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Integration of Renewable Energies in Mobile Employment Promotion Units for Rural Populations

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Abstract

The article aims to analyze, evaluate, and improve solutions for the integration of hybrid energy sources (Solar Photovoltaic PV/Batteries/Diesel Generator (DG)) in mobile service units (MSU), designed to provide services to rural populations (drug delivery, vaccination, training, employment promotion, bank, laboratory, etc.). The first objective is to evaluate the performance of two already deployed photovoltaic systems installed on the roofs of trucks, with respective powers of 2.12 and 3.54 kWp. Solar production, consumption, and SOC (State of Charge) of batteries are collected and analyzed. We modelled the energy conversion chain and simulated its behavior on all days of the year. Simulated results are then compared to the on-site measurements. Several association scenarios (PV/batteries) are then studied to propose the optimal combination, taking into account the surface offered for the installation of the PV modules (roof of the truck), the weight, and the lifespan of the batteries. The developed and deployed solution proposes more advantageous association scenarios (PV/Storage), and reduces the time of recourse to the DG. From this perspective, we simulated the operation of the hybrid system for the three battery capacities: 40,000, 31,680, and 19,200 Wh (~1667, 1320, and 800 Ah). The results reveal that the uncaptured energy for a 3540 Wp field is five times greater than that of a 2120 Wp field. On the other hand, the number of battery charge/discharge cycles is divided by ten.

Keywords: Hybrid Energy System; PV System; PV/Diesel/Battery Storage System; PV for Truck; Mobile Service Units.

1. Introduction

The depletion of fossil fuels, the increase in the demand for electrical energy, the need to decarbonize the economy, and international conflicts, such as the war in Ukraine today, are pushing the various countries to accelerate their energy independence and resort to renewable energies produced locally [1, 2]. The use of renewable energy concerns all sectors of activity (industry, transport, buildings, agriculture, etc.).

Mobile Service Units (MSU) are beginning to take advantage of these energies, which can provide them the autonomy and independence from the electricity grid [3, 4]. The MSU is a service delivery unit that brings the services provided closer to rural populations or those living far from urban centers. It is made up of a mobile team traveling using a vehicle adapted to the geographical and climatic conditions to bring services closer to the population. These units are an effective development tool in Morocco, where a significant part of the population is made up of sedentary people established in rural and peri-urban areas. The use of energy MSUs can be optimized to reduce investment costs while guaranteeing the availability of energy and mitigating the vagaries of the network [5]. Renewable energy sources (Photovoltaic (PV) in particular) and energy storage systems (batteries), combined with the use of high energy efficiency

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equipment, make it possible to provide these units with reliable, available, and low-cost energy. This article presents a study on the integration of photovoltaic energy into an employment promotion MSU. This is an aspect of the problem addressed in our thesis devoted to improving the performance of MSUs manufactured in Morocco.

After a brief review of the literature and industrial concerns about MSUs, a state-of-the-art was established and served as a reference for our study. Following the analysis of this state of the art, we noted that the constraints specific to MSUs (limited surface area for the installation of PV panels; weight constraints; maintenance requirements; the longevity of storage batteries; and limitation of the operating time of the emergency diesel generator) are not treated, which justifies our work, carried out within the framework of industrial collaboration.

We first contributed to the production of the first version of a hybrid energy source MSU equipped with PV panel (2.12 kWp)/Storage batteries (approximately 20 kWh)/Diesel generator. We monitored its operational performance in the field, and collected and analyzed operating data (PV production, MSU consumption, battery SOC, etc.). We then proposed a model of the hybrid sources and developed an algorithm that scrutinizes the energy operation of the MSU on every day of the year. Several scenarios of PV-batteries associations are presented, analyzed and compared in order to propose the optimal solution meeting the need for the load while guaranteeing the longevity of the batteries. Three battery capacities (40,000, 31,680 and 19,200 Wh) and two capacities of the PV array (3540 and 2120 Wp) are analyzed. Two combinations ("2120 Wp for the PV and 31,680 Wh for the battery" and 3540 Wp for the PV and 19,200 Wh for the battery) are retained as optimal choices.

2. Literature Review

The issue we are dealing with is topical and subject to many recent developments and advances. Isolated sites as well as those connected to weakly secured grids are increasingly powered by hybrid sources combining one or more renewable resources (PV and/or wind power …). The electrical network when it exists and/or a diesel generator only act as emergency source.

Abundant scientific literature is devoted to the power supply of hybrid systems at isolated sites in rural or peri-urban areas and, to a lesser extent, to energy systems on board mobile utility vehicles, to energy systems on board vehicles and to commercial goods vehicles. Our study focuses on a particular vehicle, straddling the cases mentioned, a case rarely encountered in the scientific literature. The vehicle in question is a mobile unit that delivers medical, training, employment promotion, banking, laboratory, etc. It consists of an office, a clinic, a medical laboratory, a workshop, etc., and moving around a given place requires energy to function, which is not always available locally. Our concern will therefore be to con-tribute to supplying these site vehicles with clean and reliable energy. The analysis of the prospected literature led us to classify the isolated sites into three categories illustrated in Figure 1.

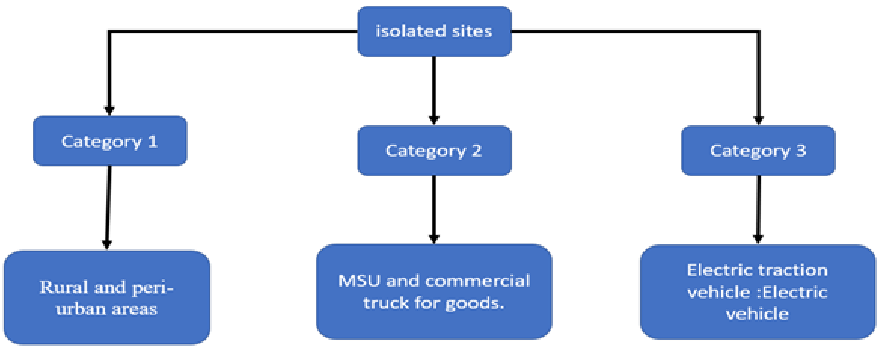


Figure 1. Categorization of isolated sites

For the three categories, the common concern is to maximize the contribution of Renewable Energies (RE) to satisfy the load and to optimally cover the intermittences of RE by suitable storage. Our site belongs to category 2. The following bibliographical summary provides an inventory of the concerns and developments made in hybrid systems for isolated sites, positions our project, and justifies its objectives and the developments carried out. Only Category 1 and 2 systems are discussed. Electric vehicles are not covered by this study.

2.1. Synthesis of the Scientific Literature Relating to Category 1 Isolated Sites

The major concerns of researchers dealing with the energy supply of isolated sites relate to the management of hybrid sources, the development of control strategies, aspects of optimization and impact on the environment.

El-Houari et al. (2020) established a technical-economic evaluation of a hybrid system ensuring the continuous power supply of 10 houses in an isolated village, Tazouta, located in the Moroccan region of Fez-Meknes. The renewable energies considered are solar, wind and biomass. The results reveal that for an average energy requirement of 91.38

kWh/day and a peak load of 6.44 kW, the unit energy cost of the optimal configuration scenario (PV-Wind-Biomass-Battery) is 0.2 $/kWh. The optimal distribution for the site corresponds to 11% wind, 41% solar, and 48% biomass. The proposed combination can reduce up to 26.48 tonnes and 28.814 tonnes of CO_2 emissions [6]. Shezan et al. (2019) designed a photovoltaic (PV)-diesel-battery hybrid system with backup power from a 5kW diesel generator. The authors observed through numerical simulation (Homer and PVSYSYST software), that the load demand of 38 kWh/day combined with a peak load of 5 kW for 37 family units for an ecotourism area of Malaysia can be met by a PV-diesel-battery hybrid source at a levelized cost of energy (COE) approaching 0.895 $/kWh and a net present cost (NPC) of 158,206$. COE and CNP have been minimized based on the current market price [7]. Murugadoss et al. (2021) focused on the design of a control system for hybrid renewable energy sources for rural areas in India, with automatic switching of power supply from the grid to the hybrid system, in the event of low voltage or power outages = blackout. Power outages result in villages in these areas receiving less than 12 hours of supply and reliance on other energy sources such as wind, solar, biofuels, etc. becomes a necessity. By measuring the state of charge (SoC) of the batteries associated with the hybrid sources, the switching of the sources can be automated using a control system that works with threshold values. When a power source fails, the power automatically switches to the next priority source. The designed hybrid system does not need an Internet connection to operate but it guarantees a continuous power supply [8].

Kamalesh and Kulkarni (2020) designed and evaluated using the PVsyst software a PV solar roof with a power of 2kWp (close to the power implemented in our study). The authors have optimized their system via numerical simulation to bring production closer to the load profile. Consumption needs are met over the year, but with a share of unconsumed energy estimated at 30% of the energy produced. This surplus could be used for battery storage or injected into the grid [9]. Haffaf and Lakdja (2019) deal with the optimization of a hybrid PV/Diesel system with storage intended to supply electricity to an isolated rural site in M'Sila (Algeria). Using the computer model implemented in the Homer® software, the authors proposed a configuration optimizing on the one hand, the dimensioning of the PV modules, the capacity of the storage batteries and the capacity of the diesel generators, and the cost overall system, on the other hand. The results obtained were applied to a pilot site whose daily consumption is estimated at 9.8 kWh/day with a maximum power demand of 2.1 kW. 86% of the site's energy production is produced by the photovoltaic generator the rest (14%) is provided by the conventional energy source (diesel). Maintaining the minimum battery charge greater than or equal to 30%, the generator set only operated for 839 hours with 64 starts per year. The annual reduction in CO_2 emissions achieved is around 90%. The optimization and the PV/Diesel combination used have also made it possible to reduce the sizes of the photovoltaic generator and the storage capacity, thus reducing the total cost of the investment [10]. Barun and Mahmudul (2021) proposed a more complex hybrid system, consisting of PV/Diesel/PHS (Pump Hydro Storage), to meet the energy need of an isolated community of 50 households in Bangladesh. Several configurations (PV/PHS, Diesel/PHS and PV/Diesel/Battery) are compared using the HOMER software and an application based on genetic algorithms. This study showed that the PV/Diesel/PHS system is more expensive but more efficient than the hybrid PV/Diesel/Battery system [11].

Krishan et al. (2019) carried out the techno-economic analysis to meet the residential and agricultural electricity demand of a small rural community in India. The HOMER software is used to determine the optimal configuration among the following scenarios: Wind/Battery, PV/Battery, and Wind/PV/Battery. The Wind/PV/Battery configuration has been found to have the best NPC and COE to meet demand. This optimal configuration was subsequently modeled by MATLAB Simulink to provide detailed information on the different components and the control strategy used for energy management in the proposed system. The simulation results demonstrated that the proposed system maintains the active power balance between supply and demand with 0% unmet demand regardless of variations in solar radiation, wind speed and load connected [12]. Moien et al. (2019) present a palliative solution to the problem of electricity in Gaza, Palestine, which is only available 4 to 10 hours a day for political reasons. The proposed system includes PV modules associated with a hybrid inverter and a battery, and connected to the electricity grid. It is sized for the needs of a home consuming daily energy of around 10 kWh. The simulation results obtained show that the monthly energy produced by the PV system exceeds the energy consumption for nine months (from March to November). The excess energy produced will be partly used to recharge the battery pack and the other part injected into the grid. During the remaining three months, characterized by low solar radiation, the PV energy produced barely meets the load's needs. Over the entire operating time, the SOC of the battery varies between 40 and 85%. Its minimum value never drops below 40% even during the most unfavourable months (December-February) [13].

Javed et al. (2020) compared the different combinations of renewables (solar, wind) combined with storage technologies (battery, pumped hydro storage, hybrid storage) for an off-grid power system in an island. The authors examined nine different solar/wind/battery/PHS con-figurations and two scenarios based on ESS self-discharge (0 and 1%). The study reveals the importance of HPBS in the off-grid RE environment, enabling more flexible power management, helping to ensure 100% power supply with minimum cost and reducing power consumption. The sensitivity analysis carried out by varying the load demand and the energy balance made it possible to show the efficiency of the two storage units in hybrid mode. Energy storage in hybrid mode increased the total energy coverage by 48% and reduced the COE, which reduced the direct dependence of RE intermittency [14]. Lanre Olatomiwa (2016) assessed the optimal renewable energy con-figurations of a hybrid source for dispensaries in three off-grid rural villages in Nigeria. The simulation of operation by the HOMER software led to the selection of a PV-Wind-Diesel-Battery hybrid system as the optimal solution for two sites and a PV-Diesel-Battery system for one site. The generator-only system is considered the worst configuration with the highest NPC and COE, despite its low capital cost. The integration of renewable energies in the sites studied made it possible to avoid between 87 and 96% of CO2 emissions [15].

Through the literature synthesized, we see that developments are constantly progressing to achieve increasingly ambitious objectives in terms of reliable hybrid sources, off-grid and off-GE operating autonomy, wider coverage radius, investment and operating cost. The design of solutions that often use software such as PVSYST and HOMER and based on advanced optimization algorithms (genetic algorithms, etc.). These developments will be exploited in our study. It is noted that the issues of longevity of the components of hybrid sources, in particular that of the batteries, are not sufficiently addressed and this important point will be developed in our study.

2.2. Synthesis of the Scientific Literature Relating to Category 2 Isolated

The inventory concerns, here, mobile service units or transport vehicles carrying products that need energy on board such as refrigerated trucks or mobile cliques.

Refrigerated semi-trailers have undergone extensive research aimed at generating energy through photovoltaic panels mounted on the roof of the trailer. Excess energy is stored in an onboard battery for use by the refrigeration system during hours of dark-ness. This solution advantageously replaces systems based on diesel generators that generate high maintenance costs and environmental impacts. With regard to mobile installations, dedicated approaches are developed, in particular for long-distance transport covering hundreds of kilometers with variable climatic zones per day.

