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DIRECT CURRENT NANOGRID PROVIDING ENERGY FOR WATER PUMPING: A COMPARATIVE STUDY IN A RIVERSIDE COMMUNITY IN THE AMAZON

Victor Parente de Oliveira Alves*, Wilson Negrão Macêdo,
Marcos André Barros Galhardo

Federal University of Pará (UFPA), Institute of Technology (ITEC), Group of Studies and Development of Energy Alternatives (GEDAE), Augusto Corrêa 01, 66075-110 Belém, Brazil

* corresponding author: victor.oliveira.alves@itec.ufpa.br

Abstract. Water pumping systems are crucial for improving the quality of life for riverside communities. In the Amazon, most of these systems still rely on fossil fuels. However, new off-grid electrification structures using Direct Current Distribution Nanogrids (DCDN) offer better energy efficiency, resilience, cost savings, and reduced environmental impact. This article presents a comparative theoretical and experimental study of various water pumps in Ilha das Onças, Pará, Brazil, where an open structure DCDN with distributed photovoltaic generation and energy storage was implemented to power eight residences and a church. The case study monitored a residential pumping system, analysing the performance before and after installing the DCDN, focusing on various energy supply types (fossil fuel, AC via inverter, and DC connected to the grid), as well as the economic and environmental impacts associated with the energy supply on the island. The results show potential savings of up to $4.5 million in gasoline costs over 25 years, and the equivalent annual CO_2 emission can be reduced by 123 tons annually, considering the replicability to other nearby residences, showcasing the benefits of the solution and positive technical, economic, and environmental impacts.

Keywords: Amazon, water pump, D.C. nanogrid, energy efficiency, comparative performance.

1. Introduction

An additional electricity demand of approximately 938 TWh is expected in 2025 [1]. New power plants, especially those using renewable sources, are needed to meet this electricity demand. Global electricity production from primary and renewable energy sources is expected to reach 12 400 TWh in 2027, an increase of up to 60 %, with photovoltaic solar energy being one of the main contributors [2]. In 2021, photovoltaic solar energy represented 3 % of the electrical energy production in the world, increasing to 4.5 % in 2022 [3, 4]. In Brazil in 2023, there was a significant increase in renewable energy sources for electricity production. The biggest highlight was wind energy generation. Thus, around 93.1 % of the country's energy generation comes from renewable sources [5].

Despite this increase in energy generation and the use of renewable sources, the world experiences a contradiction. Even with the growing demand for electrical energy for industrial processes, urban mobility, domestic use, and other purposes directly impacting people's quality of life, a significant part of the world's population remains without electricity. In the Brazilian panorama, most inhabitants without access to electricity are in the region characterised as the Brazilian Legal Amazon. In Brazil, the Legal Amazon covers nine states and has a total area of 5 015 146 008 km^2, corresponding to around 58.93 % of the national territory [6].

The lack of access to energy in the Amazon region presents a significant challenge, particularly for rural and isolated communities that are not connected to the conventional electricity grid. Many of these communities rely on traditional methods of generating electricity, frequently relying on fossil fuel-powered generators, such as diesel or gasoline. This reliance on fossil fuels contributes to adverse environmental impacts and results in elevated operational costs, which can strain family budgets due to fuel expenses. Moreover, the irregular electricity supply adversely affects critical sectors, including health and education, as schools and healthcare facilities require reliable electricity source to operate effectively.

Implementing microgrids and nanogrids powered by renewable energy sources offers a viable technical and economic solution to the electrification of these isolated communities. Direct Current (DC) systems present notable advantages, including enhanced efficiency for specific loads, as they eliminate the need for conversion between Alternating Current (AC) and direct current. Furthermore, their inherent flexibility allows for installation in a variety of configurations.

Access to energy is essential for these isolated communities, particularly when incorporating renewable energy sources, as it enables residents to fulfil fundamental needs such as running water. The ongoing development of solar water pumping systems has made significant progress over the years, even when the costs associated with photovoltaic solar technology were higher than they are today. For example, [7, 8] have demonstrated successful real-scale applications in this area. In [9], an extensive literature review concerning pumping systems powered by renewable sources has affirmed the feasibility of effectively integrating these systems.

Another important focus in water pumping projects is optimising existing systems, as replacing equipment already in operation is often not feasible. Works addressing the optimisation issue include [10, 11]. Additional practical approaches for increasing the efficiency of water pumping systems can be found, with one example presented in [12]. Despite its rich water resources in the Amazon region, several isolated communities struggle to access it during the dry season. These communities are sometimes up to 1 km from water collection points [13]. This work highlights the challenges faced by such communities. In the context of electrifying isolated areas not connected to the conventional grid in the Amazon, the Group of Studies and Development of Energy Alternatives (GEDAE) from the Federal University of Pará (UFPA) in Brazil has been working on this topic for three decades, and some of the group's actions are available in [14]. Currently, the group focuses on DC systems, which have been designed and installed in the form of a DC nanogrid in the Ilha das Onças community.

The decision to use an open structure was based on its resilience; this type of grid can operate autonomously, with all subsystems (composed of photovoltaic solar panels, a battery bank, and a charge controller) accessing and contributing energy to the nanogrid. The project began in 2017 with four residences, a recharge station, and an electric storage prototype developed by GEDAE. The project has expanded to support eight residences and a church, with plans to provide electricity for three additional homes.

Notably, one of the primary uses of electricity in Ilha das Onças is pumping water and refrigerating food. For residents, this water is essential for activities such as bathing, washing dishes, and for livestock. While not applicable to the studied community, irrigation is another critical use for pumped water, as discussed in [15–19]. However, the solutions and systems outlined in those works could be adapted and implemented in other regions of the Amazon.

Based on the above, this work aims to present a new, technically viable alternative for supplying energy to remote communities, specifically focusing on its use for water pumping. To illustrate this, a case study is conducted in a residence connected to a DCDN that uses various models of water pumps powered by different energy sources. This approach can be adapted and replicated in other regions of the Amazon, and even globally, where similar living and environmental conditions exist. The benefits of these solutions can be emphasized in terms of technical, economic, and environmental advantages.

