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Off-grid Photovoltaic Systems Implementation for Electrification of Remote Areas: Experiences and Lessons Learned in the Pantanal Sul-Mato-Grossense Region of Brazil

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HIGHLIGHTS

- The lack of national standards difficulties the electrification of remote areas.
- Logistic planning and design resulted in the most critical phases.
- Simplified commissioning methods proved needed to expedite the SPSs installation.
- Short-term advantage of Lithium-ion based batteries over lead-based ones to facilitate remote areas PV system implementation.

Abstract: Rural electrification is a critical issue in many countries. In Brazil, through the Federal Government's Light for All Program, universal access to electricity in rural areas was partially made possible, benefiting approximately 16 million people by 2018. In remote areas where conventional grid electrification is impossible due to technical, geographical, and environmental obstacles, electrification by stand-alone photovoltaic systems is an attractive alternative. However, in practice, this solution is challenging and, if it is exhaustively not researched, it may become unfeasible. Therefore, this article reports the lessons learned from real experience with 23 prototypes installation of stand-alone photovoltaic systems with energy storage systems in the remote region of the Pantanal Sul-Mato-Grossense in Brazil, the major flooded surface in the world. It makes electrification a challenge that requires rigorous planning stages to ensure the lowest cost of future maintenance and meet quality performance indices. Recommendations and lessons learned based on experiences and field data are presented to improve the universalization of electrification in remote regions. Finally, opportunities for research and improvements in isolated PV systems are highlighted.

Keywords: Renewable sources; photovoltaic system; remote systems; rural electrification; developing countries.

INTRODUCTION

In rural areas the lack of access to electricity is a critical factor in their severe economic and social development, influencing the quality of life, job opportunities and having a relevant impact on poverty alleviation [1], [2]. Several countries, such as England [3], China [4], South Korea [5], and Spain [6], have undertaken rural electrification according to their economic, social, environmental, and geographical conditions, seeking to reverse the consequences of the lack of electric power.

Worldwide energy access policies have helped reduce the quantity of the population without access to electricity, which fell to 771 million in 2019, concentrated mainly in developing regions. Also, if we analyze the disparity between urban and rural access, the difference is about 44% in Africa [7].

According to [8], the critical factor for the implementation of off-grid rural electrification in South Asia is that the quality standards for the equipment that makes up PVs are established by the country in which the equipment is manufactured, and these standards are not satisfactory in terms of the operating conditions at the installation sites. The same issue is reported in [9], where the authors also highlight the selection of inverters as critical. In rural Odisha, India, electrification initiated by the non-governmental organization Alternative for Rural Movement had as its main barriers high operation and maintenance (O&M) costs, dependence on external incentives and support, and lack of accessibility [10]. In South Africa [11] the authors highlight the high cost of maintenance as a critical point, bringing as an alternative to delegate activities to the users themselves to reduce costs with specialist technicians and with displacements. In Singapore [12], the main obstacles were the lack of standardization of care and the absence of a clear regulation with a legal and technical definition of the systems to be implemented. Countries such as China [13] and Australia [14], which are considered 100% electrified, highlight distance, climatic and geographical conditions as rural electrification's main challenges. For them, the use of local energy resources was a differential in the universal electrification of their countries, especially the use of PVs in Australia and small hydroelectric power plants in China.

In Brazil, according to the International Energy Agency, in 2019, Brazil had 99.7% of the universalized population of Public Electric Energy Services, and approximately 600 thousand people were not yet enjoying the service [7]. The 2019 official Brazilian percentage of households with access to electricity is slightly similar with 99,8% [15]. As in other countries that are not yet fully electrified, most regions in Brazil without electricity are remote or distant from the main cities located near the Atlantic Ocean, making electrification a challenge, mainly due to the lack of profitability [16,17], long distances between the load centers, high load dispersion, high cost of investment and maintenance and low-income level, among others [12, 18, 19]. Nevertheless, the expectation is that 42,475 off-grid systems will be implemented by 2022 for the electrifications of rural and remote regions due to government incentives. Which aimed to universalize access to electricity in the country with a focus on rural electrification, the federal and state governments introduced the Light for All Program (LfA) in 2003 through Law 10438/2002 [20]. The LfA contemplates as electrification alternatives both the extension of conventional networks and, for remote areas, decentralized generation systems as stand-alone photovoltaic systems (SPSs) and Rural Microgrids (RMgrid), [21]. Thus, current the challenge is mainly focused on the isolated regions of the country, and consequently, for several utilities, the National Electricity Agency (ANEEL) has given a short target by 2022 to achieve universalization by using either LfA subsidies or by recognizing the investments in the fee, according to specific criteria of the program.

However, even with the government incentive, there are several obstacles to the success of electrification in remote areas of developing countries. In Brazil, several rural electrification project initiatives considering PVs have been undertaken, mainly in the Amazon rainforest region, as presented in [22] and [23]. The power company Eletrobrás, in the case study of the electrification of three isolated communities in the Amazon Forest, presents the lack of local skilled labor and user participation as improvement points necessary for a satisfactory system performance [24].

