Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 79, No 4, 2026

ENGINEERING SCIENCES

Renewable energy

INTEGRATED MONITORING AND PERFORMANCE ANALYSIS OF OFF-GRID PHOTOVOLTAIC SYSTEMS USING MPPT CONTROLLER, SMARTSHUNT, AND TEMPERATURE SENSORS

Dinko Stoykov

Received on December 12, 2025
Presented by Ch. Roumenin, Member of BAS, on March 31, 2026

Abstract

Off-grid photovoltaic systems are increasingly deployed in mobile and remote applications, where reliable operation depends on accurate monitoring of energy generation, storage, and load behaviour. This study evaluates a compact off-grid PV system installed in a campervan, integrating a Victron MPPT 100/20 charge controller, a 150 Ah AGM battery, and a Victron SmartShunt for high-resolution measurements. Operational data were collected over a one-month period under varying weather and usage conditions. The results show that combining MPPT-based control with shunt-based monitoring provides detailed insight into daily energy cycles and highlights key factors influencing energy autonomy, including temperature effects, shading, and high-demand loads. Battery behaviour emerges as a primary determinant of overall system stability. The findings demonstrate that even small mobile PV systems can significantly benefit from advanced monitoring, enabling more informed energy management and improved reliability in off-grid environments.

Key words: photovoltaic systems, off-grid, MPPT, SmartShunt, battery monitoring, energy efficiency

Introduction. Growing interest in self-sufficient energy systems has accelerated the adoption of off-grid photovoltaic (PV) solutions in both stationary and mobile contexts. Their appeal lies not only in the ability to operate independently

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`https://doi.org/10.7546/CRABS.2026.04.10`

from unstable or inaccessible electrical grids, but also in their capacity to support a wide range of applications, ranging from rural households and remote monitoring stations to recreational vehicles. As recent studies show, a key challenge for such systems is maintaining stable power delivery despite fluctuating irradiance, variable load patterns, and battery degradation over time. MACABEBE et al. [1] show that high transient loads and poor battery health can significantly reduce off-grid system performance, highlighting the importance of continuous monitoring.

Recent developments in solar power research demonstrate increasing attention to system optimisation and monitoring. Several authors have explored enhanced PV performance through thermal or structural improvements. SOFIJAN et al. [2] show that passive cooling techniques can significantly increase module efficiency in hot climates. Others have focused on system sizing and economic feasibility. KARMAKAR et al. [3] highlight that even relatively simple off-grid configurations can achieve long-term financial benefits if loads are accurately assessed and components are selected to match real-world demand. More elaborate system designs, such as the large residential installation described by ABU SAMAH and TAPRI [4], show how careful planning of voltage level, protection devices, and storage capacity is crucial for meeting daily consumption requirements. Studies of hybrid or region-specific designs, such as the work of EMIRALIOGLU et al. [5] and OZOGBUDA and IQBAL [6], similarly emphasise the importance of aligning energy generation, storage, and consumption patterns with local conditions and user needs.

Despite these advances, relatively limited research focuses on compact, mobile off-grid systems used in campervans or other nomadic settings, where available roof area, battery size, and daily load variations impose strict constraints on energy management. Such systems often rely on user intuition rather than proper diagnostic information, which may lead to poor utilisation of the battery, suboptimal loading of the solar modules, or premature component degradation. The emergence of intelligent MPPT charge controllers and high-precision current shunts, such as the Victron SmartShunt, creates an opportunity to overcome these limitations by enabling detailed, continuous, and non-intrusive monitoring of the system.

This study aims to address this gap by presenting a practical and data-driven evaluation of a complete off-grid PV system installed in a campervan. By combining MPPT-based solar regulation, temperature-aware charging, and shunt-based load characterisation, we analyse how the system behaves under real operating conditions, including variations in weather, shading, and user activity. The month-long dataset provides insight into daily energy cycles and highlights which factors most strongly influence energy autonomy. Ultimately, the work contributes to a better understanding of how small off-grid systems can be monitored, interpreted, and optimized, offering guidance for both recreational users and designers of lightweight autonomous power platforms.