Therefore, the article is organised as follows: firstly, it discusses the structure of the DCDN and the location where the work was carried out, then it focuses on using different pumping systems on-site. A comparison of four cases is presented below as the study results, evaluating technical, economic, and environmental aspects and considering the possibility of eliminating fossil fuel-based systems for nearby residents. Finally, the article concludes with final considerations.

2. Materials and methods

2.1. DC nanogrid implemented

Ilha das Onças is in the municipality of Barcarena, state of Pará. It comprises several communities, including one situated along the banks of the Piramanha River on Ilha das Onças, where this research was carried out. The total area of Ilha das Onças is approximately 92 km^2, home to around 3 300 residents [20]. Access to the location is only possible by the river, and the distance to Belém (the state capital) is approximately 10 km, considering the boat's departure point, with an average travel time of 1 hour.

Figure 1 depicts the map of Ilha das Onças, indicating the residences (R), the church, and the charge station supplied by the Direct Current Distribution Nanogrid (DCDN).

The DCDN created in the community has an open structure configuration formed by connecting several blocks called Generation and Storage Systems (GSS) to the nanogrid with off-the-shelf equipment from different manufacturers. This reduces costs since there is no need for a specific component for the grid to function, e.g., specific D.C./D.C. converters to access and control the grid. Commercial components also contribute to system modularity, making future expansion easier. The DCDN is classified as unipolar with two conductors (+) and (-), and having a nominal voltage of 24 VDC, with radial architecture. The nominal voltage was chosen considering safety against electric shock, availability of equipment that operates at 24 VDC, and the compatibility of the input voltage level of inverters in residences.

The GSS comprises a photovoltaic generator (PVG), a charge controller, and a battery bank (BB), with components installed along the residences. Power distribution is carried out using multiplexed aluminium cables with a cross-section of 35 mm^2, and currently the nanogrid has a length of approximately 330 metres to serve all consumer units. This configuration has some advantages, such as more GSS blocks and loads can be easily added to the system in the case of an expansion. It is also worth noting that not all connected homes have GSS in the DCDN. Moreover, batteries with lead-acid and lithium-ion LFP technologies are used for energy storage to perform operational tests in different configurations. Figure 2 illustrates a diagram that considers the residences and their respective GSS in the DCDN.

Many techniques exist to improve the current sharing in this type of system, such as those presented

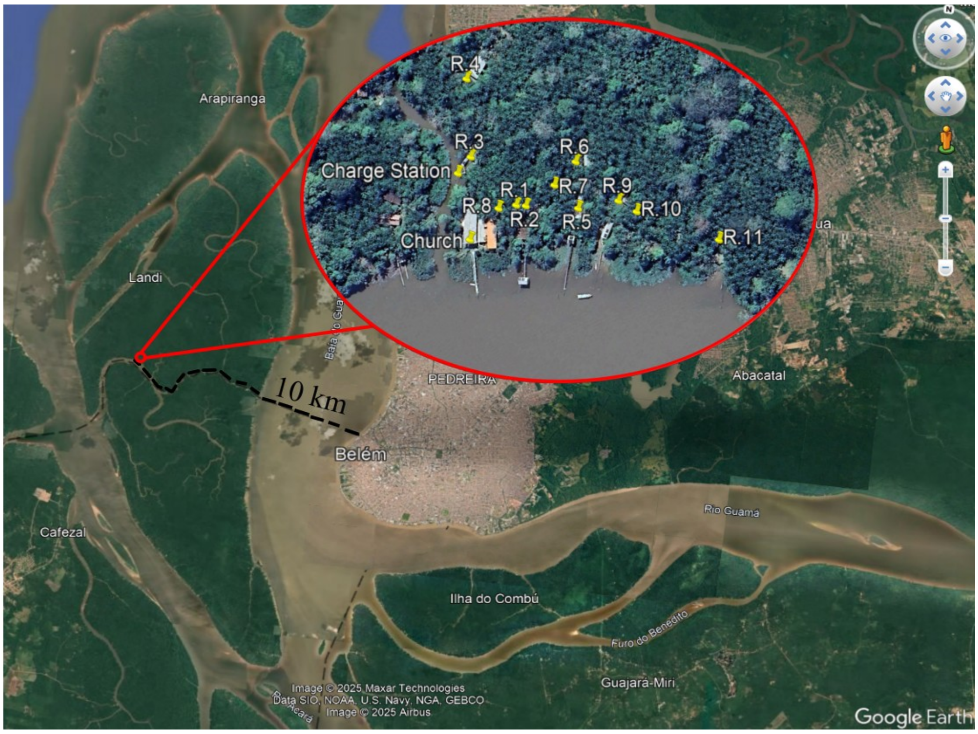


Figure 1. Community supplied by the DCDN on Ilha das Onças. Satellite image from [21, 22].

