

## Article

# Micro Pumped Hydro Energy Storage: Sketching a Sustainable Hybrid Solution for Colombian Off-Grid Communities

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**Abstract:** Currently, electricity generation in off-grid communities is done through polluting and often inefficient diesel generators. When renewable energies are implemented, they are often coupled with chemical batteries, whose specificities do not fit well with remote and harsh environments. As a more sustainable alternative, this paper looks at micro pumped hydro energy storage coupled with solar photovoltaic production. Rural electrification in Colombia is selected as the best potential context for such a solution. Several electrical machines are considered for energy conversion (associated with one pump also utilized as turbine for robustness and cost reasons) and rated over-dedicated criteria: reactive power, efficiency, price, flexibility of power intake, complexity, and robustness. This sketching phase highlights two machines, induction and permanent magnet synchronous machines, both coupled with a variable frequency drive. Two microgrid configurations are also selected that best suit this storage technology to the needs of Colombian non-interconnected zones. A pursuit of low-tech, robust solutions is carried in this paper for reasons of costs, maintenance, and local appropriation.



**Citation:** Guignard, N.; Cristofari, C.; Debusschere, V.; Garbuio, L.; Le Mao, T. Micro Pumped Hydro Energy Storage: Sketching a Sustainable Hybrid Solution for Colombian Off-Grid Communities. *Sustainability* **2022**, *14*, 16734. <https://doi.org/10.3390/su142416734>

Academic Editor: Alberto-Jesus Perea-Moreno

Received: 16 November 2022

Accepted: 10 December 2022

Published: 13 December 2022

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**Keywords:** pumped hydro energy storage; off-grid communities; rural electrification; solar photovoltaic; energy conversion; design

## 1. Introduction

Balancing electricity production and consumption is one of the main issues in a world aiming at reducing the use of on-demand fossil-fuel-powered electrical plants. The global trend is to increase the penetration of renewable electricity production [1], the main technologies being wind and solar photovoltaic. Such technologies are intermittent and present challenges in the predictability of resources in time. Hence, to provide the same service as the thermal plants they are replacing, one needs storage to meet the demands in times of insufficient production if no other flexibility lever is available.

The main storage technology for power systems is reversible pumped hydro (PHS). It is a mature technology with the first plant starting its operation in 1907 in Switzerland and being widely spread by the 1930s in the industrial countries of Europe and Northern America. As of 2017, it represented 97% of installed power [2] and 97% of generated electricity from storage [3]. Most facilities are of a high-power rating (>100 MW) [4], present a round trip efficiency of around 75 %, and have a long lifespan (30 to 50 years or more for the main infrastructure) [3]. It is a capital-intensive technology with capital expenditures (CAPEX) ranging from 600 to 2000 USD/kW [3] and very low operational costs with yearly operational expenditures (OPEX) from 1.5 to 2% of CAPEX [5]. This brings the levelized cost of storage (LCOS) at 150–200 USD/MWh over a 20-year lifespan [6]. The necessity of having an altitude elevation of around 100 m and the infrastructure to create large artificial bodies of water make the opportunities in Europe mainly exhausted. The main regions for PHS development are south-eastern Asia, the Americas, and Africa [7].

Though most pumped storage hydropower plants are large and connected to wide power grids, there is a movement to adapt this technology to small off-grid communities that present prohibitive costs of connections to national or regional grids. In locations where sufficient water and altitude elevation are present, it represents an alternative to the current means of production: diesel generators [8]. This paper explores to what extent such micro-PHS associated with a photovoltaic solar array (PV) can replace or significantly reduce diesel dependence for isolated off-grid communities and even provide reliable and extended electricity coverage. With more than 1900 identified communities that are not connected to the main grid and mostly rely on diesel generators, the Colombian context is selected as a case study because a large potential for PHS is also detected.

