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Monitoring and Effectiveness Analysis of a Hybrid PV Battery System in Real Conditions

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Abstract: The use of solar energy is a common subject of conversation, especially within the context of Sub-Saharan African local and national governments. Concerns about the challenges of sustainable development, as well as the desire to manage running expenses in the face of growing diesel prices, promote a close examination of the "solar PV battery" alternative for charging exploitation. In this paper, we provide a detail description of the 300 Wp of solar power erected at the University of Joseph KI-ZERBO. This autonomous PV system (APS) provides electricity to meet the basic electrical needs of the Laboratory of Materials and Environment (LAME), which was established for this purpose. A data acquisition campaign is conducted in order to operate and monitor the study's APS. The collected data used to examine the effectiveness characteristics of the APS are explained and discussed. The experimental results obtained throughout the measurement campaign revealed that the PV system functions normally, with PR values ranging from 82% to 98%. Then, a sensitivity study is performed using behavioral models related to the correlation coefficients, and the outcomes are compared to experimental evidence. The monthly average performance ratio with Lame Lab PV modules was 4.76 percent higher than the average performance ratio found in the literature.

Keywords: Monitoring, Acquisition System, Reliability, PV System

1. Introduction

Currently, the world is experiencing a rapid transition to renewable energy (RE) production [1]. Indeed, increasing the use of renewable energy sources such as solar, wind, biomass, and hydroelectricity is critical to meeting the world energy needs and also slowing the rate of greenhouse gas emissions. In these circumstances, RE is the best option for rural areas that are isolated or remote. The main drawback with renewable energy, such as solar energy, is the intermittent phenomenon. Photovoltaic systems in Burkina Faso, like those in most sub-Saharan African countries, are often subjected to extreme weather conditions such as heat, passing clouds, dust and dirt particles, shade, etc. [2, 3]. These issues have been identified as the primary factors contributing to the reduction of the efficacy of photovoltaic system power generation [3]. As with any other industrial process, a PV system can experience errors and abnormalities that cause performance to suffer. However, in order to mitigate the impact of the aforementioned challenges on supply safety, a storage system is typically employed in conjunction with alternative energy sources. To this end, extensive analyses of hybrid PV systems created by the authors [4] revealed that they are more appealing than single PV systems in terms of reduced battery bank size and reliability of the power supply. Numerous studies have been conducted in the literature to examine the performance of PV systems that are connected to the grid [5-7]. In this research, performance evaluation is mostly based on how much power or energy is fed to the grid. This means that the efficacy ratio can be compared to various losses in the PV system such as connection loss, mismatch loss, conversion loss, etc. [8-12].

In the literature, reports about how well stand-alone PV systems work are not often mentioned. However, a solid grasp of both electrical demands and manufacturing processes is essential.

This research aims to evaluate the performance of a 300-Watt solar PV system installed on the roof of the LAME facility. Indeed, the supervision of this research PV system enables the monitoring of production performance, as well as the quality of operation of the PV modules and inverters. Subsequently, a sensitivity study is performed based on behavioral models linked to correlation coefficients, and the results are compared with experimental data. The remainder of the paper is organized in the following manner: Section 2 outlines the PV system located on the Lab rooftop. This section provides a comprehensive overview of the modeling of PV system component, specifically the PV generator and storage system. Then, the DAS and measurements bench for the PV monitoring installation are outlined, and a methodology for data analysis is elaborated upon. In section 3, the results of various parameter analyses are discussed in a diagnostic way. Finally, the works conclusions are provided in Section 4.

2. Description of the PV and Data Acquisition Systems

2.1. PV System

The solar power plant is located at the University of Joseph KI-ZERBO in Burkina Faso (12 ° 21 '51' N; 1 ° 32 '18 'W). The experimental site is well irradiated and could benefit from installing solar energy equipment. Figure 1 provides a panoramic view of the PV modules positioned on the laboratory roof.

The two PV modules that comprise the PV array are oriented south with a 15-degree tilt. Table 1 highlights key data from the PV module. The area of the PV array is not shaded by nearby buildings or other barriers.

Table 1. *Main parameters of the PV modules at standard test condition.*

Parameters	Values
Peak power (Pmax)	150 W.
Open-circuit voltage (Voc)	32.3 V
Rated current (Imp)	8.2 A
Short circuit current (Isc)	8.8 A
Reference temperature Tref (°C)	47
PV module efficiency ηref	13%
efficiency temperature factor γ (/°C)	0.0045
Solar irradiance at STC GSTC (W/m²)	1000

Figure 1. *Overview of PV modules.*

Figure 2 shows an experimental schematic diagram of the PV system, which includes a solar array, a battery bank, an inverter, and various types of laboratory electrical demand. The PV array and battery systems are connected to a DC bus in this electrical diagram, whereas the electrical loads are connected to an AC bus via a 1.5 kW DC/AC inverter. The maximum power point tracking (MPPT) approach is used for the PV array generator to extract the maximum output power owing to variations in solar irradiation under operational conditions. The battery storage system consists of a series connection of two batteries (12 V, 100 Ah each), which are loaded by the voltage generated by the PV array system, and their load is controlled by a DC/DC controller. Table 2 summarizes the general specifications of the battery bank. A DAS Keithley 2701 is used to record the necessary measured information in order to investigate the PV system, while LABVIEW is used on a desktop computer to process the measured data.