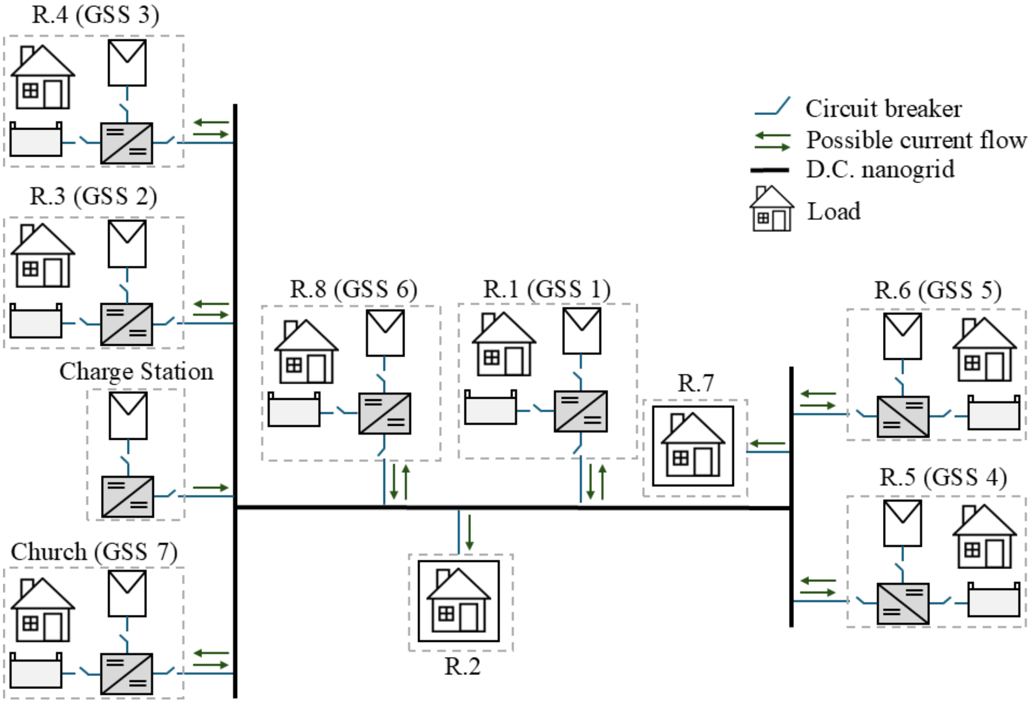


Figure 2. DCDN diagram.

in [23]. However, for the DCDN, there is no specific control method to manage the grid as it has a passive voltage-regulated DC bus that varies depending on the state of charge of the storage subsystems in BBs distributed along the DCDN, as well as in the nanogrid presented for [24]. The choice of not integrating a control method is to reduce the system complexity and explore possible native configurations of the equipment used.

Furthermore, there is a power exchange between the distributed GSSs, which is one of the main characteristics of this type of grid structure. The charge station was configured to a PVG-Load mode, which means that the energy generated by the solar modules is transferred into the grid to help recharge BBs or is directly used by in the case of a high demand. Additionally, residences R.2 and R.7 are loads to the system since they don't have a GSS.

Each residence has both DC and AC loads, therefore, in addition to the GSS, an inverter is connected to the DC bus, as shown in Figure 3. In residences without a GSS, the DC bus is connected only to the DCDN, DC loads, and the inverter.

Designing a suitable DC system involves many factors, such as architecture, protection, and topology [25]. Despite the challenges of implementing the DCDN, e.g., logistics and searching for a better configuration of the commercial components introduced, the design of this DCDN structure offers an alternative for supplying remote communities in Amazon with electricity. In addition to providing energy for those not connected to the conventional AC grid, the DCDN is used for studies and research. Several works have already been done using the system implemented in Ilha das Onças [26–31]. Replicability is also considered since many communities in the Amazon region could use this type of grid. Currently, in addition to the DCDN, the GEDAE also has an experimental nanogrid presented in [24] and recently finished one more DCDN in another Amazon community, which will be presented in future papers published by the group.

Using DC loads connected to the DCDN is more efficient, since it reduces DC/AC conversion losses. Because of that, it is desirable that all residential loads will be DC loads in the future. For the case study presented in this paper, a water pump was chosen as the load to demonstrate the benefits of using the system configuration previously mentioned. Monitoring was considered in residence R.8, as different motor pumps were used over time. Information on the operation and consumption before and after the implementation of the DCDN and performance measurements of the current solution were obtained.

2.2. Water pumping systems

Two changes were made to the water pumping system in residence R.8. As is common in isolated communities like Ilha das Onças, water is pumped from the river using a gasoline-powered water pump. After the implementation of the nanogrid, the system was modified to an AC-motor pump powered by an inverter and used in conjunction with a soft starter, as will be discussed in more detail in later sections. This setup has since been replaced with a DC pump with a brushless direct current motor (BLDC) connected directly to the DCDN without an intermediate stage, which is more efficient. Additionally, DC water pumps with BLDCs have a margin for application of optimisation techniques, such as those presented in [32–34], reaching even higher equipment efficiency.

Table 1 outlines the main characteristics of each model used in the residence before and after these changes.

There is a notable distinction between the maximum flow rate of the gasoline motor pump and other available solutions. According to the information provided by the residents, this oversizing can be attributed to two key factors. The first is that the equipment with the required power is widely available on the local market. The second factor is that the resident preferred a rapid reservoir filling, even if acquiring this specific motor pump model necessitated a more significant financial investment.

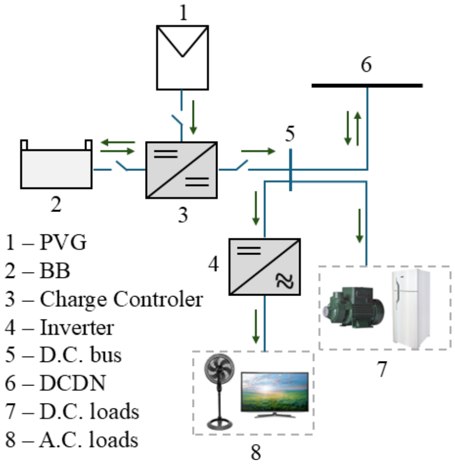


Figure 3. Internal residence diagram.

Regarding the operating conditions of the water pumps, the residence has two water tanks, one with 1 000 litres and the other with 1 500 litres of storage capacity. The first is coupled to a rainwater collection system and connected to the pump; thus, during rainy periods, it is pumped to the main water tank, which has a hydraulic connection to the residence.

Adjusting the hydraulic valves also allows water to be pumped directly from the river to the main tank. This second case occurs mainly during periods of low rainfall in the region. All hydraulic connections are made with 1-inch cross-section pipes except for the rainwater collection system. Figure 4 shows a record of the actual hydraulic installation for pumping water in the residence.

With the water pumping systems presented, the methodological focus is to analyse the benefits of a direct current nanogrid applied to a case study of pumping water. The study involves an electrical and economic evaluation of the systems. Thus, the initial analysis considers the energy efficiency of the direct current and alternating current pumping systems.

Regarding economic aspects, a 25-year study is presented to demonstrate the monetary benefits of the replacement of the gasoline model. Furthermore, an analysis of the literature shows the main environmental impacts associated with not using fossil fuels for water pumping.

