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AN ISLANDED MICROG+RID TO INCREASE QUALITY OF LIFE AND SUPPORT AGRICULTURAL ACTIVITIES OF RURAL COMMUNITIES IN MARRACUENE, MAPUTO: CHALLENGES, SIZING, AND VALIDATION

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Sustainable Islanded Microgrid, Solar Photovoltaic Energy, Energy Poverty

ABSTRACT
This paper deals with the design, sizing, and validation of an islanded microgrid to aid agricultural activities of rural communities, in which a water pumping system (WPS), a set of dc electric loads, and an energy storage system (ESS) are powered by solar photovoltaic (PV) panels. In this regard, four operation modes are considered and validated by performing computer simulations, namely: (i) solar PV panels to water pump (PV2WP); (ii) solar PV panels to loads (PV2L); (iii) solar PV panels to batteries (PV2B); (iv) batteries to loads (B2L). Despite being intended for implementation in Marracuene, Maputo, the proposed sustainable islanded microgrid solution must present an easy replicability character, low cost, and power expansion capability, independently of the geographical location. Thus, the main challenges regarding idea conception and social impact are addressed, gathering and analyzing power electronics equipment to mitigate energy poverty, increase the community quality of life (QoL), and respond to its daily needs. Simulations results prove the self-sustainable character of the islanded microgrid, with all the proposed operation modes presenting total independence from the electric power grid and without limitations regarding power flow management.

INTRODUCTION

In remote and isolated geographic locations, where the utility grid presents severe flaws or is even inexistent, the main, and sometimes, only available electricity source, are diesel generators, a reliable and cheap technology but inefficient and responsible for the increase in CO_2 emissions to the atmosphere. This fact is reflected in a large number of people without access to electricity worldwide, more specifically in poor regions and countries, e.g., India, South America, Sub-Saharan Africa, among others (Blechinger et al., 2019). According to the Community of European Committees, the absence of access to electric energy is often reflected in shortages of piped water and lack of basic health equipment (e.g., refrigerators), lighting, transportation systems, mechanized irrigation technologies, and modern means of communication. In other words, electricity can be, in part, seen as the basis to improve the quality of life (QoL) of rural communities, providing the conditions to stimulate education and health.

It is crucial to change the current economic, socio-cultural, technological, and environmental paradigm, creating the means to foment scientific innovation, entrepreneurship, and train the community to reach self-sustainability. Due to the lack of piped water, agricultural production and animal husbandry are severely affected, thus leading to malnutrition problems and poverty. In Mozambique, particularly, more than 70% of the population does not have access to electricity and as expected, a great part of the population lives in rural areas (Chilundo, Neves, et al., 2019). Since agriculture is an integral part of the daily quotidian, it is essential to improve the traditional cultivation methods by introducing technological practices and devices, automating ancient systems, and providing training to technicians, women, and children. Contact with technology is vital to boost the economic development of such populations, and consequently, of the country. Among several measures, self-sustaining agricultural practices must be adopted, the populations may be responsible for the equipment maintenance and repair, and nutrition programs must be implemented (Chilundo et al., 2018).

To mitigate the above-mentioned vulnerabilities, the propagation of islanded microgrids based on renewable energy sources (RES), namely solar photovoltaic (PV), is seen as a pertinent and suitable solution (Pinto et al., 2017). In the region of Sub-Saharan Africa, given the geographical location and terrain morphology, solar PV is the RES that presents the greatest potential for development according to the values of solar radiation. However, if weather conditions were suitable, other RES may be considered, e.g., hydro and wind power (Baghaee et al., 2017; Housseini et al., 2017; Kusakana, 2015). This issue is of great importance for the replication of microgrid technology in other geographic regions where the sun is not the most predominant RES. Additionally, by adopting more than one RES-based technology, the operating power range and independence from energy storage systems (ESS) are also increased (Wang et al., 2018).

Besides the environmental advantages, by combining RES and ESS, the intermittent production profile of the former is mitigated, a condition considered indispensable for meeting the basic needs of rural communities. The constant access to electricity throughout the day, independently of the weather conditions, allows the development of a new lifestyle for the communities, focused on improving their QoL from the technological, educational, and health points of view. However, and as already mentioned, it is crucial to also allow access to piped water to stimulate and improve agriculture practices, which, in several cases, may not be so simple (Meunier et al., 2019). Predominantly, the only available water sources are rivers or lakes, which, sometimes, are polluted, thus extremely increasing the risk of disease or even death due to the lack of sanitary conditions. In this regard, the water may be captured from a borehole, however, depending on the terrain morphology, it can be found with greater or lesser difficulty, requiring an analysis prior to drilling.

Field preparation is a task that receives special prominence and involves the community. In some geographic locations, the rainy season can be very severe and lead to constant floods, which causes difficulties to access the terrain and irreparable damage to food crops. In addition to the social-cultural context of each country (possible theft of electronic equipment, etc.), it is vital to foresee climate behavior throughout the year. Periods of great drought must also be considered during the conception of the microgrid. In this regard, it is vital to dynamically adapt the type of cultivated crop to the season in question, e.g., watering in accordance with the climate conditions, rainfall, humidity (Chilundo, Maure, et al., 2019).

Thus, this paper provides a technological and socio-cultural overview related to the establishment of an islanded microgrid in the region of Marracuene, Maputo, in which a water pumping system (WPS), an ESS, and electric loads are powered by solar PV panels. As above-mentioned, technological innovation needs to be promoted, processes and practices must be automated, and all microgrid variables controlled dynamically and in real-time. Among several aspects, it is vital to analyze the main challenges, address limitations concerning water storage in the tanks, size the WPS, ESS, and solar PV panels, forecast losses, calculate power values, and, lastly, conclude the main precautions, limitations, and advantages of each possible configuration for the power system (Fuentes-Cortés et al., 2019).