Kühnel et al. (2017) developed an algorithm for calculating a weather profile along a given trajectory, including solar irradiance, ambient temperature, and wind speed. The simulations, for three utility semi-trailer trucks operating in Germany, gave a potential annual energy yield of 3 to 7 MWh depending on the cell technology used. The potential energy gain due to head wind cooling is estimated at between 20 and 75 kWh per trailer per year [16]. Vulpe et al. (2019) developed a viable method of integrating photovoltaics in truck trailers, based on algorithms and control structures for photovoltaic mi-cro-grids; which reduced specific disturbances and provided better predictability. The power generated by the PV source is measured through the use of photoresistors [17]. Kutter et al (2021) investigated the potential of vehicle-integrated photovoltaics (VIPV) on commercial trucks and vans in Europe. They considered the motion pattern in the yield calculation to determine the share of solar yield harvested during standby and while driving. Break-even analysis showed that irradiation, electricity prices, and vehicle charging efficiency are critical factors that impact the profitability of VIPV systems. However, break-even points ranging between 3.5 and 7 can already be reached [18]. Mingyang et al. (2021). Studied the current application of solar, wind, and fuel cell power in ship power systems. The authors carried out an economic and environmental analysis of the hybrid system. The analysis results demonstrate that the optimal hybrid energy system can reduce CO_2 emissions by 151,467 kg and provide 2.92% electricity for the ship's belt per year with a payback period of 2.3 years [19].

Few scientific articles in the literature deal with the issue of the integration of renewable energies in MSU which, on the other hand, have been the subject of industrial achievements in several sectors: mobile banks, mobile clinics, mobile training units, etc. For example, Higier et al. (2013) designed and developed a mobile medical clinic powered by renewable energy with a hybrid system combining PV, wind and Lithium batteries, all backed up by a generator. The prototype produced is deployed in the Dominican Republic. The thin-film photovoltaic panels are integrated on the roof of the tent which serves as a clinic and generate 4.8 kW of power as well as two wind turbines with a unit power of 1 kW. The system provides 3 kW of continuous power with a maximum renewable energy output of 6.8 kW. A control system is designed for battery charge management, power distribution and generator set automatic start/stop [20-24]. This solution is impractical due to the necessary installation space, time and qualified human resources for assembly and dismantling operations at each site served. Hussein et al. (2017) studied a PV renewable energy system for a mobile hospital in Libya and showed that the combination (PV, battery, and backup GE) is a suitable solution to power mobile units in the regions without electricity [25-29]. The study was limited to the design and simulation of operation without experimental validation.

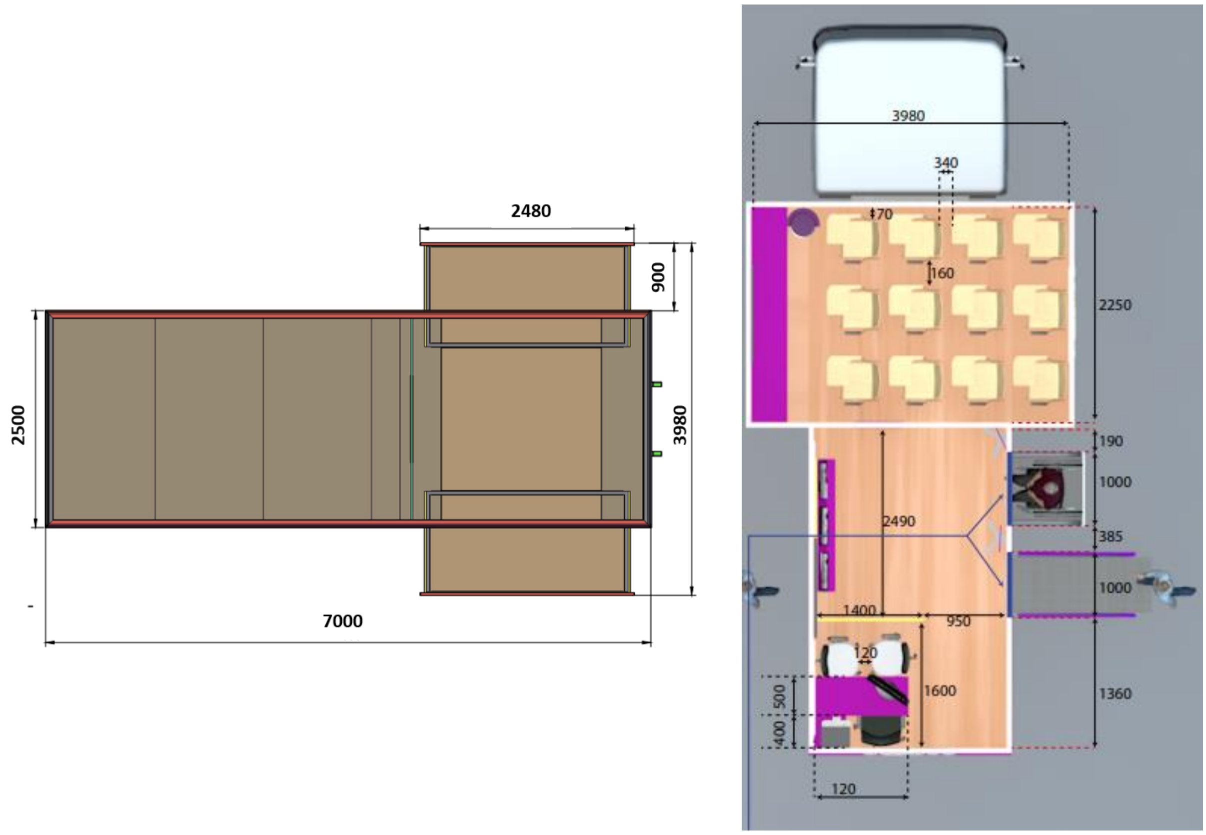
In all the cases mentioned above, the constraints of the surface available to fix the PV panels, combined with the constraints of the volume and the weight of the batteries as well as the generator are not dealt with. Furthermore, the optimization solutions studied do not take into consideration the imperative of minimizing the charge/discharge cycles of the batteries (for greater longevity) and the intervention time of the emergency generator (to save energy and reduce the pollution). Our contribution, presented in this article, constitutes a contribution that addresses these shortcomings.

3. Martials and Methods

The MSUs subject of our study is those acquired or in the process of being acquired by the National Agency for the Promotion of Employment and Skills (ANAPEC). In-tended for rural and peri-urban populations, they have been used since 2019 to provide services to young job seekers via mobile counselors made available to them by ANAPEC. Figure 2 shows two types of these MSUs. The inside of the truck consists of: One office; Reception area with 3 shelves; Meeting room for 10-15 people with projection equipment (Figure 3).

(a) (b)

Figure 2. Examples of MSU in service at the ANAPEC: (a) MSU commissioned in 2019 (14 T); (b) MSU commissioned in 2021 (18 T)



(a) (b)

Figure 3. Plan and exploded view of the MSU 14 T: (a) Plan MSU; (b) Exploded view

3.1. Energy Requirement

The power demanded by the MSU is calculated from the power balance of the various sheltered equipment (Table 1).

Table 1. MSU power balance (Abundant powers)

Local	Abundant Power (W)
Training room	1 968
Job space	1 753
job interview desk	185
Sanitary	465
Various	1 415
Total (W)	5 786
Total Abundant (W)	4 340

It is rated at 4.3 kW. The daily energy needs are also estimated. Average consumption is assessed at 11 kWh based on an average power demand of 1.6 kW during active hours (10 a.m. to 4 p.m.) and 80 W elsewhere (1.6×6 + 0.08 × 18 = 11.04 kWh).

3.2. Solar Producible

The surface available on the roof of the vehicle to accommodate the PV panels is equal to 17.5 m². This surface made it possible to install 8 panels with unit power of 265 Wp, i.e. a total of 2120 Wp (Figure 4).

Figure 4. PV modules were installed on the roof of the truck

Based on an average producible of 1700 kWh/kWp, the expected average daily production is estimated at 10 kWh/day. This corresponds well to the estimated consumption need.

3.3. Sizing of Battery Requirements

To size the capacity of the batteries, we considered a consumption requirement of up to 15.6 kWh to take into account seasonal variations (Value from a field benchmark):

$$C = (Ec \times N) / (D \times U) \quad (1)$$

where C is battery capacity in ampere-hours (Ah), EC is energy consumed per day (Wh/d) (according to the power balance), N is number of days of autonomy, D is maximum permissible discharge (0.8 for lead batteries), U is battery voltage (V). By choosing U = 24 V with a depth of discharge of 80%, a day of autonomy would lead to a capacity of 15,600×1/ (0.8×24) = 812.5 Ah or 19,500 Wh.

3.4. Adopted Configuration

The adopted architecture of the hybrid power supply is illustrated by the following block diagram (Figure 5).

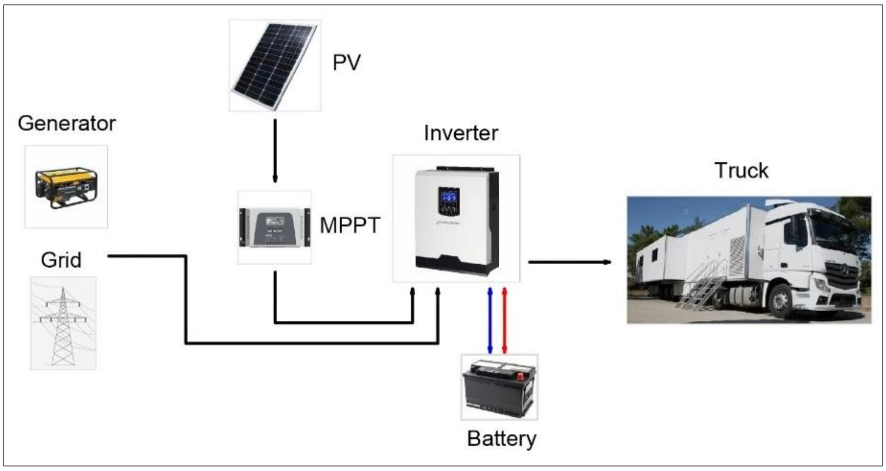


Figure 5. Synoptic diagram of the adopted hybrid source solution

The described components (Solar panels, batteries) are complemented by a charger converter that can be automatically connected to two independent AC sources. This choice gives the possibility of connecting an emergency generator but also of connecting to the grid when it is available on the site served. The power of the generator set (8 kVA) is chosen on the basis of the established power balance. Table 2 summarizes the characteristics of the main components of the considered hybrid source.

Table 2. Components of the MSU power supply system

Elements	Quantity	Unit characteristics	Total
PV panels	8	265 Wc	2120 Wc
Battery	12	2V/800Ah	19 200 Wh
Diesel Generator	1	8 kVA	Provides backup in the event of insufficient power (PV + batteries) and lack of connection to the Grid

Figure 6. Installation of the components of the solar system under the frame

The specifications for the realization of the hybrid system presented were drawn up by us after a technical and financial optimization. The objective is to respond to the first urgent request from ANAPEC and to evaluate performance in the field for improvements that will be applied in an upgrade framework and to be implemented in future MSU. The manufactured unit has been deployed in the field since 2019 and since then it has been regularly monitored. We collected and analyzed the results with a view to proposing solutions for improvement.

4. Analysis of MSU Energy Monitoring Results

Field monitoring of the units has shown that the need for electrical energy is, in the majority of cases, satisfied by the couple (PV + batteries) without the need to call on the network or the generator.

4.1. Typical Readings across the Kingdom

The monitoring in the field focused mainly on the powers produced by the PV source and that consumed by the MSU as well as on the SOC of the battery, through recordings and measurements taken at time intervals of a few minutes during the operation of the MSU. We have processed and analyzed the data collected for the different geographical areas served by the MSU. Figure 7 are some examples of results obtained in the Marrakech-Safi region and the Beni Mellal-Khénifra region.

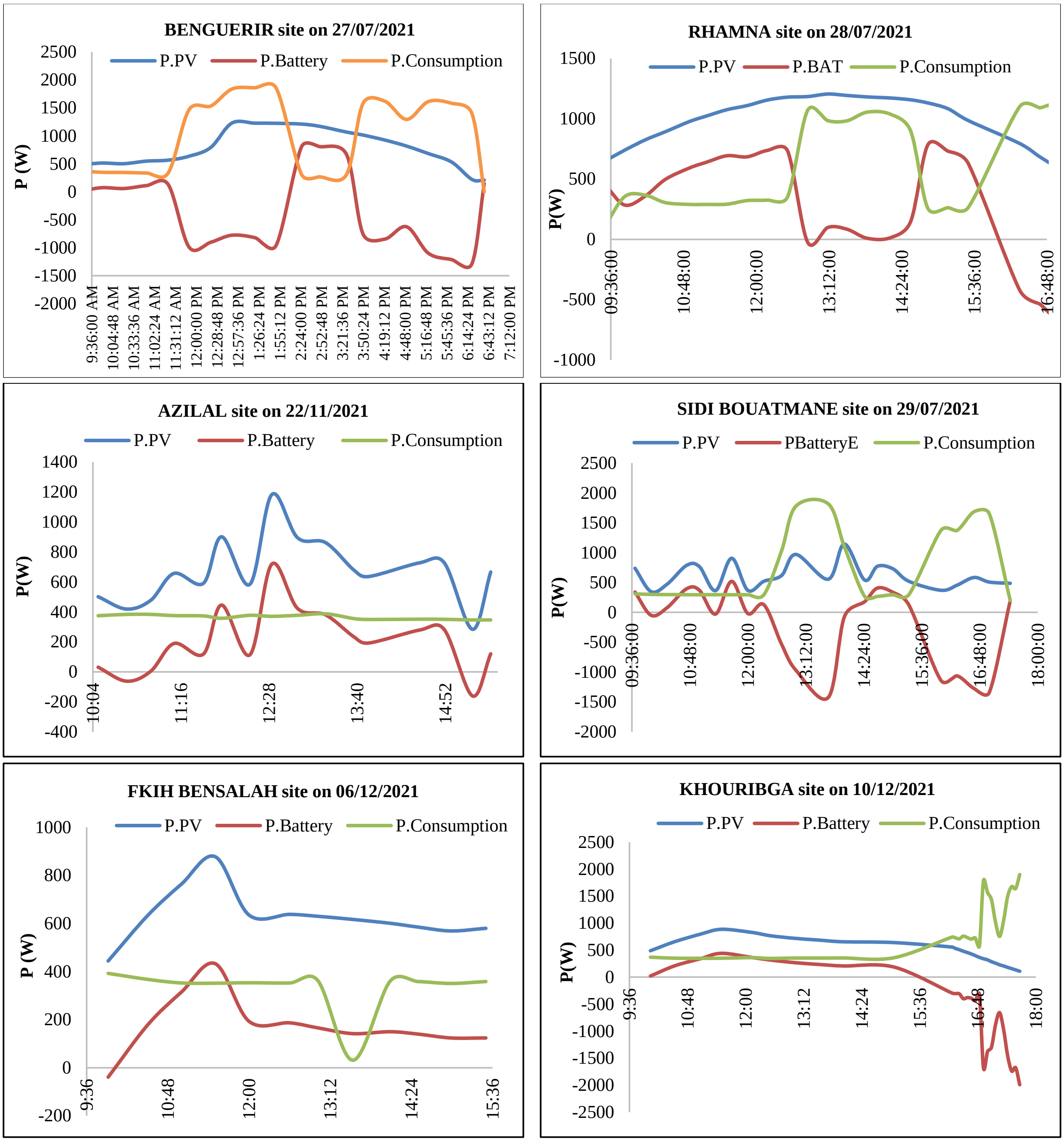


Figure 7. Example of the evolution of PV power, power consumed, power supplied or received from the batteries during a day on a given site

We were able to follow the MSU over almost a year in order to analyze the impact of sunshine which affects PV production and the impact of the HVAC (Heating, ventilation, and air conditioning) system which affects the load. We noted that over the entire period explored, it was not necessary to use the network or the DG. The hybrid power system only ran on PV backed up by the batteries.