3. Comparative cases and discussions

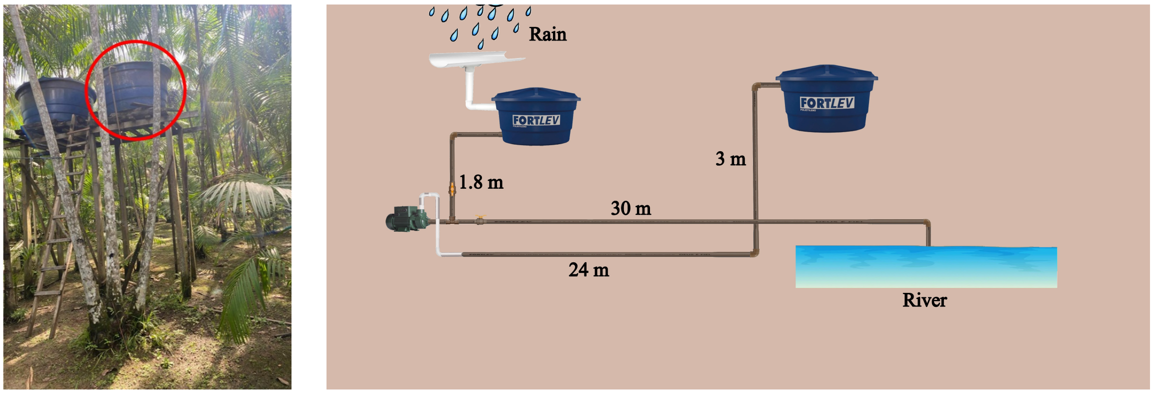
3.1. Electrical aspects

Three different cases involving pumping water in residence R.8 were compared. Additionally, a hypotheti-

Water Pump Model	**Fuel**	**Type of Energization**	**Nominal Voltage**	**Nominal Power [W]**	**Max. Flow $[\frac{l}{h}]$**	**Max. Head [m]**
1	Gasoline	-	-	4 101	36 000	30
2	-	A.C.	127 $V_{A.C.}$	370	1 700	22
3	-	D.C.	44 $V_{D.C.}$	272	1 500	34

TABLE 1. Parameters of the water pumps.

(A). Lateral view of the secondary tank. (B). Front view of the secondary tank.



(C). Main tank. (D). Simplified 2D schematic of hydraulic connections.

FIGURE 4. Hydraulic connections for water pumping.

cal case of using model 2 (an AC motor pump supplied by an inverter but without a soft starter) is added to the present study, which did not happen, but is technically possible.

In conducting the comparative study, it is essential to note that the average water consumption for the residence is approximately 1 500 litres per day. Residents of Residence R.8 actively use the stored water. Due to the volume of water stored and the demand of the residence, daily water pumping is necessary.

In the first case, the water pump used was model 1, and it was the pump with the highest power among the three. However, using this model involves burning fossil fuels and impacts on the environment through noise pollution, polluting gases, and greenhouse gases. Furthermore, another disadvantage of the model is that, according to the manufacturer, it is a model for sporadic use and is unsuitable for continuous operation under different climatic conditions. The model in question has a fuel tank with a capacity of 3.6 litres and can pump a total volume of 12 500 litres of water, according to the documentation.

Model 2 began to be used shortly after the residence was connected to the DCDN. However, the AC motor pump draws a high initial starting current, triggering the safety mode of the inverter used, whose nominal power is 500 W, forcing it to shut down to avoid any damage. As a result, soft starter equipment was added to the set, smoothing the start and making the inverter capable of meeting the load.

Model 3 is a native direct current load and can be connected directly to the photovoltaic generator, as it has an internal controller to regulate the electrical current that flows through the equipment. The motor pump was, therefore, connected directly to the DCDN, and a circuit breaker was added for turning it on and off, and for protection.

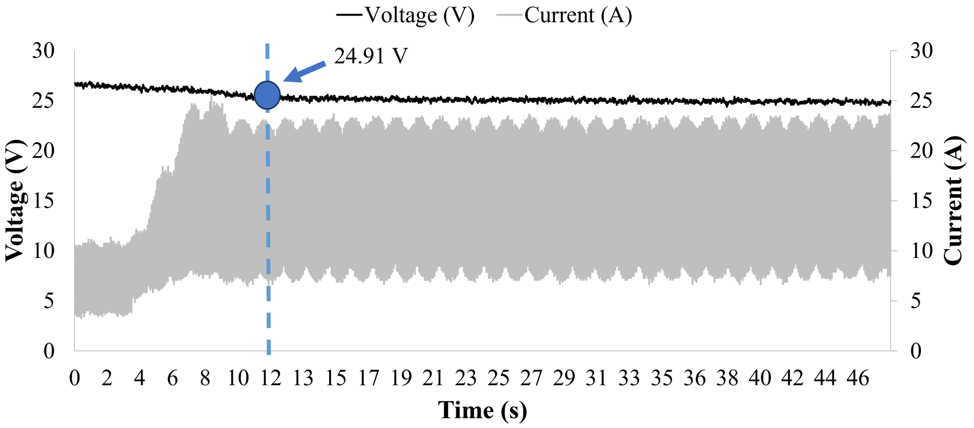


Figure 5. Model 2 water pump operation.

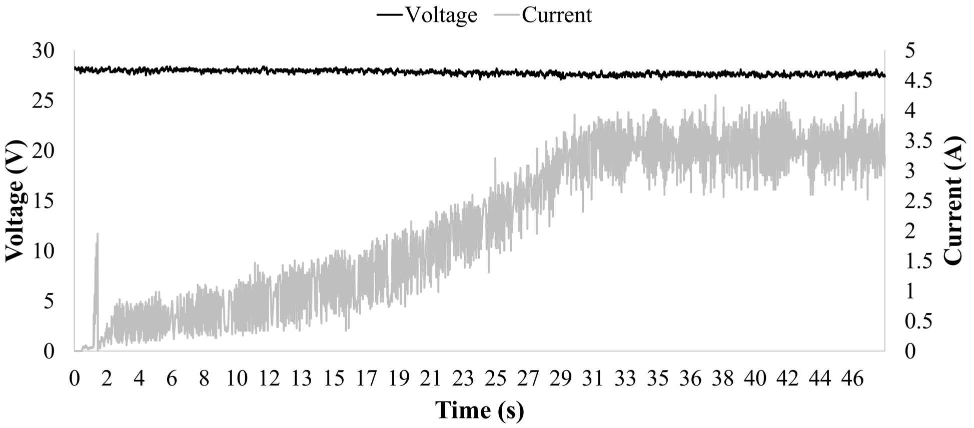


Figure 6. Model 3 water pump operation.