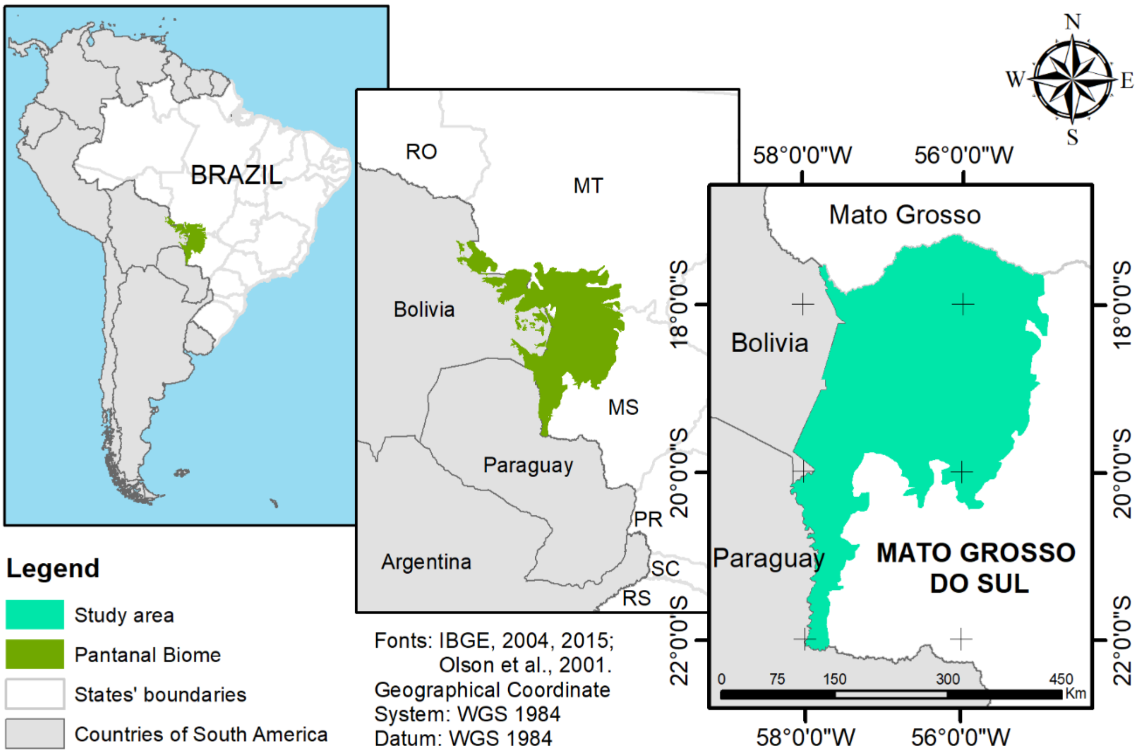
Therefore, for the success of electrification of remote regions, where the abundance of a non-intermittent primary source could be insufficient, it is necessary to carefully plan the installation and commissioning stages, preferably by pilot projects, testing diverse technologies, and solutions. With this in mind, this work presents the results of the first step experience of an electrification program with SPSs and energy storage in a vast remote seasonally flooded region, named Pantanal Sul-Mato-grossense (PSMG), distinct from the Brazilian Amazon region, which is complex to access and ecologically sensitive, with socially diverse and spatiality dispersed consumers. The massive electrification of this region with 2001 SPSs is started in the second half of 2021 and will end in 2022, so the installation of twenty-three SPS prototypes with energy storage systems, reported in this work, aimed to define the best SPS technological solution to meet the universalization program. The prototypes were formed by storage technology and strategically distributed in the PSMG area, where the conventional distribution power system does not reach. Also, it was purposely considered equipment and materials from different manufacturers and technologies to study their advantages and disadvantages in terms of transportation and installation facilities, technical performance, safety, maintenance and operation, and after-sales services.

This work also discusses the critical points for the success of the electrification of remote regions with the alternative of SPSs, providing recommendations that can be instituted elsewhere, mainly regarding the planning activities and logistic challenges. The rest of the paper is structured as follows: Section II is divided into three parts – a description of the study area; prototype requirements; and the methodology used in the SPSs implementation process. Section III presents an analysis of the results obtained. Section IV presents lessons learned from field experience and recommendations for PVs expansion in remote areas and finally, section V presents the conclusions.

MATERIAL AND METHODS

The study area of Pantanal Sul-mato-grossense

The Pantanal is part of a sedimentary basin located in central South America that occupies a total area of 624,320 km² between Brazil, Bolivia, and Paraguay. Occupying an area of approximately 150,355 km² the Brazilian Pantanal, in the middle of Figure 1, is larger than countries such as Portugal (92,392 km²), Greece (131,940 km²), and Austria (83,858 km²). The PSMG, at the right of Figure 1, is a southern part of Pantanal and is located in Mato Grosso do Sul State in the mid-western region of the country with an area of 90,000 km² [25]. Its biome is under the direct influence of the Amazon, the Cerrado (tropical savanna ecoregion), and the Atlantic Forest. The region is one of the largest surfaces in the world to get flooded, and it is recognized by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) as a Biosphere Reserve and a World Heritage Site [26].



Fonts: IBGE, 2004, 2015; Olson et al., 2001.
Geographical Coordinate System: WGS 1984
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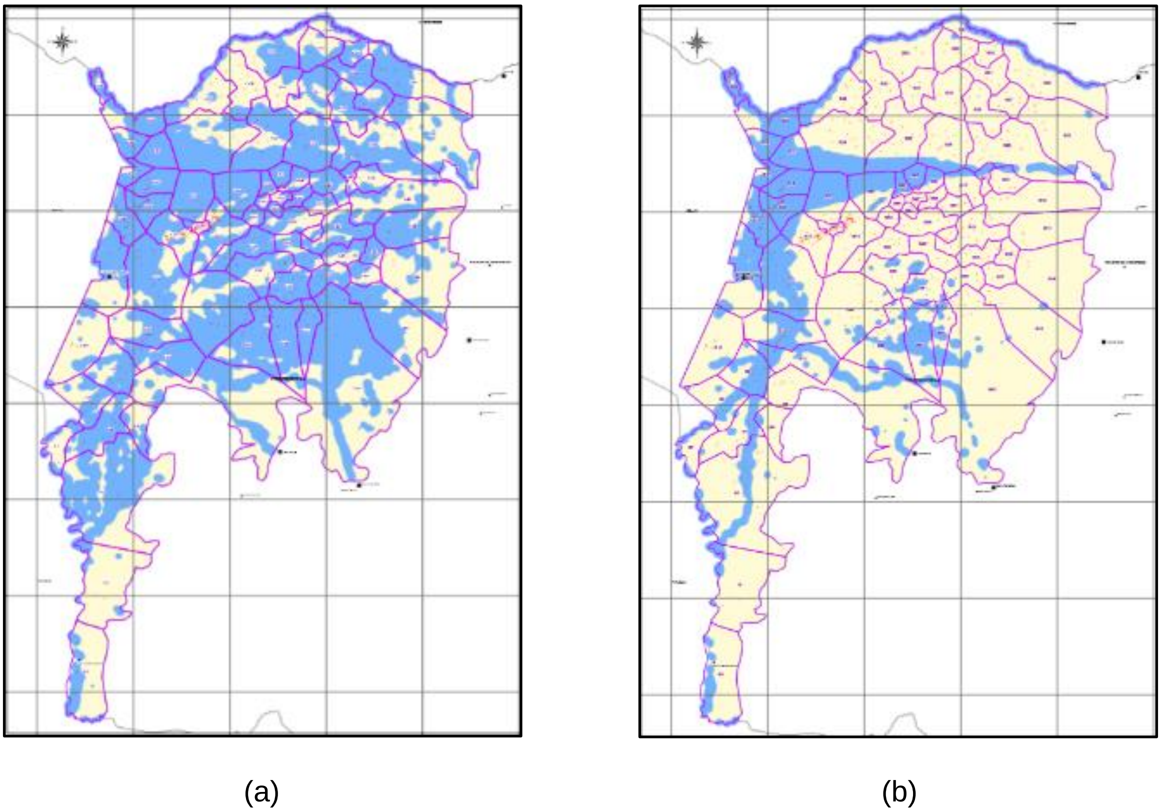
Figure 1. Sul America and the study area of the PSMG [25]