4.2. Assessment of the Performance of the PV Source on Board the MSU

We compared the results of measurements taken on the MSU during its operation at Ben Guerir (Morocco) on 07/27/2021 and those generated by simulation using the PVGIS software [30, 31]. The coordinates of the site (32.14 N latitude; 7.96 E W longitude, height of 474 m) are entered into the calculation software, as well as the power of the PV source. The theoretical production curve is finally compared with the measurements of the day in question.

Figure 8 shows the powers produced as well as the trend curve while Figure 9 gives the superposition of the power measured and that obtained via PVGIS.

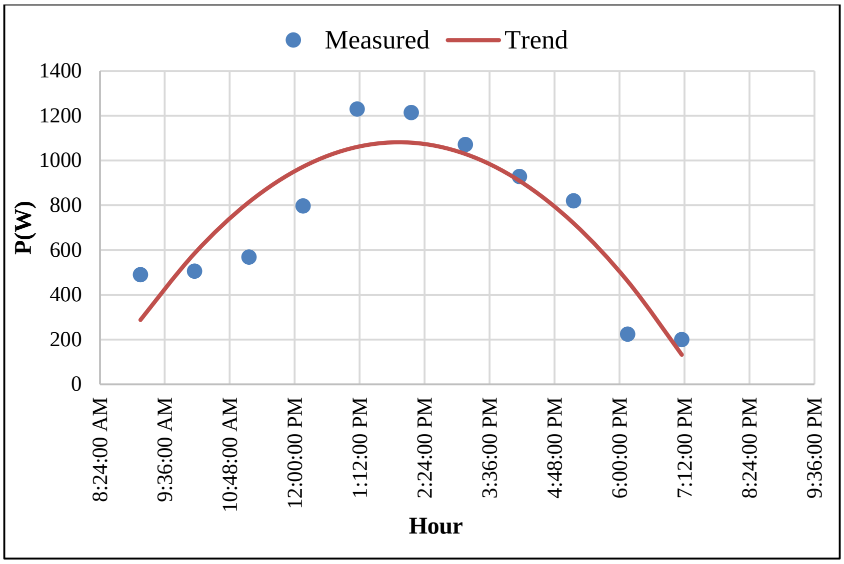


Figure 8. Measured generated PV power and its trend curve

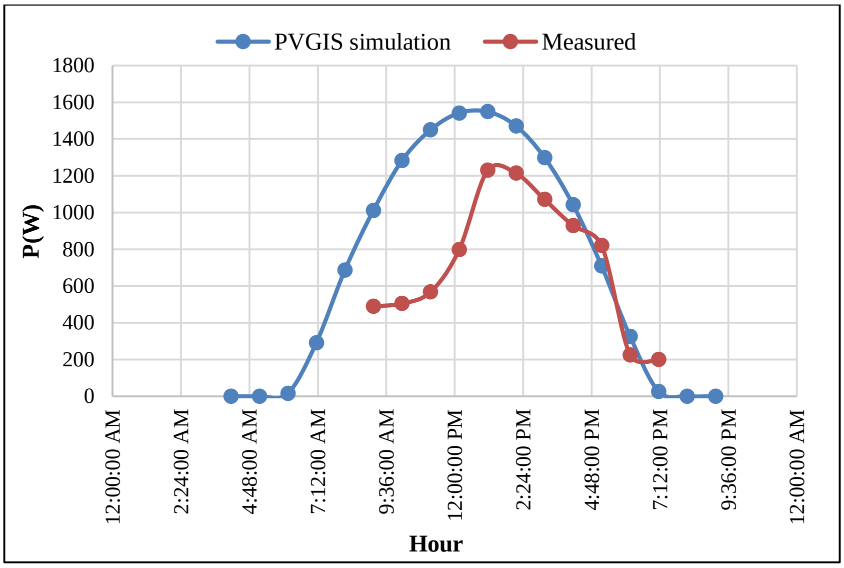


Figure 9. Observed PV production vs. production given by simulation with PVGIS on 07/27/2021

The observed deviation is attributed to local weather conditions which would not be identical to those of the same day given by PVGIS, to aging, and to dirt deposited on the PV modules. We also compared the SOC calculated from the initial battery charge and the production given by PVGIS to the SOC (Figure 10).

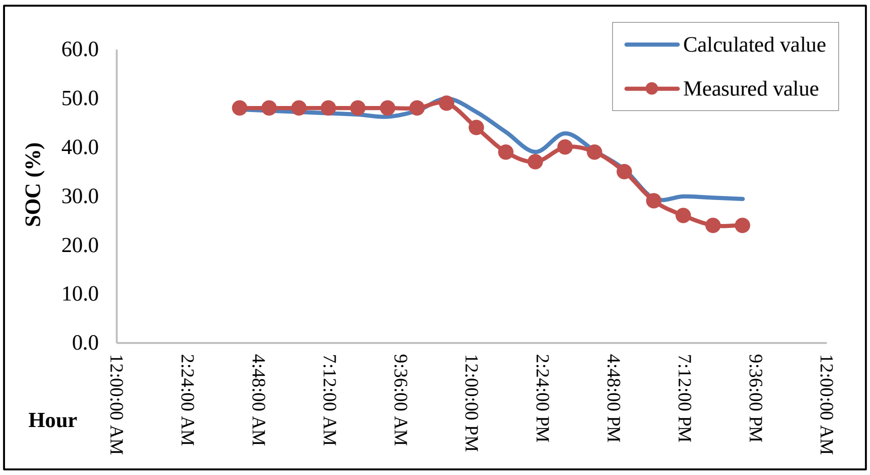


Figure 10. Evolution of the battery SOC during the day of 07/27/2021

During the day of observation, the battery charge was initially at a level slightly below 50%. At the end of the day, it went almost to the SOC limit of 20%. We will come back to this situation later.

5. Modeling and Simulation of the Operation of the Hybrid Energy Supply Source of the MSU

The design of the energy source solution on board the MSU carried out is based on an average annual model. Daily, weekly and monthly variations are not taken into consideration as well as the impact on the battery charge and discharge cycles. In order to achieve an optimal solution, we proposed modeling of the hybrid system and analyzed several PV/Battery combinations in order to best reduce the call on the grid and/or generator.

5.1. Presentation of the Modeled System

The hybrid energy source that equips the studied MSU is composed of:

- PV modules covering the roof of the vehicle;
- The energy storage battery;
- The hybrid inverter;
- The generator;
- The cable reel can be connected to the electrical network when possible.

The hybrid system can be schematized as in Figure 11.

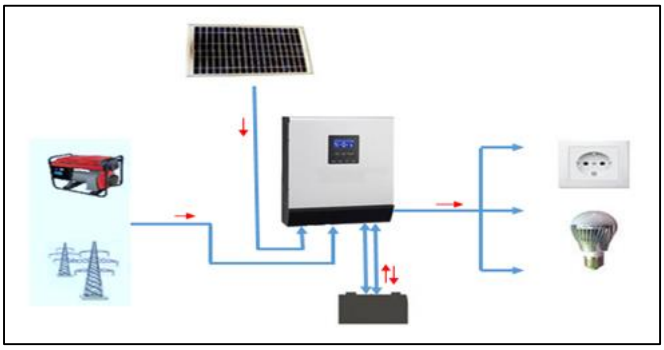


Figure 11. Schematization of the hybrid source to be modeled

At every moment, PC is calculated using Equation 2:

$$\mathrm{PC} = \mathrm{PPV} + \mathrm{PG} + \mathrm{PBat} \tag{2}$$

where, PPV is Power supplied by the PV source, PG is Power supplied by the grid or the Diesel Generator, $PBat$ is Power exchanged with the battery, PC is Power demanded by the load.

The load is supplied primarily by the PV source with the following scenarios:

- If the need is satisfied, the surplus is used to recharge the battery until its maximum level is reached and there, the residual is not recovered (Energy not recovered).
- If the need is not satisfied by the PV, the battery provides the rest as long as its charge EB (expressed in Wh) is greater than the minimum threshold EBM associated with the battery.
- If the need is not satisfied by the PV and the battery reaches Ebm, the grid or the generator set comes into action to satisfy the use and charge of the battery.

5.2. Functional Modeling

The operation of the system is modeled over an entire year on the basis of:

- Daily solar production (Hourly data: from midnight 0 to 23 h. with a step of h = 1 hour) provided by the PVGIS simulation (A free tool for simulating solar production anywhere in the world). The PV power is given in the form of a column matrix of 326 × 24 = 8760 elements.
- The battery is initially charged to its maximum energy (EBM, expressed in Wh).
- The time matrix T also contains 8760 points, successively 1, 2,3,……, 24, 25, …, 8760

Figure 12 shows the flowchart of the proposed operating algorithm.

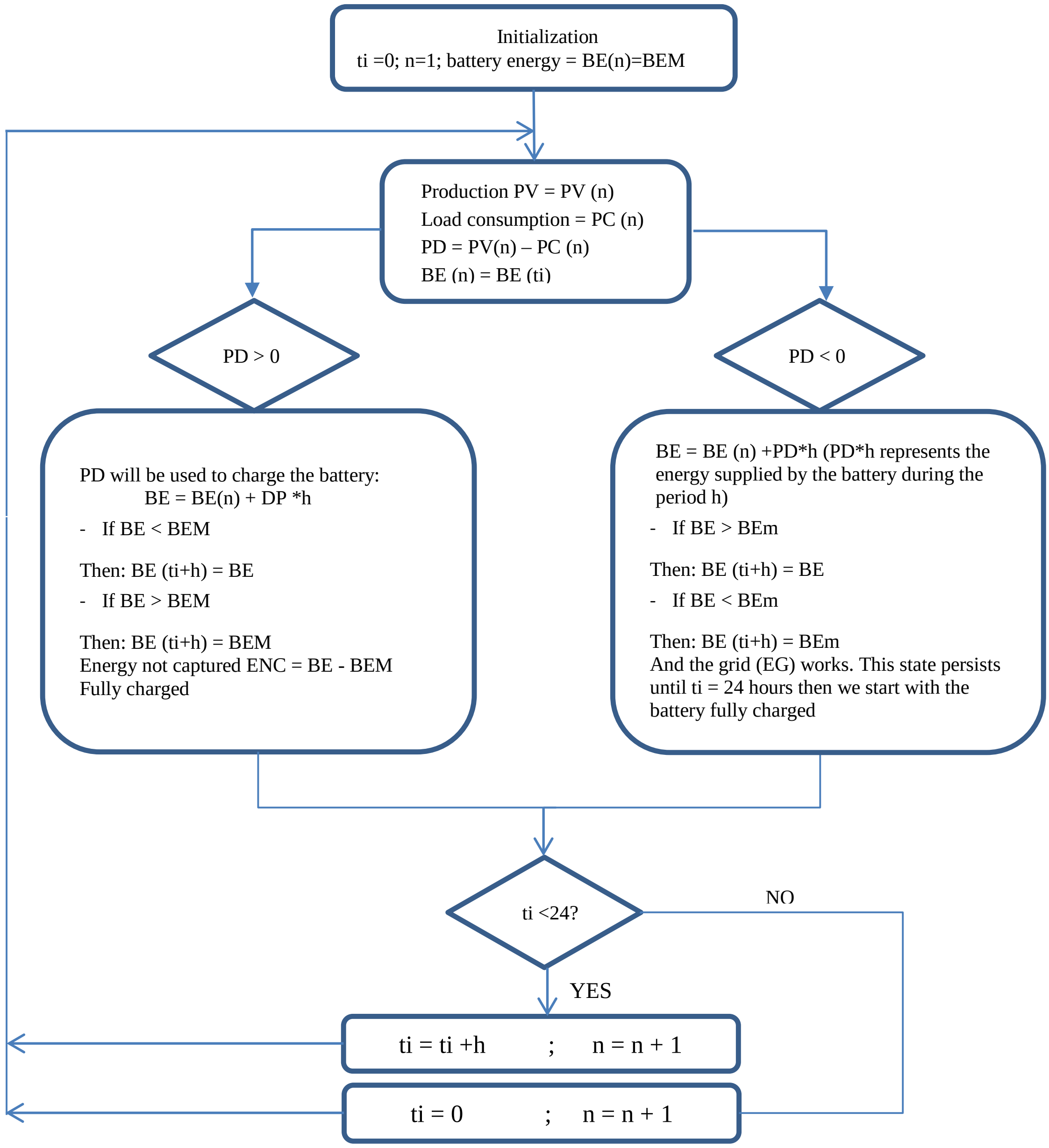


Figure 12. Flowchart of the proposed operating algorithm

Starting from an initially charged battery, the PV power (PV) produced is compared to the power demanded by the load (PC). Let PD = PV – PC. Two situations arise:

- PD > 0 (PV power higher than consumed power). This excess is captured by the battery and its charge is valid until it is fully charged (BE < BEM). If it is charged, the excess (BE > BEM) is simply lost (Energy not recovered)
- PD < 0 (PV power lower than consumed power). The deficit will have to be extracted from the battery as long as the authorized depth of discharge has not been reached (BE > BEM)
- If BE reaches BEM, the Diesel Generator (or the grid if it exists) operates to supply the load and charge the battery.

When the depth of discharge of the battery is reached (generally at the end of the day or cloudy sky), it is agreed to continue in this way until 0 hours. At 0:00 the cycle restarts.

5.3. Simulation of MSU Operation Carried Out

5.3.1. Load Profile Considered in the Modeling Phase

The synthesis of the measurements and recordings made in the field made it possible to obtain the actual load profiles. As can be seen, they differ slightly from the profile evaluated at the design phase of the MSU power supply. In the operating simulation that follows, we have considered the average profile obtained in the field (listed in Table 3).

