24th International Conference on Renewable Energies and Power Quality (ICREPQ'26)
Santander (Spain), 10th to 12th June 2026
ISBN-13: 978-84-09-82044-3

Stand-Alone Solar Systems: an Educational Platform for Undergraduate and Graduate students

V. Boitier[1], J.Dedieu[2] and H. Martinetti[2]

[1] LAAS-CNRS, Université de Toulouse, CNRS, Toulouse, France
[2] Université de Toulouse, Toulouse, France
vboitier@laas.fr

Abstract. This work features two off-grid photovoltaic systems, each with a power of 400 Wp, equipped with a battery storage system (24V 110Ah). One is designed to power 24 V DC loads, the other 230 V AC loads. Both installations are fitted with monitoring equipment (measuring electrical parameters, irradiance and temperatures) and the measurements are recorded in a database. These installations offer numerous opportunities for students from undergraduate to postgraduate level. Quite simply, a screen allows real-time analysis of energy transfers and operating modes throughout the day. For more complex long-term analyses, the database created enables the evaluation of solar resources, analysis of system operation and validation of its design. It also allows for energy assessments, evaluation of efficiencies, comparisons with a system simulation results , etc.

Key words. Photovoltaic, Autonomous System, Database, Monitoring

1. Introduction

The study of photovoltaic systems includes a theoretical part, but the practical element enables students to gain a thorough understanding of the concepts, best practices and limitations of these systems.

Photovoltaic systems can be divided into two groups: grid-connected systems [1] and energy-autonomous systems [2]. The work presented in this article focuses on the installation and use of off-grid photovoltaic systems [3], capable of supplying power for DC or AC loads.

Setting up practical work for autonomous photovoltaic systems with an electrical power of 200 to 400 Wp from the photovoltaic generator becomes complex when it comes to moving a 2 m² solar panel weighing 26 kg. Whilst a spotlight can be used as a substitute for sunlight when powering small solar panels, this becomes difficult to install and justify from the perspective of sensible energy use when it comes to lighting large solar panels.

Consequently, the panels in this study are installed outdoors on the roof, with cables connecting them to the classroom where the rest of the equipment is installed.

A major drawback using photovoltaic is the intermittent nature of solar energy. In order to demonstrate the different possible operating phases regardless of sunlight conditions, two 375 Wp stand-alone solar systems have been set up in a practical work room. These systems have been instrumented [4-8] with a recording of the measurements on a computer. A screen displays the system layout, shows the power flows in real time and graphs show the measures for the last 24/48 hours.

The DC or AC loads can be easily modified according to the objectives.

Analysis of the data previously recorded [9] provides an understanding of how these systems work, distribution of powers and their limitations under various configurations (variable weather conditions, battery charge levels, modular loads, etc).

For beginners, these systems serve as a basis for understanding electrical design. For more expert audiences, the results obtained are also analysed and compared with the results from system simulations. The generated database is here perfectly known and mastered and complements the existing offer [10].

The simulations are carried out using PVGIS, PVsyst, or a software developed in our laboratory [11] using meteorological data provided by SoDa or NASAPower. Simulations works are not presented in this paper.

To summerize, these two systems are used for practical work and design tasks. It offer students the opportunity to work on a wide range of topics:

- Analysis of the design / Validation of the design
- Measurements and related calculations (efficiency,…)
- Instrumentation and calibration
- Database management
- Simulation with effective simulation/measurement comparison.

Having described the systems set up in Part Two, Part Three presents some experimental results. Finally, future prospects are discussed to complement the experimental training in photovoltaics provided at the university.

2. Description of the two systems

The experimental platform is composed of two systems **System 1** and **System 2** exhibited respectively on Fig. 1 and Fig. 2. Each of the systems is equipped with measurement instruments (current, voltage) to measure the input or output power.

Fig. 1 shows System 1 from the perspective of the wiring connections. Fig. 2. provides a clearer understanding of power exchanged between the stages (green arrows). Both systems share the same basic structure, but with a few notable differences.

The following sections describe these structures in detail.