Due to its vast area and the influence of various biomes, the PSMG contains districts, as displayed in Figure 3, that differ in their environmental, climatic, and geological characteristics and specific access modes. In all, teen districts make up the PSMG, as follows [26]:

- Paiaguás is 26,200 km² in area, consists mainly of rural properties, and has livestock as its primary source of livelihood. In the south are riverside communities where livelihoods depend on farm work and organic food and animal production;
- Nhecolândia makes up 22.5% of the total area of the PSMG. Consisting of large rural properties, the economic activity here exclusively revolves around livestock
- Corumbá and Amolar include environmental protection areas, indigenous lands, riverside areas, and a military detachment. Fishing is the basis of subsistence in the riverside communities in both districts. Some small pasture-shaped properties have some livestock and dairy cattle;
- Albuquerque, Miranda, and Aquidauana are already connected to the National Interconnected System (NIS) and are regions close to urban areas;
- Coimbra and Porto Esperança are areas that experience constant flooding, with access by the Paraguay river or by land;
- Porto Mortinho contains the triple border between Brazil, Bolivia, and Paraguay and is connected to the NIS despite access being difficult from Corumbá by the Paraguay River.

Two well-defined periods define the climate of the PSMG. Typically, the rainy season is from December to March. However, due to the influence of the El Niño phenomenon, it is not possible to accurately determine the flood and drought periods, which vary from year to year and from region to region. The map shown in Figure 2 has been elaborated based on both images from Sentinela 2 and Lansat 8 satellite and a Normalized Difference Water Index (NDWI) index to analyze better the flood dynamic and logistic planning support. It is noticeable during the flood period that there is a significant increase in the flood area (blue area), making land access impossible. It is common to monitor water level fluctuations for better access predictability by employing river-level measuring rulers; public authorities provide such information. However, flood and drought periods are complex on the logistics of access to the Pantanal region.



(a) (b)

Figure 2. Map of the Pantanal Sul Mato Grosso: (a) with areas subject to flooding in the flood period; (b) with areas subject to flooding in the drought period

The authors in [27] did a data survey about the logistic model's requirements. The result has shown the main methods of transport in the region were land (4x4 vehicles and tractors) and river (boat). About 21% of the properties have river access strictly; 47% had land access only, as is the case in the Nhecolândia district; and 32 % had river and land access, requiring multiple modes of transport. Access by air occurs during the flood months when land and river access is unfeasible; however, only about 30% of the properties have a runway, and not all of them are in good condition, with runways flooded during the flood period. Therefore, logistics, climate, and environmental conditions are the main barriers to extending conventional grids. It is true also to do the design, implementation, and O&M activities of SPSs challenging [27]. Current, the primary sources of electricity in the region are small diesel generators that operate inefficiently and are housed poorly in most cases. These generators run at night for short periods or when the owners of farms visit the workers in the main house. The average monthly fuel expenditure is 350 liters per property (about USD 400 per month).

Description of stand-alone photovoltaic systems

Twenty-two prototypes are strictly SPSs, and the last one is a rural microgrid (RMgrid) with no load management capability. The choice to implement SPS in the region is due to the long distances between properties and environmental obstacles, such as conservation areas and the presence of large rivers that prevent the installation of grids or microgrids on a larger scale [25]. An RMgrid, however, was implemented on a farm that has four internal consumer units, making it possible to implement a low voltage grid to connect them to the source. According to [27], this situation represents only 20% of the cases in the PSMG.

All prototypes are composed of a photovoltaic panel, battery, charge controller(s), and inverter(s) described as follows:

- Have been considered OPzS, PbC, and lithium-ion (LiFPO4) battery technologies to get performance field experience. Therefore, were contemplated several equipment suppliers, even if this strategy increases the complexity and cost of PVs. The purpose of the analysis is to determine the most appropriate technology to expand service in the study area;
- ANEEL standardized the 13–80 kWh/month systems size for isolated regions of Brazil. A larger size is possible but with customer financial participation. Therefore, the larger 160 and 300 kWh/month size systems are modules of the 80 kWh/month system [28]. Homer Energy software [29] was used to size the prototypes, considering the data from the lowest irradiation day and the characteristic electricity consumption estimated by a survey on the actual and future habits and possession of electric appliances;
- The prototypes were installed dispersed throughout the study area, as shown in Figure 3, to enable different experiences due to the diverse logistical, social and environmental complexity characteristics of each region of the PSMG;
- The inverters may be connected in parallel, aiming to increase the system power and deliver the power at the frequency of 60 Hz. The main advantages of this feature are the ease of maintenance, the possibility of modularity between the systems, and keeping critical loads energized. The disadvantage is that some inverters act in the master-slave scheme, causing an unbalanced degradation rate between batteries if not relayed properly.