Table 3. Load profile used in the simulation

Time	Power (W)	Energy (Wh)	Time	Power (W)	Energy (Wh)
00:00	50	50	12:00	1230	4040
01:00	50	100	13:00	1214	5254
02:00	50	150	14:00	1071	6325
03:00	50	200	15:00	928	7253
04:00	50	250	16:00	820	8073
05:00	50	300	17:00	224	8297
06:00	50	350	18:00	200	8497
07:00	100	450	19:00	100	8597
08:00	490	940	20:00	50	8647
09:00	505	1445	21:00	50	8697
10:00	568	2013	22:00	50	8747
11:00	797	2810	23:00	50	8797

It is this load profile that will be used in the rest of this article for the optimization of the hybrid energy source of the MSU.

5.3.2. Input Elements for Numerical Simulation

The input elements used for the numerical simulation of the operation of our hybrid source are as follows:

- The productions of a 2120 Wp solar field (provided by PVGIS) placed on the roof of the vehicle, operating in the geographical area of Ben Guerir, Morocco (Figure 12);
- The average daily consumption profile of the MSU (Table 3);
- Storage batteries totalling energy of 19200 Wh (Table 3);
- The objective is to evaluate the performance of the solution adopted and to explore more advantageous association scenarios (PV-Storage).
- For this purpose, we considered three storage capacities: Installed (19200 Wh), 40000, and 31680 (Wh).

Secondly, we considered the new mobile units (18 T) provided with a PV capacity of 3540 Wp. The different results are analyzed and compared.

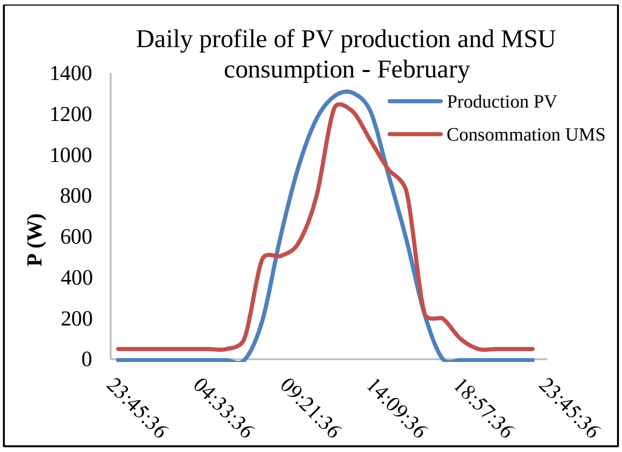
5.3.3. Production vs. Consumption for the Different Periods of the Year

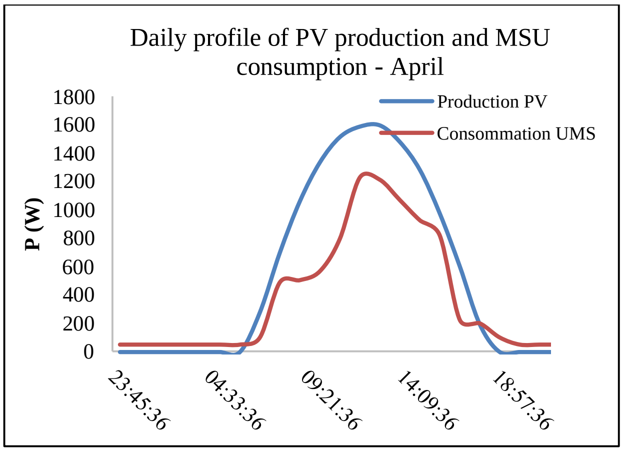
We compared the power produced and the power consumed throughout the year. Figures 13 illustrate the results obtained. It is clear that throughout the year, the need for consumption is largely met by PV production. However, the seasonal fluctuation of PV production generates either a surplus of production (cases of April and July), or a deficit (cases of December). The adjustment between production and consumption must be best fulfilled by the battery.

The battery must ensure the assigned function under the best conditions, in particular:

- Limit the use of the grid or the generator.
- Limit the number of charge-discharge cycles for longer battery life.

To this end, we simulated the operation over the year, of our system for three battery capacities: 40,000, 31,680, and 19,200 Wh for two PV powers: P1 = 2120 Wp corresponding to the present situation and P2 = 3540 Wp corresponding to the new MSU object of the continuation of our study. The results are interpreted and commented on in the following.





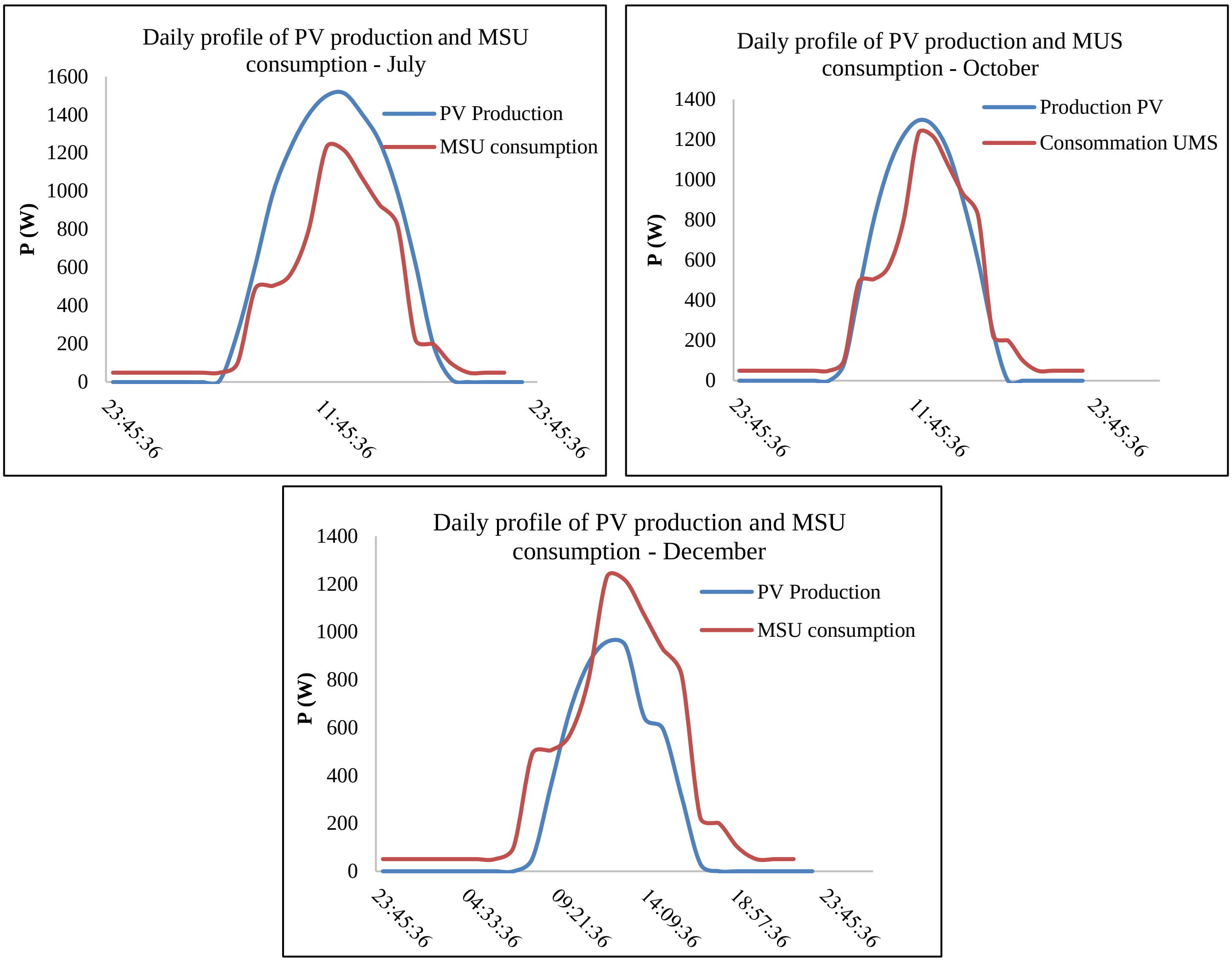


Figure 13. Daily profiles of PV power produced and MSU power consumption

5.3.4. Case of a 19200 (Wh) Battery and a PV Power of 2120 (Wp)

Table 4 and Figure 14 give the energy balance over one year of operation of the MSU completed and currently in operation. We remind you that the MSU has a 2120 Wp solar roof and has a fleet of GEL-type batteries, totaling 19200 Wh, and an 8 kVA generator.

Table 4. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	192,67	272,71	4,96
February	199,48	255,11	1,11
March	279,55	272,71	4,45
April	335,52	263,91	70,72
May	345,21	272,71	95,91
June	376,67	263,91	96,32
July	362,10	272,71	89,42
August	332,66	272,71	60,03
September	284,29	263,91	19,89
October	221,47	272,71	1,18
November	162,38	263,91	0,00
December	156,41	272,71	0,00
Total (kWh)	**3248,40**	**3219,70**	**443,99**
%	**1**	**99,11**	**13,66**

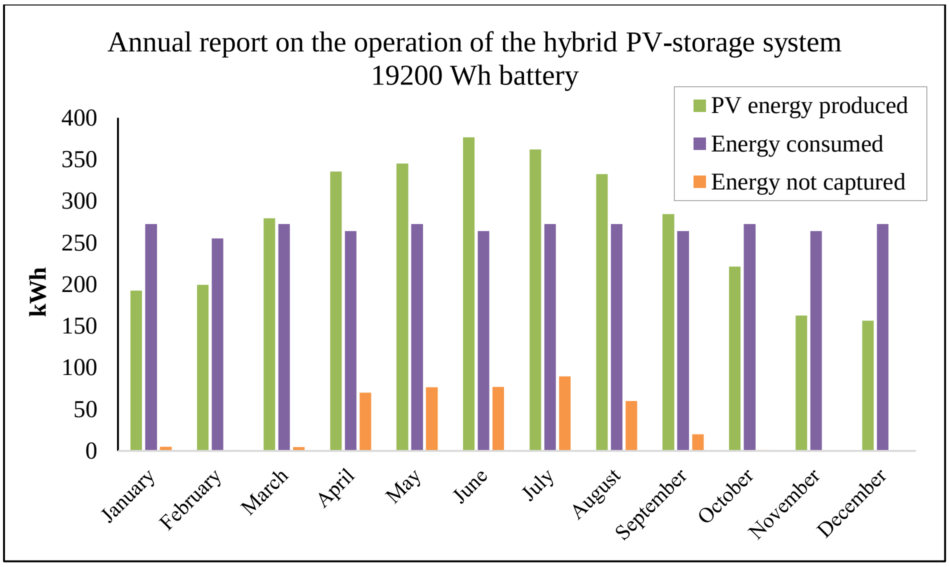


Figure 14. Annual operating report of the hybrid PV-storage system

Figure 15 give the monthly charge/discharge behavior of the battery (SOC expressed in %).

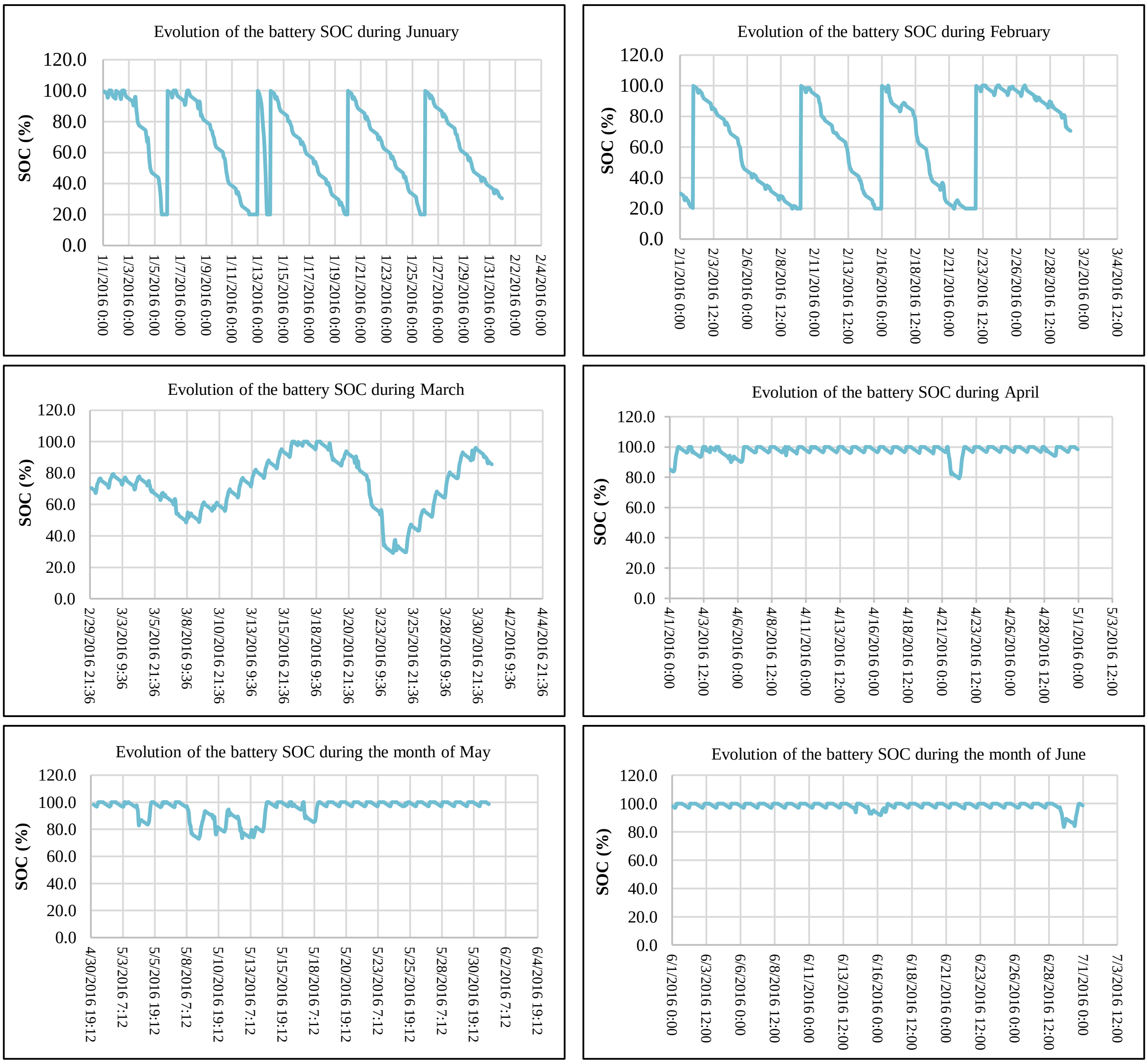


Figure 15. Evolution of the SOC Battery during the year

Over the year, we listed 21 complete charge/discharge cycles, i.e. 21 days when the generator operated, in the absence of a connection point to the electrical network. These cycles essentially occur practically between the months of October and February when PV production is reduced due to the decrease in solar radiation (autumn and winter season). In addition, over the year 444 kWh of energy produced by PV was not used (energy not recovered), i.e. approximately 13% of the energy produced.