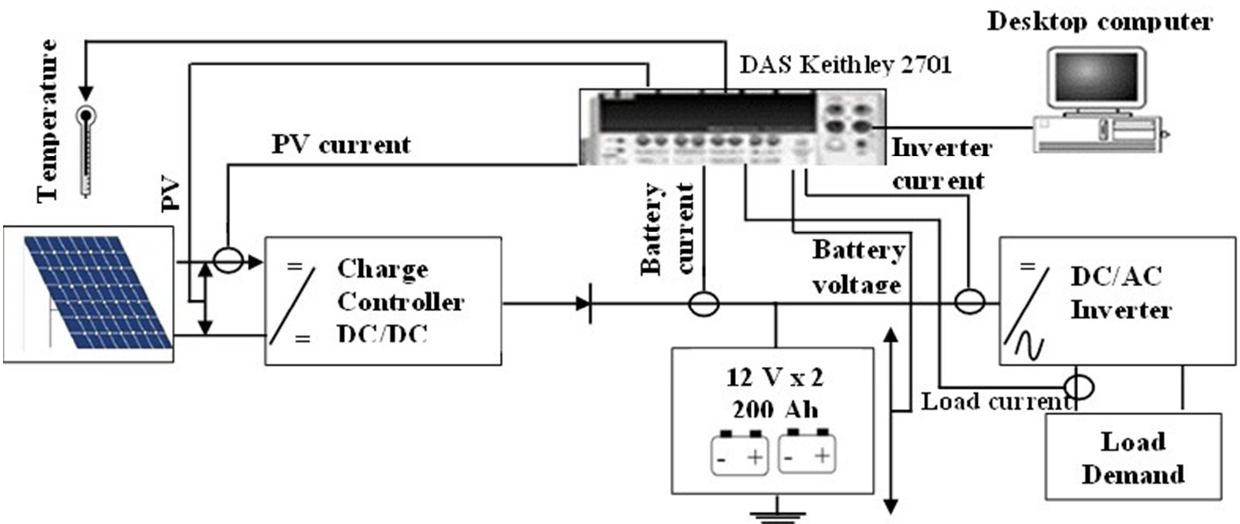

Figure 2. *Experimental diagram depicting the PV system.*

Table 2. *Electric appliances used in this study.*

Battery	
Type	BK
Nominal voltage	12 V
Nominal Current	3.8 A
Nominal capacity	100 Ah
Charge threshold voltage	15 V (50°C)
Discharge threshold voltage	10.5 V (30°C)
Electrolyte density	1.23 kg/l

2.2. Data Acquisition System (DAS)

To record the required data produced by the various devices, a Keithley model 2701 data acquisition system is used. The registered variables provide information about the electrical output, such as currents and voltages in the PV modules, the battery bank, the power consumed by the laboratory's basic electrical demands, ambient and PV array temperatures, solar insolation, relative humidity, and so on. For the solar insolation measurement, a calibrated standard cell is used as the irradiance sensor shown in figure 3. The main characteristic of the standard cell corresponds to a calibration value of 1000 W/m² for a voltage of 73.9 mV.

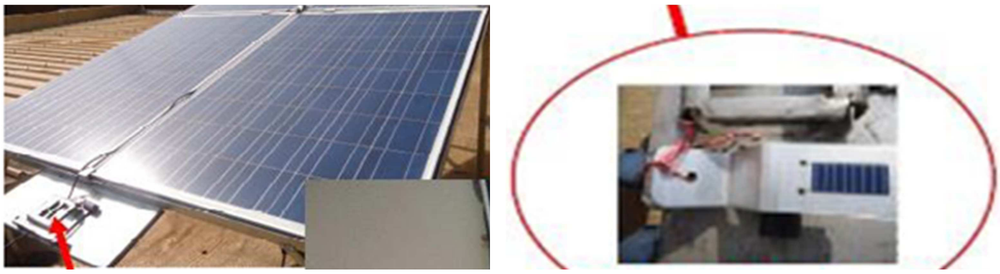

Figure 3. *Overview of the insolation sensor.*

More specifically, the calibration factor for each PV module is determined by comparing it to a reference pyranometer under natural sunlight on a clear day [13]. The calibration graph obtained by adjusting the voltage in relation to insolation is shown in Figure 4.