The main technical requirements for the equipment are:

- According to operation up to 45 °C and humidity up to 95%;
- Controller/inverter compatibility with batteries technology and with the capability of parallelism on the AC side;
- Storage system operating voltage of 24–48 Vdc;
- Maximum power point tracking (MPPT) and Pulse Width Modulation (PWM) controllers with load stages (load full, regulated charge, and float charge equalization) according to the battery’s technology;
- Lightweight and compact for ease of transportation;

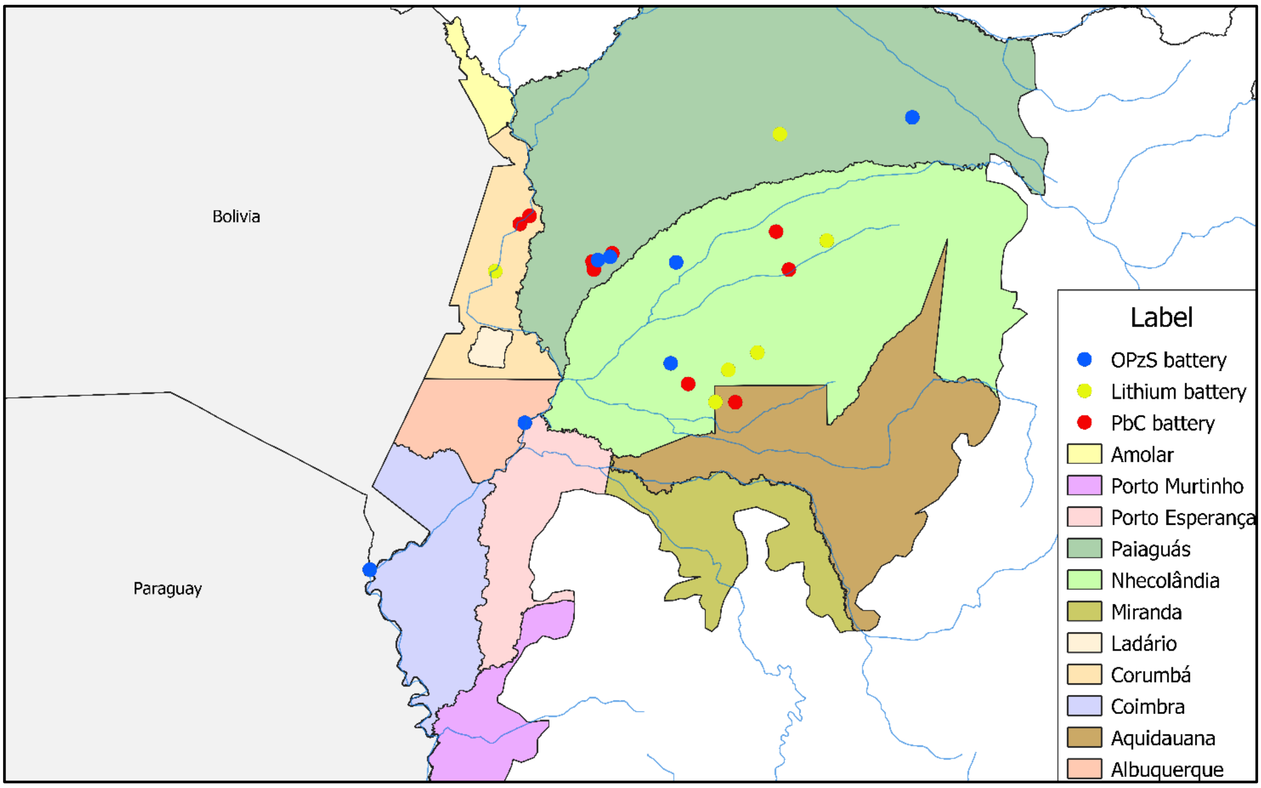


Figure 3. Distribution of prototypes in the districts of the Pantanal Sul-Mato-Grossense (PSMG) with a total area of about 90 thousand km^2

Method

In this work, the methodology described in [30] was applied to perform the task of documenting lessons learned. Firstly, the map of the stakeholders that should be involved was carried out, such as the utility, customers, and society. The results are of interest to the regulatory agency, manufacturers, researchers' centers and universities, and the public bodies that assess the quality of life and environment.

The learning process focuses on better understanding which interventions will work by collecting causal relationships and replicating steps in a principal process (universalization process). The learning process is more directed towards project engineers while the lessons learned (outcomes) aim to support decision-making by managers, directors, and the regulatory agency, regarding management material and human resources in the large-scale installation of SPSs.

Regarding the spatial scale, the implementation of SPSs in remote regions is a long-term process that encompasses several scales, with the planning beginning at a prototype scale influenced by local, national, and also international regulations, and the implementation generally - but not always - ending at the large scale site level. Learnings must be documented at each scale, through workshops, training, and courses.

According to [30] on the temporal dimension, lesson learning should be carried out from the beginning in an ongoing work plan, helping to promote the lesson learning process and ensure that it can deliver much more than just a report at the end. Regular reassessments of lessons learned can also help capture and make explicit some lessons that may have emerged in the course of implementation.

In this work lessons collection was achieved through a document review, direct observations, post-project evaluations/reviews, and case study exercises. Field teams were asked to provide a travel diary with reports and evidence of all obstacles faced so that a qualitative analysis was possible. An analysis phase was needed to transform the information collected into a series of clear, comparable, and useful lessons. Also, according to [30] the lessons can be categorized according to the level at which they are collected, specifically, the project phase, the overall project, the program level, or also, as related to the process, results, or transformations. Importantly the parameters around lessons learned need to be explicit. In other words, the conditions under which lessons can be applied mean that they might not be valid in a different situation. Process lessons are related to what is observable at a project level. On the other hand, results lessons refer to the results and knowledge generation, while transformation lessons are those results that can make a difference in projects, policies, or future scientific advances.

According to this methodology, the following sections present the SPSs implementation process, in a categorized way, by stages starting with the executive project, inspection and pre-assembly, logistical planning, and finally, the installation and the commissioning.