To reduce the number of battery discharge cycles and calls for the generator, we resumed the simulation by increasing the battery capacity. Two values are tested: 31,680 Wh then 40,000 Wh.

The results are interpreted and commented in the following.

5.3.5. Case of a 31680 (Wh) Battery and a PV Power of 2120 (Wp)

Table 5 and Figure 16 give the energy balance over one year of operation of the MSU carrying a solar roof of 2120 Wp and a bank of GEL-type batteries, totaling 31680 Wh and also carrying an 8 kVA generator.

Table 5. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	192,67	272,71	1,22
February	199,48	255,11	1,11
March	279,55	272,71	4,00
April	335,52	263,91	69,14
May	345,21	272,71	72,48
June	376,67	263,91	112,74
July	362,10	272,71	89,42
August	332,66	272,71	60,03
September	284,29	263,91	20,67
October	221,47	272,71	1,16
November	162,38	263,91	0,00
December	156,41	272,71	0,00
Total (kWh)	**3 248,40**	**3 219,70**	**431,96**
%	**1,00**	**99,11**	**13**

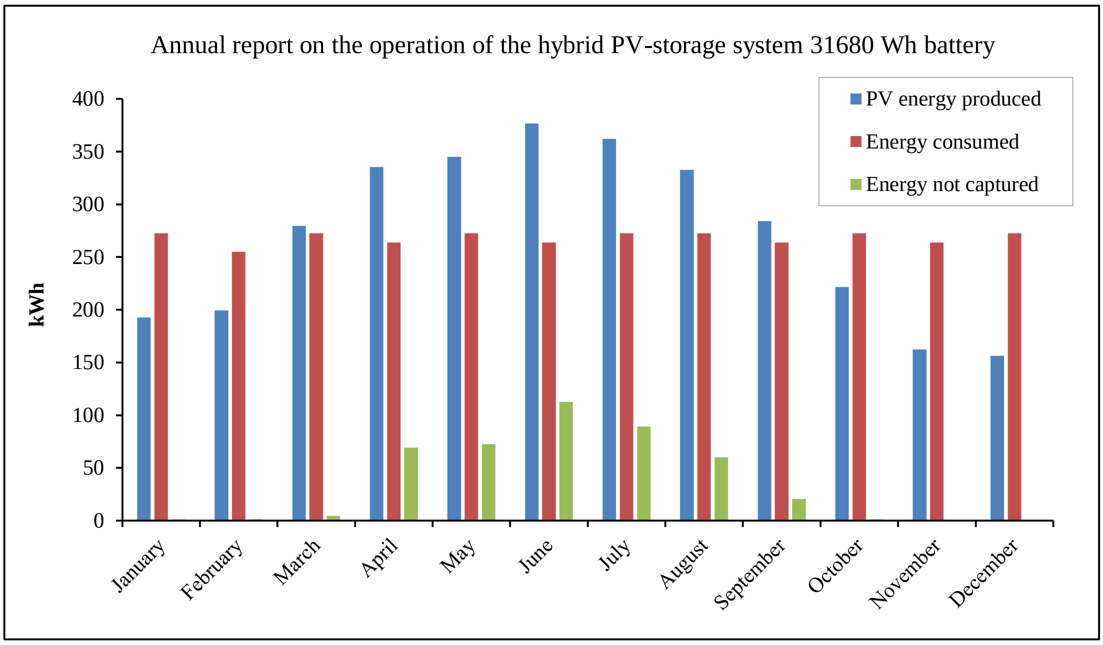
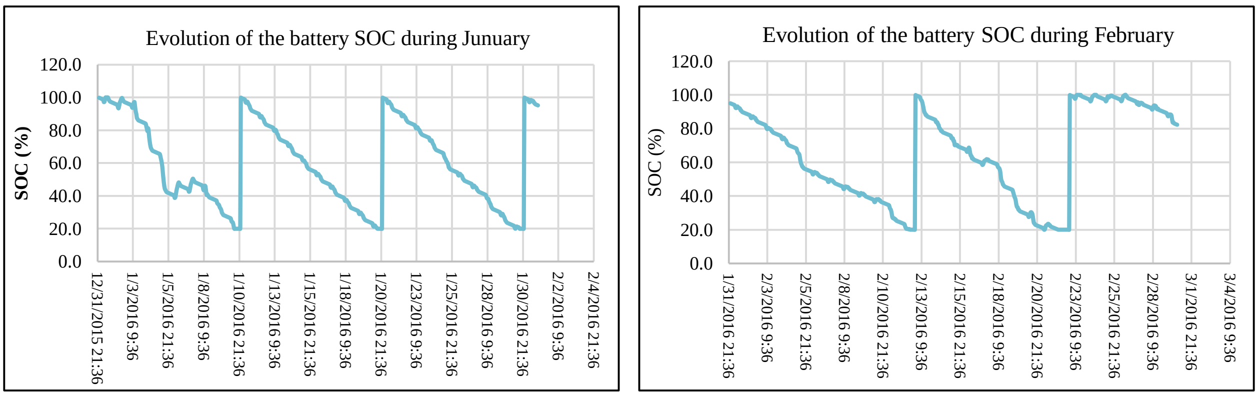


Figure 16. Annual operating report of the hybrid PV-storage system

Figure 17 give the monthly charge/discharge behavior of the battery (SOC expressed in %).



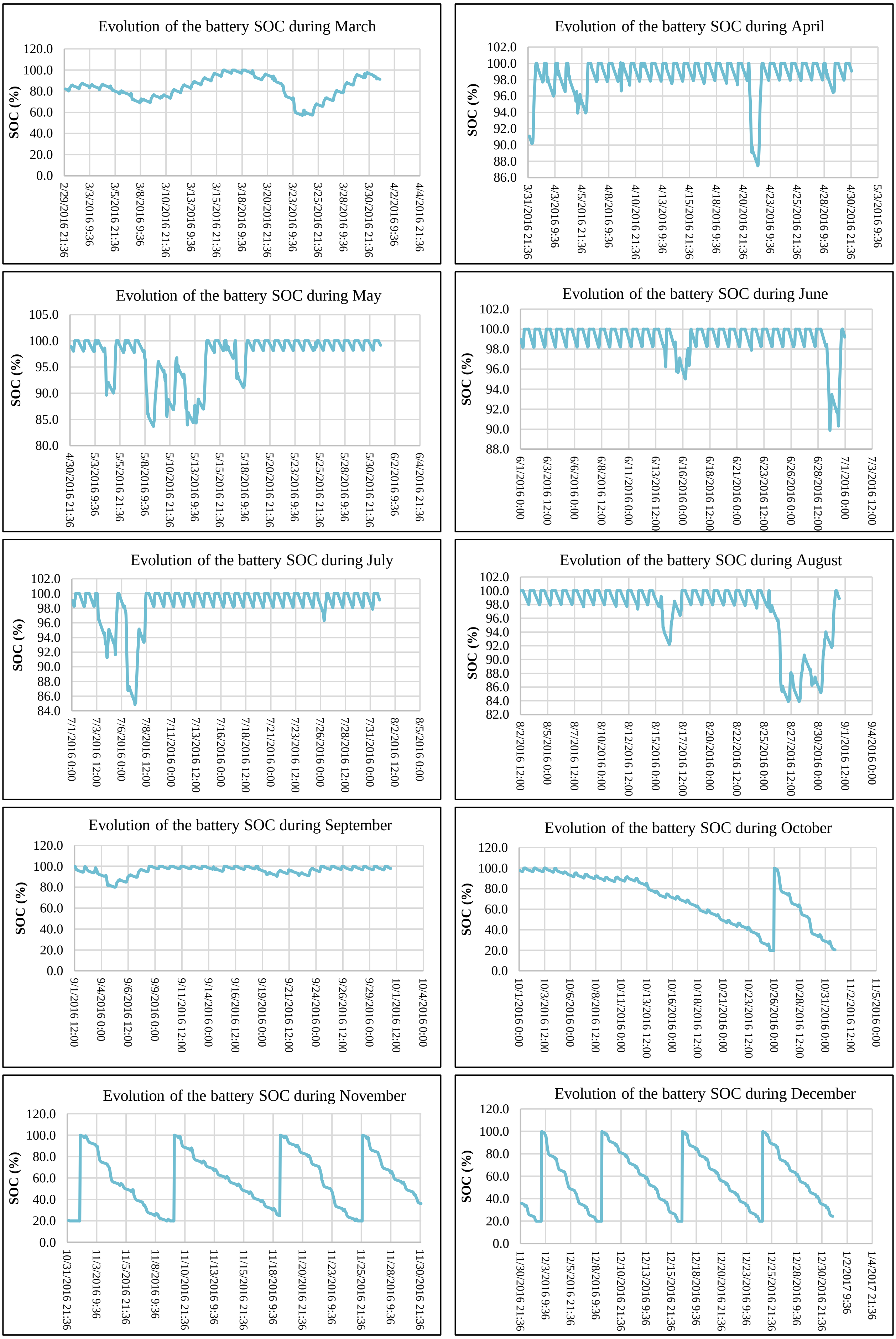


Figure 17. Evolution of the SOC Batteries during the year

Over the year, this time we have listed 13 complete charge/discharge cycles, i.e. 13 days when the generator operated, in the absence of a connection point to the electrical network. These cycles essentially occur practically between the months of October and February (autumn and winter season). On the other hand, the unrecovered energy hardly changed since the PV production was the same.

5.3.6. Case of a 40000 (Wh) Battery and PV Power of 2120 (Wp)

Table 6 and Figure 18 give the energy balance over one year of operation of the MSU carrying a solar roof of 2120 Wp and a bank of GEL type batteries, totaling 40000 Wh and also carrying an 8 kVA generator.

Table 6. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	192,67	272,71	2,13
February	199,48	255,11	1,11
March	279,55	272,71	4,45
April	335,52	263,91	70,13
May	345,21	272,71	72,48
June	376,67	263,91	112,74
July	362,10	272,71	86,26
August	332,66	272,71	63,18
September	284,29	263,91	20,67
October	221,47	272,71	1,16
November	162,38	263,91	0
December	156,41	272,71	0
Total (kWh)	**3248,40**	**3219,70**	**434,30**
%	**1**	**99,12**	**13,37**

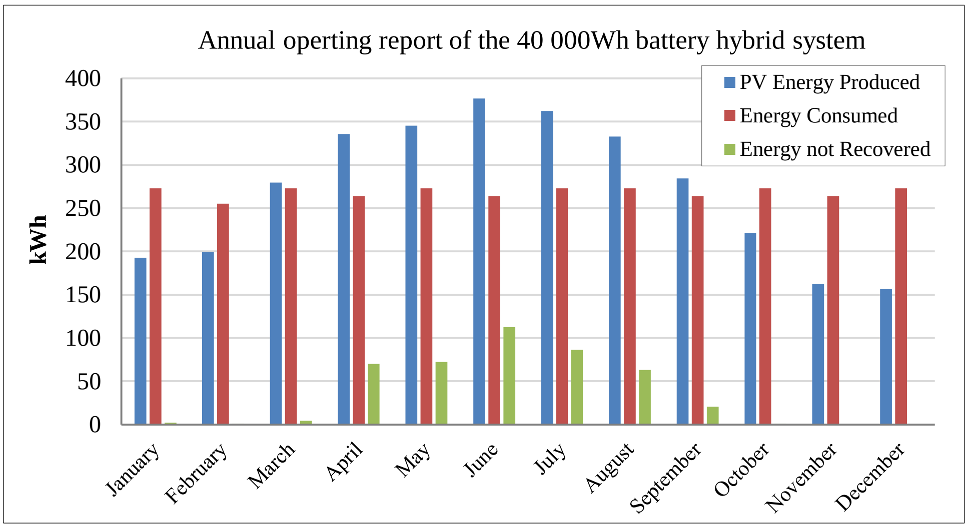
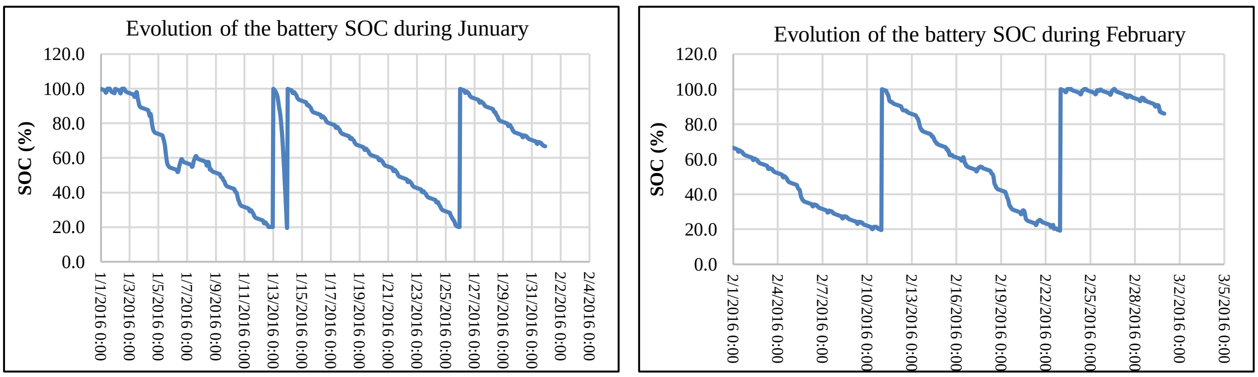


Figure 18. Annual operating report of the hybrid PV-storage system

Figure 19 give the monthly charge/discharge behavior of the battery (SOC expressed in %).