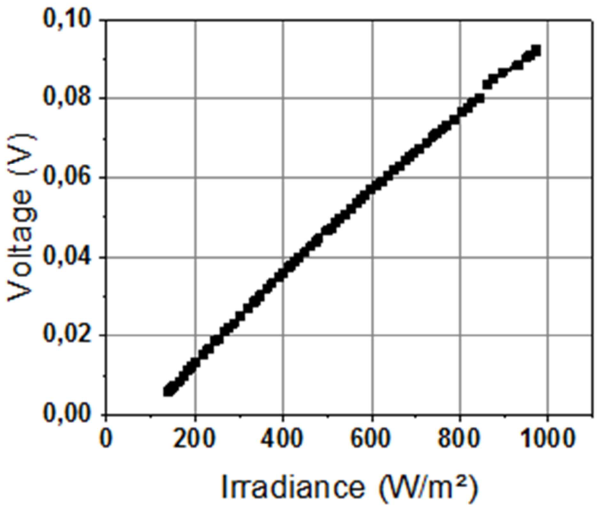

Figure 4. *Reference PV module calibration curve.*

Two thermocouples are used to measure the temperatures of the top and bottom surfaces of the PV modules. One thermocouple is mounted to the back of each PV module and shielded from direct sunlight (model: S103 AT-II, RYL, C0499). The thermocouple connection is set at a resistance of 10 k, as recommended by the manufacturers. An analog DC ammeter (0.32% accuracy) and an analog DC voltmeter (0.20% accuracy) are used to measure the solar array current and voltage. The charge controller measures battery voltage and charging current, and the results are displayed and transferred to a nearby computer via the Keithley DAS. It is noteworthy that the overall inaccuracy of all measurements is less than 2%. these parameter values have been captured daily with a 5-to 10-minute interval and saved in Excel files by dates, months, and hours.

2.3. Load Assessment

Load is an important part of any power generating system that makes power and can have a substantial impact on how it is designed. Table 2 illustrates the different appliances used to size the studied system. The laboratory electrical load is rated at 259 W, and the number of hours of operation of the electrical loads in the existing system varies based on the requirements of the occupants.

Table 3. *Electric appliances used in this study.*

Appliances	**Power demand (W)**	**Usage time (Hour)**
Refrigerator	74	6
Computer	65	24
Lamps	40	6
Data Acquisition System	80	24

3. Results and Analysis

3.1. Short -Circuit Current, Open-Circuit Voltage and Irradiance in Relation to Time

Figure 5 depicts the short circuit current (I_{SC}) and open-circuit voltage (V_{OC}) on June 12, 2022, in relation to the time of day. It is obvious that I_{SC} and V_{OC} grow proportionally with time, reaching their maximum levels in about 12 hours. However, the V_{OC} varies logarithmically, but the I_{SC} is directly proportional to the intensity of the incoming light [14]. The V_{OC} curve shows a slight decrease around 12 hours and 15 minutes, which could be attributed to factors like the soaring temperatures experienced during this time of day. Figure 6 shows that the effectiveness of solar PV modules decreases with increasing irradiance. The study location experiences significant irradiation exposure, as depicted in Figure 6, as a result of its geographical position. When severe temperatures are not taken into account, coupled with a significant variance in irradiance, it can result in under-sizing of PV systems, which may lead in losses or failure of the PV system [15].

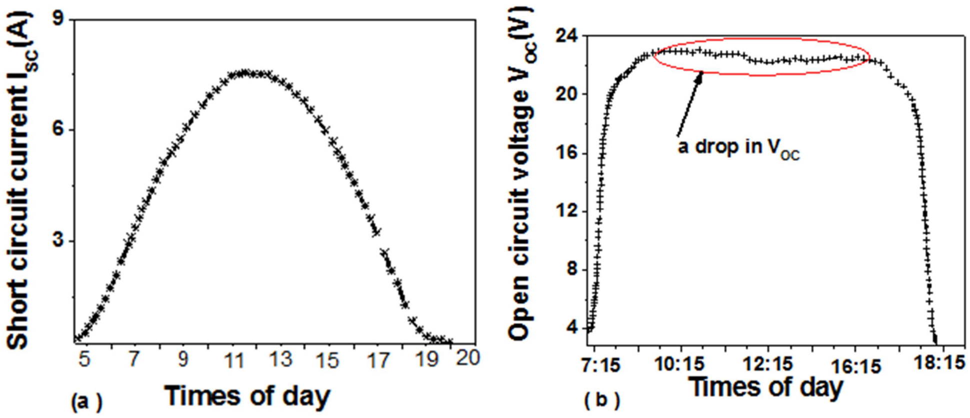

Figure 5. *I_{SC} and V_{OC} variations in relation to time of day on 12 June 2022.*

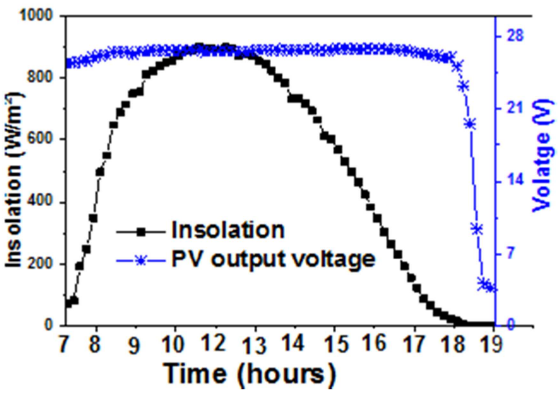

Figure 6. *PV output voltage and insolation in relation to time of day on 12 June 2022.*