Executive project

The requirements for the project design and equipment specification must meet general guidelines given by ANEEL (related to minimal energy consumption fulfillment), the climatic conditions of the installation sites, and the places of each consumer unit to assess the logistics access difficulty to each one. Requirements can be subdivided into general and specific criteria, as follows.

The most important general criteria are:

- Low self-consumption in all modes of operation;
- Compliance with logistics and environmental characteristics;
- Easy O&M system;
- Safety and security requirements.

To meet logistical and environmental constraints, equipment and materials must be compact and light, and the design should consider the impracticability of transporting weighty materials, such as large structures. In addition, due to logistical difficulties, the system should be easy to operate and low in maintenance, reducing operating costs.

Being an environmental protection area it must be ensured before, during, and after installation that all environmental requirements are complied with so that the system does not influence or degrade the local flora and fauna. In Brazil, the national resolution SEMADE 09/2015 [31] indicates a series of studies to be conducted before SPSs installation.

Specific criteria requirements are related to the field-level design for parts of the systems. National standards are used to begin in the design of SPSs, however, the lack of a national standard in Brazil is a limiting problem. Therefore, international standards like the IEC / TS 62548:2016 [32] and IEC / TS 62257:2015 [33] may be considered as references together with the national ABNT 5410 low voltage electrical installation for buildings standard. For photovoltaic panels, IEC 61215:2021 [34] and IEC 61730: 2016 [35] were considered. Inverters must meet the standards IEC 62477:2012 [36], IEC 62109:2010 [37], and IEC 60364-7-712 [38] and be compatible with power quality national requirements [39]. The power storage system must meet the IEC 61427-1:2013 standards [40] regarding strength and durability (requirements for the secondary batteries used in photovoltaic energy systems, valid for the three battery technologies used in the project) and must meet the standards set out in IEC 60896-11:2002 [41] and IEC 60896-22:2004 [42] for lead-acid batteries. An important aspect was the compliance with the Brazilian Institute of Metrology and Local Standardization (INMETRO) ordinance 004/2011 [43] except for some charge controllers, inverters, and LiFePO4 and PbC batteries manufactured abroad.

Also, safety electrical projects promote the safety of users, for which were proposed the low voltage standards ABNT 5410 [44], IEC 60364:2005 [45], and (IEC 62305: 2020) [46]. Although the rules are not specific for SPSs basic recommendations were followed.

For short circuit protection on the AC side of the inverter, a thermomagnetic circuit breaker curve C (according to IEC 60898-1) is used sometimes for inverter control and protection box manufacturers.

The use of residual current devices (RCDs), according to IEC 61008:2010 [47], requires individual analysis for each inverter used. On the market are inverters that allow effective grounding in neutral (TN-S network, for example) and others that have no connection to earth (IT network). Note that the IT network as earthing arrangement is not typical in Brazilian residential electrical installations and is applied only in cases where safety requirements do not allow ground faults, such as in medical applications [44]. For that, in this project were preferred TN-S inverters. The RCD must be sized so that it always actuates when the fault reaches the actuation threshold so that the fault current path impedance is low enough for the device to actuate.

Inspection and pre-assembly

This step is done before equipment and materials are transported to the field to ensure all of them are working properly to reduce the risk of an unsuccessful installation.

The pre-assembly of complex parts, such as the electrical cabinets, was made to optimize the time it takes to carry out the activities in the field. Due to the long distances and poor travel conditions, there is high travel time, making it relevant to optimize the installation time to meet the schedule and reduce staff fatigue due to long campaigns.

Logistic planning

The logistical planning includes the development of field support activities (accommodation, food provision, extra fuel) in addition to determining the transport and routes to be used to meet the schedule of activities. It must be dynamic to consider the unexpected variations of the Pantanal's environmental conditions and be flexible enough to meet the access needs of each SPS installation place. Different types of modal transportation were necessary, boats and vessels for river transportation and pickup truck for land transport.

River transport allows accessing the riverside communities and small residences at the Paraguai and Taquari Rivers. It is noteworthy that the rivers are well signposted and navigable throughout the year.

Land transport presents a variety of access types. The first type was landfill roads (exclusively made of sand), which cause instability of the vehicles during the dry season and require maximum attention. The second type was dirt roads covered by native vegetation where no indication of a path. The third type was wet grassland and muddy terrain, where the team came across several flooded areas. Due to the flooded areas of the PSMG, the vehicles are enhanced with snorkels that increase the engine air intake protecting the engine.

Installation and commissioning

In this project, the installation of the SPS comprises the assembly of the structure, installation of the photovoltaic panels on it, fixing the cabinets with the power conditioning and energy storage systems, and monitoring systems. On the side of the customer includes the connection of the power input branch and verification of the adequacy of the internal electrical installation. Finally, commissioning was carried out according to information from the equipment manufacturers and the experience reported in [48] for photovoltaic systems in general.

RESULTS

Table 1 shows the incidence of the most critical issues experienced during installations related to the SPS's safety, cost, and performance. The incidence was calculated based on the number of installations in which the issue occurred divided by the total number of SPS.

Table 1. Critical field issue analysis

Issue	Cause	Incidence
Grounding connections not under the executive project	Misunderstanding of the grounding scheme for some inverters	43%
Failure to install one or more main equipment (PV array, controller, inverter, battery bank)	Delay in the delivery of materials by suppliers or equipment operating tests showed that it was in trouble	52%
Incomplete installation of SPSs	Lack of materials and equipment in the field due to not performing the inspection and pre-assembly step properly	17%
No installation of electrical panels	Panels were damaged in transport between the supplier and the local warehouse	14%
Equipment or material damaged	Transport and handling without proper transportation precautions recommended by the supplier (i.e., PV panels)	13%
No commissioning	Climatic conditions were not always favorable for commissioning, which required minimal radiation or lack of equipment needed to complete the commissioning	24%
Postponed installation	The soil was flooded yet and not suitable for installation, needing to allow more time for the soil to dry sufficiently to receive the structure	5%
Difficulty receiving technical support during commissioning	There was no 3G/4G signal for communication. 2G coverage is spatially and temporally limited near to Corumbá city	65%

Based on the collected data, it was possible to carry out a qualitative analysis of the obstacles to implementing SPSs in remote regions like the PMGS, as shown below:

Executive Project

One of the main difficulties related to the executive project was the lack of national standards for SPSs and microgrids in Brazil hampered both the validation of the technical specifications of the equipment and to fulfillment of the protection and safety requirements. The use of general standards for low voltage electrical systems did not address the specific characteristics of small isolated systems and was thus insufficient, requiring adaptation based on designers' experience. A simple example was the unavailability of commercial off-grid inverters in Brazil with AC voltage at 127 V, 60 Hz, necessary since this voltage is the rated for low voltage distribution system in the Mato Grosso do Sul state, where the study area is located.