Theoretical background. Research on off-grid photovoltaic systems spans applications from agricultural automation to residential and mobile energy supply. In controlled-environment agriculture, BOUARROUDJ et al. [7] demonstrate that IoT-based monitoring combined with adaptive control can stabilize operating conditions and improve energy efficiency – an approach also relevant for mobile off-grid systems with limited energy resources.

Reliable operation further depends on real-time system visibility. SOBOTIK et al. [8] show that long-term monitoring of energy balances is essential for identifying inefficiencies and properly sizing components, with even modest improvements in data collection enhancing system stability.

Energy storage remains a key performance factor. ALAM et al. [9] report that lithium-ion batteries require smaller PV capacities than lead-acid systems due to superior charge-discharge efficiency, a conclusion reinforced by HASAN and ALTINOLUK [10], who highlight the role of advanced charge-controller topologies in extending battery life and improving energy throughput.

Economic and performance optimisation has also been widely studied. UZAIR et al. [11] identify daily load demand, maintenance, and financial parameters as dominant cost drivers in off-grid BIPV systems, underscoring the importance of careful parameter selection, particularly in space-constrained mobile installations.

Data-driven approaches increasingly shape solar energy research. ALAY et al. [12] show that large PV datasets require distributed computing platforms for efficient training of deep learning models. Related studies by KIHTIR and OZTOPRAK [13] and ABAD-ALCARAZ et al. [14] demonstrate that machine-learning-based solar radiation forecasting significantly improves prediction accuracy and supports adaptive energy management.

Similar trends appear in maximum power point tracking research. Learning-based MPPT controllers outperform classical algorithms under dynamic conditions. YOUNAS et al. [15] and ROY et al. [16] report improved power extraction using LSTM-based controllers, while reinforcement learning approaches, such as the DQN-based method by GIRALDO et al. [17] and the evolutionary neural-network strategy of KHAN et al. [18], enable accurate global maximum power point tracking.

Methodology. The experimental setup is based on a compact off-grid photovoltaic system installed in a campervan and designed for autonomous operation under varying outdoor conditions. The overall system architecture and energy flow are illustrated in Fig. 1, which presents the connection between the PV array, charge controller, SmartShunt, battery, and DC loads.

The system consists of three main subsystems: (1) photovoltaic generation, (2) power management and monitoring, and (3) energy storage and load distribution. The PV array comprises two 170 W monocrystalline modules connected in series, providing a nominal capacity of 340 W. Energy from the panels is regulated by a Victron SmartSolar MPPT 100/20 charge controller, selected for its

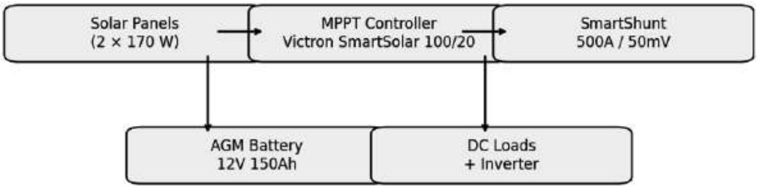

Fig. 1. Architecture of the off-grid PV system installed in the campervan

high tracking efficiency, 100 V input tolerance, and maximum charging current of 20 A. System-wide current flow, battery state of charge (SOC), and cumulative energy balance are monitored using a Victron SmartShunt 500 A/50 mV installed on the negative bus.

Energy storage is provided by a 12 V, 150 Ah AGM deep-cycle battery (Kraft Plus), configured with standard AGM charging parameters (absorption voltage 14.7 V and float voltage 13.7 V). All DC loads, including a compressor refrigerator, ventilation fan, lighting, and a 12 V inverter, are connected downstream of the SmartShunt to ensure complete monitoring coverage. The system employs a single-bus DC architecture, with all negative connections terminating at the SmartShunt SYSTEM – terminal, allowing accurate measurement of all charging and discharging currents. Positive branches are individually fused to ensure safe operation in a mobile environment.