To predict the behavior of the adopted power electronics system architecture, its operation may be validated by performing computer simulations, analyzing in detail each operation modes. Posteriorly, but outside the context of this paper, the technical procedures related to the installation and operation of all the microgrid equipment should be analyzed so that statistical data and testimonies that prove the benefits for the community may be obtained.

Thus, in the next section of the paper, the adopted architecture and operating principle of the islanded microgrid are detailed, enumerating and explaining each operation mode. Posteriorly, the geographical context of Marracuene is depicted, analyzing weather conditions throughout the year in order to foresee the system behavior. The islanded microgrid sizing is presented in the fourth section of the paper, in which the power values of the solar PV and ESS are defined and losses in the WPS are forecasted. The operation modes considered for the microgrid are validated with the aid of computer simulations in the fifth section and, conclusions are given in the last section.

GEOGRAPHICAL CONTEXT OF MARRACUENE, MAPUTO

Mozambique is located in Southeastern Africa, presenting a coastline of more than 2500 km and six land borders, namely, the countries of South Africa, Swaziland, Zimbabwe, Zambia, Malawi, and Tanzania. Given the economical context of Mozambique, its population primarily lives from agriculture and cattle raising, however, such activities are severely affected by the lack of piped water, extensive periods of drought, and frequent floods. Such a scenario is even further aggravated without access to electricity, which have an impact on a large portion of the Mozambican population. Thus, to overcome such limitations, the use of diesel generators in rural communities is still a strong reality due to its low acquisition cost. On the other hand, concerns regarding energy efficiency and environmental issues are leading to a continuous paradigm shift focused on the adoption of decentralized power systems, in which RES assume a central role. Despite the innumerous advantages regarding reliability and suitability, the inclusion of several emerging technologies in the electrical power system is arising problems related to flexibility, safety, and capacity to respond to failures, thus being necessary to employ new technologies and methodologies.

Among several issues, the intermittent energy production profile of RES must be smoothened, which can be achieved by introducing an ESS or, less frequently, by combining more than one type of RES, e.g., solar PV and wind power. Nevertheless, it only makes sense to resort to a determined RES if the geographical context of the implementation site is considered appropriate, i.e., climatic conditions and terrain morphology must be suitable for each RES. In the case of Marracuene, solar PV technology can be adopted since higher values of solar global horizontal irradiation (GHI) are registered throughout almost the entire country, as seen in Figure 1 (a). Given that Mozambique is a tropical country located in the southern hemisphere, solar GHI values are much higher during the rainy season, i.e., from October to March, as seen in Figure 1 (b). However, during this period, the temperatures are also higher, which will result in slightly lower solar PV panels' efficiency. Nonetheless, considering the average solar GHI values in this region, as in entire

Southeastern Africa, the suitability of solar PV technology is extremely high, as proven by observing the monthly solar GHI and the average maximum, mean and minimum temperatures (Figure 1 (c)) graphics of Marracuene (25°39'09.4"S 32°40'59.7"E). Solar GHI map of Mozambique was prepared by Solargis, funded by ESMAP, and published by the World Bank Group, whilst temperature and solar GHI data values were obtained by combining Homer Pro software and PVGIS-SARAH database, being referred to the time period from 2005 to 2016 at the provided coordinates.

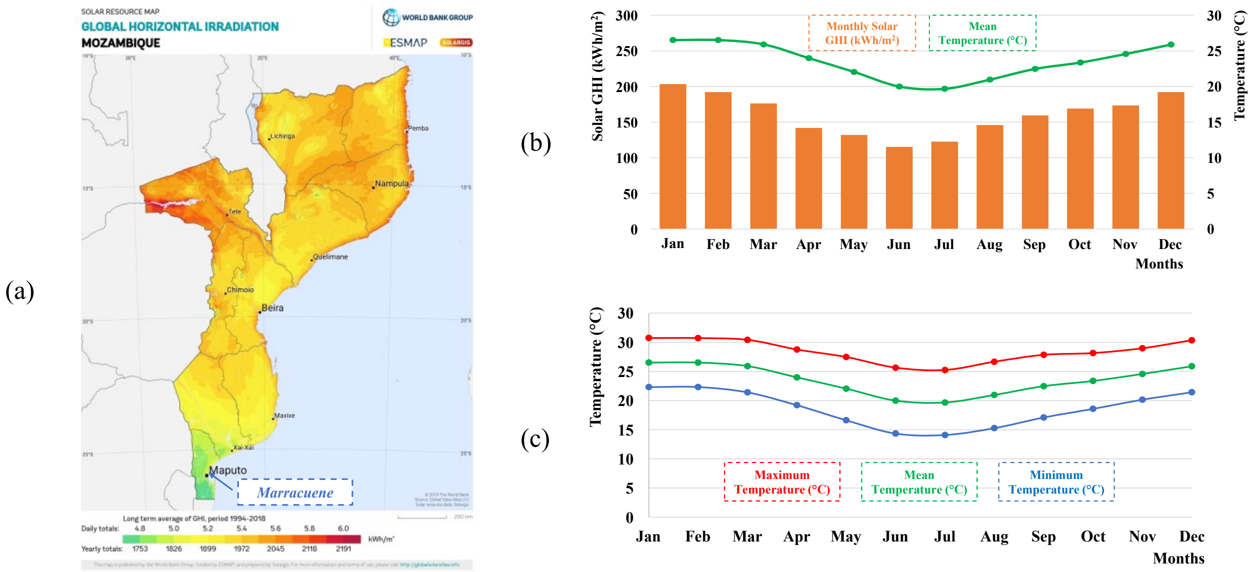
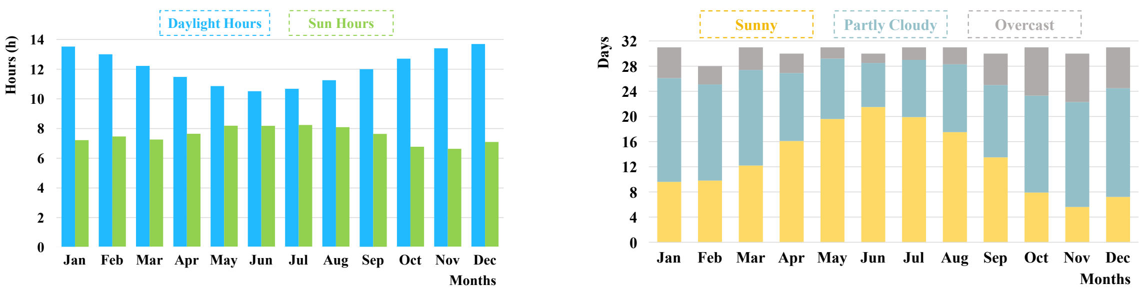