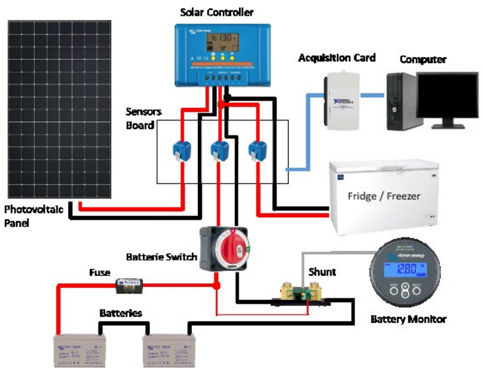

Fig. 1 Schematic diagram of ***System 1****.*

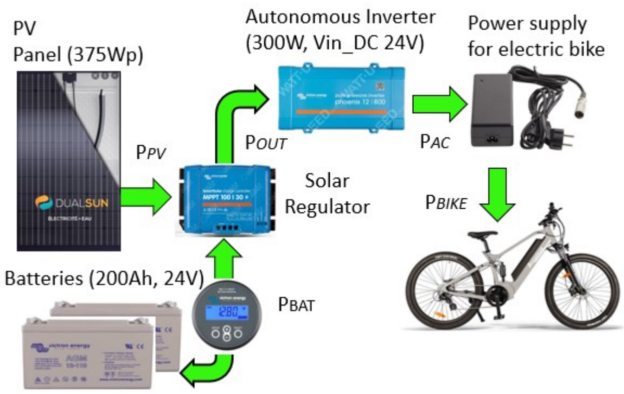

Fig. 2 Visualization of powers on ***System 2****.*

A. Around solar panels

Four solar panels (Fig. 3) are installed above the practical work room. To avoid compromising the building's waterproofing, they are attached to the side wall of an adjoining lecture theater, which has constrained their positioning: facing 58° northeast, tilted 28° from the horizontal for the Dualsun panels and 8° for the Voltec panels.

The two panels used permanently to power System 1 and Sytem 2 are Dualsun Spring 375 Shingle Black panels (375 Wp, Voc 48.9V, Vmp 40.4V, Isc 9.89A, Imp 9.28A @ STC: 1000W/m², 25°C, AM1.5, 1.65x1.14 m², 26.3kg). Water can circulate behind each panel to ensure cooling. Initially, one of these two panels was connected to a chiller so that performance could be compared at different temperatures, but the refrigeration unit's electricity consumption was too high in summer. This option was abandoned and the water was removed from the panel.

To allow for future system upgrades, or for other tasks that can be carried out without having to access the panels outside, two other panels (Voltec VSPS 250-L, 250 Wp, Voc 37.6V, Vmp 30.6, Isc 8.64A, imp 8.2A @ STC: 1000W/m², 25°C, AM1.5, 1.65x0.99 m², 18kg) are also installed on the roof.

The connections for the four panels are routed to the practical work room and connected to the systems via a switch/disconnector closed to the electrical cabinet. This switch allows you to disconnect the panels if you wish to work safely on the installation.

The Dualsun panels are equipped with sensors: 2 thermocouples measure the temperature at the back of each panels while another thermocouple measures the ambient temperature 20 cm behind the panel. A SPLite2 pyranometer measures the irradiance (W/m²) in the same plane as the Dualsun panel with an accuracy around 5%. These four measurements are wired and sent back to the room.

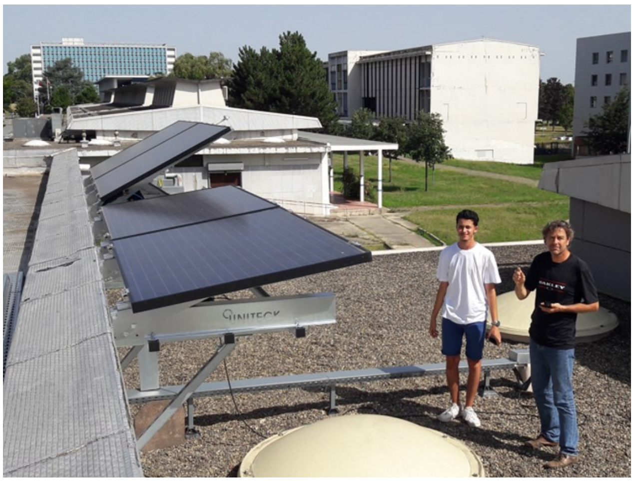

Fig. 3 Solar panels above the practical work room.

