Use of renewable energies as part of the strategy to increase the access of energy to remote communities. A Colombian case: Isla Múcura

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Abstract. Use of renewable energies in remote places with no access to main electrical infrastructure becomes fundamental to guarantee equity as well as affordable and clean energy, impacting the United Nations Sustainable Development Goals (UN SDGs). There is also fundamental correct and effective capacitация to operators, to avoid expected-lifetime reductions due to malfunctioning or maloperation. In this paper, the case of Isla Múcura is studied: Photovoltaic (PV) system and storage diagnosis, recovery and community capacitация activities were performed in a fishing and tourism-based community with no knowledge about electrical infrastructure. It was detected that correct capacitация and reliable information devices are fundamental to improve maintenance, operation, and management of the overall generation system

1. Introduction

Use of self-generating power plants became a suitable solution for remote locations where electrical energy is required, but geographical or economic conditions are not appropriate to implement a physical splice with interconnected electrical networks. Colombia, due to its complex geography and remarkable population concentrations in main cities, focused the coverage of electrical service through National Interconnected Grid (SIN by its Spanish translation) for almost 97% of citizens [1], located in approximately 50% of Colombian territory.

Aiming to increase the access of nationals to electric fluid, Colombia created government entities as the institute for Planification and Promotion of Electrical Solutions in Non-Interconnected Zones (IPSE by its Spanish translation), which is intended to identify, promote, foment, develop and implement energy solutions for non-interconnected zones; improving life conditions of settlers, building peace and equity in the country, as well as pushing forward the use of renewable energies [2]. Isla Múcura is a 30ha island part of the Colombian territory, located in the influence area of the “Corales del Rosario” National Natural Park. This place and its inhabitants keep a fishing and tourism-based economy. Life conditions there are characterized by the lack of provision in public services, however, electricity supply is provided by a 30 kWp PV array + storage based on lead acid battery cells donated from Japan Government to IPSE and the Island, as well as a 145 kVA Diesel self-generating power plant.
Most importantly, the energy system management oversees the local community, who were not properly trained to operate and maintain the PV system in optimal conditions, this has led to detriment in the capacity of the PV plant and storage system. On the other hand, due to lack of consumption information, there is not a fair economic recognition system for used energy. To determine the status of the overall system, energy generation and storage profiles were obtained as shown in section 2. Batteries recovery tests were studied, the results can be found in section 3. Energy consumption measurement system was implemented to monitor the usage of energy resources, as mentioned in section 4. Electrical recommendations to improve the functionality of the PV system are in section 5. Finally, social impact and conclusions are in section 6 and 7, respectively.

2. Preliminary Diagnosis
Several field inspections were performed to establish the multi-line diagram and the status of each one of the components, part of the system. In general terms, the 30kWp PV plant is composed of 3 clusters which are two parallel arrays of 20 PV modules each one. The general characteristics of the array are shown below. Each cluster is connected independently to a 10kW DC/AC power inverter, which are attached to a single AC bus.

| Table 1. PV modules array electrical characteristics. |
|------------------------------------------------------|
| **PV Plant**                                         |
| **PV Power**                                         | 30 kWp |
| **Voc**                                              | 748 V  |
| **Isc**                                              | 52.98 A|
| **Vmpp**                                             | 602 V  |
| **Impp**                                             | 49.86 V|

The electrical system also has a DC storage stage connected directly to the AC general bus, which is composed by two independent AC/DC inverters in configuration Master (1) – Slave (2). Energy storage is composed of 96 lead acid cells working at 2V and 2500Ah (C120) each one, distributed in two sets controlled by power inverters. Two strings are connected in parallel composed by 48 series arranged cells, conforming a 48V and 10kAh storage system.

As energy back-up, a 145kVA and 416VAC diesel generator is used altogether with a reduction transformer to match the AC bus voltage. The diesel generator is oversized compared to the overall connected load and operates when storage level is critical. The automatic transference is not working and so the process is performed manually. From the general inspection, a multi-line electrical diagram was sketched (Fig. 1) considering energy generation sources, the storage system, and main loads.
2.1. PV Modules

