around 12 h/day in Romania).

During the summer months, which are characterized by sunny days with high temperatures and long days (around 16 h of light), the Li-ion battery was fully charged all the days. Also, during the period June–August, the PV system has fed the consumers and fully charged the Li-ion battery. Because the battery was slightly discharged during the night, it took a small amount of energy to fully charge it during the day (in Figure 8, it can be seen that the battery voltage varies from 47 to 57 V—on March 10, 2024, the minimum battery voltage was 56 V, which means that the next day, the energy needed to fill the battery was less compared to March 16, 2024, when the minimum battery voltage was 47 V). So a large amount of energy produced by the PV panels was lost. The high temperatures during the summer affected the quantity of energy production, but the PV system generated enough energy for the house consumers and to fully charge the Li-ion battery.

Over the summer period, the system produces more energy than is needed, while during the winter, the system produces less energy because the sun is shining less. During the month of December 2024, there were more consecutive days with sunshine duration under 1 h. The PV system's energy production during a week of reduced solar radiation is shown in Figure 11. This is the longest period of low solar irradiation since 2024, which poses a risk to the generation of electricity available to consumers. It could be observed that the sunshine duration and global radiation have a direct impact on energy generation.

Table 6: Settings of the simulation program.

PV system simulation	Parameters values
Solar radiation database	PVGIS-SARAH3
Installed peak PV power (Wp)	4770
Battery capacity (Wh)	28,000
Discharge cutoff limit (%)	10
Consumption per day (Wh)	9000
Slope (°)	45
Azimuth (°)	17

Energy production has been influenced by the weather conditions (temperature, rain, etc.). The solar panels operate most efficiently at temperatures between 15 and 25°C, from May to September 2024, Figure 12. In the graph below, the average value of the temperature for each month has been considered.

To evaluate the functionality and performance of the proposed PV system, a simulation was carried out using the PV resources software [27].

Table 6 shows the configuration of the simulated off-grid PV system. It was taken into consideration a consumption of energy of 9000 Wh/day (24 h). The analysis has been done for the period of March–December 2024.

Figure 13 compares the real average energy produced per day by the off-grid PV panels with the simulated energy output per day for each month from March to December 2024. The simulated values consistently overestimate the energy output

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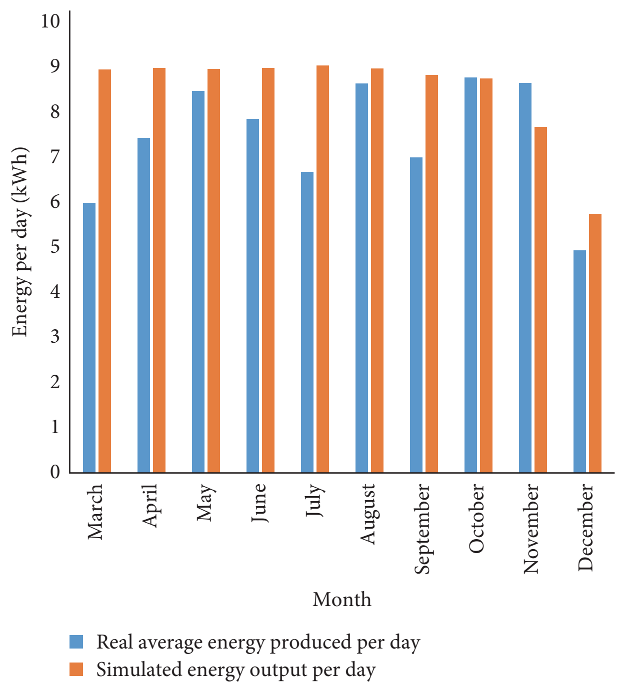

FIGURE 13: Real energy produced per day vs. simulated energy output per day.

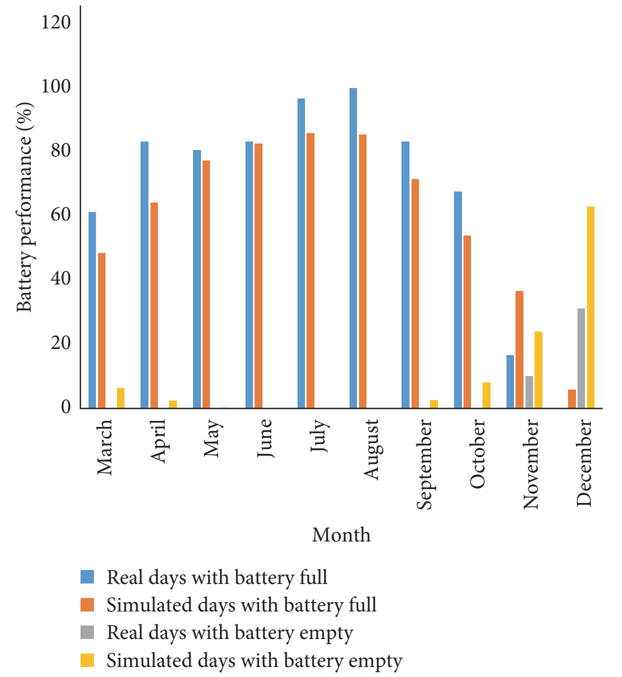

FIGURE 14: Battery state of charge (SOC).

compared to the real measured values. This suggests that the simulation model may not fully account for real-world inefficiencies such as system losses, dust, or weather variability. While the simulation provides a useful estimate, real data highlights the importance of factoring in local weather patterns and operational conditions when forecasting solar energy output.