Fig. 4 Photo of the two systems installed in the electrical cabinet. (The batteries are under the table, the stand-alone inverter is on the table with the measurement PC and active loads. The solar panel connections are at the top right.).

B. Solar Controller.

The solar controller is essential. It is connected to the solar panel, the battery and the load. It must protect the battery (against overcharging and deep discharge) and, where possible, optimise the harvesting of solar energy when the battery is not fully charged (MPPT function: Maximum Power Point Tracking).

Two different Victron regulators are used. **System 1** uses a BlueSolar PWM DUO LCD&USB 12/24V 20A charge controller. This regulator is a **PWM** type (The panel voltage is equal to the battery voltage when the battery is not full. The panel switches to open circuit when the battery is charged). It offered two battery connections, but only one is used here. An USB output (5V,2A) can be used to charge a phone if necessary.

System 2 features a Victron SmartSolar 100/20 charge controller with a **MPPT** function (Based on a buck totopoly, it accepts a maximum PV voltage of 100V, a battery voltage of 12, 24, or 48V, and a PV or battery current of 20A, PV nominal power : 580W at 24V). A Bluetooth app allows you to configure the regulator remotely on your mobile and to view currents and voltages.

C. Around Batteries.

Both systems are designed to operate at 24V DC, taking into account the voltage of the solar panels and the selected loads (fridge, off-grid inverter).

Each system is connected to two lead-acid batteries connected in series (Victron Energy Blue Power, Gel 12V 110Ah@20h, Standby: 13.5V 13.8V@25°C, Cycle: 14.4V, 14.7V @25°C). Close to the batteries, there is also a 30A fuse in series to protect against short-circuiting of the batteries. Outside the cabinet, on each system, a bipolar battery switch (400A 12V/24V/48V) allows to disconnect the batteries during maintenance phases.

For safety reasons, the batteries are placed in a plastic tray with natural ventilation.

On each system, a Victron Energy BMV 712 Smart Bluetooth battery monitor measures the current (via a 500A 50mV shunt) and the battery voltage, and also displays those values, and the battery's state of charge.

D. DC and AC Load.

Various loads are implemented:

System 1 powers a DC-powered Load : a Steca PF166-H 12V/24V A++ 166 liter **fridge/ freezer** with a power rating between 50 and 70W. It can be used either as a refrigerator or a freezer. It will operate here at the battery voltage, which is approximately 24V.

System 2 powers various AC-powered loads such as an electric bike charger or a laptop charger. In both cases, the load requires an alternative voltage, 230VAC 50Hz, which necessitates the use of a stand-alone inverter. A Victron Pure Sinewave Phoenix inverter 24V/250 (200W@25°C, 175W@45°C, DC low shut down : 18,6V) model was chosen and is connected between the regulator output and the load.

For specific tests, we also use an RS PRO RS-KEL103 active load (300W 0-30A 0-120V), which can simulate different consumers. For example, you could simulate charging an electric bike every day to see if the system would be capable of handling this.

E. Monitoring.

For each system, 3 voltages and 3 currents are measured at the battery, panel, and load levels. Two similar circuit boards have been produced and calibrated simultaneously using a power meter (Fluke Norma 4000). They are designed to convert the measured quantities to voltages compatible with the data acquisition boards. On each board, three voltages are measured using suitable voltage divider circuits (accuracy < 0,5 %). The three currents are measured using three LEM LTS-25 NP Hall-effect sensors. This sensor outputs a voltage proportional to the current flowing through it and allows measurements up to ±25A with an accuracy better than 0,7%. Its 5V power supply is provided by a 24V/5V power supply unit continuously powered by the battery.

This data, combined with 3 temperatures and irradiance data, are collected on acquisition cards (NiUSB6210, Ni6009 for voltages (accuracy < 0,2 %) and DAQ9171 for temperatures) and then recorded in a daily .csv file.