Tests were carried out for water pump models 2 and 3 to obtain electrical parameters and verify their operational performance and possible impacts on the network. The DC side was monitored (connection of the load to the DCDN) in the tests, and a significant voltage drop on the residence's DC bus was found for pump 2.

Figures 5 and 6 show voltage and current profiles monitored during operational tests performed at different times when using motor pumps 2 and 3 in the DCDN. For motor pump 2, Figure 5 shows a voltage variation of 26.78 VDC before triggering to 24.91 VDC when the equipment reaches the standard operational regime; this decay is evident in the first seconds after the water pump is turned on, when the current reaches 25.45 A.

When water pump 3 began operating, the same test procedures were repeated. The voltage drop is lower for this model, with voltage drop values of around 0.70 VDC as illustrated in Figure 6, while in the previous case, this value was around 1.87 VDC.

Another possibility is presented for the energy supply of water pumps without the soft-starting equipment. In this circumstance, the current inverter would be replaced with a more powerful unit. For example, a 1 500 W inverter from the same manufacturer as the inverter currently in use could be used since the model selected for the analysis can supply the current requested by the load without the need for a starting stage.

It should be noted at this point that the manufacturer has inverter models with a nominal power of 1 000 W (at a lower cost than the selected model) in its portfolio that would be capable of serving the water pump at the start up; however, they are not widely available on the national market.

An important aspect to consider in this scenario is that a higher-power inverter for the application in question would operate at a low load at a steady state, affecting its efficiency. As off-grid inverter manufacturers generally do not easily provide the efficiency curve, a test was carried out in the GEDAE laboratory to obtain the efficiency curve of the inverter model currently operating within the DCDN to supply the water pump and other loads. The efficiency curve obtained when testing the inverter in the laboratory is shown in Figure 7.

For calculations and the comparative study, the curve pattern presented in Figure 7 will also be considered for the highest power inverter used in scenario 4.

Regarding fuel and electrical energy consumption in the cases considered, the average usage time of water pump 1 was 30 minutes under real operating conditions. Therefore, the equipment's average fuel

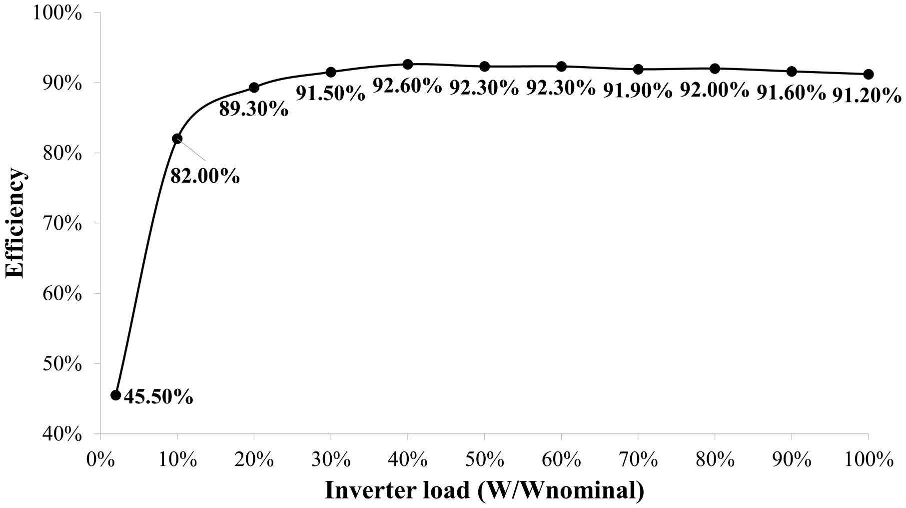


FIGURE 7. 500 W inverter efficiency curve.

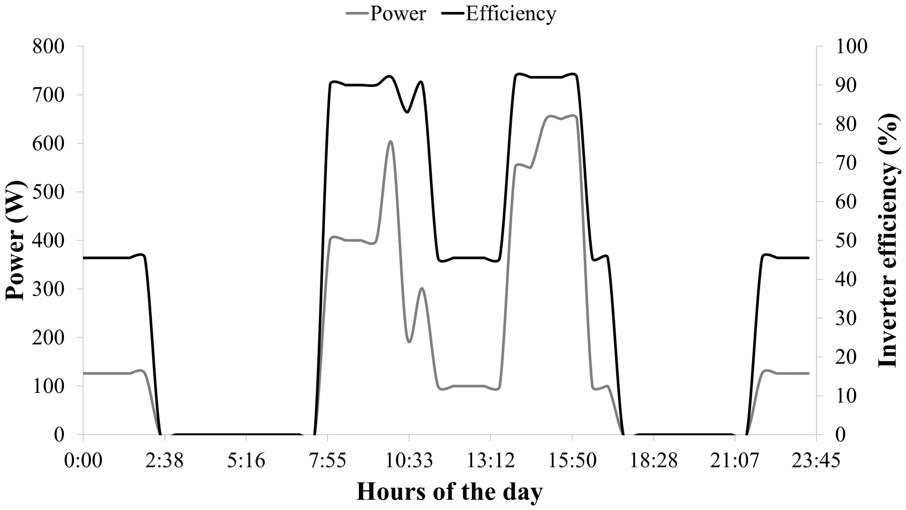


FIGURE 8. Power demand and inverter efficiency profile.

consumption was around 0.45 l day^{-1}. The total time required for the electric models to fill the two reservoirs was 2 hours and 40 minutes. Therefore, considering the efficiency curve of each inverter as previously mentioned, the electrical energy used from the nanogrid for the three other scenarios during the task was calculated.

A higher power inverter requires a little more energy from the grid (DC side), 1 123.83 Wh; compared to the lower power inverter, for which it is 1 099.4 Wh. During water pumping, the 1 500 W inverter operates at a lower load, which directly affects its efficiency, causing it to operate with more significant losses. The DC water pump is the most efficient, with a daily energy consumption of approximately 232.82 Wh.