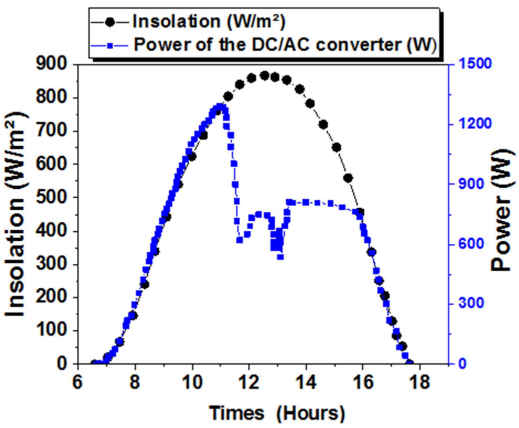

Figure 7. *Power of the converter and insolation in relation to time for a clear sky.*

3.2. PV Output Power and Insolation as a Function of Time

Figure 7 shows the time fluctuation of the DC / AC converter output and the insolation for a clear sky. Despite more daylight, the power output of the converter significantly drops between 11 am and 4 pm in this situation. Figure 8 depicts the power output of the converter profile during a day with cloud cover. The power profile of the converter, when compared to one shown in figure 7, follows the fluctuation in the insolation data, as shown in this graph. The fluctuations in the profile of the converter's output power seen in Figure 7 may be explained by the converter's behavior as a result of the storage system's state of charge and the low energy demand within the laboratory during the day.

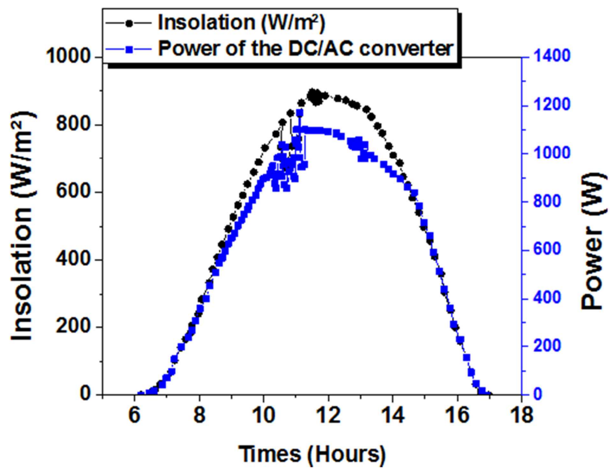

Figure 8. *Power of the converter and insolation in relation to time for a cloud day.*

3.3. Energy Management Strategy of the PV System

Weather and battery charge play a role in determining the capacity of the hybrid PV system to meet load demands. It is important to control how much energy goes from the solar PV module to the battery by using an energy management approach, as shown in Figure 9. An initial step in the algorithm is to determine the desired thresholds for various parameters such as PV power, battery voltage, and temperature. The system continuously measures and compares these parameters to the desired thresholds and generates alerts in the event of any threshold being exceeded. In this strategy, the PV system focuses on providing electricity to the load for the day. When the storage system voltage exceeds 80%, both the PV and battery systems will meet the load requirement. When the storage system is less than 20% full, the energy management switches to load shedding mode to protect the remaining storage system until the PV system is turned back on.