The months of May, August, October, and November exhibit the highest levels of real energy production, closely aligning with the simulated values. This suggests favorable weather conditions and optimal performance of the PV system during these periods.

The greatest differences between real and simulated data appear in March, July, and September, where actual output lags significantly behind the simulation. These differences could be due to unexpected cloudy or rainy weather. Summer months (May–August) generally show higher energy production, as expected due to longer daylight hours and stronger irradiance. December shows the lowest real and simulated energy output, aligning with the winter season and reduced solar radiation.

Figure 14 presents the SOC data spanning the period from March to December 2024, disaggregated by real-world observations and simulated results and further categorized based on whether the battery was fully charged or depleted at the end of each day. For the spring and summer period, SOC reaches its highest levels, with a substantial proportion of both real and simulated days showing a fully charged battery. The summer months exhibit optimal SOC, which may be attributed to extended daylight hours and more favorable weather conditions for energy generation.

During September and October, a gradual decline in SOC is evident, with a noticeable reduction in the proportion of fully charged days, particularly in the simulated data. Concurrently, battery depletion begins to appear, most prominently within the simulated results.

In November and December, battery SOC undergoes a significant decline. Both real and simulated data show a considerable decrease in the number of days with a fully charged battery. At the same time, the number of days ending with a drained battery, particularly in December, rises sharply. In contrast, performance during the winter months, especially in December, is notably weak, highlighting potential difficulties in maintaining reliable energy storage during times of reduced solar input.

Fara and Craciunescu [18] used polycrystalline silicon PV panels and conducted simulations based on two solar irradiance scenarios: clear sky and partially cloudy conditions. The temperature range considered in their analysis was between 15 and 85°C, which was set as part of the simulation parameters rather than taken from real-life data. In contrast, the current research used monocrystalline PV panels and relied on real-life solar irradiance and temperature values. Instead of simulated conditions, the analysis was based on actual environmental data, making the results more reflective of real-world performance.

In both the simulated and real-world scenarios, the daily power curves of the PV system closely mirror the corresponding solar irradiance patterns throughout the day. The variation in battery power over the day–night cycle is strongly influenced by the level of solar irradiance. On partially cloudy days, unlike clear sky conditions, the battery power experiences significant fluctuations due to the intermittent nature of sunlight. Moreover, the battery's power profile is also affected by the energy consumption patterns in both scenarios.

The research [19] presents a standalone PV system operating in the Danube Delta, Romania. To achieve an average

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production capacity of 27 kWh across all seasons throughout the year, the system utilizes 30 PV panels, each with a rated power of 265 W. In the month of June 2020, the maximum production was 10 kWh/day. This means a maximum yield of 1.25 kWh/W installed, reflecting good efficiency under the region's specific climatic and operational conditions.

In comparison, the current research proposes a solution with 4.77 kWh of installed solar power with 18 solar panels of 266 W each, achieving an annual average per day of energy production of 8.38 kWh and an annual average yield per day of 1.75 kWh/W installed, which is higher than the yield of the system in [19]. This suggests that while the current system is smaller in terms of installed capacity, it is operating at a higher efficiency per watt, possibly due to better optimization, different climatic conditions, or system configuration. Potential reasons for yield differences are as follows:

- Climate conditions, such as more frequent cloud cover or lower solar irradiance. The solution presented in research [19] operates in the Danube Delta, which is an area characterized by warm summers and milder winters, but low rainfall and high humidity. In contrast, the proposed system in this research operates in a mountain area in Romania, which is characterized by a severe mountain climate with long, frosty winters and shorter, cooler summers. Rainfall is much heavier, especially in the form of snow, and high-altitude winds are an important feature.
- Differences in energy consumption patterns where the battery charging/discharging behavior or load demand may impact the effective energy output. In research [19], the system is applied to a mooring pontoon with limited activities. In contrast, the current research proposes a solution that must meet the energy demands of consumers 24 h/day.

While both systems aim to provide off-grid solar energy, the current research system is more efficient in terms of energy production per watt installed, despite having a smaller capacity. On the other side, the Danube Delta system in research [19] achieves good efficiency but likely faces design constraints that limit its yield relative to the size of the system.