The case mentioned only refers to the equipment for pumping water. However, the efficiency of the higher power inverter is also affected throughout the day, when considering other AC loads present in the residence. To survey the electricity consumption profile of the residence, the residents were interviewed to check the time of use of each AC electrical equipment.

Electrical equipment, especially the water pump, is not turned on at the same time every day, as its operation depends on the river level, which varies daily. To survey the consumption profile, a scheme in which all loads are used daily was considered with for the residence. As seen in Figure 8, the inverter efficiency is less than 50 % at various times of the day.

Using a higher power inverter to eliminate the soft start stage during water pumping results in more significant energy losses due to operation with a low inverter load and more pronounced voltage drops when starting the motor pump. As already mentioned, Figure 8 presents a power demand profile considering the situation of all loads being activated in one day. However, it is identified that in a confirmed case of using AC equipment, the inverter load is even lower, and consequently, so is its efficiency.

3.2. ECONOMIC ASPECT

This section presents acquisition, operation, and maintenance costs, and possible savings for each scenario in a 25-year analysis, since this is the warranty period

System number	Items	Individual cost [USD]	Total [USD]
1	Water pump model 1	259.00	259.00
2	Water pump model 2 500 W inverter Soft starter	43.09 161.59 40.93	245.61
3	Water pump model 3	198.22	198.22
4	Water pump model 2 1 500 W inverter	43.09 430.74	473.83

Table 2. Purchase costs of water pumping systems.

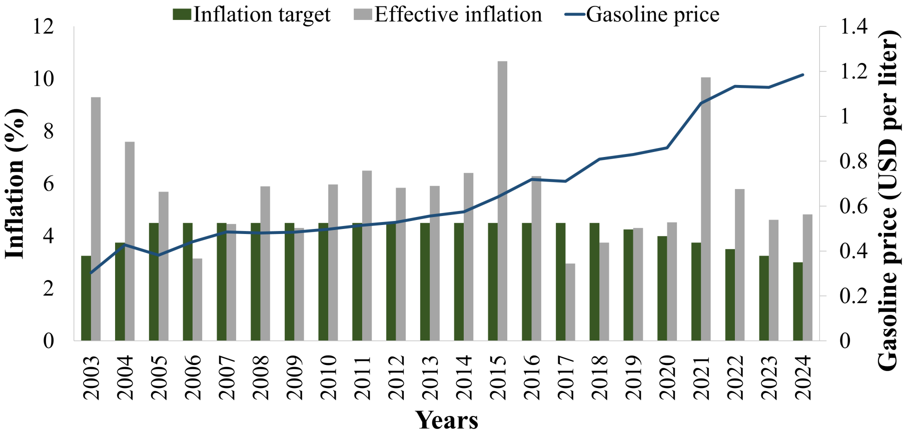


Figure 9. Variation in inflation and average gasoline prices in Brazil from 2003 to 2024.

usually provided by photovoltaic module manufacturers. As these are the system equipment with the most extended warranty period, exchanging the other main components that make up a GSS is already included in the case presented.

For the GSS of residence R.8, the storage system consists of 4 lead-acid batteries with a nominal voltage of 12 V and a capacity of 111 Ah, with two series arrangements connected in parallel, totalling in 24 V and 222 Ah. An interval of 4 years was considered for replacing the battery bank. Regarding the charge controller and inverter, a life cycle of 10 years was chosen. Since this is usually the warranty period given by the equipment manufacturers. Furthermore, at the same time, water pumps were replaced based on research related to the life cycle of this type of equipment.

Still, as an objective of this section, it is presented how the saved resources can be applied to the maintenance of the direct current nanogrid, since the implementation of the DCDN on site did not generate costs for residents, as it is a research project. The primary savings occur from not using the Model 1 pump, since it requires to purchase fuel and carry out the maintenance schedule specified by the manufacturer. Furthermore, for all compared models, there is also the cost of acquiring the discussed solutions.

For cases involving model 2, specifically, it is also necessary to calculate the acquisition value of both the inverter and the soft starter, and the highest power inverter, even if the inverter is not used exclusively to service the water pump.

Table 2 presents the values of the items that make up each system mentioned in this article on the Brazilian market, not considering logistical costs. The values are presented in US dollars and are based on an average exchange rate of December 2024, 1 USD = 5.80 BRL.

Two crucial indicators considered in the economic analysis are the inflation and changes in the price of gasoline. Figure 9 condenses information on these indicators from 2003 to 2024, officially made available by the Central Bank of Brazil [35] and the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels [36]. The economic analysis considered the information presented in Figure 9.

Average inflation in the presented period is approximately 5 % with a standard deviation of 2 %; this average value was mainly leveraged by 2015 when the country faced political instability, and in 2021, due to the COVID-19 pandemic, inflation increased above 10 %. The annual variation in the country's average price of gasoline was 7.27 % in the same period. Therefore, three situations were analysed: average inflation of 5 % in the analysis period, 3 % inflation considering an optimistic scenario, the future projection of inflation in Brazil, and 7 % inflation for a pessimistic scenario with two percentage points above the aver-

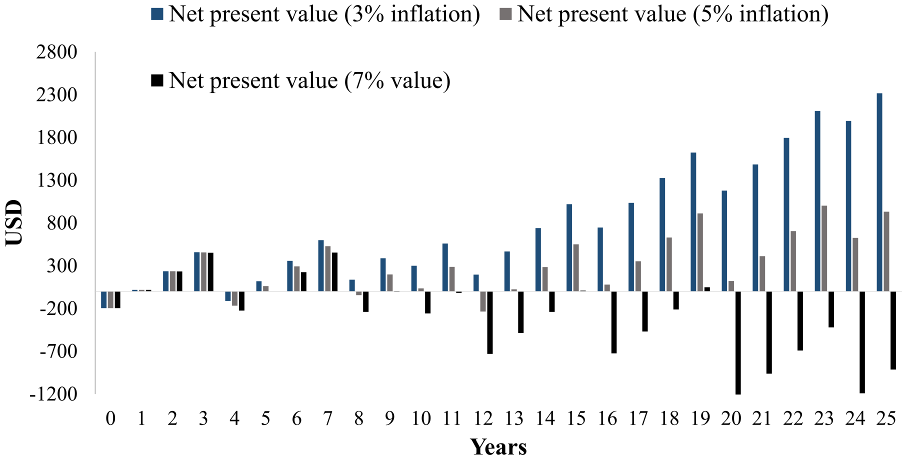


FIGURE 10. NPV for 3 %, 5 %, and 7 % inflation.