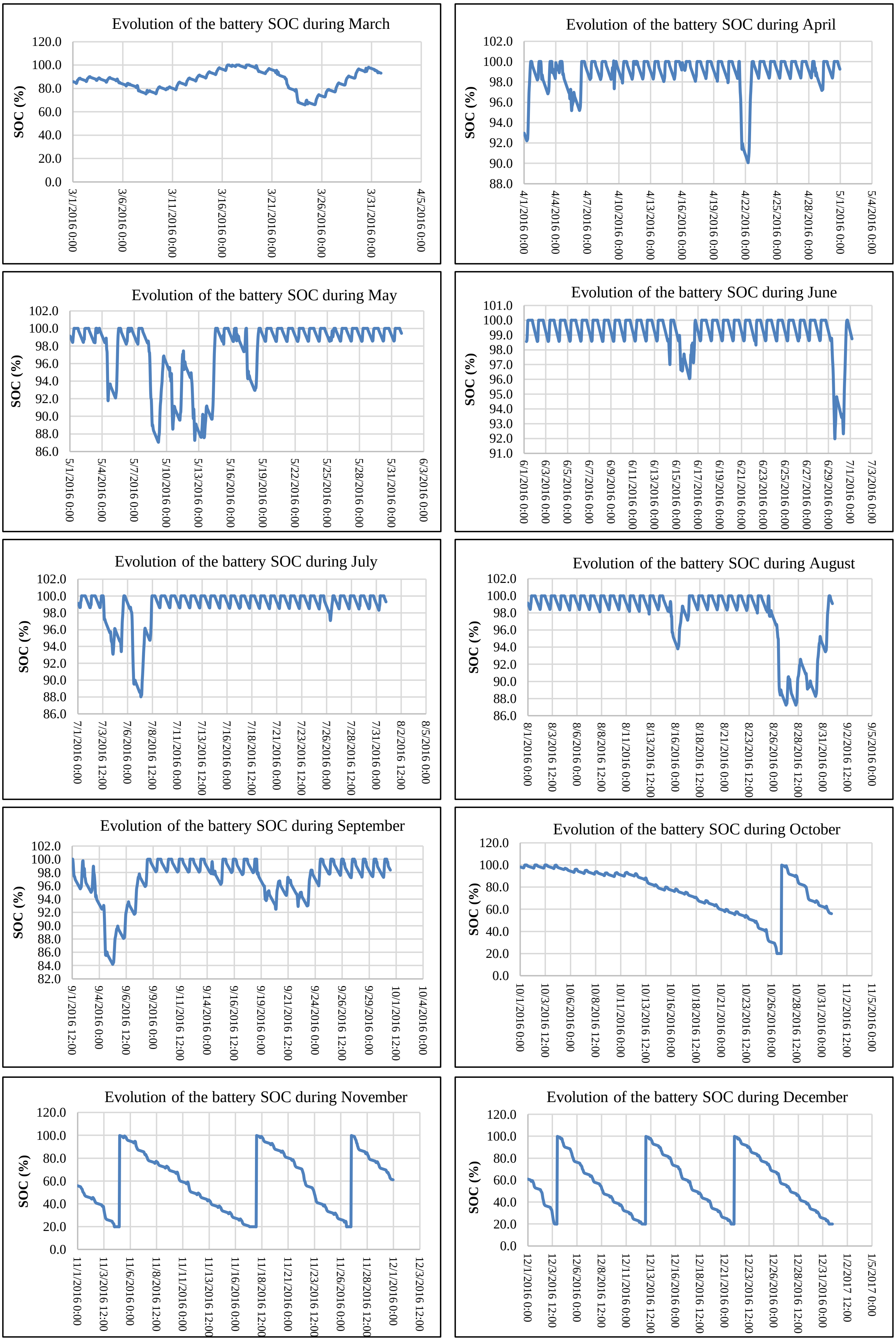


Figure 19. Evolution of the SOC Battery during the year

Over the year, this time we have listed 13 complete charge/discharge cycles, i.e. 13 days when the generator operated, in the absence of a connection point to the electrical network. Also in this case, these cycles essentially occur practically between the months of October and February. On the other hand, the unrecovered energy hardly changed since the PV production was the same. Changing the battery capacity from 31,680 kWh to 40,000 kWh has practically no impact on the result. Reinforcing the capacity of the batteries becomes unnecessary beyond 31 kWh. The optimal storage capacity will be the subject of an in-depth study later.

5.4. Simulation in the Case of the MSU 18 T Commissioned at the Beginning of 2022

This new MSU is currently equipped with solar panels totalling a power of 3540 kWp, installed on the roof of the vehicle (18.75 m²), and carrying a battery capacity totalling 31680 Wh and an 8 kVA generator. The same simulations above are performed on this MSU.

5.4.1. Case of a 31680 (Wh) Battery and a PV Power of 3540 (Wp)

Table 7 and Figure 20 give the energy balance calculated over one year of operation of the new MSU.

Table 7. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	315,51	272,71	44,59
February	329,47	255,11	76,48
March	445,43	272,71	171,65
April	553,89	263,91	290,28
May	572,95	272,71	300,20
June	610,54	263,91	346,59
July	587,46	272,71	314,79
August	539,78	272,71	267,11
September	464,87	263,91	201,16
October	366,62	272,71	104,02
November	269,28	263,91	25,94
December	260,79	272,71	0,00
Total (kWh)	**5316,59**	**3219,70**	**2142,82**
%	**1**	**60,55**	**40,3**

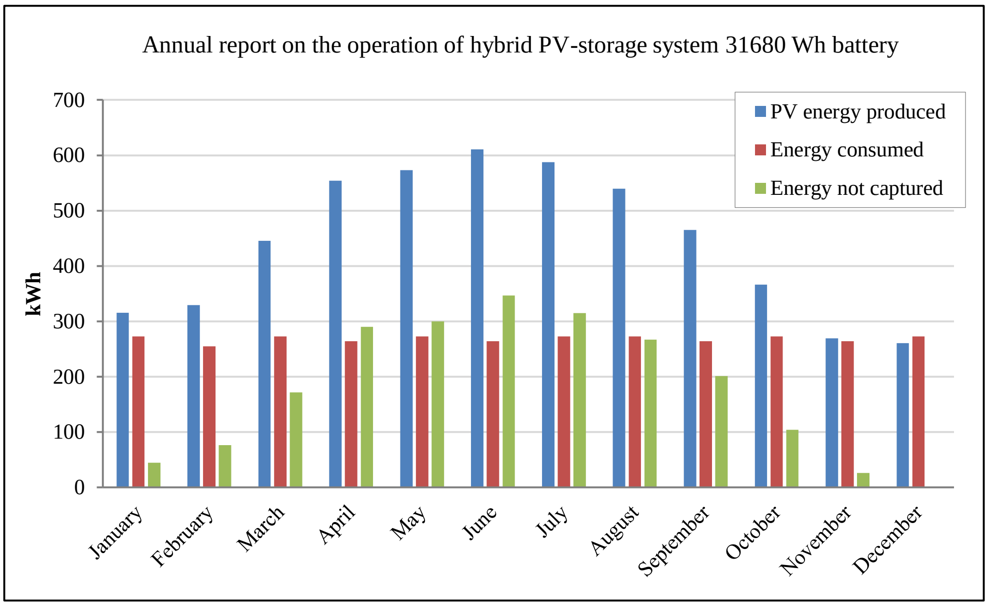
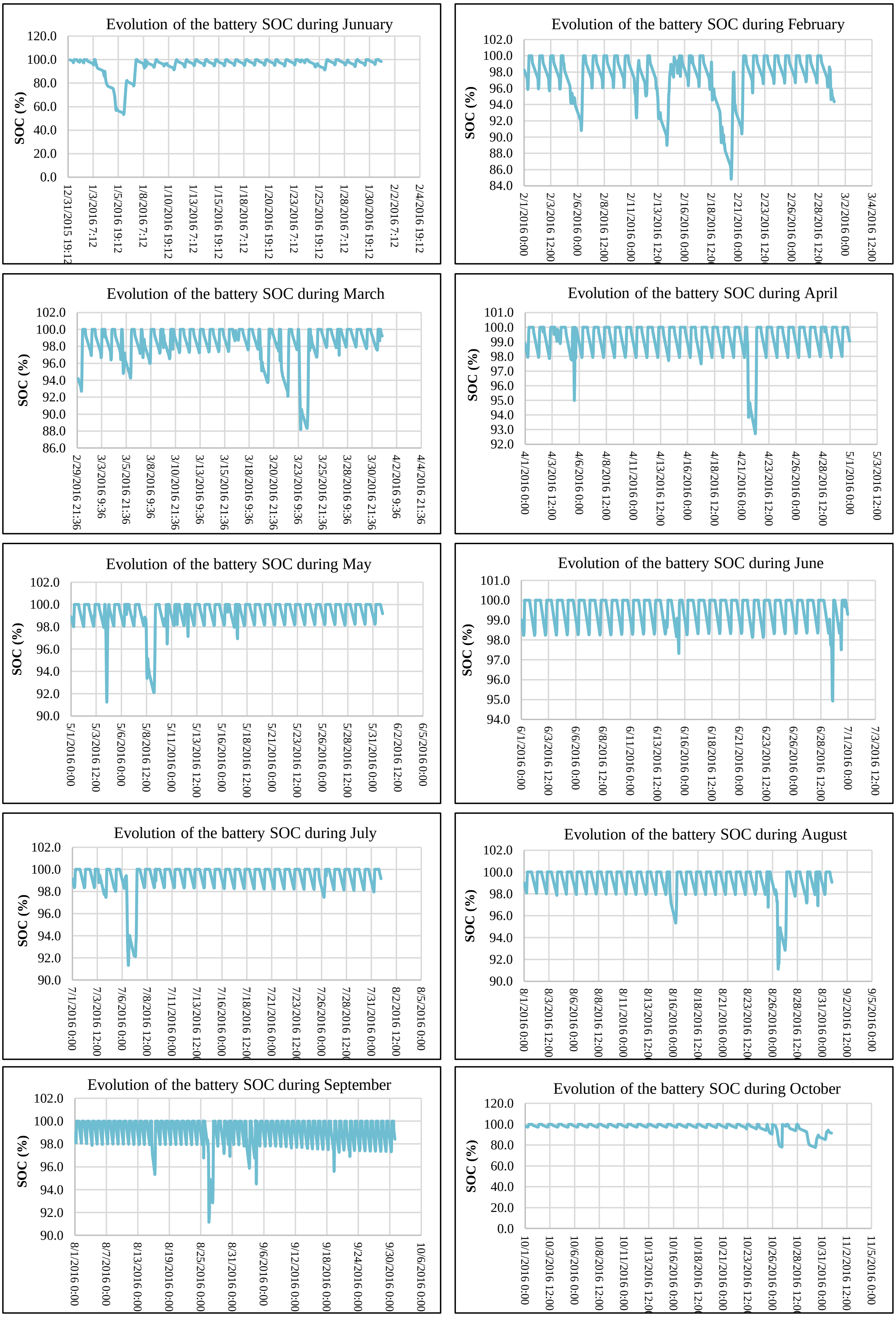


Figure 20. Annual review of the operation of the hybrid PV-storage system

Figure 21 show the monthly charge/discharge behavior of the battery (SOC expressed in %).



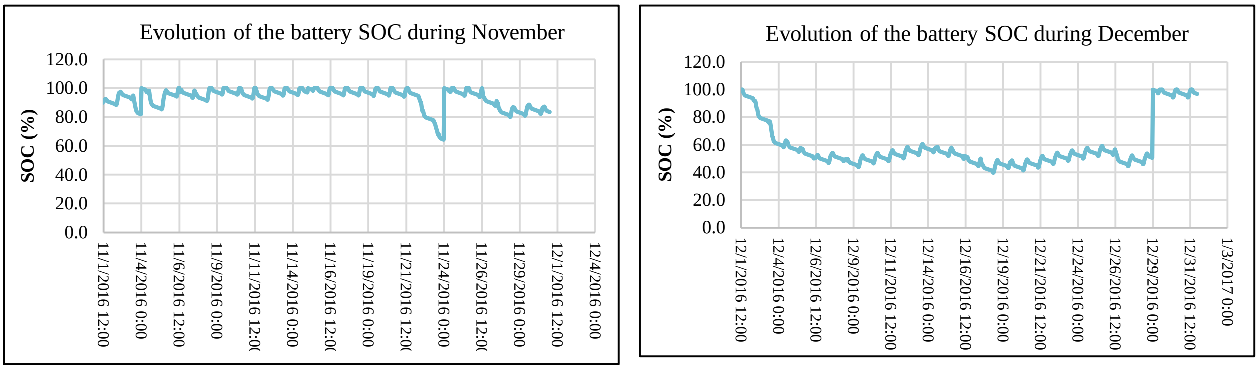


Figure 21. Evolution of the SOC Batteries during the year

For the same load profile as the first MSU, the operation was ensured every day of the year without any complete discharge of the batteries, therefore also without ever calling on the generator. On the other hand, the unrecovered PV energy is worth 2143 kWh, or 40% of the PV energy produced. The energy source on board the MSU is therefore oversized, which has led to overinvestment.

5.4.2. Case of a 19200 (Wh) Battery and a PV Power of 3540 (Wp)

Table 8 and Figure 22 give the energy balance calculated over one year of operation of the new MSU but reducing the capacity of the batteries to 19200 Wh.