Charging parameters were configured via the VictronConnect application using Bluetooth communication. Temperature compensation was applied at −24 mV/°C for the complete 12 V AGM battery (−4 mV/°C per cell across six cells). The SmartShunt was calibrated and synchronized with the charge controller to improve SOC estimation accuracy.

Operational data were recorded continuously using the VictronConnect interface, providing access to battery voltage, current, SOC, PV input power, PV voltage, and load consumption. Historical logs stored by the SmartShunt captured charging cycles, energy throughput, voltage extrema, and load profiles over a 30-day period covering typical campervan usage, including stationary operation, driving conditions, and varying weather scenarios. The resulting CSV datasets were processed in Python using Pandas for data preparation and Matplotlib for visualisation, ensuring traceability and reproducibility of all figures presented in this study.

Results and discussion. The month-long dataset collected from the MPPT controller and the SmartShunt provides a clear representation of the campervan system's daily energy balance. Overall, the results confirm reliable operation under varying environmental conditions, while also revealing several factors that strongly influence performance and energy autonomy.

Daily solar production (Fig. 2) follows the expected diurnal profile, with peak generation occurring around midday and a rapid decline after sunset. Weather

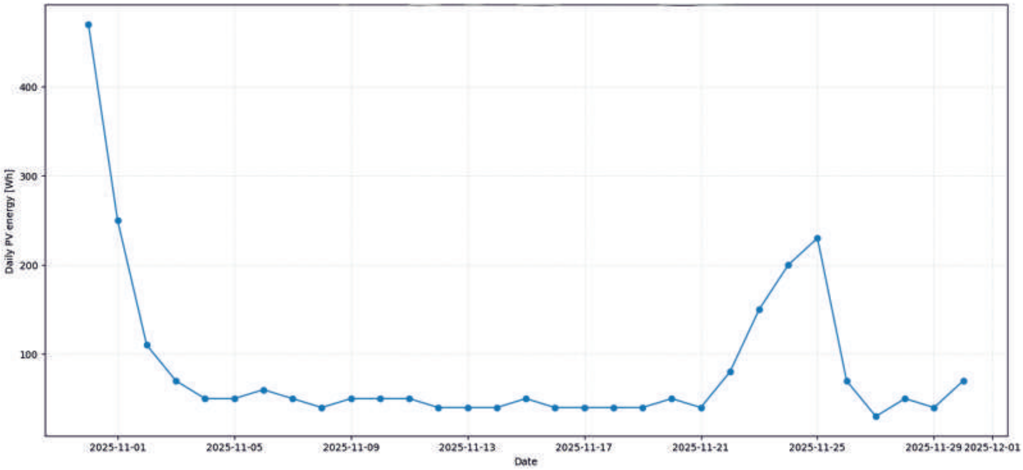

Fig. 2. Daily solar energy yield of the campervan PV system

conditions exert a strong influence on system output: during overcast days, daily energy generation falls to less than half of clear-sky levels, and peak charging currents rarely exceed 8–10 A. In contrast, sunny conditions regularly produce charging currents of 15–18 A, approaching the upper operational range of the MPPT controller. These observations underline the importance of continuous monitoring, as available solar energy can vary substantially not only between days but also within a single day.