At each acquisition cycle, the software developed using Labiew® collects 1,000 data points sampled at 1 kHz for all parameters, corresponding to an acquisition time of 1 second, and retains only the average of these values with an accuracy better than 0,7% on measured votage, 0,9% on measured current and better than 2% on calculated power. The temperature measurement provides a value at each cycle. A measurement cycle is initiated approximately every 4 seconds. This implies that the measurements are only carried out for about 25% of the time but this does not decrease the quality of the results because the variations remain slow.

The actual data is displayed on the computer screen (see Fig. 5). Two days of measurements are also displayed on the PC screen (cf Fig. 7) .

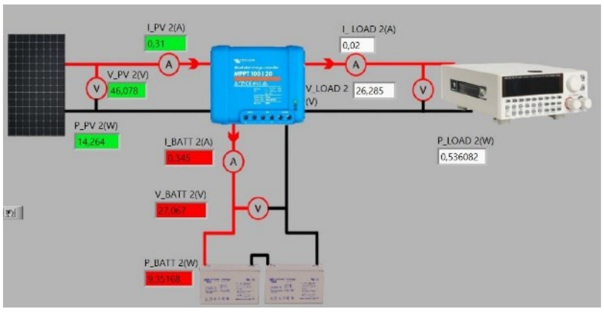

Fig. 5 Display of electrical values live on the computer (green for the PV generator, red for the battery and white for the load.

3. Somes Results

A. Validation of the sizing.

As a first step, students must verify that the main components of the system have been correctly sized, which requires them to search for and study the technical documentation.

1) Voltage validation.

The battery pack voltage is 24V. All the loads are compatible with this voltage level; the fridge adjusts automatically its input voltage (12/24V) and the stand-alone inverter is specifically designed for a 24V voltage. Controllers for System 1 and that for System 2 automatically adapt to the battery voltage (12/24V for one, 12/24/48V for the other).

2) Current validation.

Let us consider the extreme cases.

No load to power. The selected panel can deliver 10A and 375 Wp. For PWM regulator 1 (**System 1**), in the absence of a load, the current in the battery will therefore be the PV current with a maximum of 10A, which is acceptable (20A rated). For MPPT regulator 2 (**System 2**), assuming 100% efficiency, with a power output of 375 Wp, it should supply the battery (@24V) with a current of 15A, which is entirely acceptable for both the battery and the regulator. Indeed, the documentation for the 110 Ah battery shows maximum C1 curves, which corresponds to a current of 110A, and the regulator's documentation shows that it accepts 20A.

During the night. The photovoltaic power is zero. The freezer requires a maximum power of 70W, which, at 24V, equates to a current draw of 3A from the battery. It is therefore more than compatible. Infact, the off-grid inverter can supply a load of 200W. It is therefore important not to exceed this limit to avoid damaging the inverter. The power consumption figures we tested are well below this: charging an electric bike at 80W, powering a computer at 50W. For a maximum consumption of 200W, assuming an efficiency of 80%, the inverter draws 250W and therefore, at 24V, requires a current of 10A from the battery.

The system is therefore correctly sized.

B. *One day visualization of variables*

In the second stage of the exercise, students must analyse the daily curves (current, voltage and power, in relation to irradiance and the loads in use). They can view the graphs directly on the control screen (which show the last two days' measurements) or use the recorded data to analyse various weather conditions, for example.

The analysis provides a clear understanding of how the systems operate throughout the day. Some typical graphs and explanations are presented and analysed below.

1) *System 1.*

Fig. 6(a) shows, for **System 1**, the voltage of the photovoltaic panel, the battery voltage and the load voltage. Below (Fig. 6(b)), the irradiance and the battery power are displayed.