From visual inspection to the PV array, it could be determined that cleaning maintenance is not easily possible without fall risk, complementary to this critical situation, several birds and animals step up over the PV modules leaving excretions and shading several cells, generating localized heating and expected-lifetime reduction. To determine the generation capacity of the array, a silicon reference cell was installed and compared with the generation profile of the plant. Considering the measured irradiance at a selected point (Fig. 2), the corresponding output power from the three installed clusters, and the ambient temperature operation of PV modules, it is possible to obtain the overall efficiency for the generation plant. As result of the analysis, the total generated power of the plant at 15:00 hrs with an irradiance value of 620 W/m² was 15.3 kW measured at the output of cluster connection. From measured irradiance profile and thermal measurements, it is possible to determine that the expected power generated at 620 W/m² is 17.2 kW.

\[
P_{\text{expected}} = (30 \text{ kW})(620)/(1000)(0.925) = 17.205 \text{ kW}
\]

\[
\eta_{\text{PV Plant}} = (15.3 \text{ kW})/(17.205 \text{ kW}) \approx 90 \%
\]

The detected decrease in generation can be directly associated with shades formed by trees, lack of maintenance, uncertainty in the measurement process, and the aging of PV modules.

2.2. PV inverters

Through instantaneous power measurements in each cluster, it was determined that all the PV inverters were operating correctly, showing a regular conversion profile. Nevertheless, the display for PV inverter No. 2 was not working properly. To confirm the correct operation of PV inverters, power measurements were performed, obtaining the generation profile shown in Fig 3.
Figure 2. Irradiance profile over PV array for diagnosis purposes. This information was compared to
DC power generated at 15:00 hrs. (3:00 PM), obtaining an efficiency of 90% from expected nominal
power corrected by thermal decline.

Figure 3. Instantaneous power of PV plant along the time. It is possible to see the generation profile,
with two zero crosses due to activation and deactivation of the storage system around 13:00 hrs. and
16:00 hrs. The operation is performed manually due to inconveniences with automatic transference.

2.3. Storage inverters
According to voltage and current data obtained from the internal acquisition system of storage
inverters and compared to external measurements, the corresponding management given to the storage
system by the community was determined. Empirically and with no instructions or indications at all,
the operator of the electrical system of the island connects the main load around 13:45 hrs. just before
the storage group reaches the inverter’s output voltage. Then, at 16:00 hrs. the island’s load is
disconnected to charge the batteries again. At 18:00 hrs. the main loads are connected again, and the
diesel generator operates feeding the loads until 23:00 hrs. to finally use the remaining resource saved
in batteries until the next day. It is possible to identify a higher charge voltage over storage group No.
1 when charging current is high, which can correspond to an improper configuration of the storage
inverters. This behavior does not match with storage group No. 2, which shows constant charge
voltages and smooth decrease during battery charge process.
2.4. Storage system
As a preliminary diagnostic, it is evident that the energy storage system is not properly used due to lack of information and unknown real status of batteries in real time. The minimum average load percentage reached in batteries is around 60%, showing a positive index for battery cells, guaranteeing up to 3000 cycles according to manufacturer’s information.
On the other hand, there are poor maintenance practices for battery cells. The Pb–acid batteries require frequent liquid change for the electrolyte, corresponding to a mixture of sulfuric acid diluted in water. To determine the current characteristics of electrolytes and charge of cells, specific gravity is measured. It was found that several cells were completely dry, identifying a critical scenario for batteries.

3. Battery recovery tests
From the current status of battery cells, it is concluded that to preserve and maximize the life-time cycle of the storage system, it is necessary to recover the functionality of the cells diminishing the quantity of sediments formed and deposited on the electrodes, due to a lack in electrolytic solution caused by a poor preventive maintenance [3].
Several activation tests aimed to recover the nominal capacity of battery cells are now available in the literature. They are also performed on sulfated cells and are no longer working properly. Three different recovery methods and their results were studied and compared as follows:
3.1. **High voltage method**
It involves the application of a load voltage between terminals in the range of 1.3 and 1.5 times the nominal voltage of the cell during a short time, assuring that the cell’s temperature does not exceed 45°C to avoid an important gasification of electrodes [4]. From the performed tests, it was concluded that this method is recommended for low sulphation levels, because it represents an important risk for the cells due to fast rising in cell’s temperature.

3.2. **Full charge and discharge cycles method**
It is aimed to restore cells diagnosed with small damages, looking for the activation of active substances (transformation of Pb-sulphate to active components of the battery)[5]. This test consists in the full charge and deep discharge of the corresponding cells, and it was concluded from the performed tests that it is necessary to rigorously follow the methodology, as an erroneous performance of these cycles can easily lead to a fatal damage of the battery.