Figure 1: Solar GHI and ambient temperature in Marracuene, Maputo; (a) Solar GHI in Mozambique; (b) Monthly comparison between solar GHI and mean temperature; (c) Monthly maximum, mean, and minimum temperature.

During the rainy season, despite the higher temperatures and solar GHI values verified throughout the entire country, the number of sun hours and sunny days is more reduced, which can constitute a disadvantage for electricity production from solar PV technology. On the other hand, as observed in Figure 2 (a) and Figure 2 (b), the number of daylight hours is more reduced from April to September, but the number of sun hours is higher and the number of partly cloudy and overcast days is lower. However, and as already mentioned, during this period, solar GHI values are more reduced. In conclusion, despite the small disadvantages in both the dry and rainy seasons, solar PV technology is considered extremely suitable for energy production in Marracuene throughout the entire year given the number of sunny days, daylight/sunny hours, mean ambient temperature, and solar GHI values.



(a) (b)

Figure 2: Monthly weather analysis in Marracuene, Maputo: (a) Daylight and sunny hours; (b) Sunny, partly cloudy, and overcast days.

As explained, ESS is the commonly used technology to mitigate the intermittent production profile of RES. On the other hand, if the climatic conditions are considered adequate, this profile can also be smoothened by combining the action of several renewables in a given implementation site. Thus, in the case of Marracuene, e.g., solar PV could be integrated with wind power systems if suitable conditions regarding geographical context, terrain morphology, and public investment, were met.

Since the northern region of Mozambique is characterized by the existence of mountain ranges and a large plateau, wind speed is more reduced when compared to the south half of the country. In this particular part of the country, in which Marracuene is located, large flatlands are carved by river valleys, thus resulting in higher wind gusts. As detailed in Figure *3*, wind speed is also more accentuated during the rainy season (from October to March), in which the number of sunny days is more reduced and higher temperature and solar GHI values are registered. Notwithstanding, in a typical meteorological year, wind speed in Marracuene is extremely low for wind-based electricity production. As seen on the right side of Figure 3, regardless of the month, the average wind speed in Marracuene is just slightly above the cut-in wind speed (around 13-15 km/h), i.e., the minimum value to start turning the blades of the turbine and generate electricity. In other words, it is concluded that such wind speed values are insufficient for wind power production since the rated wind speed (full capacity) is normally between 50 km/h and 60 km/h. Wind speeds above 90 km/h (cut-out wind speed) are extremely high and considered improper for wind energy production as they would damage the turbine. Above this value, the turbine must be stopped (Yeh & Wang, 2008).

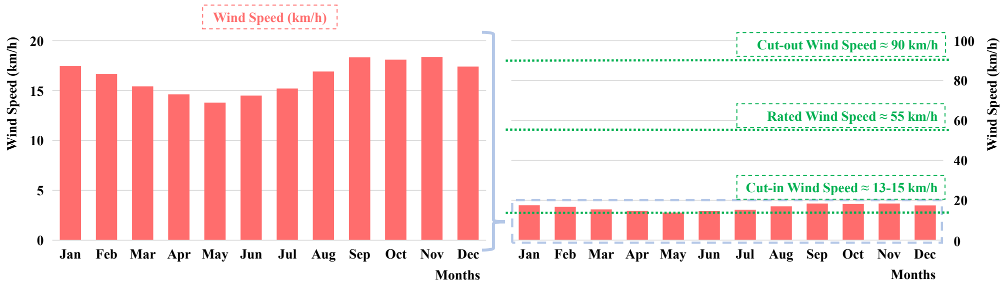


Figure 3: Monthly wind speed in Marracuene, Maputo, during a typical meteorological year.

Since wind power systems are recognized as unsuitable in Marracuene, only solar PV energy will be considered for electricity production. Thus, to mitigate the intermittence of this particular RES, an ESS must be used to allow the constant supply of energy to the community, being necessary to define the main operating principle of the islanded microgrid, size the constituting devices of the WPS and solar PV systems, forecast losses, and validate the concept of the project by developing computer simulations.