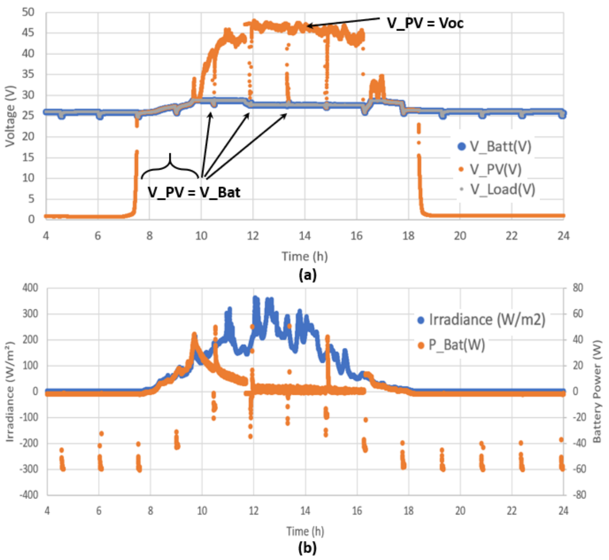

Fig. 6 monitoring of the **System 1**.(2025.02.09)

When the battery power is negative, this indicates that the battery is discharging. The load here is the fridge, with a power consumption of either zero or approximately 60W, cycling approximately four times in six hours.

When the sun rises, the battery is not fully charged (it has discharged overnight), so the PV voltage is equal to the battery voltage, which is typical of a PWM-type regulator (cf Fig. 6(b) between 7.45 am and 9.45 am). Then, when the battery is fully charged, the panel remains in open-circuit mode (between 12:00 and 16:00). The power received by the battery is then zero.

Between these two states, the system alternates at a low frequency (a few Hz) between VPV = VBAT and VPV = Voc, but as the measurement records the average value over a 1-second time interval, we simply see an average value changing over time between the two values. The closer <VPV> gets to Voc, the more the PBAT power decreases (this corresponds in Fig. 6(b) to the time interval between 9.45 am and 12 noon).

Between 12 noon and 4 pm, there are a few instances where the VPV voltage returns to the same level as VBAT; this occurs when the fridge starts up, causing VBAT to drop sufficiently for the regulator to determine that the battery is not fully charged. It then reconnects the panel to the battery.

As expected, this figure also shows that the load voltage is equal to the battery voltage, which is normal as there is no output voltage regulation stage on this type of regulator.

2) *System 2*

Fig. 7 below shows part of the dasshboard It shows the evolution over two days of the voltage of **System 2** which use a MPPT regulator. The regulator's operating phases are clearly visible. When V_{PV} is closed to Vmp ≈ 40V with a ripple, it indicates that the system is operating close to the maximum power point (the controller is then in MPPT mode). When the battery is sufficiently charged, the system then switches to floating mode (regulating the battery voltage to VBAT = 27V; the photovoltaic input compensates for the load demand during this phase). As consumption was low that day, VPV is close to Voc (PPV = 0 @Voc)

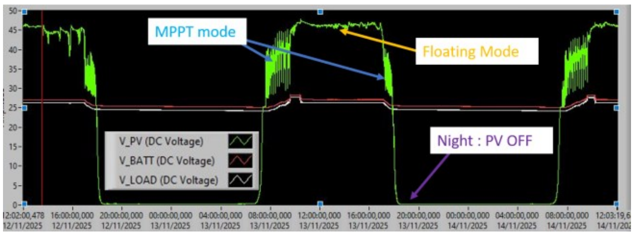

*Fig. 7 Two-day visualisation of variables (here, **system 2** voltages)*

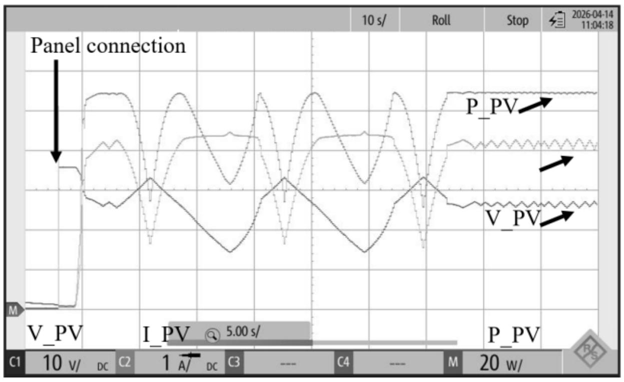

*Fig. 8. Start-up after connecting the solar panel (**system 2**)*

It should be noted that the data acquisition system has a limitation. As only a 1-second average is recorded every 4 seconds, this makes it difficult, if not impossible, to visualise certain fairly rapid phenomena, such as the system start-up. In this case, a Rhode & Schwarz

RTH1002 oscilloscope with isolated inputs and a Fluke i30s current probe is used to display voltage and current. Fig. 8 thus shows the start-up when the solar panel is connected. It can be seen that, after a one-minute transient, the system settles into MPPT mode with a small ripple close to the maximum power.