Battery behaviour (Fig. 3) further clarifies system performance. SmartShunt data show that the AGM battery typically returns to float voltage (13.6–13.8 V) on sunny days, indicating full charge recovery. During extended cloudy peri-

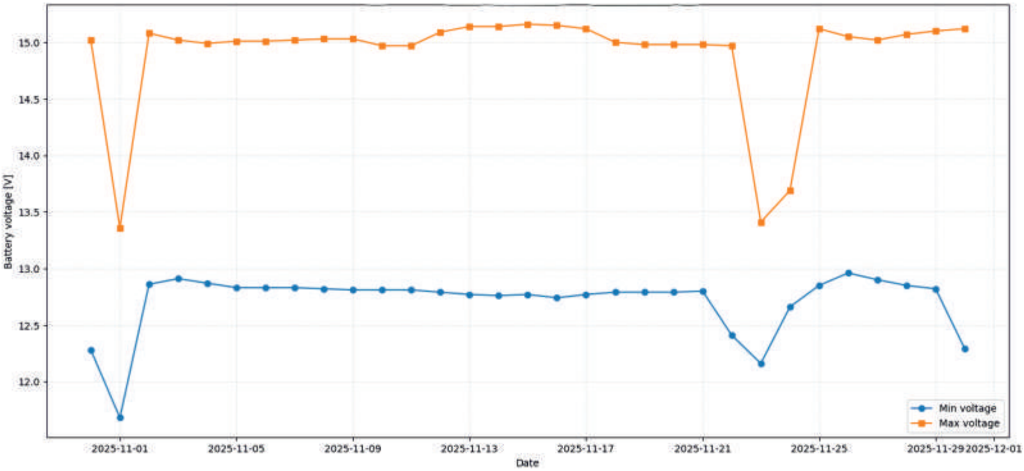

Fig. 3. Daily minimum and maximum battery voltage

ods, minimum voltage occasionally drops to the low 12-V range, reflecting partial depletion. While still within safe limits for AGM chemistry, sustained low state-of-charge may accelerate ageing. Short load surges, such as refrigerator or fan activation, also reveal the relatively high internal resistance characteristic of lead-acid batteries.

Load data reveal consistent usage patterns. Base loads, mainly the refrigerator, ventilation fan, LED lighting, and auxiliary electronics, create a nearly constant daily demand of approximately 120–200 Wh. Short peaks occur when multiple appliances operate simultaneously. Although brief, these peaks impose a disproportionate load on the battery due to its limited usable capacity. SmartShunt measurements show noticeable voltage drops even at moderate currents of 10–15 A, highlighting the value of detailed monitoring for understanding real-world behaviour in small autonomous systems.

A key trend in the dataset is the charging-discharging mismatch typical of off-grid operation: energy generation is concentrated during daylight hours, while most consumption occurs in the evening. Although battery storage compensates for this imbalance, the results confirm that storage capacity and battery health remain the primary constraints on energy autonomy. This observation is consistent with previous studies identifying battery sizing as a dominant limiting factor in off-grid systems [3, 10]. While the AGM battery performs adequately under moderate loads, the data suggest that a lithium-iron-phosphate ($LiFePO_4$) alternative would offer improved usable capacity, reduced voltage sag, and greater resilience during multi-day cloudy periods.

Additional insight is obtained from the analysis of charging stages (Fig. 4). The MPPT controller maintains stable maximum power point tracking under high irradiance, with only minor deviations during rapid cloud transitions. This