For short circuit protection on the AC side of the inverter, a thermomagnetic circuit breaker curve C (according to IEC 60898-1) is sometimes used for PV control and protection board. However, field experiments show that the selectivity between curve C breakers and inverters does not work correctly. Certainly, the misunderstanding resides in the application, by the understanding that curve C circuit breakers must be dimensioned to protect the conductors against high circuit currents, but that in inverters used in SIGFIs they may not appear. On the other hand, the actuation of the inverters against phase-ground and phase-neutral faults generates stress on the internal components and also the need to restart the equipment. Therefore, it is recommended to use circuit breakers of curve Z or B to ensure selectivity with the inverters.

In addition, if the project uses an IT network, the RCD acts only on the second failure, so it will be necessary to use an insulation monitoring device to indicate the occurrence of the first failure.

Regarding the climatic characteristics, even with the lightning density index in the PMGS region averaging 14 lightning strikes per km² per year, calculations according to the IEC 62305:2020 standard [46] have shown that the use of a lighting protection system is not required. Even so, the output of the SPD Class VII inverters was incorporated to act in the event of a voltage surge, in addition to the use of the grounding ring as a complementary measure, ensuring an equipotential system and protection against shocks for people who may touch the structure in a lightning situation.

Inspection and pre-assembly

The inspection and pre-assembly stage proved to be of paramount importance for time and cost optimization. Before this stage, according to Table 1, 17% of installations were incomplete due to the lack of materials inspection, which forced the staff to return to the base city and exchange materials to complete the installation, leading to unnecessary expenses.

Logistic planning

The logistic planning based on the climatic characteristics of the regions proved to be essential to optimize travel costs. However, during the campaigns, even though the northern area of the Pantanal was at a low river level, as expected according to Figure 2b, the southern was still flooded, avoiding access and causing schedule changes. Also, when the prototype installations started, there was an anticipation of rain for three months, which was even more challenging to access some areas, especially those with land access only. It was also necessary to wait for the soil to dry sufficiently to place the photovoltaic module structures. In this sense, based on historical water level data, it was defined as an equipment cabin location height of 80 cm from ground level to avoid the water getting in touch with the equipment.

Regarding the modes of transport used, despite being adequate to travel around the region, several problems were found that impacted the travel time and consequently the logistic cost. Although river transport has the advantage of ease of access regardless of the drought or flood period, there were specific difficulties in each one. During the flooded period were found several island formations of aquatic plants. The concentration of these plants can become large enough to obstruct navigable canals. During the drought period, the boat often runs aground due to the low level of the river, being necessary for the support of the residents to complete the transport. Then, the relationship between distance and displacement time has not been strictly linear, as shown in Figure 4. For the multimodal route (land+river), the non-linearity between distance and displacement time is more evident because even when carrying out the work in the dry season, logistical unforeseen events are very likely, and in general, the linear correlation between distance and time is weak as can be seen from Figure 4.

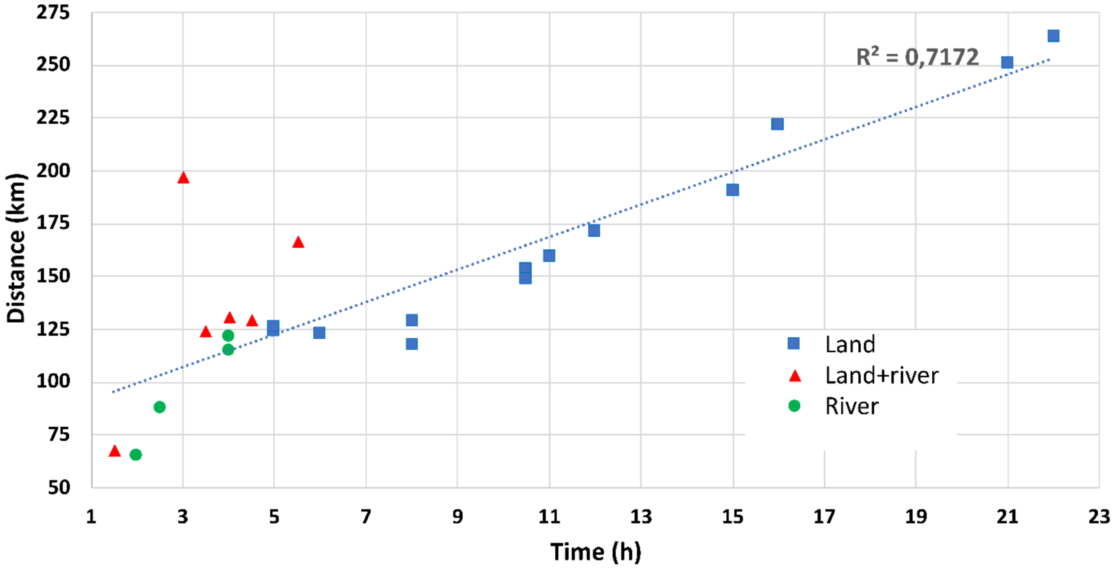


Figure 4. Distance and displacement time relation from the base cities to the installation site of the 23 SPSs

The difficulty in the following planning is mainly related to the climatic aspects and the struggle to access remote regions. It made it challenging to transport equipment, highlighting the importance of defining strategies that help optimize the transportation and assembly of systems. For this, the project followed the inspection, pre-assembly, and logistic planning steps, which were necessary to maintain the equipment integrity and elaborate efficient planning, considering the difficulties of prototyping and assembly. The transportation of equipment, especially batteries that are considered hazardous products, was carried out according to the manufacturer's recommendations and in compliance with national regulations [49] - [55] and the laws of the environmental agency [56]. The dimensions and weight of the equipment also had to be carefully considered. For example, PbC and OPzS battery banks are more difficult to transport than lithium battery banks, mostly due to their volume and weight.