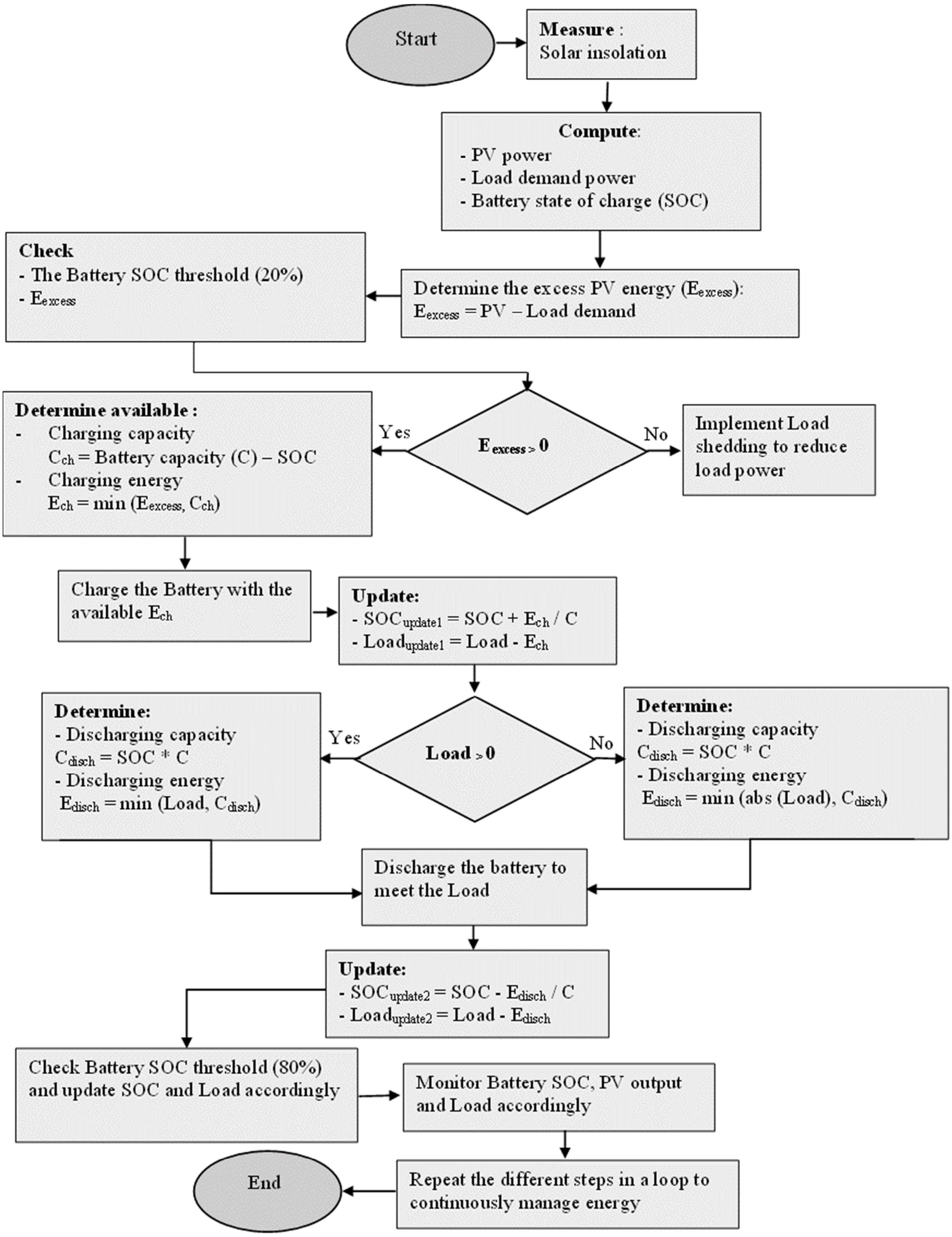

Figure 9. *Energy management flowchart.*

The energy management strategy for the hybrid PV system relies on a thorough evaluation of the load power, PV output power, and battery state of charge (SOC), whose varying characteristics are illustrated in figure 10 for four days. During these four days of monitoring, the PV output is estimated to be 523.75 W, the minimum load power is 128.788 W, the minimum threshold (SOC) and maximum threshold (SOC) are 53.226% and 70.10%, respectively, and the battery voltage is 27.975 V. When the supply of solar panels exceeds the demand, both battery voltage and state of charge rise. In periods of overproduction, excess energy is stored in the battery bank, which is used to meet the lab electricity needs at night.

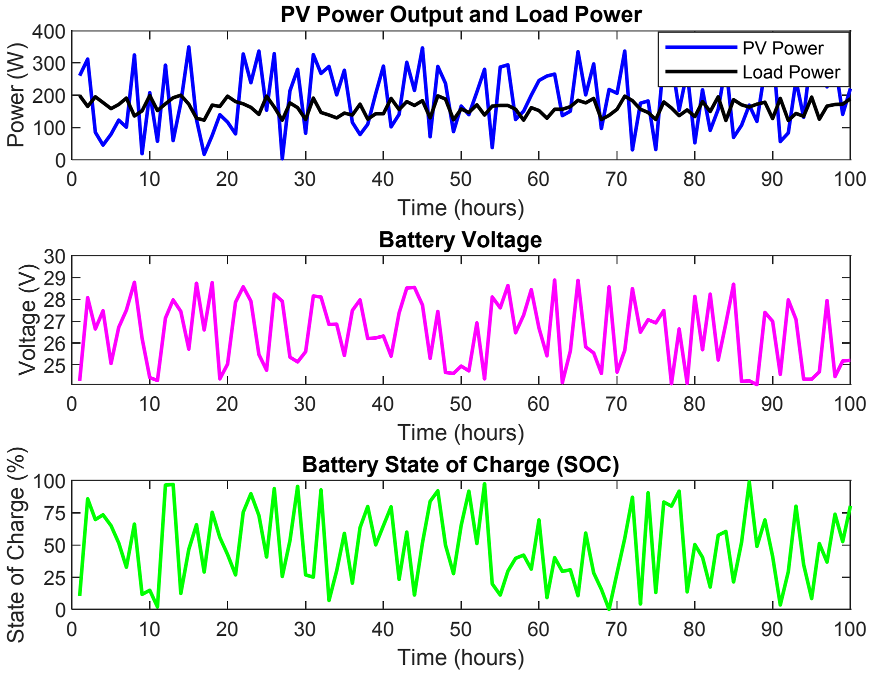

Figure 10. *PV output power, load power, battery voltage and state of charge (SOC) in relation to the time.*

3.4. Effectiveness Parameters of the PV System

The International Energy Agency (IEA) has set performance characteristics for analyzing the reliability of a solar PV system, which are described in the standardized specifications (International Electro-Technical Commission) IEC 61724. Normalized rapport values [16] are used to examine the functioning of a PV system, that is, the reference yield (Y_r), the PV array yield (Ya), the final yield of the PV system (Y_f) and the performance ratio (PR):

Reference yield (Y_r)

The reference efficiency (Y_r) is the proportion of total incident irradiance (G_0) on the PV module's surface to irradiance (G_{ref}) at the reference condition. This metric denotes the number of peak solar hours at the reference irradiance, as defined by equation (1):

$$Y_r = (G_{ref})^{-1} \times G_0 \qquad (1)$$

With $G_{ref} = \frac{\int_{hour} G_0(t)dt}{G_{0,stc}}$

Where $G_{0,\,stc} = 1\text{kW/m}^2$

PV array yield (Y_a)