C. Complete Autonomy

To ensure the system is completely off-grid, the PC that stores the measurements and powers the data acquisition cards must not be connected to the University's power network. Consequently, it is powered by System 2 via a stand-alone UPS. Unfortunately, the old PC used and its monitor are hungry consumers

At t0 (14:00 on February 10, 2025), the PC switches from a conventional power supply via the electrical grid to a power supply from the output of the autonomous inverter. The consumption of the PC and the inverter is practically constant and measured at 57.7W. As it can be seen on the Fig. 9 and Fig. 10 curves, the battery recharges partially during the day, but insufficiently. After 2 days and 11 hours, the autonomous inverter disconnects in the morning of the 4th day as the battery voltage has fallen below the the minimum allowed threshold. It stops the measurements (time t1 on the Fig. 10).

The balance sheet between t0 and t1 shows :

- Energy consumed by the load (PC and inverter) Eload = 3382 Wh,
- Energy given by the solar panel Epv = 1409 Wh
- energy received by the battery Ebat = -2301 Wh. Ebat is negative as the battery gives energy to the load.

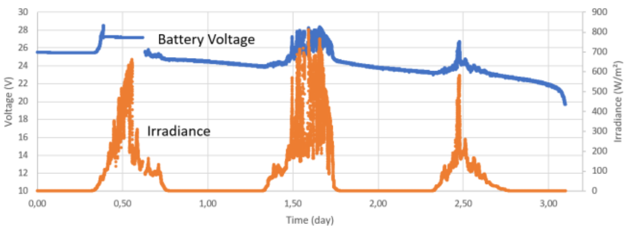

Fig. 9 Battery Voltage and Irradiance

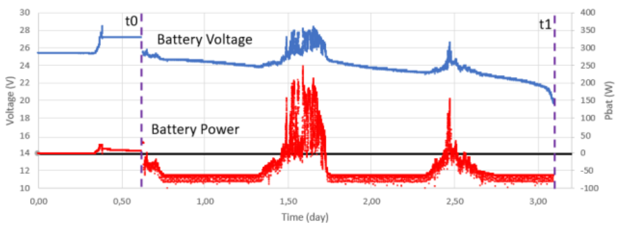

Fig. 10 Battery Voltage and Battery Power

The global efficiency during this period is noted η_{GLOB} and defined as following:

$$\eta_{GLOB} = (Eload) / (Epv + |Ebat|) \qquad (1)$$

$\eta = 91\%$
during the same period,

The global PV efficiency η_{PV} can be calculated as follows :

$$\eta_{PV} = (Epv) / (Irr) \qquad (2)$$

With

$$Irr = \int_{t0}^{t1} G(t).S\, dt \qquad (3)$$

G is the sun irradiance expressed in W/m² and *S* is the PV surface S = 1,88m².

η_{PV} = 19,3%. This value must be compared with the efficiency of the PV panel in STC : η_{PV_STC} = 20%. This means that during this period, System 2 was still operating in MPPT mode and that the MPPT command is efficient.

C. Visualization of refrigerator consumption.

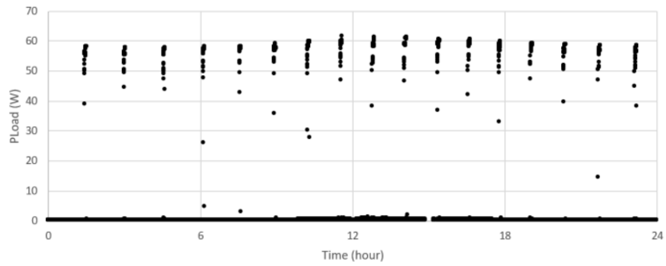

Fig. 11 Refrigerator consumption.

The measurements also enable consumption of electrical loads to be calculated. For example, based on consumption records and integration of the power (see Fig. 11), daily consumption for the refrigerator is found to be 71 Wh in feb.2025 which is very low with a average power of 3Watts.