System	USD
D.C. water pump	2 359.05
A.C. water pump + 500 W inverter + soft starter	1 872.27
A.C. water pump + 1 500 W inverter	1 587.94

TABLE 3. NPV after 25 years for each system.

age. The analysis used inflation to consider its impact on equipment prices and the maintenance cost of the pumping system and GSS.

As savings are still the leading investment chosen by residents of riverside communities in Pará, the discount rate applied was 6.17 %. Regarding maintenance costs, following each manufacturer's manual, only the Model 1 water pump recommends replacing some components over time. Therefore, based on the equipment manual, over the 25 years considered, the extra cost avoided by replacing components is USD 409.01.

Considering the use at home, the amount saved on fuel purchases is USD 7 078.25. Using the values mentioned earlier, the Net Present Value (NPV) for inflation-related circumstances is presented in Figure 10. 2023 is considered "year 0" of the analysis horizon since the direct current water pump was installed in that year.

The calculations were carried out according to Equations (1) and (2), considering the effects of inflation and annual fuel adjustment:

$$\text{outlay} = -(\text{AM}_{\text{GSS,WP}} + \text{ER}) \times (1 + \text{infl.})^{t-1}, \quad (1)$$

$$\text{income} = (\text{FC} + \text{AM}_{\text{GWP}}) \times (1 + \text{AFA})^{t-1}, \quad (2)$$

where $\text{AM}_{\text{GSS,WP}}$ refers to the annual maintenance costs for the GSS and the water pump, ER is the replacement cost of the equipment that makes up the GSS. It is equal to 0 until the year in which the lifespan of one piece of equipment is reached, and a replacement is necessary. Infl is the inflation and t is the period. Concerning Equation (2), FC stands for fuel cost stavings, AM_{GWP} is the cost saved on the maintenance of the gasoline water pump, AFA is the annual fuel adjustment, and t is the period.

As cash flow is the difference between income and costs, the NPV variation was calculated using:

$$\text{NPV}_t = -C_0 + \sum_{t=1}^{N} \frac{\text{CF}_t}{(1+i)^t} + \text{NPV}_{t-1}, \quad (3)$$

where $-C_0$ is the initial investment, CF is the cash flow in the period, i is the discount rate, t is the period, and N is the total time.

Even for a situation in which the average inflation in the simulation is close to the average of the last 20 years, at the end of the analysis period, there is a positive NPV (USD 949.43) even with the replacement of the water pump, battery bank, and other GSS equipment over the years. The NPV increases to USD 2 359.05 for the 3 % projection. In the worst case, at 7 % inflation, there is a negative NPV of USD 929.14 after 25 years. However, it is worth noting that although replacing all the equipment is impossible, changing the battery bank every 4 years is possible, as planned.

Comparatively, considering the optimistic scenario with the projected inflation of 3 %, this was Brazil's inflation forecast for the next few years, according to the Central Bank. Table 3 shows the NPV at the end of the 25 years analyzed for the D.C. pump, A.C. supplied by an inverter soft starter, and A.C. provided by a 1 500 W inverter. Even if all values are positive, the system with the direct current water pump still proves advantageous financially.

Another scenario has also been verified, considering the trend towards using lithium-ion batteries. Lithium-ion batteries offer several advantages over

System	USD
D.C. water pump	3 080.95
A.C. water pump + 500 W inverter + soft starter	3 177.05
A.C. water pump + 1 500 W inverter	2 892.66

Table 4. NPV after 25 years considering lithium-ion batteries.

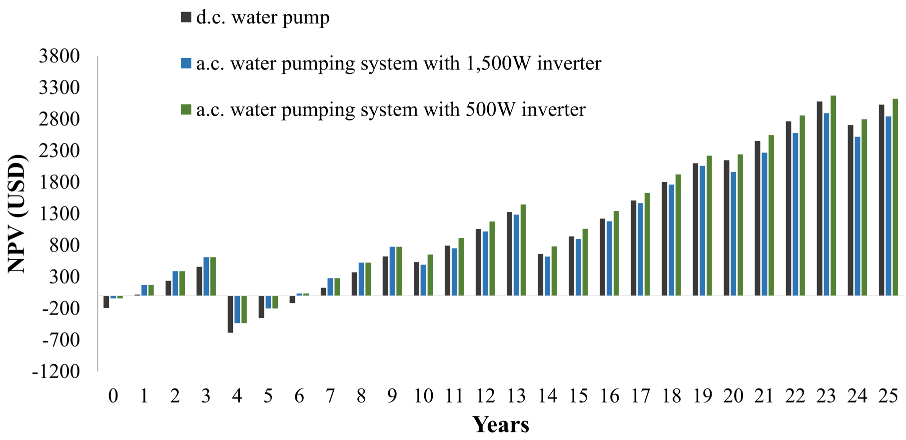


Figure 11. NPV variation for each system considering lithium-ion batteries.

conventional lead-acid batteries, especially in off-grid systems for isolated communities. Firstly, they have a higher energy density. Lithium-ion batteries have a longer lifespan, often lasting several times longer than lead-acid batteries, reducing the frequency and cost of replacements. Moreover, advancements in battery management systems (BMS) contribute to improving the safety of this type of battery.

In the national market, the average price of a lithium-ion battery with a nominal voltage of 24 V/100 Ah is USD 1 507.26. Adopting an average life cycle of 5 000 cycles, in the economic analysis, the lead acid battery bank was replaced with lithium-ion batteries in year 4, and in years 14 and 24, the lithium-ion batteries were replaced. Therefore, the values obtained after 25 years, with inflation of 3 %, are presented in Table 4. Furthermore, Figure 11 shows the variation for the three systems throughout the analysis, considering the use of lithium-ion batteries.