The PV array yield is defined as the ratio between the PV array energy output ($E_{dc,t}$) and the PV array nominal power (P_{ref}) at reference circumstances, as specified in Equation (2). It is used to calculate the energy production of the solar array at its nominal maximum power rating [17].

$$Y_a = (P_{ref})^{-1} \times E_{dc,t} \qquad (2)$$

final yield of the PV system (Y_f)

The final yield of the PV system is the ratio of the final AC energy output ($E_{use,t}$) to the PV array nominal power (P_{ref}), as calculated by equation (3). This figure represents the number of hours the PV field had to operate at full power.

$$Y_f = (P_{ref})^{-1} \times E_{use,t} \qquad (3)$$

Performance ratio (PR)

The performance ratio (PR) represents the overall efficiency quality of the PV system in terms of all the effects that are implied in various parts of the PV system's energy conversion. PR is a dimensionless number that is defined as the ratio of Y_f and Y_r.

$$PR = Y_r^{-1} \times Y_f \qquad (4)$$

Figure 11 shows graphs of PV system yield Y_f versus reference yield Y_r or two days on 15 May 2021 (figure 11a) and 12 June 2022 (figure 11b). The data point distribution is quite narrow and has a strong connection with the polynomial fit line. Figures 11 a and b show the coefficients of reference yield dependency. We can assume from these plots that the inclinations are nearly identical. We can extrapolate from the scatter of data around the polynomial fit line that the PV system underperforms owing to issues such as rising temperatures.

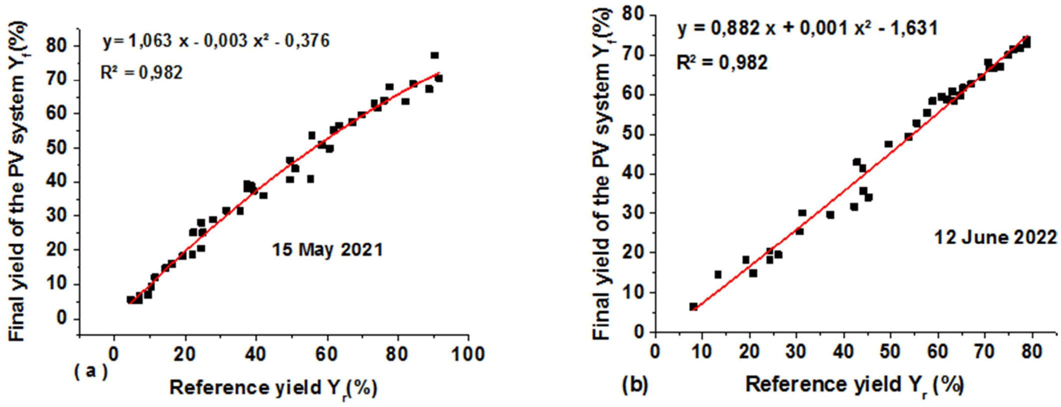

Figure 11. *Final and reference yields of the PV system.*

The PV system yield Y_f and performance ratio PR are plotted against the reference yield Y_r to produce the analysis graph shown in Figure 12. Apart from some inflections at the start and end of the day, there is a solid match in terms of performance for the rest of the day on May 15, 2021. These inflections are natural and can be related to temperature variations and the photovoltaic module. Figure 12-b shows the measured data from the same PV system on June 12, 2022. For the two time periods studied, the hourly PR values ranged from 72% to 98%. This suggests that between 2% and 28% of the potential energy produced during these monitoring periods could not be used due to factors such as conductivity losses or thermal losses. As a result, the findings indicate the health condition of the PV system during the monitored period. However, as illustrated in Figure 12, the photovoltaic system suffers more from high temperatures.

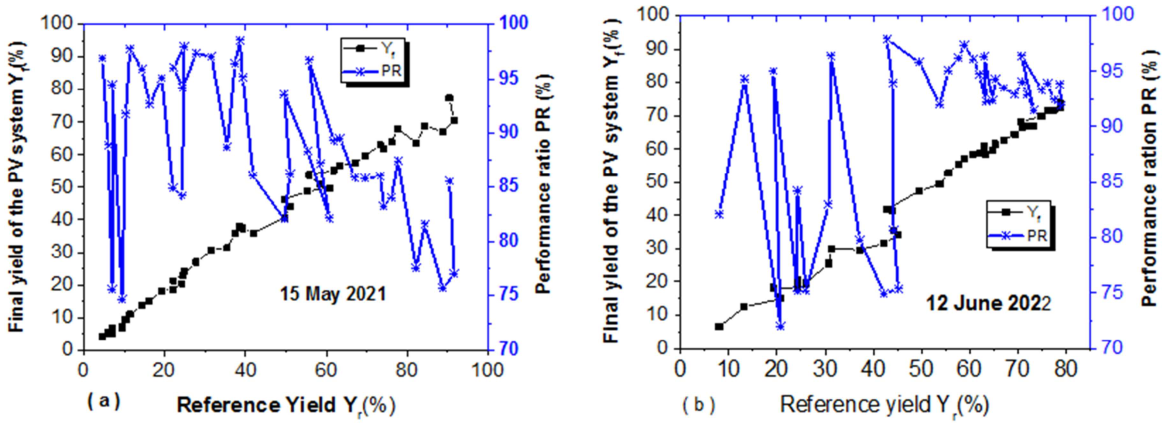

Figure 12. *PV system yield Yf and Performance ratio PR in relation to reference yield Yr.: a) 15 May 2021 and b) 15 June 2022.*