Installation and commissioning stage

The main issues encountered during the implementation of the SPSs were due to failures in the execution of planning (52%) and the misunderstanding of installation patterns in isolated residential applications (43%).

Another obstacle encountered was the difficulty of technical support due to limited communication. Table 1 shows that this issue affected 67% of the installations. It is also important to mention that due to the lack of telephone coverage, the teams acquired satellite phones, but even so, the communication difficulty remained as a result of the instability of the signal in the region. This shows the importance of training and preparing teams before field activities.

In the context of customer service, the regulatory power energy limits did not meet consumer expectations, being necessary awareness activities about energy efficiency and the system limitations. In some SPSs with verified overload conditions poor system performance was confirmed, especially SPSs with lead-acid batteries that require more daylight time to recharge than LiFePO4 batteries.

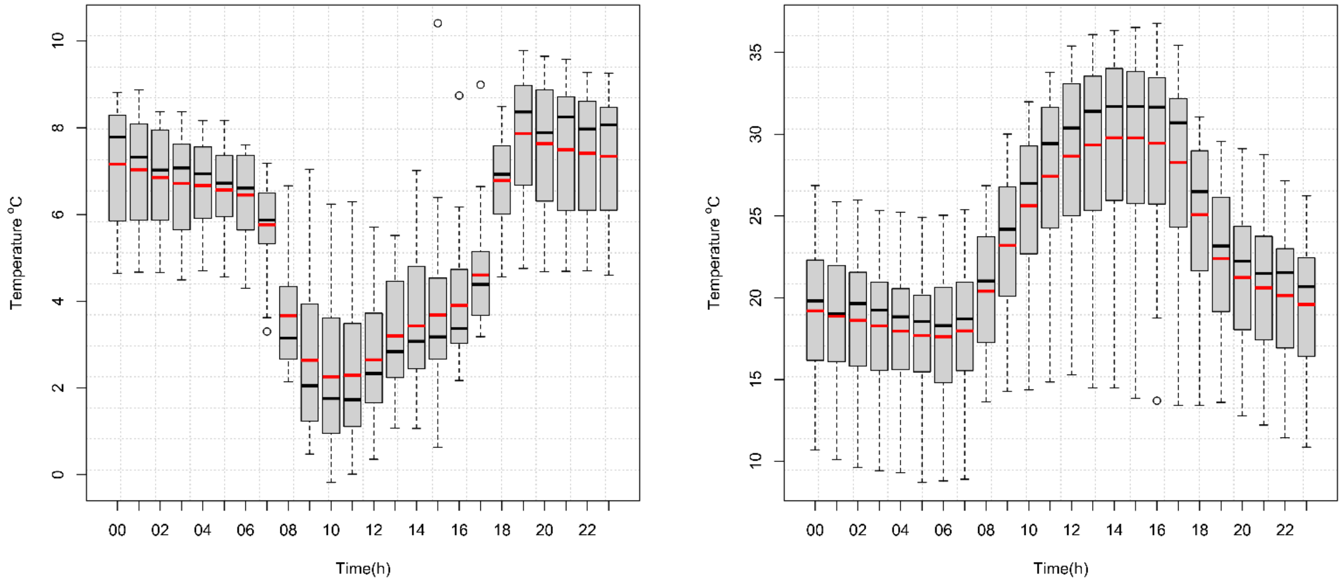
LESSONS LEARNED FROM FIELD EXPERIENCES

This topic brings recommendations to facilitate the implementation of SPS and microgrids in remote areas based on the analysis of the main obstacles encountered. To facilitate the reader's understanding, we follow the same structure presented in the methodology:

Executive Project

- Prospect national and international technical standards for SPSs and recommendations of equipment manufacturers. It is necessary to draw up national norms not only for the standardization of equipment but also for the standardization of operating procedures of SIGFIs, aiming to meet loads in either direct current or alternating current. In this sense, for example, according to [57] 99.1% of 40,200 SPSs and rural microgrids implemented from 2009 up to 2020 in Brazil do not use a measurement system;

- Conduct a sampling soil study to avoid possible failure in the structure's foundations of the PVs. Moist sandy or clayey soil was often encountered during installation in Pantanal, which made it challenging to install the anchor-type foundation of the structure. It is advisable to do a soil study based on the collection of samples and maps of the soil types of the region to allow the stratification of the results;
- Forced ventilation was not required as SPSs are small off-grid systems. Batteries operated properly at temperatures considered near to normal only with wall thermal insulation of aluminum fiber and a window at the bottom side of the battery cabinet. As can be realized in Figure 5a thermal insulation was competent to keep the internal temperature of the cell $LiFePO_4$ battery (related to the external temperature shown in Figure 5b) controlled during the daytime (the mean below the median). However, at night periods the internal temperature was always higher than the external one. It is a call to improve the design of battery shelters while still maintaining natural ventilation. Then, it is recommended to make a window at the topside protected with a screen, at the cost of reducing the degree of protection against dust and eventually water. It accepted that any gain in temperature reduction translates into benefits in battery life;



(a) (b)

Figure 5. Hourly temperature distribution from 04/05/2020 to 08/05/20 at Cascavel SPS located in the district of Nhecolandia: (a) from BMS temperature sensor of Lithium-ion- battery; (b) ambient temperature. The mean temperature is black and the median one is red