ISLANDED MICROGRID ARCHITECTURE AND OPERATING PRINCIPLE

In the case of Mozambique, from a technological and social point of view, the implementation of islanded microgrids on the basis of RES and ESS is still a very recent topic with a lack of innovation and volume of projects. Besides the power electronics features and technical aspects, the great pertinence of this work lies in its capability to increase the QoL of isolated rural communities, by allowing access to water, electricity, and, consequently, better education and general health. The adopted architecture for the islanded microgrid, exposed in Figure 4, must respect such parameters and be in accordance with the daily needs of the rural community. According to the geographical context of Mozambique and the main objectives adjacent to the establishment of an islanded microgrid in Marracuene, i.e., mitigation of energy poverty and improvement in the basic conditions to support agriculture, four basic devices are on its genesis: solar PV panels, ESS, water pump, and a set of loads.

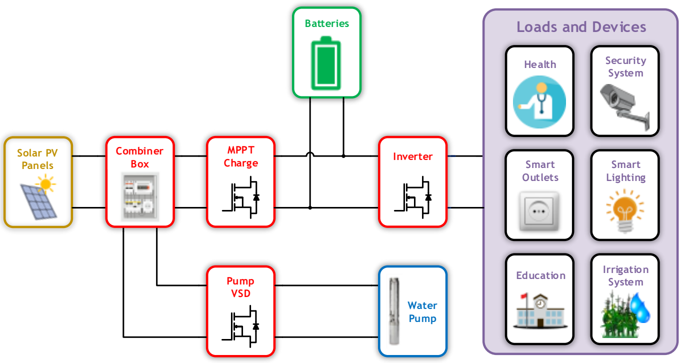


Figure 4: Adopted architecture for the islanded microgrid.

According to the current technological panorama and average temperatures in Marracuene, the ESS will purely consist of batteries. Nevertheless, hybrid ESS are being increasingly used in microgrids, combining the advantages of more than one type of technology, e.g., batteries, supercapacitors, and flywheels. On the negative side, the acquisition of a hybrid ESS is more costly, thus being necessary to assess whether the advantages justify its application, which normally only succeeds in very specific cases, as is the case of electric mobility.

Therefore, concerning community social and economic needs, 4 operation modes are outlined for the islanded microgrid, namely: (i) solar PV panels to water pump (PV2WP), seen in Figure 5 (b); (ii) solar PV panels to loads (PV2L), seen in Figure *5* (c); (iii) solar PV panels to batteries (PV2B), seen in Figure 5 (d); (iv) batteries to loads (B2L), seen in Figure *5* (e). Through the analysis of the flowchart of Figure *5* (a), it is concluded that water pumping is prioritized over the remaining system functionalities, i.e., if a set of conditions is met, any other operation mode will be interrupted to start

PV2WP. Such conditions are related, in the vast majority of the cases, to the time period in which it is intended to pump, however, this process will only be performed if there is water availability in the borehole, the reservoirs are not full, and, obviously, if there is enough sunlight to produce energy in the PV panels.

On the other hand, the water pumping period occurs for a limited and substantially inferior time to the number of sun hours on a given day in Marracuene. Thus, when the level switch indicates that the reservoirs are completely full, the energy produced by the solar PV panels must be redirected to the batteries (PV2B), so that, at night or on days of lower irradiation, the loads may be fed through it (B2L). In turn, when the batteries are fully charged and there is sunlight, the set of loads will be directly powered by the solar PV panels (PV2L). As soon as there is not enough irradiation to produce energy, and as already mentioned, it will be the batteries that will supply the loads, nevertheless, in the case of the total discharge, energy availability becomes null. Thus, for this reason, the sizing of the solar PV system plays a critical role in the operation of the microgrid, which must be performed in accordance with the energy needs of the isolated rural community and consequently mitigate energy poverty.

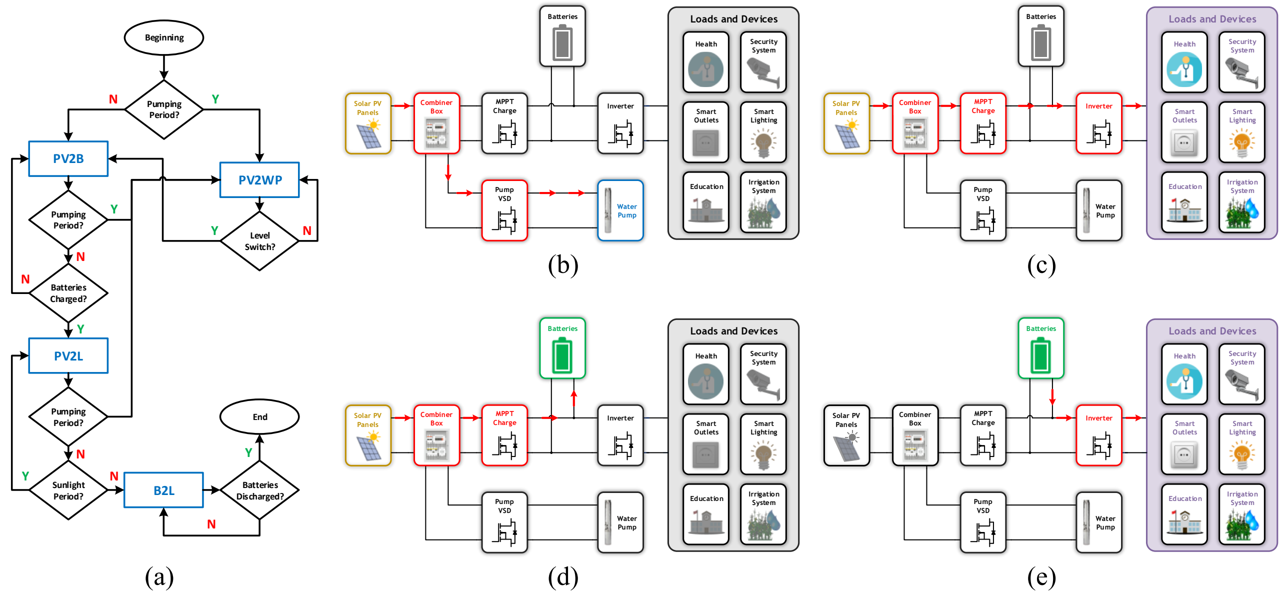


Figure 5: Islanded microgrid operation modes: (a) Flowchart; (b) PV2WP; (c) PV2L; (d) PV2B; (e) B2L.