Table 8. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	315,51	272,71	44,59
February	329,47	255,11	76,48
March	445,43	272,71	171,65
April	553,89	263,91	290,28
May	572,95	272,71	300,20
June	610,54	263,91	346,59
July	587,46	272,71	314,79
August	539,78	272,71	267,11
September	464,87	263,91	201,16
October	366,62	272,71	105,99
November	269,28	263,91	25,94
December	260,79	272,71	5,35
Total (kWh)	**5316,59**	**3219,70**	**2150,14**
%	**1**	**61**	**40**

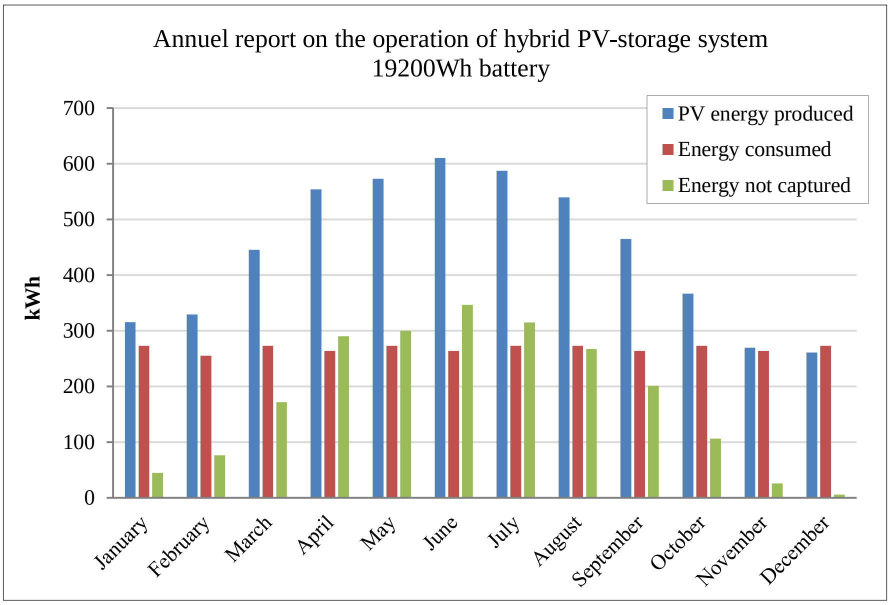
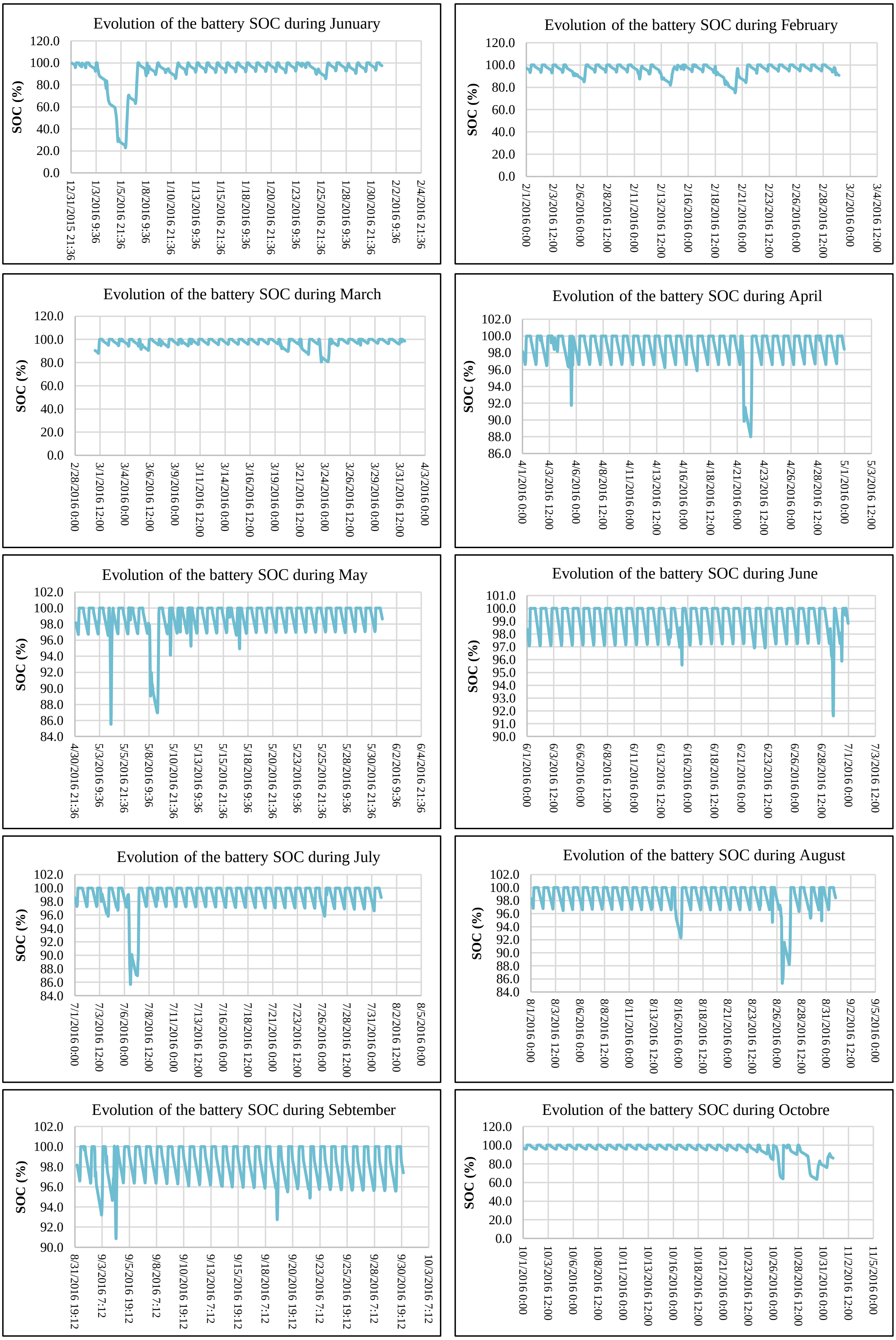


Figure 22. Annual operating report of the hybrid PV-storage system

Figure 23 show the monthly charge/discharge behavior of the battery (SOC expressed in %).



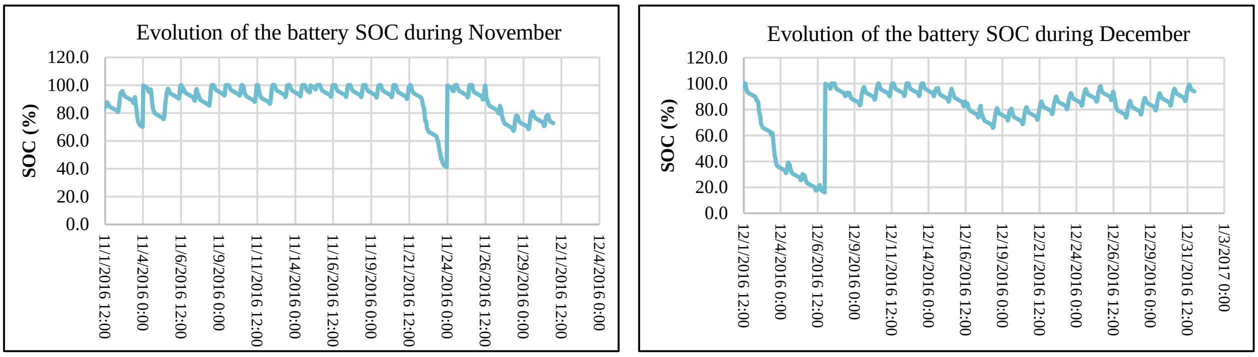


Figure 23. Evolution of the SOC Batteries during the year

Over the year, this time we listed 2 complete charge/discharge cycles, so 2 days when the GE worked. On the other hand, the unrecovered energy is always the same as in the previous case (around 2150 kWh, i.e. 40% of the PV energy produced) since the installed PV power is the same. This solution is optimal in terms of battery capacity and weight.

5.4.3. Case of a 40000 (Wh) Battery and a PV Power of 3540 (Wp)

Table 9 and Figure 24 give the energy balance calculated over one year of operation of the new MSU but reducing the capacity of the batteries to 40,000 Wh.

Table 9. MSU annual operating report

Month	Production PV (kWh)	Consumption (kWh)	Energy not captured (kWh)
January	315,51	272,71	44,59
February	329,47	255,11	76,48
March	445,43	272,71	171,65
April	553,89	263,91	290,28
May	572,95	272,71	300,20
June	610,54	263,91	346,59
July	587,46	272,71	314,79
August	539,78	272,71	267,11
September	464,87	263,91	201,16
October	366,62	272,71	104,02
November	269,28	263,91	8,74
December	260,79	272,71	0,00
Total (kWh)	**5316,59**	**3219,70**	**2125,62**
%	**1**	**60,59**	**39,98**

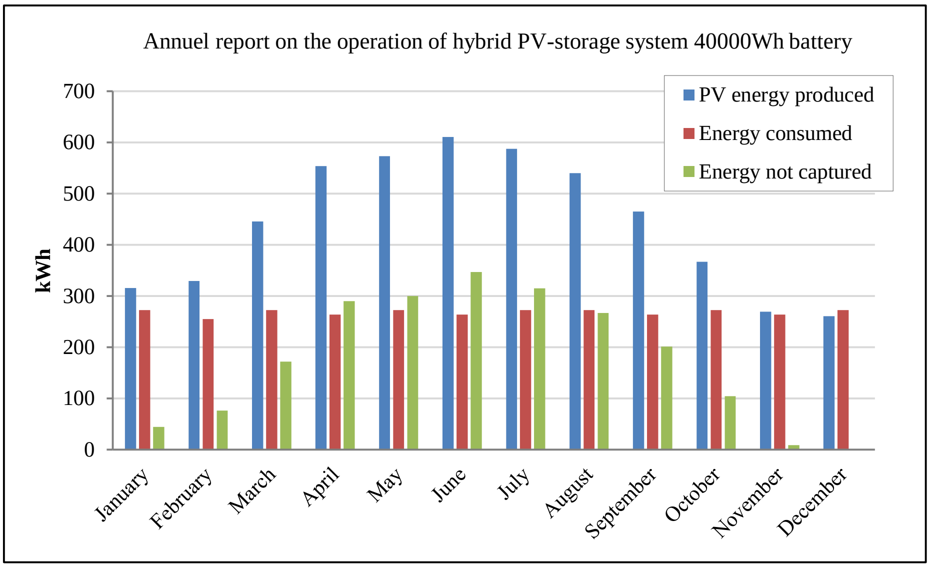
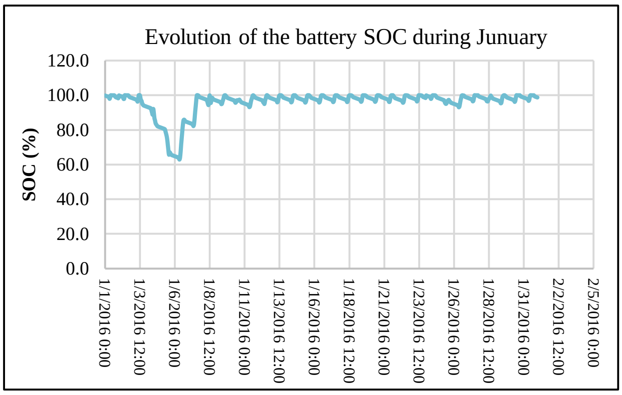
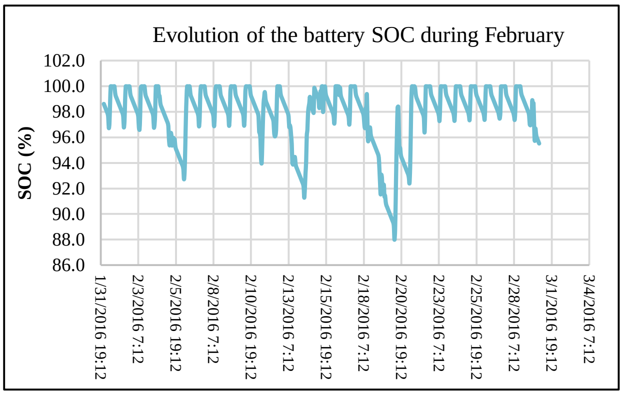
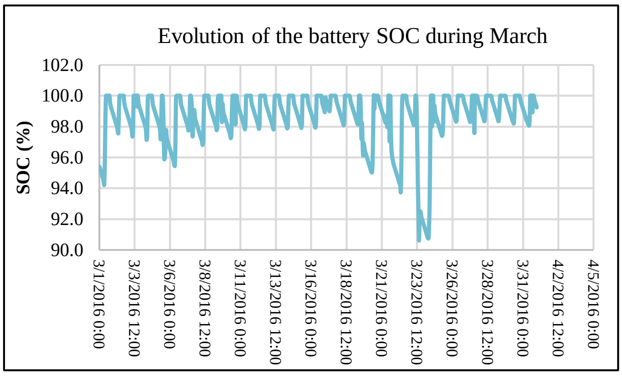


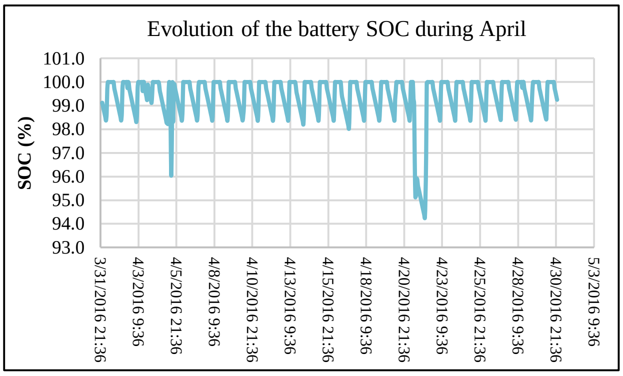
Figure 24. Annual operating report of the hybrid PV-storage system

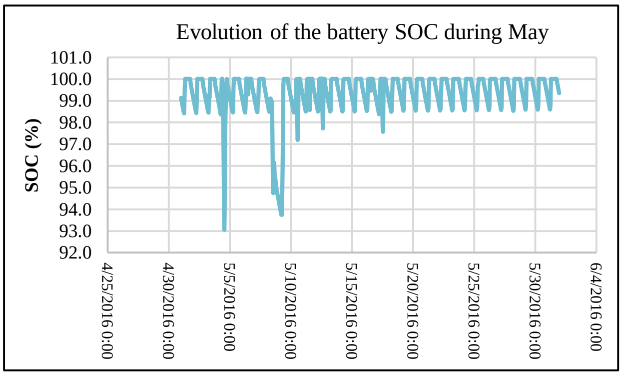
Figure 25 show the monthly charge/discharge behavior of the battery (SOC expressed in %).