4. Improvements and prospects

We recently replaced the old computer with a more efficient laptop, which consumes much less energy and finally allows to have a completely energy-independent system that does not rely on the electrical grid. Its consuption is around 17 W.

To complete the offer of photovoltaic systems, we have also had a 2kWp grid-connected photovoltaic installation on the university campus for the past 15 years, which transmits data on irradiance, temperature and electrical parameters (current,voltage, power).

Finally, to cover the diversity of photovoltaics, we will supplement the systems and implement a 3kWp system combining both connection to the power grid and Lithium battery storage.

In the near future, the data will also be available via the University's open database, which will make it easier for students to use.

5. Conclusion

The two systems presented in this paper have now been installed for three years and work without any problems.

Students can see inside the electrical cabinet and at the same time look at the displays. This allows them to fully understand how it works and its limitations. The use of data recorded on long duration offers many opportunities for study, making these systems truly interesting at different levels of students knowledge.

These systems and the database we have built open up many possibilities that have not been explored in this paper. For example, when working with the data, our students process CSV files using Matlab or Excel, which enables them to hone their skills in these software programmes and in managing large files. The system can also serve as a platform for work related to instrumentation (including calibration). Finally, for ongoing research, we are currently using this data to compare irradiance predictions under partial shading with results from simulations.

Acknowledgement

This project was partially funded by the Interreg Sudoe Tr@nsnet project.

References

[1] F. Zalamea-León , M. Astudillo-Flores et al., Incidence of non-working days on limiting photovoltaic potential on a building with day-hours high power consumption, without storage and grid injection, 22nd Int. Conf. on Renewable Energies and Power Quality (ICREPQ'24), Bilbao, June 2024

[2] V.Boitier , K.B.K. Cao et al., Solar Power Supply for Sensor Applications in the Field : A Guide for Environmental Scientists, Solar, Nov. 2024, 674-693, doi.org/10.3390/solar4040032

[3] Hong T. T. Vu, B.Delinchant et al., Autonomous Electrical System Monitoring and Control Strategies to Avoid Oversized Storage Capacity, 6th Int. Conf. on Environment and Renewable Energy, Feb 2020, Hanoi, Vietnam. hal-03259954

[4] P. Kuznetsov, V. Gubin et al., Autonomous solar measurement system for sustainable solar energy, Int. Journal of Energy and Water Resources (2025) doi.org/10.1007/s42108-024-00312-0

[5] F. Sanchez-Sutil, C.R. Baier et al., Design and implementation of a low-cost, open-source power quality analyser for smart grids, Internet of Things, Volume 37, May 2026, 101922

[6] S. Mohanty, P. Sahu et al., Integrated Solar Microgrid with Real-Time Data Acquisition and Web-Based Dashboard for Monitoring, 2025 IEEE 2nd Int. Conf. on Green Industrial Electronics and Sustainable Technologies (GIEST), Jamshedpur, India, 2025, pp. 1-4, doi: 10.1109/GIEST66547.2025.11387284..

[7] C.A. Petilla, E. M. Querikiol, Design and implementation of a localized monitoring for gel-type battery with fault detection and identification, Journal of Engineering and Technology for Industrial Applications, DOI: 10.5935/jetia. v11i56.2704

[8] J. P. Garhewal, A.Lal et al, Real Time Date Monitoring of PV Solar Cell, Journal of Engineering and Technology Management 73 (2024)

[9] Norridah Amin et al, Towards Smart Campus of Universiti Malaya: Realization of Real-time Building Energy Monitoring System (BEMS) 2025 ,IOP Conf. Ser.: Earth Environ. Sci, 1560 012065

[10] X. Chen , B. Li et al. Open data sets for assessing photovoltaic system reliability, Applied Energy 395 (2025) 126132, doi.org/10.1016/j.apenergy.2025.126132

[11] V. Boitier; V. Mahout et al., Mermoz© simulator : Use of a database to estimate the photovoltaic input on a UAV. Application to a transatlantic voyage, Drone Systems and Applications, aout 2025, doi.org/10.1139/dsa-2025-0003