In addition to the above-mentioned basic components, i.e., solar PV panels, ESS, water pump, and loads, complementary devices (presented in red in Figure 4) are also required to regulate each operation mode throughout the day. In this regard, a combiner box, a maximum power point tracking (MPPT) charge controller (MPPT CC), a voltage source inverter (VSI), and a pump variable speed driver (VSD) are integrated into the islanded microgrid architecture. The combiner box is the main control element of the system, being responsible for the commutation between each operation mode according to the readings made by the sensors. Moreover, given the power values involved in the islanded microgrid, protection devices are also included, as well as power relays to switch the operation between the WPS and solar PV subsystem. In turn, and as with any solar PV system, an MPPT CC is used so that the maximum instantaneous power may be extracted, regardless of weather conditions, from the solar modules. This device, in most cases, is also endowed with the functionality of controlling the battery charging process (cf. Figure 5 (d)), thus allowing the extension of its lifetime and state-of-health.

When it is intended to supply the loads, e.g., irrigation systems and education and/or health devices, a VSI is required to converter the dc voltage generated by the solar PV panels or stored in the ESS. However, through literature analysis, purely dc or hybrid ac/dc architectures have been also studied and applied more frequently in the base structure of microgrids. Even so, for simplicity and technology consolidation reasons, an ac structure is used to connect the set of loads to the solar PV panels (PV2L) and/or batteries (B2L). Note that the loads presented in Figure 4 are merely exemplificative, existing the possibility of connecting other types of devices.

As already stated, and also seen in Figure 5, the ESS only supplies energy to the loads (cf. Figure 5 (e)), not interfering with the WPS. Water pumping is only performed during a specific time period and when there is sunlight, otherwise, the ESS would have to be oversized and the costs would far outweigh the benefit. Bearing in mind that solar energy, throughout the day, does not assume a constant profile, it is crucial to associate a VSD with the water pump. Since the former is connected to the solar PV panels, in addition to including the necessary sunlight sensor and multiple protection devices, it must also contain an integrated MPPT to extract the maximum instantaneous power. In turn, regarding the irrigation system, and as above-mentioned, watering is mainly performed by gravity and in a dynamic way, adapting this process in function of water availability, the crop, season, etc. Notwithstanding, despite the relevance associated with the design and sizing of the irrigation system, such objectives are out of the scope of this paper.

SIZING, VALIDATION, AND SIMULATION RESULTS

The sizing of the WPS and solar PV system depends, fundamentally, on the quantity of water to be stored in the reservoirs, which, posteriorly, will be used by the community in irrigation systems to support agricultural activities. Thus, to calculate the flow of water (Q_h) to be pumped, a maximum time for the filling of the tanks must be stipulated. As shown in (1), a water flow of 7.5 m^3/h was calculated for the island microgrid addressed in this paper, in which it is intended to fill a reservoir with a total volume of 30 m^3 (V_T) in 4 hours (t_h).

$$Q_h = \frac{V_T}{t_h} = \frac{30}{4} = 7.5\ m^3/h \tag{1}$$

During the water pump selection, the head, i.e., the manometric height, must also be interpreted as a key aspect, being necessary to ensure that the WPS is capable of pumping water with the pre-calculated flow (7.5 m^3/h) up to the vertical height of the reservoir in relation to the water level in the borehole. As it would be expected, the greater the stipulated head and water flow, the greater the power consumed by the pump (P_{pump}). For a determined pump and a pre-defined head, depending on the variation in solar GHI values throughout the day, the water flow will also change, reducing as the irradiation is also lower. In this regard, and as analyzed by observing the graphic of Figure 6, it is concluded that the water pump selection lies on the combination of 3 major factors, namely the head, power, and water flow. For this case study, it is defined a head of 25 m, and considering the previously calculated flow of 7.5 m^3/h, the value of P_{pump} for the exemplificative water pump is 1050 W.

Notwithstanding, in addition to P_{pump}, the existence of losses in the WPS must also be considered (P_{losses}). Besides electrical losses related to the efficiency of the VSD and combiner box, the total power to be consumed by the WPS (P_{WPS}) is also influenced by the mechanical losses, mainly concentrated in the pipes (line losses) and in the accessories, as is the case of valves, filters, and 90° curves. Such values will also be different considering the use of submersible or surface water pumps, with the latter presenting constraints regarding the maximum height to which a column of water can be drawn up by suction. Moreover, surface pumps may also face problems related to cavitation and reduced efficiency, which justifies the increasing use of submersible pumps in a wider range of application scenarios.

That said, and as shown in (2), the electric power provided by the main energy source of the system in standard test conditions (STC), i.e., the solar PV panels (P_{PVmpp}), must be of a similar order to P_{WPS}, resultant of the sum of P_{pump} (1050 W) with P_{losses}. In Table 1, where solar PV electric data of a given panel under STC are presented, it is seen that P_{PVmpp} assumes a value of 1200 Wp, resulting from the association of 2 strings, each of them constituted by 3 solar PV modules connected in series. In this way, P_{PVmpp} assumes a very approximate value to PWPS, an essential condition for the continuous operation of the water pump at a nominal regime.