- Because the battery technologies examined (lead-based and Lithium-ion) have some risk of explosion or gas emission, they should not share cabinets with power conditioning equipment. In 12 months of operation was evidenced with swelling only one pack of $LiFePO_4$ battery. However, swelling of cells can result when deep over-discharge occurs [58] and not necessarily be a manufacturing imperfection;
- Give attention to the technical characteristics of the inverters and charge controllers against the indicated grounding system type either on the direct or alternating current side, due to the electrical protection and safety procedures for people in the PV installation begin from this definition;
- The technical-economic advantage of using high-frequency type inverters (pure sinusoidal) must be judged since they may not offer a ground reference for application in TN systems. If these inverters were chosen, depending on local regulations, it could be necessary to install supervisory insulation devices, with costs comparable to those of the inverters themselves.
- Inverters and charge controllers must consider low self-consumption and efficiency above 90% during the entire operational range. In Brazil, the Inmetro [43] considers 30 mA for charge controllers and a limit of 3% of nominal power for inverters for self-consumption;

- In terms of generation performance, the irradiation conditions of Pantanal-MS are very good. An average of 5.70 kWh/kW and 5.61 kWh/kW for Cascavel and Nova Estancia SPS locations were calculated from irradiance measurements, respectively. Therefore, in this case, we did not observe the advantage of MPPT (costly) over the PWM (low-priced) charge controller technology for small PV systems, in agreement with [59].
- It was found SPS inverter manufacturers do not report current ripple content. Then, be aware of the negative impact of ripple current generated by the inverters over the useful life of the battery cells [60] and the energy conversion efficiency of a photovoltaic power system [61]. It's necessary to conduct more research to get normative levels of ripple currents from SPS inverters.

Inspection and pre-assembly

- Pre-assembly of small elements when possible;
- Test controller and inverter operation
- Inspect equipment and materials before the transportation to the field.

Logistic planning

These recommendations are split into two parts, first for the planning and second for the logistic and transport stage. In the planning stage the recommendations are:

- Survey of applicable environmental regional laws and transportation regulations;
- Assess environmental, climatic, and geographical characteristics of the region by the use of satellite or field-collected data;
- Develop dynamic logistical planning to deal with the varying climatic aspects of the region;
- Identify local temporal bases in the field with adequate infrastructure to accommodate human and material resources;
- Maintain direct contact with residents, when possible, to collect information about weather conditions, access, and transportation. The involvement of communities must be carefully preserved so that they actively support field activities. Several projects have failed to consider this involvement, such as Peru, Chile, and Ecuador in South America [62];
- Consider and schedule for possible delays in travel due to access difficulties and unforeseen weather.

To the logistic and transport stage:

- Obstacles to land transport included gates, deep ebbs, and jams that damaged the vehicles. Therefore, hire experienced local guides as much as possible and give them appropriate vehicles to meet regulatory safety standards;
- Besides that, the great distances between the properties, 30 km on average, and wild animals with nocturnal habits. Because of these obstacles and the team's security, transport occurred in daylight whenever possible;
- Due to the poor road conditions in remote regions, as shown in section II, the transport of panels and batteries must be carried out carefully, breakage of panels and leaks of fluids should be avoided by carrying on conditioning procedures;
- PWM charge controller technology is more advantageous logistically than MPPT one due to its lower weight and volume like Lithium-ion based battery technology.

Installation and commissioning stage

- It is preferable to train local personnel staff than to take specialists from large cities and metropolises. Adverse conditions in these regions negatively impact the performance of non-resident people, then also SPS maintenance can be critical shortly, so qualify and train local technicians in advance to carry out fieldwork. It is a positive social impact effect of decentralized photovoltaic systems;
- Due to the high logistical cost and possible damage in the transport of the equipment, is recommended the handling of spare parts;
- Simplified methods of SPSs commissioning are needed to expedite the installation and optimize massive maintenance independent of climatic conditions.

Other recommendations

We can also add other recommendations not related to critical installation issues, namely:

- When looking for the best site for SPS installation take into account the constraints of tree pruning according to environmental authorities' laws;
- As a negative point, we have experienced the informality in conducting business and contracting services by local people, but their impacts have been controlled;
- Perform the user awareness regarding the system limitation and energy efficiency actions;
- Theft of SPSs equipment components is a reality in remote regions in Brazil, even with security and tracking devices installed. For example, PbC acid lead-carbon batteries, although with a higher energy density than OPzS batteries, were not a good choice, as they can be used in vehicles as motorboats in the region. Therefore, the operating voltage of the batteries must be carefully analyzed to avoid secondary uses and to prevent theft;
- To carry out the corrective maintenance of the SPS, it would be ideal if some information of the damage will be known in advance, this would allow moving from the base cities with the true replacement parts, speeding up the return of electricity. Remember that displacements from base cities to SPS places can take up to 24 hours. Therefore, it is recommended to implement an intelligent algorithm into a low-consumption and cost-effective programmable logic controller that activate LED light signals identifying the location of the problem, for example, panel, inverter, controller, or battery. So, the consumer can identify the defective equipment and inform the utility of an indication of the malfunctioning part to be replaced. In this sense, lithium batteries have advantages when self-diagnostic functions are implemented built-in the battery management system. The research team has published a methodology to deal with the resource planning of preventive maintenance for SPS in remote regions [63].

CONCLUSION

Rural electrification may be feasible with government incentives, but the difficulty of implementing power generation systems in isolated areas inhibits investments in these areas. The installation SPSs prototypes in the PSMG discussed in this work allowed an assessment of the difficulties experienced, allowing it possible to generate recommendations to facilitate both the universal electrification of the region and the implementation of these systems in different isolated areas of the world.

Based on the qualitative results presented, we conclude that logistic planning and design are the most critical phases, so it must get special attention to researching the best practices and current technology to maximize global benefits. We must also emphasize that the participation of residents is essential for any step that one wishes to take. Therefore, the approach with associations and local representatives was fundamental to the dissemination of the objectives of the work.

Challenges were seen in the lack of local technical standards and qualified labor to install and commission and shortly in the corrective maintenance activities. Regarding the technologies, we have evidenced the short-term advantage of Lithium-based batteries over lead-based ones, but not yet the impact on the long-term maintenance cost, because little is known about premature failures and the maintenance needs of lithium-ion batteries in off-grid PV systems, so more research should be carried out to consolidate the application of this technology.

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