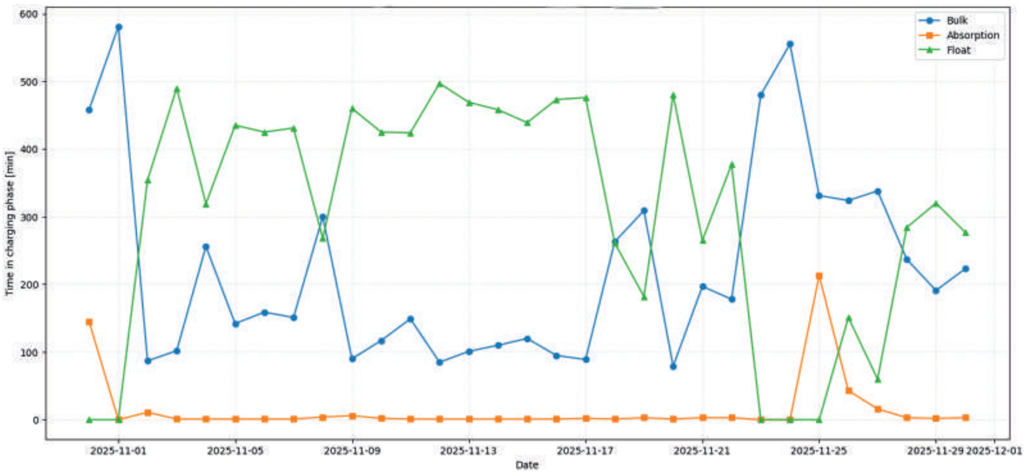

Fig. 4. Daily time spent in bulk, absorption and float charging phases

behaviour is consistent with findings reported in comparative MPPT studies [15]. The distribution of time spent in bulk, absorption, and float stages closely follows irradiance conditions, with extended float periods on clear days and prolonged bulk charging during overcast conditions. This pattern further illustrates the strong coupling between weather variability and achievable energy autonomy.

The dataset further demonstrates the value of temperature-compensated charging. The controller appropriately increases absorption voltage during colder conditions and reduces it during higher temperatures, in line with manufacturer recommendations. This regulation helps protect the AGM battery from overcharging or undercharging and is particularly important in a campervan environment, where temperature fluctuations are common.

Overall, three key findings emerge. First, combining MPPT logging with high-resolution shunt measurements enables a clear and reliable assessment of real-world system performance. Second, the AGM battery represents the primary limitation to energy autonomy, especially during extended low-irradiance periods or high-load events. Third, the results indicate clear optimisation pathways, including increased PV capacity, $LiFePO_4$ battery upgrades, and predictive energy management strategies similar to those proposed in recent forecasting and optimisation studies [12, 14].

Conclusion. This study investigated the performance and operational dynamics of a compact off-grid photovoltaic system installed in a campervan, based on high-resolution measurements collected by a Victron MPPT controller and a Victron SmartShunt over a one-month period. The results confirm that even small mobile solar installations can provide reliable energy autonomy when properly configured and continuously monitored. Despite the modest installed capacity of 340 W, the system regularly reached absorption and float charging stages, indicating that the 150 Ah AGM battery was generally maintained within healthy operational limits.

The analysis highlights the pronounced seasonal sensitivity of small PV systems. Daily energy yield varied considerably, with most days remaining below 100 Wh and only one day exceeding 400 Wh. This underscores the importance of realistic expectations when sizing campervan solar installations, particularly during periods of reduced irradiance and shorter daylight hours. Battery voltage trends and recorded charging stages further revealed periods of deeper discharge, which, if frequent, could negatively affect battery longevity.

A key strength of the proposed setup lies in the integration of high-resolution current and energy monitoring via the SmartShunt, enabling transparent energy auditing and early identification of potentially harmful operating conditions. These findings align with previous research emphasising the role of continuous monitoring in improving reliability and preventing premature degradation in off-grid PV systems. Even at small scale, data-driven oversight proves valuable for understanding real-world system behaviour under variable and unconstrained operating conditions.

Overall, the study demonstrates that the combination of an MPPT charge controller with precise shunt-based monitoring provides a robust foundation for energy autonomy in mobile off-grid applications. Future work may explore larger storage capacities, $LiFePO_4$ batteries, or predictive models for solar generation and load demand, contributing to more adaptive and resilient off-grid energy systems.

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Department of Electronics and Technological Education, Technical Faculty,
South-West University "Neofit Rilski", 66 Ivan Mihaylov St, 2700, Blagoevgrad, Bulgaria
e-mails: `dinkostoikov@gmail.com`, `dinkostoikov@swu.bg`
(`https://orcid.org/0000-0003-3361-0617`)