Despite the higher acquisition cost, lithium-ion batteries have a considerably longer lifespan than lead-acid batteries, meaning the number of replacements over 25 years is lower. As seen in Table 4, the NPV for all systems is close. For this situation, technical aspects must be considered in addition to the economic ones, such as the DCDN's energy demand and the inverter's operating efficiency, as mentioned in Section 3.1.

The price of gasoline is the main factor in savings when replacing a Model 1 water pump. Only a considerable reduction in the cost of fuel would compromise the economic viability of using the DCDN to pump water in the community. However, due to several factors, such as the military conflicts that are taking place in parts of Europe and the Middle East, which are affecting the world market, there is no indication that this reduction will occur over the next few years. The energy availability brought by the DCDN added to the energy savings due to the use of native direct current loads such as the model 3 motor pump and the refrigerators present in the community, which made it possible to start selling fruit chop, a trendy type of dessert in the region, generating extra income for residents of the residence where the present study took place. Notably, residents of other homes currently powered by the DCDN also started a business due to the supply. This highlights the importance of projects of this type for the energy supply of riverside communities not connected to the conventional electricity grid.

Based on field observations in the Rio Piramanha community and the neighbourhoods, the average number of residents in each residence is five people. Thus, it is estimated that there are 660 houses throughout Ilha das Onças. If all these residences were powered by the DCDN and the DC pumping system, considering a water consumption profile similar to that of the R.8 residence, projected inflation of 3 %, replacement of battery technology (lead-acid for lithium-ion), after 25 years, the amount saved with the purchase of gasoline would be in the order of USD 4 671 644.36 and the net present value of USD 2 033 427.96.

In this context, new businesses could be started in the region, following the example of the previously mentioned residences. Furthermore, with a significant regional problem, access to electricity is mitigated. Ilha das Onças residents could demand investments from the local government in other essential sectors, such as health and education, benefiting the population. Another investment possibility concerns improving the infrastructure to encourage eco-tourism in the locality, bringing more visibility, sources of income, and new benefits to the residents.

3.3. Main environmental impacts

After implementing the DCDN, the use of fossil fuel motor pump models and diesel generators that previously supplied homes with electric energy, the greenhouse gas emissions and air and noise pollution were reduced. As a positive effect, residents have reported the reappearance of some animal species in the region, especially birds.

With the information on the time of use of the equipment provided by the family patriarch in residence R.8, the energy consumption for the operation of the gasoline pump was estimated at approximately 61.51 kWh monthly and 732.12 kWh annually. Therefore, to quantify the environmental impact caused by the Model 1 water pump, the calculations presented by The Ministry of Science, Technology, and Innovation of Brazil [37] were applied to the account in a simplified way for equivalent CO_2 emissions. CO_2 emission factors from fuel burning are around $0.249\,\frac{\mathrm{kg}\times\mathrm{CO_2}}{\mathrm{kWh}}$, which results in the equivalent emission of 186.36 kg of CO_2 per year.

In a more comprehensive situation, considering the use of fuel pumps in the 660 residences in Ilha das Onças, since the use of these machines for pumping water is common in the region and, again, a consumption profile similar to that of residence R.8, the equivalent annual CO_2 emission jumps to the order of 123 tons, and 3 075 tons in 25 years only considering Ilha das Onças. However, this amount of equivalent CO_2 emissions can be much higher in an extended scenario since the data from the Brazilian Federal Government [38] indicate that the number of riverside families with the same socioeconomic profile as the case study presented in this paper is 30 493. Hence, with these numbers, it is possible to include the project in carbon credit actions in the Amazon, such as presented in [39, 40], especially after the carbon credit market in Brazil was regulated by by-law number 15 042 in 2024 [41].

Another approach to verifying the project's environmental impact is to apply the methodology presented in [42], which involves a detailed analysis of carbon sequestration rates and their relationship to various vegetation types. In this scenario, approximately 754 trees are needed to offset the aforementioned volume of CO_2 in one year. These indicators highlight the importance of the transition to a more sustainable energy, given the possible negative environmental impacts caused by using equipment powered by fossil fuels.

4. Conclusion

This article presented a technically viable solution for providing electricity to areas isolated from the conventional electrical grid, implemented in a riverside location in the Amazon, with energy supply through an open structure direct current distribution nanogrid. The operational characteristics of this type of system allow replicability and scalability in locations with similar characteristics in the state of Pará, in other states in Brazil, and even in other countries that have communities with similar socioeconomic aspects.

Furthermore, it was found that there are different ways to pump water, and this type of power usage is essential for residents. Based on all the above, the most economical and energy-efficient alternative, given the scenario presented, is the option with pump Model 3. This reinforces that direct current systems are worth investing in for native DC loads, resulting in greater efficiency, reduced electrical losses, and a smaller impact on voltage.

The money saved by not using the fossil-fuel water pump is enough to replace the DC water pump, power conditioning, and storage equipment for each GSS. Additionally, when installed and maintained properly, the system can operate correctly for an extended period of time. Regarding the environment, the combustion motor pump Model 1 for pumping water was replaced entirely due to the increased energy availability resulting from the implementation of the DCDN in the community. There was also a considerable reduction in the use of diesel and gasoline generators, activated in specific cases and for a short interval during possible network failures. As a result, the operation of the DCDN directly contributes to reducing greenhouse gas emissions and noise pollution caused by equipment powered by fossil fuels.

Finally, the importance of this work stands out, as it directly and positively impacts the quality of life of people who still live without access to energy through the conventional electricity grid. Not only must electricity be provided for essential activities, but energy availability must also be increased so that the electrical equipment necessary to improve the quality of life in the riverside community in the Amazon can be better used.

List of symbols

A.C.	Alternating Current
AFA	Annual Fuel Adjustment
$AM_{GSS,WP}$	Annual Maintenance Costs for the GSS and Water Pump
AM_{GWP}	Annual Maintenance Costs for Gasoline-powered Water Pump
BB	Battery Bank
BLDC	Brushless Direct Current Motor
D.C.	Direct Current
DCDN	Direct Current Distribution Nanogrid
ER	Equipment Replacement Costs
FC	Fuel Costs
GSS	Generation and Storage System
Infl	Inflation
NPV	Net Present Value
PVG	Photovoltaic Generator

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