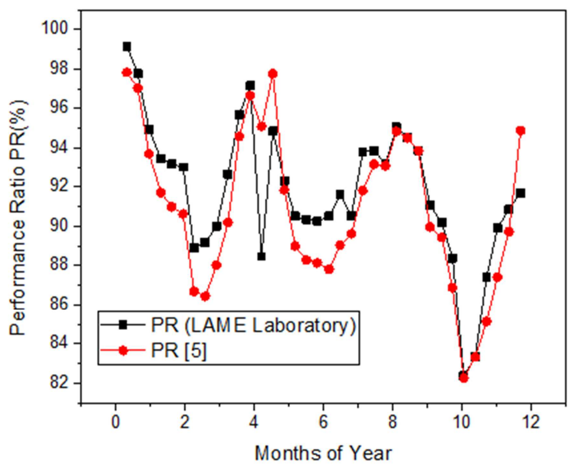

Figure 13. *Comparative monthly average values of the performance ratio.*

Figure 13 illustrates the changes in monthly average PR values over one year for two monitored PV systems. As depicted in this figure, a decline in PR is noticeable in the two monitored PV module technologies. The PV module from LAME Lab demonstrates higher PR values, while the PR values for LAME Lab's PV module and the reference [5] PV module are quite comparable. However, the reference [5] PV module exhibits the lowest PR values. The monthly average performance ratios for systems utilizing Lame Lab PV modules were observed to be approximately 4.76% higher in comparison to those found in the reference study [5]. This suggests that PV systems employing polycrystalline modules are better suited for Sahelian climate conditions in terms of their performance ratios.

To gain a comprehensive understanding of the PV system's performance as it relates to previous research conducted locally, Table 4 offers a condensed overview of the performance metrics described in Figure 13.

Table 4. *Average performance ratio values on a monthly basis.*

Considered Month	Monthly PR (%)	References
January	99.17	Present study
	97.04	Ref [5]
February	91.70	Present study
	86.44	Ref [5]
April	88.89	Present study
	96.64	Ref [5]
May	90.51	Present study
	88.14	Ref [5]
June	90.55	Present study
	87.81	Ref [5]
July	93.79	Present study
	89.04	Ref [5]
August	95.06	Present study
	94.52	Ref [5]
September	93.87	Present study
	93.87	Ref [5]
October	82.37	Present study
	82.26	Ref [5]
November	89.90	Present study
	87.41	Ref [5]
December	91.70	Present study
	94.98	Ref [5]

For comparison, it's notable that all these earlier investigations indicate satisfactory performance. However, the climatic conditions at the laboratory site, mainly in Ouagadougou City, yield the most favorable outcomes. The performance of the study system significantly improved in January, primarily because of the lower insolation levels (temperature), in contrast to the results observed in April.

4. Recommendation

Based on the aforementioned analyses, it is clear that the proposed PV system has the capacity to power more electrical appliances during daylight hours. To improve overall system performance, the daytime load in the laboratory can be used for lighting activities without affecting the electricity peak demand. To reduce temperature losses, the design could be improved by incorporating a self-cooling mechanism within the PV arrays and ensuring proper spacing between them. Additionally, keeping a regular cleaning schedule for the PV modules can effectively address soiling issues.

After evaluating battery performance, there are several recommendations for the laboratory managers to contemplate:

1. reconsider the necessary autonomous storage days to attain a more efficient system and extend the battery lifespan.
2. optimize the configuration of energy allocation and autonomous storage days to ensure energy supply security, enhance system efficiency, and prolong the battery life cycle.
3. despite the significant potential for increased electricity demand, implement load management in advance and concurrently with the process of resetting users' energy limits.

The specific case study conducted, focused exclusively on an autonomous PV/battery system with consistent power demands. The logical next phase of this research involves implementing the approach for the same system with variable consumption profiles. To achieve this, it is essential to consider the monthly or seasonal variations in the load that needs to be serviced.

5. Conclusion

The main discovery of this work is the development of a supervisory system that uses a standard DAS to operate and monitor an autonomous photovoltaic system built at LAME Lab. An examination of the performance of PV energy production in the lab is presented on the basis of the measurement data. The experimental results obtained throughout the measurement campaign revealed that the PV system functions normally, with PR values ranging from 82% to 98%. However, it is more vulnerable to environmental factors, such as high temperatures. Following that, an analysis to assess sensitivity was performed using behavioral models linked to the correlation coefficients, and the results were compared to the experimental data. Monthly average performance ratios for systems using Lame Lab PV modules were found to be 4.76 percent higher than those found in the reference study [5]. In terms of performance ratios, this suggests that PV systems using polycrystalline modules are better suited for Sahelian climate conditions.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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References

[1] Ascensión López-Vargas, Manuel Fuentes, Marta Vivar, Current challenges for the advanced mass scale monitoring of Solar Home Systems: A review, Renewable Energy, Volume 163, 2021, Pages 2098-2114, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2020.09.111.