3.3. **Pulsed loads or Phoenix method**
This method consists in the continuous injection of voltage peaks between the electrodes of the battery, aimed to break the precipitations of Pb-sulphate and diminish their existence and growth. Its principal objective is to weaken the sulphate depositions without generate additional damages to the cell[6], [7]. The method is based on the resonant frequency of sulphate crystals. Due to the high harmonic components of pulsed peaks, it is possible to excite the depositions with their resonance frequency which principally depends on their size, physical form, and molecular structure.
It was found that big deposition crystals respond and disintegrate under the excitation of low frequencies, meanwhile small particles are sensible to high frequencies, allowing to decompose them and perform a sweep in the cases it could be necessary. The capacity of the battery can be recovered partially with outstanding results compared to the two previous methods.

4. **Energy consumption management**
Grid connection and management is performed manually because of a fatal failure of the automatic management set up, caused by absence of preventive and corrective maintenance. Then, a worker oversees the operation and monitoring of generation and storage systems, who connects and disconnects the different elements of the grid, according to the experience, the time and a display which shows the charge status of the batteries.
On the other hand, the access and usage of energy is ruled by demand, under common agreement. Every inhabitant reports the energy needs according to the type and quantity of electrical appliances planned to feed from the grid and then, monthly, the chief of the local action board collects the corresponding payment associated with the electrical active equipment in each house to buy fuel for the diesel generator. This methodology, despite is currently working, does not fully represent the real energy consumption for each customer, leading to misunderstandings about the monetary compensation.
Fig. 5 shows the daily management operations for the different stages of the system. Diesel generation is present for 4 hours a day to supply loads and battery charge, which leads to additional costs assumed by the community. The island’s economy is based towards fishing and tourism, then it is identified a minimum consumption profile for devices that are connected 24 hours a day, as well as the increase of nocturnal use of appliances as TVs, sound equipment, among others.
Figure 5. Daily management operations for the system’s elements. Negative battery state means it is discharging while positive, charging. Positive states for PV and Diesel, mean they are generating energy, while a positive state in Load means it is connected.

Considering the consumption practices performed by locals and tourists, two methodologies were proposed to adapt the quantification and collection of energy rates, according to their real consumption:

- Include metered-based energy quantification for each user and establish a kWh flat rate to determine the apports from each consumer. This is the most optioned strategy because it represents the real energy consumption of each one of the users of the grid. In contrast, it requires an energy – meter for each consumer, increasing the implementation costs for the total solution.

- Include metered – based energy quantification for user groups and establish a base fare for all the users as well as a minimum energy coverage for each one of the consumers. This cost will be increased according to the difference in the energy user and will be divided in the whole group. This strategy strongly reduces costs of implementation, but it requires a careful selection of groups looking for equity in that conformation.

The following strategy was followed to implement a measurement system that helps to acquire data and establish the real consumption of energy per user: electronic meters were acquired, their software and hardware were adapted using current transformers, voltage dividers, and programming its digital processor unit capable of power calculations in the four quadrants to finally come up with an energy – meter with precision of seconds.

The technology used in these devices allows to monitor up to six independent single-phase loads and centralize the measurements in the same unit, the information can be accessed by local wi-fi connection by the inhabitants through their electronic devices. In this way, daily or weekly monitoring will help users to determine how much energy they are using, as well as indicate the wage they must pay for the energy service. Even more, if a stable internet signal is present, data can also be sent to the cloud, this feature would also help future operation if remote monitoring by agents outside the community is implemented, in this way, operation costs of the system will reduce since no operator needs to be physically present in the island. Proper implementation of this internet connection would also increase the amount of data available for generation/load analysis.
Even though energy-meters were tested prior its installation, put in service and their functionality was validated a couple of days, their operation failed almost after a month of service in the island, this was due to improper design of lightning protection system, which provoked overvoltage failures in the main digital board. However, implementation of these measurement scheme still preserves high potential for usage as a guidance tool to achieve a fairer charge for energy consumption.

5. Electrical system improvement and recommendations
From the collected data and the identification of generation and consumption profiles, the following elements were identified as improvements in the performance of the electrical system from final user’s side:
- Usage of the PV array to feed batteries and essential loads (refrigeration) during the day. This to dynamize the generation – consumption system and reduce the operation cycles for the batteries.
- Identify the generation efficiency of a PV system when the Diesel generator is used, recognize energy losses that can be used to charge the batteries without diesel fuel, and then reduce the operation costs of the electrical system.