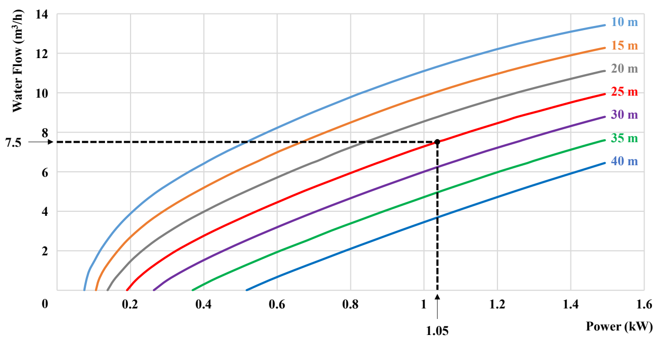


Figure 6: Water pump operation chart.

Table 1: Solar PV electric data (STC).

$I_{SC(m)}$	5.85 A
$V_{OC(m)}$	45.62 V
$V_{mpp(m)}$	36.49 V
$I_{mpp(m)}$	5.50 A
$P_{mpp(m)}$	200 Wp
Nr. of strings	2
Modules per string	3
I_{SC}	11.7 A
V_{OC}	136.86 V
V_{mpp}	109.47 V
P_{PVmpp}	≈ 1200 Wp

In Table 2, the voltage and current operation limits of each system device (MPPT CC, VSI, and pump VSD) are presented, being mandatory that the solar PV panel short-circuit current (I_{SC}) and open-circuit voltage (V_{OC}), 11.7 A and 136.86 V, respectively, do not exceed any of these values to not compromise the system operation. Note that, also in Table 1, voltage, current, and power values of each module are detailed ($I_{SC(m)}$, $V_{OC(m)}$, $V_{mpp(m)}$, $I_{mpp(m)}$, and $P_{mpp(m)}$), used to calculate the I_{SC}, V_{OC}, V_{mmp}, and P_{PVmpp} of the solar PV panel.

$$P_{WPS} \approx P_{pump} + P_{losses} \tag{2}$$

Table 2: Voltage and current operation limits of each system device.

	V_{min} (V)	I_{max} (A)	V_{max} (V)
MPPT Charge Controller	$V_{bat} + 5$	35	150
Voltage Source Inverter	38	32	66
Pump Variable Speed Driver	-	14	200

That being said, to validate the proposed system, computer simulations were performed with PSIM software. In Figure 7, the block diagram of the power electronics system to be simulated is presented, in which it is clear to see an approximation to the architecture shown in Figure 4. Thus, as observed, a dc-dc boost-type converter is used to interface the solar PV panel, whilst, to allow battery charging and discharging, a dc-dc bidirectional buck-boost converter is adopted. Additionally, a resistive load was used to emulate the set of loads previously mentioned, employing an isolated dc-dc dual active bridge converter and an H-bridge inverter to obtain an ac architecture for the microgrid. Lastly, also an H-bridge inverter was applied to interface the water pump, represented in the simulation environment by a dc machine.

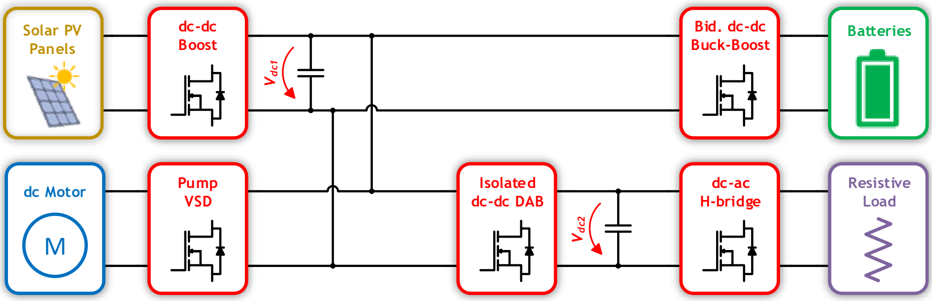


Figure 7: Block diagram of the proposed power electronics system to be simulated.

Water pumping using solar PV energy (PV2WP), as considered the base activity to support agriculture, has to be prioritized in relation to the other operation modes. Thus, in Figure 8, it is presented a graphic that shows the convergence of the rotational speed of the water pump (n) with its nominal speed (n_{ref}), which, in this case, assumes a value of 1200 rpm. In this regard, a PI algorithm is implemented to control the speed of the dc motor, whilst an MPPT algorithm is applied to the dc-dc boost-type converter that interfaces the solar PV panel. As seen, n_{ref} is reached at the time instant t=13 ms, remaining constant thereafter. Nevertheless, in a real application scenario, n will be influenced by the solar irradiation on the solar PV panel, which will result in slight fluctuations in the measured values.

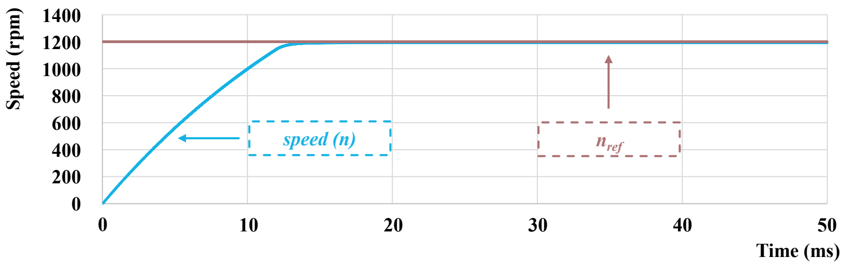


Figure 8: Rotational speed of the water pump converging to its reference during PV2WP operation mode.