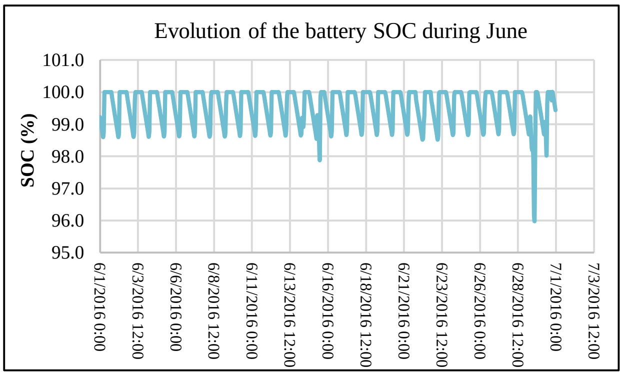

Evolution of the battery SOC during Junuary
SOC (%)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1/1/2016 0:00
1/3/2016 12:00
1/6/2016 0:00
1/8/2016 12:00
1/11/2016 0:00
1/13/2016 12:00
1/16/2016 0:00
1/18/2016 12:00
1/21/2016 0:00
1/23/2016 12:00
1/26/2016 0:00
1/28/2016 12:00
1/31/2016 0:00
2/2/2016 12:00
2/5/2016 0:00

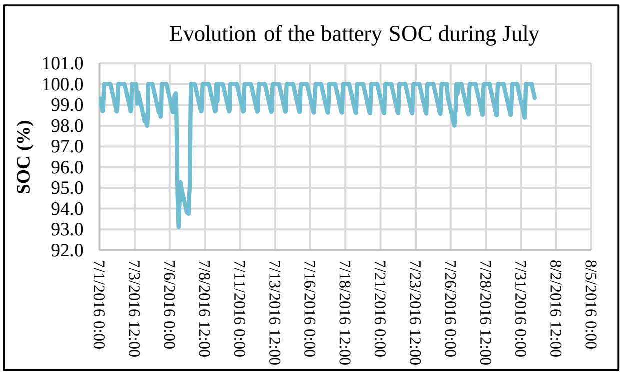

Evolution of the battery SOC during February
SOC (%)
102.0
100.0
98.0
96.0
94.0
92.0
90.0
88.0
86.0
1/31/2016 19:12
2/3/2016 7:12
2/5/2016 19:12
2/8/2016 7:12
2/10/2016 19:12
2/13/2016 7:12
2/15/2016 19:12
2/18/2016 7:12
2/20/2016 19:12
2/23/2016 7:12
2/25/2016 19:12
2/28/2016 7:12
3/1/2016 19:12
3/4/2016 7:12

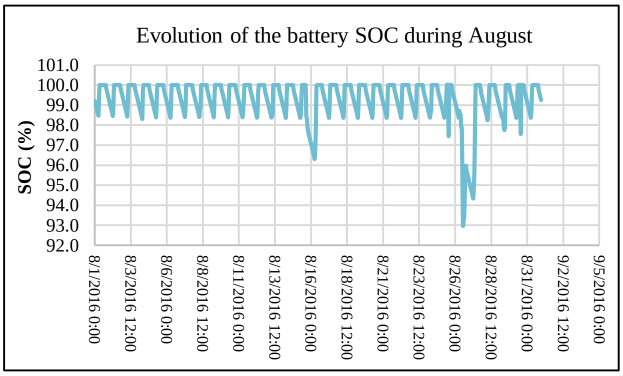

Evolution of the battery SOC during March
SOC (%)
102.0
100.0
98.0
96.0
94.0
92.0
90.0
3/1/2016 0:00
3/3/2016 12:00
3/6/2016 0:00
3/8/2016 12:00
3/11/2016 0:00
3/13/2016 12:00
3/16/2016 0:00
3/18/2016 12:00
3/21/2016 0:00
3/23/2016 12:00
3/26/2016 0:00
3/28/2016 12:00
3/31/2016 0:00
4/2/2016 12:00
4/5/2016 0:00


Evolution of the battery SOC during April
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
3/31/2016 21:36
4/3/2016 9:36
4/5/2016 21:36
4/8/2016 9:36
4/10/2016 21:36
4/13/2016 9:36
4/15/2016 21:36
4/18/2016 9:36
4/20/2016 21:36
4/23/2016 9:36
4/25/2016 21:36
4/28/2016 9:36
4/30/2016 21:36
5/3/2016 9:36


Evolution of the battery SOC during May
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
4/25/2016 0:00
4/30/2016 0:00
5/5/2016 0:00
5/10/2016 0:00
5/15/2016 0:00
5/20/2016 0:00
5/25/2016 0:00
5/30/2016 0:00
6/4/2016 0:00


Evolution of the battery SOC during June
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
6/1/2016 0:00
6/3/2016 12:00
6/6/2016 0:00
6/8/2016 12:00
6/11/2016 0:00
6/13/2016 12:00
6/16/2016 0:00
6/18/2016 12:00
6/21/2016 0:00
6/23/2016 12:00
6/26/2016 0:00
6/28/2016 12:00
7/1/2016 0:00
7/3/2016 12:00


Evolution of the battery SOC during July
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
7/1/2016 0:00
7/3/2016 12:00
7/6/2016 0:00
7/8/2016 12:00
7/11/2016 0:00
7/13/2016 12:00
7/16/2016 0:00
7/18/2016 12:00
7/21/2016 0:00
7/23/2016 12:00
7/26/2016 0:00
7/28/2016 12:00
7/31/2016 0:00
8/2/2016 12:00
8/5/2016 0:00


Evolution of the battery SOC during August
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
8/1/2016 0:00
8/3/2016 12:00
8/6/2016 0:00
8/8/2016 12:00
8/11/2016 0:00
8/13/2016 12:00
8/16/2016 0:00
8/18/2016 12:00
8/21/2016 0:00
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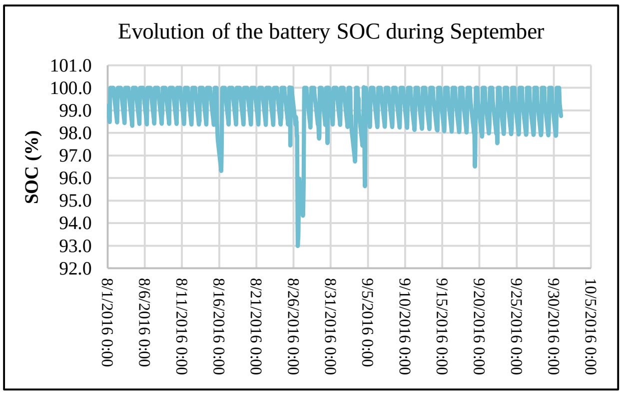
8/28/2016 12:00
8/31/2016 0:00
9/2/2016 12:00
9/5/2016 0:00


Evolution of the battery SOC during September
SOC (%)
101.0
100.0
99.0
98.0
97.0
96.0
95.0
94.0
93.0
92.0
8/1/2016 0:00
8/6/2016 0:00
8/11/2016 0:00
8/16/2016 0:00
8/21/2016 0:00
8/26/2016 0:00
8/31/2016 0:00
9/5/2016 0:00
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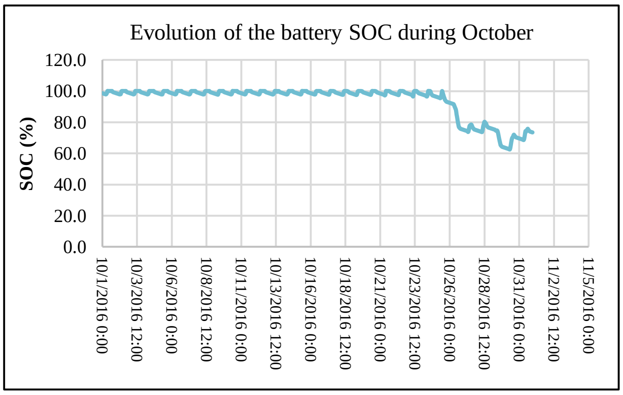
9/30/2016 0:00
10/5/2016 0:00


Evolution of the battery SOC during October
SOC (%)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
10/1/2016 0:00
10/3/2016 12:00
10/6/2016 0:00
10/8/2016 12:00
10/11/2016 0:00
10/13/2016 12:00
10/16/2016 0:00
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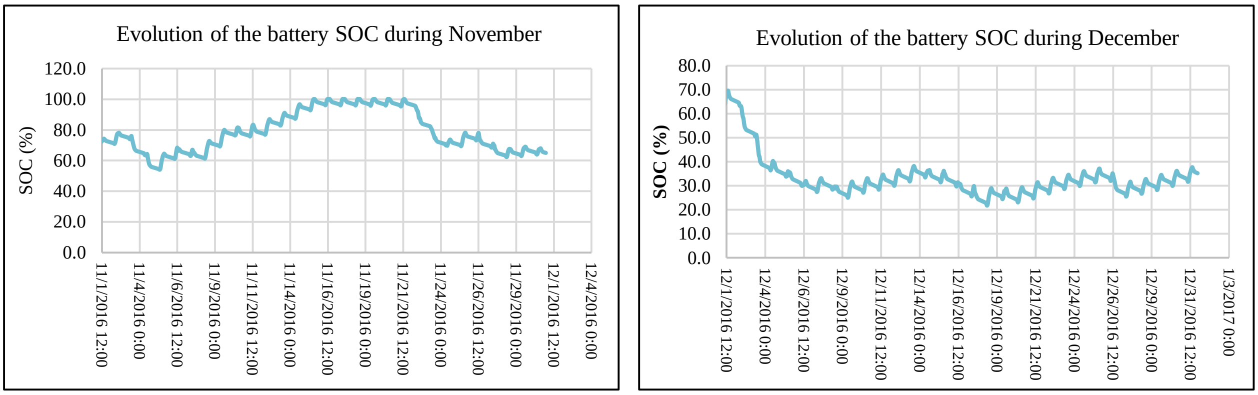

Figure 25. Evolution of the SOC Battery during the year

As in the case of a battery capacity of 31680 Wh, the operation was ensured on all days of the year without any complete discharge of the batteries, therefore also without ever calling on the generator. Of course, the unrecovered energy remains the same. This scenario is ruled out.

Table 10 summarizes the simulation results of the different scenarios studied.

Table 10. Summary table of MSU operating results

Power (Wp)	2120			3540		
The capacity of the Energy Battery on (Wh)	40000	31680	19200	40000	31680	19200
Annual PV energy produced PV (kWh)	3248,4	3248,4	3248,4	5316,59	5316,59	5316,59
Energy consumed (kWh) per year	3219,7	3219,7	3219,7	3219,7	3219,7	3219,7
Energy not captured (kWh) per year	434,3	433,09	443,99	2125,62	2142,82	2150,14
Percentage of energy not captured (%)	10,3	13,33	13,66	39,98	40,3	40
Number of deep charge/discharge cycles	12	13	21	0	0	2

The following observations emerge from Table 10:

For the first MSU, studied, produced, and monitored in the field carrying a PV field of 2120 Wp, batteries totaling 19200 Wh:

- Simulation of year-round operation showed that the batteries experienced 21 full charge/discharge cycles over the year and 21 calls to GE operation. Unrecovered energy represents 13% of the PV energy produced.
- The simulation of operation by increasing the capacity of the batteries to 31680 Wh, made it possible to reduce the number of charge/discharge cycles to 13 instead of 21 (therefore also the number of calls to the GE). Since the installed PV power is the same, the unrecovered energy has not changed.
- The simulation of operation by increasing the capacity of the batteries to 40,000 Wh did not have a significant impact on the number of charge/discharge cycles (12 instead of 13), meaning unnecessary.

For the new MSU, studied and built, carrying a PV field of 3540 Wp, batteries totaling 31680 Wh (The results of deployment in the field are being collected):

- The simulation of operation over the whole year (with the same load profile as in the case of the first MSU) showed that the batteries did not undergo any full charge/discharge over the year and that no call to the Diesel Generator operation is recorded. The unrecovered energy this time represents 40% of the PV energy produced. We are in a situation of oversizing both in terms of installed PV power and on-board battery storage.
- The simulation of operation by reducing the capacity of the batteries to 19200 Wh, showed 2 charge/discharge cycles over the year (therefore also 2 at the GE). Since the installed PV power is the same, the unrecovered energy has not changed. This scenario turns out to be better suited to the operation of the MSU.
- The simulation of operation by increasing the capacity of the batteries to 40000 Wh is similar to the first case (31680 Wh), therefore an even greater excess and useless for the operation of the MSU.

The scenarios considered led to the following:

- For the first MSU: An installed PV power of 2120 Wp combined with a battery capacity of 31680 Wh.

- For the new MSU: An installed PV power of 3540 Wp combined with a battery capacity of 19200Wh.

As indicated in the analysis of the different scenarios, the best combination (PV, storage, load) should be refined by a more in-depth technical and economic study.

6. Conclusions

As part of the issue dealing with the performance of mobile service units (MSU) intended for rural populations (health, training, banking, etc.), which is the subject of our university thesis, we have focused in this article on energy efficiency and the integration of renewable energies in MSU.

The bibliographic analysis of the scientific literature and industrial achievements relating to the subject revealed that MSU has been the subject of little academic research. The bibliographical review led us to categorize the isolated sites supplied with renewable energy into three categories: fixed isolated sites, fixed and movable isolated sites, and mobile sites with electric traction, which do not fall within our field of study. MSU belongs to category 2. We have noted that problems specific to MSU, such as space constraints for the installation of solar panels, volume and weight constraints of equipment such as inverters, batteries, and the generator (GE), are not processed. Operation and maintenance issues, including battery longevity and generator operating frequencies and times, are not sufficiently addressed. All these points have been the subject of our study. In this article, we arrived at the following main results:

- Following the realization of a first version of the MSU equipped with a hybrid PV/battery source (2120 Wp and 19200 Wh of battery capacity) backed up by a GE, we were able to validate the concept developed in the field. Monitoring of the deployment of the MSU confirmed the expected performance. The slight discrepancies observed between the measurements and the theoretical simulation are mainly due to the cleanliness of the panels and the weather conditions.
- The modeling of the operation of the hybrid source and the simulation of several PV/Battery combination scenarios provides information on the optimal solutions to be achieved with the best compromise between the size of the PV field, the capacity of the batteries, and the minimization of non-energy recovered. In addition to the financial constraints, the weight of the batteries and the limited reception surfaces of the PV modules should be the subject of an optimization study planned in the continuation of this work.
- For the new MSU to be completed at the end of 2021, equipped with a PV field of power of 3540 Wp and 31680 Wh, we have shown that the battery capacity chosen is oversized and recommend reducing it to 19200 Wh.

For the perspectives and the continuation of our work, we have retained the following main points:

- In addition to the results achieved, the proposed combinations (PV, storage, load) will be refined through modeling and an in-depth technical and economic study. This task is already in progress.
- The results obtained are being applied to mobile medical units. The completed units are currently being monitored and evaluated in the field. The results of the study will be the subject of a forthcoming publication.
- The potential energy gain due to wind cooling when moving the MSU is interesting to consider in the projected improved modelling.

7. Declarations

7.1. Author Contributions

Conceptualization, A.L. and A.S.; methodology, A.L.; software, A.La. and M.M.; validation, A.L., A.La., A.S. and M.M.; formal analysis, A.L. and A.LA.; investigation, A.L., and A.LA.; resources, A.S. and M.M.; data curation, A.L. and A.La.; writing—original draft preparation, A.L.; writing—review and editing, A.L. and A.S.; visualization, A.La. and M.M.; supervision, A.L. and A.La.; project administration, A.S.; funding acquisition, A.L. and A.S. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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