3.1. Economic Results. In Romania, the household electricity unit price is 0.24 euros/kWh. The total annual energy cost is estimated to be 1157.38 euro. The payback period is therefore estimated at 5 years.

Considering the following data: average hours of sunshine in Romania per year is 2100 and the total energy produced per year by the PV system is around 9870 kWh, and the payback period is 5 years. The LCOE obtained is around 0.11 euros/kWh.

Given the storage system efficiency of 90%, an LCOE of 0.11 euros/kWh, and charging the battery using solar energy, the resulting LCOS is −0.157 euros/kWh. The negative LCOS indicates that the cost of charging energy (adjusted for storage losses) is substantially higher than the value of the stored energy based on the LCOE. This means that under these conditions, storing energy is not economically favorable, unless compensated by other factors like grid incentives, peak-shaving value, or resilience needs.

The PV system under consideration has an estimated operational lifespan of 10 years, characterized by minimal maintenance requirements and the absence of anticipated major component (PV panels, batteries, and inverter) replacements within this period. Although PV panels typically have an operational lifespan of ~25 years, the batteries are expected to last around 10 years, and the inverter between 5 and 10 years. Consequently, for the purpose of this analysis, the overall lifespan of the pV system is considered to be ~10 years, reflecting the shortest-lived critical components. During the first 5 years of operation, the system is not expected to require any operational or maintenance expenses, as demonstrated by its performance thus far. It has operated for ~2.5 years without incurring any such costs. The system's initial capital investment totals 5790 euros, comprising PV panels (1286 euros), battery storage (3757 euros), AC/DC inverter (502 euros), and cabling (245 euros). Given the minimal maintenance context, the annual operation and maintenance (O&M) costs are conservatively estimated at ~1% of the initial investment, amounting to 57.90 euros/year. Over the 10-year lifespan, this corresponds to a cumulative O&M expenditure of roughly 579 euros, representing 10% of the initial capital cost. It is acknowledged that, subsequent to this timeframe, key components such as the inverter and batteries may require replacement or technological upgrades due to wear or evolving standards, which would influence the overall lifecycle costs. This conservative O&M cost estimate aligns with typical values reported for utility-scale PV systems with limited maintenance needs.

4. Conclusions and Future Work

Exploring the design and economic feasibility of standalone PV systems not only addresses the immediate energy needs but also contributes to long-term sustainability goals. With the right strategies, off-grid PV systems can play a vital role in achieving energy independence and enhancing quality of life, particularly in underserved regions. This article describes the design and implementation of a standalone PV system that can be used successfully by a family with four members in a mountain area in Romania. The PV system will operate for 10 years with minimal maintenance and no major device replacements. Then components may need renewal or enhancement due to wear or advances in PVs. The system has been in operation for ~2.5 years without necessitating significant equipment replacements. The PV system designed and implemented in this research consists of 18 monocrystalline PV panels (which are configured in two strings of nine PV panels each), inverter, Li-ion battery pack (with 14.7 kWh capacity with a round-trip efficiency of 90% configured in a 14-series by 110-parallel arrangement and it supports up to 1000 cycles at 70% DoD) and a remote monitoring and control system based on Wi-Fi connection. The proposed system assures the energy needs all over the year, especially in winter months when the energy production is lower and the consumers could remain without electricity as the energy demand is greater than the energy

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production. The performance of the proposed PV system has been analyzed, and it has been concluded that the total energy production of the PV system is impacted by sunlight, seasons, temperature, rain, or other weather conditions. During November and December, the system generates reduced electricity output, and the battery does not reach full charge on all days due to diminished solar radiation in these months. Consequently, in cases of battery depletion, the system may experience power interruptions lasting up to 9 days within the month of December. In addition, an economic analysis was performed for the financial evaluation. This included the payback period that is estimated at 5 years, LCOE obtained is 0.11 euros/kWh and LCOS is −0.157 euros/kWh. The O&M costs for the PV system are estimated to be ~10% of the initial investment over a 10-year period, reflecting minimal operational expenses.

A stable Internet connection is crucial for facilitating remote monitoring and control of the PV system. In the absence of connectivity, real-time supervision and system management cannot be performed. To mitigate potential interruptions in household Wi-Fi, a mobile device with a SIM card and an active Internet connection can be placed near the PV installation to maintain continuous internet access. The estimated cost of this backup solution is ~2–3 euros/month, corresponding to a standard mobile data subscription. Another limitation identified is the absence of an automated cleaning system for the PV panels. To date, panel maintenance has been conducted manually; therefore, the implementation of an automated cleaning mechanism or an alert system within the monitoring and control application to notify when cleaning is required is desired.

As future work, we plan to extend this research by improving the monitoring and control system by adding artificial intelligence functions to enhance the efficiency and reliability of the PV system and implement an automated clearing system. This future work not only aims to improve energy production but also supports the broader goal of sustainable energy management.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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