[2] Siva Ramakrishna Madeti, S.N. Singh, A comprehensive study on different types of faults and detection techniques for solar photovoltaic system, Solar Energy, Volume 158, 2017, Pages 161-185, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2017.08.069.

[3] Asma Triki-Lahiani, Afef Bennani-Ben Abdelghani, Ilhem Slama-Belkhodja, Fault detection and monitoring systems for photovoltaic installations: A review, Renewable and Sustainable Energy Reviews, Volume 82, Part 3, 2018, Pages 2680-2692, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.09.101.

[4] Dominique Bonkoungou, Sosthène Tassembédo, Sidiki Zongo, Zacharie Koalaga, "A Bottom-Up Approach to PV System Design for Rural Locality Electrification: A Case Study in Burkina Faso", Journal of Renewable Energy, vol. 2023, Article ID 8892122, 14 pages, 2023. https://doi.org/10.1155/2023/8892122

[5] Fatima Tahri, Ali Tahri, Takashi Oozeki, Performance evaluation of grid-connected photovoltaic systems based on two photovoltaic module technologies under tropical climate conditions, Energy Conversion and Management, Volume 165, 2018, Pages 244-252, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2018.03.065.

[6] Patra, A.K., Rath, D. Performance Evaluation of Grid-Connected Photovoltaic System Using EHO-Tuned VPTIDF and DQC-Based SPWM. Iran J Sci Technol Trans Electr Eng 47, 35–60 (2023). https://doi.org/10.1007/s40998-022-00541-1

[7] R. Alcharea and W. Saeed, "Evaluating Grid Connected Photovoltaic System Performance and Estimating the Produced Electric Power," 2021 12th International Renewable Engineering Conference (IREC), Amman, Jordan, 2021, pp. 1-4, doi: 10.1109/IREC51415.2021.9427842.

[8] Vaclav B, Tomae Ol, Martin Libra, Vladislav P, Jan S, Minh-Quan D, Igor T, New Monitoring System for Photovoltaic Power Plants' Management, Energies, 10.3390/en11102495, 11, 10, (2495), (2018).

[9] Hegazy Rezk, Igor Tyukhov, Mujahed Al-Dhaifallah, Anton Tikhonov, Performance of data acquisition system for monitoring PV system parameters, Measurement, 10.1016/j.measurement.2017.02.050, 104, (204-211), (2017)

[10] Rezk, Hegazy; Tyukhov, Igor; Raupov, A. Experimental implementation of meteorological data and photovoltaic solar radiation monitoring system. International Transactions on Electrical Energy Systems, (2015). doi: 10.1002/etep.2053.

[11] Jahn, Ulrike, Nils H. Reich, Stefan Mau, David Moser, Mauricio Richter and Achim Woyte. "Monitoring of Photovoltaic Systems: Good Practices and Systematic Analysis." (2013).

[12] A. Drews, A.C. de Keizer, H.G. Beyer, E. Lorenz, J. Betcke, W.G.J.H.M. van Sark, W. Heydenreich, E. Wiemken, S. Stettler, P. Toggweiler, S. Bofinger, M. Schneider, G. Heilscher, D. Heinemann, Monitoring and remote failure detection of grid-connected PV systems based on satellite observations, Solar Energy, Volume 81, Issue 4, 2007, Pages 548-564, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2006.06.019.

[13] Clifford W. Hansen, Daniel M. Riley, and Manuel Jaramillo. Calibration of the Sandia Array Performance Model Using Indoor Measurements. Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE.

[14] E. L. Meyer and E. E. van Dyk, "Assessing the reliability and degradation of photovoltaic module performance parameters," in IEEE Transactions on Reliability, vol. 53, no. 1, pp. 83-92, March 2004, doi: 10.1109/TR.2004.824831.

[15] E. E. van Dyk, A. R. Gxasheka and E. L. Meyer, "Monitoring current-voltage characteristics of photovoltaic modules," Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002., 2002, pp. 1516-1519, doi: 10.1109/PVSC.2002.1190899.

[16] Bruce Cross, Chapter III-1-C - PV System Monitoring, Editor(s): Soteris A. Kalogirou, McEvoy's Handbook of Photovoltaics (Third Edition), Academic Press, 2018, Pages 1183-1191, ISBN 9780128099216, https://doi.org/10.1016/B978-0-12-809921-6.00034-3.

[17] Mohammadreza Aghaei, Nallapaneni Manoj Kumar, Aref Eskandari, Hamsa Ahmed, Aline Kirsten Vidal de Oliveira, Shauhrat S. Chopra, Chapter 5 - Solar PV systems design and monitoring, Editor(s): Shiva Gorjian, Ashish Shukla, Photovoltaic Solar Energy Conversion, Academic Press, 2020, Pages 117-145, ISBN 9780128196106, https://doi.org/10.1016/B978-0-12-819610-6.00005-3