With the objective of allowing constant access to electricity, outside the pumping period, the energy generated by the solar PV panel is redirected to charge the batteries. Consequently, if there is still sunlight and to obtain the greatest profitability from the system's primary energy source, i.e., the sun, after charging the batteries, the panel must also be able to supply a determined set of loads. Thus, in Figure 9, 3 graphics regarding PV2B and PV2G operation modes are presented, in which the transition between the mentioned modes is verified at the time instant t=22 ms. Between the time instants t=0 ms and t=16 ms, the battery charging process (PV2B) is observed, where an MPPT algorithm was implemented to extract the maximum instantaneous power from the solar PV panel (p_{PV}). As seen in Figure 9 (a), p_{PV} follows a previously arbitrated solar PV profile for the system (p_{PV_calc}). Notwithstanding, as observed in Figure 9 (b), given the importance of keeping the voltage on dc bus #1 (v_{dc1}) constant at 100 V throughout the entire process, the battery has to be charged with a current (i_{bat}) that follows a variable reference (i_{ref_bat}), obtained as a function of v_{dc1} regulation. In other words, the reference power for the battery charge (p_{ref_bat}) will be the result of subtracting a given regulation power (p_{reg}) from p_{PV}, as seen in (3).
Battery charging finishes when the voltage at its terminals (v_{bat}) reaches the end-of-charge value (48 V), as observed, once again, in Figure 9 (b). Posteriorly, the energy generated by the panels is used to supply a set of loads (PV2G), corresponding to the time interval between t=22 ms and t=50 ms (the transition between operation modes is not instantaneous, lasting 6 ms, i.e., from t=16 ms to t=22 ms). Once more, it is crucial to keep v_{dc1} constant at 100 V, as well as on dc bus #2, in this case at 400 V (v_{dc2}). Thus, during PV2G, i_{bat} is null, the current delivered by the panel (i_{PV}) will vary in accordance with the solar irradiation, and the voltage at its terminals (v_{PV}) will remain constant. As presented in (3) and observed in Figure 9 (a), the panel's reference power ($p_{ref\_PV\_load}$) is the result of the sum of a given p_{reg} (obtained by regulating v_{dc1}) to the reference power previously arbitrated to supply the loads (p_{ref_load}). Lastly, in Figure 9 (c), the waveforms of v_{dc1}, v_{dc2}, v_{PV}, and of the ac voltage supplied to the loads (v_{load}), stipulated with a frequency of 50 Hz and a peak of 325 V (230 V RMS), are presented.

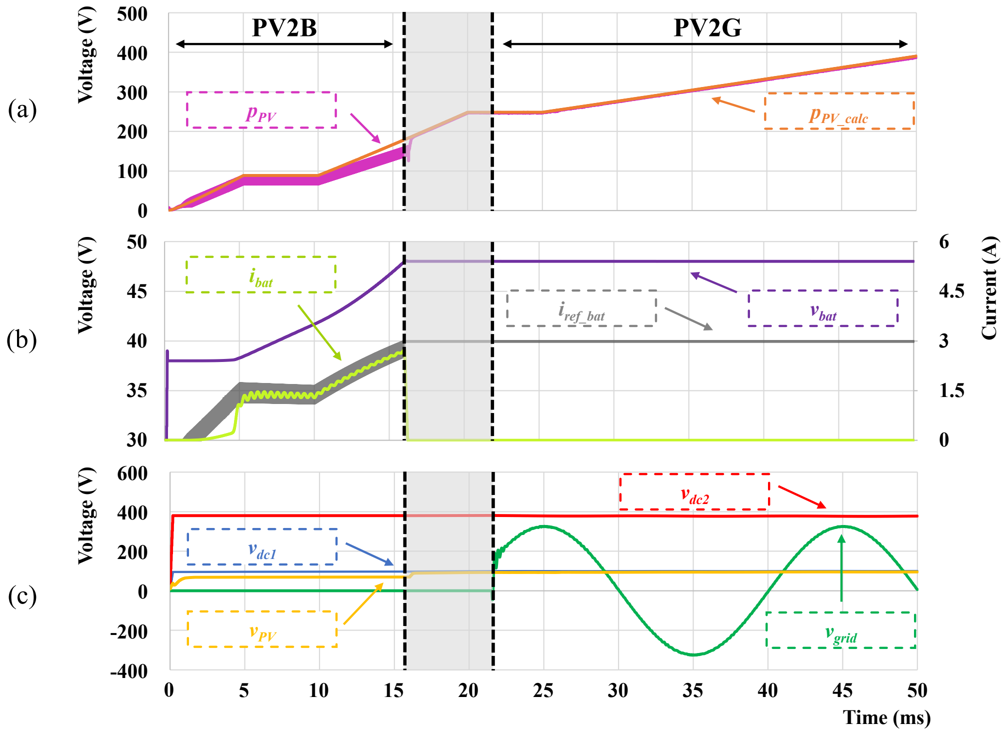


Figure 9: PV2B and PV2G: (a) solar PV panel instantaneous power and solar irradiance profile; (b) battery voltage and charging current; (c) dc bus #1, dc bus #2, solar PV panel, and grid voltage waveforms.

When the solar irradiation values are not sufficiently high for the production of solar PV energy, it will be batteries that will supply the purely resistive load. As seen in Figure 10 (a), the battery is fully charged with v_{bat} assuming a value of 48 V. As the battery discharges, v_{bat} decreases until it reaches the end-of-discharge value, in this case, 20 V. As soon as this value is reached, i_{bat} becomes null, thus meaning that there is no other power source to supply the load. In a real application scenario, such a situation would have to be foreseen beforehand by correctly dimensioning the battery bank, ensuring that it does not fully discharge until the solar PV panel is able to produce energy once again.