6. Social Impact
Energy consumption and land distribution in Isla Múcura, and more specifically, in Puerto Caracol, where the locals reside, is very inequitable. Touristic complexes take advantage of the main part of the available and habitable land, and in the same order, their energy consumption is the most representative in the whole electrical system. Nevertheless, in most cases their payments are not completely representative, compared to the total consumption. This phenomenon is related to the lack of available information about energy use profiles and the fares established in the island as a method to quantify the price of energy supply.

The development of this project gives to the whole community not only tools to clearly identify the total consumption for each user connected to the grid, but also strategies to take care of the PV generation plant, increasing its performance and its expected lifetime, but reducing at maximum the use of the diesel generator.

Training of locals about preventive and corrective maintenance of the electrical system, plays a fundamental role in two ways: First, the monitoring and maintenance of the PV plant and the storage system prevents the damage of their components, allowing the operator to take decisions based on technical and quantitative information and reducing intervention costs as well as the unavailability time. Second, the appropriation of the electrical system by the community, could achieve a closer monitoring of energy profiles and an optimization of not only the operation of the PV and diesel plants, but also of their consumption practices to achieve a higher efficiency during their daily tasks.

7. Conclusions
Colombia, as part of its strategy to increase access to electrical energy and looking for the reduction of the breaches reported by the UN worldwide, has been using renewable energies as a powerful tool to reach the most remote places of the country, as a low cost and highly effective method to provide energy to citizens.

This strategy has many advantages as well as several disadvantages that can be easily covered by giving the community decision tools and training them to give a closer look of the daily operation for the overall system. The immersion of these projects inside local communities, needs to be accompanied by socialization and appropriation of the projects, showing the advantages in terms of equity, risks, and the importance of their active participation in the durability and optimization of the new resource they have.

8. References
[1] Unidad de Planeación Minero Energética - UPME, “Índice de Cobertura de Energía Eléctrica - ICEE 2018” SIEL (Sistema de Información Eléctrico Colombiano), 2018. http://www.siel.gov.co/, (accessed Mar. 15, 2021)

[2] Instituto de Planificación y Promoción de Soluciones Eléctricas para las Zonas No Interconectadas - IPSE, “Funciones principales del IPSE” Instituto de Planificación y Promoción de Soluciones Eléctricas para las Zonas No Interconectadas - IPSE, 2021. https://ipse.gov.co/mapa-del-sito/ipse/historia/ (accessed Mar. 15, 2021).

[3] Karami H and Asadi R, “Recovery of discarded sulfated lead-acid batteries” (2009), J. Power Sources, vol. 191, no. 1, pp. 165–175, doi: 10.1016/j.jpowsour.2008.12.153.

[4] Ordoñez J, Gago E J, and Girard A, “Processes and technologies for the recycling and recovery of spent lithium-ion batteries”, (2016), Renew. Sustain. Energy Rev., vol. 60, pp. 195–205, doi: 10.1016/j.rser.2015.12.363.

[5] Jin J, Jin D, Shim J, and Shim W, “Enhancing Reversible Sulfation of PbO 2 Nanoparticles for Extended Lifetime in Lead-Acid Batteries”, (2017), J. Electrochem. Soc., vol. 164, no. 7, pp. A1628–A1634, doi: 10.1149/2.1291707jes.

[6] H. Ikeda, S. Minami, S. J. Hou, Y. Onishi, and A. Kozawa, “Nobel High Current Pulse Charging Method for Prolongation of Lead-acid Batteries”, (2005), J. Asian Electr. Veh., vol. 3, no. 1, pp. 681–687, doi: 10.4130/jaev.3.681.

[7] Zhang Y, Hou S, Minami S, and Kozawa A, “A high current pulse activator for the prolongation of Lead-acid batteries”, (2008), IEEE Veh. Power Propuls. Conf. VPPC 2008, pp. 3–6, doi: 10.1109/VPPC.2008.4677701.

Acknowledgments
The authors would like to thank the Puerto Caracol community in Isla Múcura, for their kind disposition, support, and contributions to the social and technical studies performed by the students involved as well as Universidad Nacional de Colombia for funding this case study through the Fondo Nacional de Extensión Solidaria 2018.