Moreover, it is observed that i_{bat} assumes increasing negative values, which is justified according to the adopted orientation for the current sensor in the simulation environment. Even so, its value follows a discharge reference ($i_{ref\_bat\_dis}$), calculated as a function of the regulation of v_{dc1}. As observed in (3), the battery discharge power (p_{bat_dis}) is obtained by adding a certain p_{reg} (dc bus regulation) with a pre-established reference power to supply the resistive load ($p_{ref\_load\_dis}$). Additionally, as concluded by analyzing Figure 10 (b), v_{dc1} and v_{dc2} are constant throughout the entire simulation time and v_{grid} waveform is only formed when vdc2 has a value of 380 V, thus avoiding the occurrence of overcurrent. When the battery is fully discharged, corresponding to the time interval t=30 ms, v_{dc1}, v_{dc2}, and v_{grid} begin to slowly decay until zero.

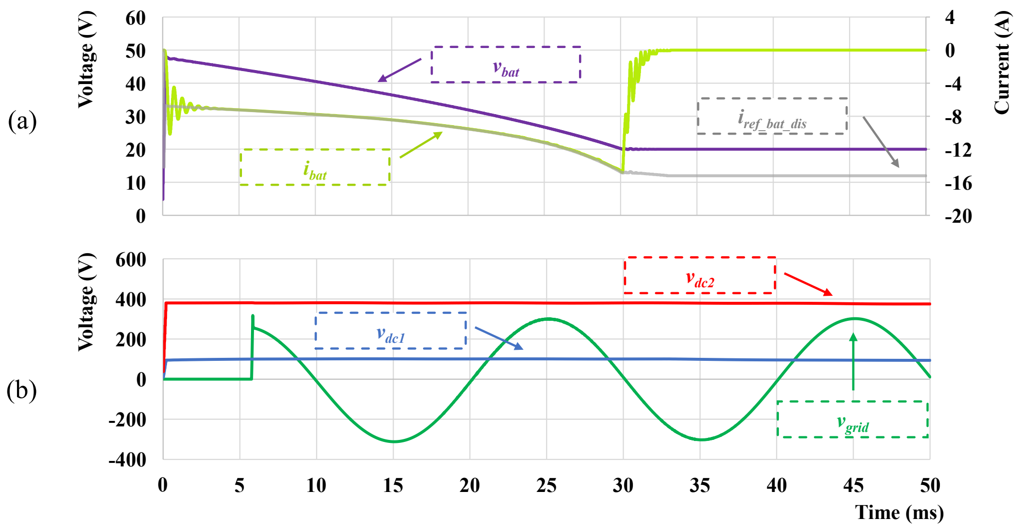


Figure 10: B2G: (a) battery voltage and discharging current; (b) dc bus #1, dc bus #2, and grid voltage waveforms.

$$p_{reg} = \begin{cases} p_{PV} - p_{ref_{bat}}, & PV2B \\ p_{ref_{PV_{load}}} - p_{ref_{load}}, & PV2G \\ p_{bat_{dis}} - p_{ref_{load\_dis}}, & B2G \end{cases} \quad (3)$$

In conclusion, and as aforementioned, regardless of the geographical location, it is important that projects similar to the one depicted in this paper present high ease of replication. In any case, a study concerning weather conditions must be firstly performed to assess which RES is the most appropriate. For the case of Mozambique, e.g., solar PV energy is the most suitable technology, while wind power is inadequate. Therefore, water pump selection comes as a function of the required water flow and manometric height, a parameter that, fundamentally, depends on the characteristics of the terrain. Even so, it is crucial to consider losses and assure that the operating electric parameters (power, voltage, and current) are compatible with the equipment chosen for the solar PV system, namely the solar PV modules, MPPT CC, and VSI. In other words, the choice of these devices will be made after (or at the limit, in parallel to) the design and selection of the water pumping system (pump and VSD). Thus, the dimension of the community (number of people, cattle, energy needs, etc.) is the factor that influences, regardless of the geographical location, the volume and magnitude of the equipment used. As expected, the larger the community, the greater the power produced, stored, and consumed, the number of devices used, and if possible, the water flow to be pumped.

CONCLUSIONS AND FURTHER RESEARCH

Given the increasing preponderance and awareness concerning self-sustainability and energy poverty mitigation in isolated rural communities, this paper is focused on the study of a social and technological solution that aims to increase the quality of life (QoL). It is intended to provide support to agriculture, allowing constant access to electricity and piped water throughout the day, which, consequently, will have extremely positive repercussions on the health, education, and economy of these communities. In this regard, and to benefit from the excellent weather conditions of Maputo, a solar photovoltaic (PV) panel was adopted as the main energy source of a system that includes a water pump, a pack of batteries, and a set of loads, thus developing 4 operation modes, namely: (i) solar PV panels to water pump (PV2WP); (ii) solar PV panels to loads (PV2L); (iii) solar PV panels to batteries (PV2B); (iv) batteries to loads (B2L).

The replicability of similar projects in different geographic areas will always depend on the detailed study of the climatic conditions at the implementation site, as well as the terrain morphology and social context witnessed in a given country or region. In accordance with the dimension of the community and the results and conclusions obtained with such a study, new methodologies may be adopted, as is the case of new renewable energy sources (e.g., wind and/or hydro power) or innovative technologies for energy storage. Notwithstanding, for each case, it is important to analyze the operating limits of all the devices used in the prototype to be implemented, which, posteriorly, may be validated with the aid of computer simulations to forecast possible failures and malfunctions.

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