The paper is structured as follows. Section 2 describes off-grid communities in Colombia (size, means of production) and discusses related operations and costs. Section 3 is dedicated to hydraulics basic models necessary to move to Section 4, which explores how a PSH can supply off-grid communities considering several electrical machines. Section 5 presents the topologies and technological solutions as a function of several scenarios of integration of micro-PHS and PV within existing diesel infrastructures. Finally, Section 6 serves as a conclusion to the study of feasibility of PV + PHS systems and their conditions of deployment in Colombian NIZ, overall serving as a decision-making tool to design PHS + PV systems in off-grid communities.

## 2. Context of the Research

### 2.1. Geographical Context

The Colombian non-interconnected zone (NIZ) is the geographical zone selected for this study. The Institute of Planning and Promotion of Energetic Solutions in the Non-Interconnected Zones (IPSE), a public entity of the National Order, affiliated with the Ministry of Mines and Energy of Colombia, promotes and finances renewable energy projects in these zones as well as tracks existing electricity generation facilities. Based on their activities, the IPSE provides relevant numbers for the studied areas with the help of other Colombian public institutions. Colombian NIZ spans over 600,000 km<sup>2</sup> (53% of the country's area), and 273 MW of installed power generates 387.8 MWh per year. It is home to almost 730,000 households, of which 500,000 do not have electricity coverage at all, spread over 1772 communities and villages (see Figure 1) [8]. Despite the Amazon representing the largest territory and the one furthest from the main population centers and infrastructure, the majority of communities and populations in NIZs are located in the Pacific region [9]

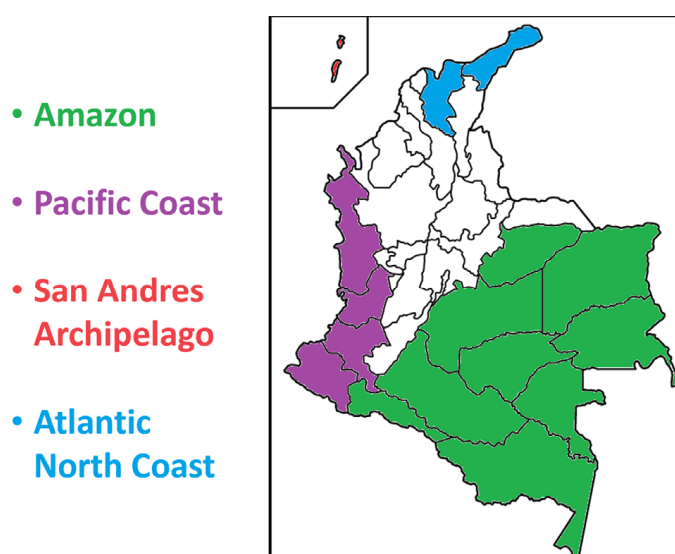


Figure 1. Map of non-interconnected zones in Colombia [8].

## 2.2. Energy Mix and Consumption Profiles

The IPSE and the Colombian National Center for Monitoring (CNM) also provide detailed data on the 1772 identified communities as of 2021. A total of 97% of communities are powered by diesel gensets only, and 1% by renewable energies.

To further add to the data on diesel gensets: the average total installed power in a community is 150 kW (median 40 kW), 90% of communities less than 115 kW, and 95% under 170 kW. An important point in Table 1 is the 71 localities with 0 h of electricity coverage. This means a full month without any power whatsoever. A total of 48 can be attributed to fuel shortage and 18 to diesel genset failure. Other communities may have experienced short blackouts (1–2 days) but are not counted in the 0 h category. The “No Info” category signifies a lack of report from the community to the IPSE and the CNM (either technical or administrative failure). This shows the level of energy precarity in Colombian NIZs, knowing that they rely in general on one type of energy production (diesel gensets) and often a single machine (see Table 2). Altitude elevation in Colombia goes in the direction of investigating how the energy mix of those communities can be alleviated through a PHS coupled with solar PV [8].

**Table 1.** Electricity coverage in Colombian NIZ.

	Hours of Electricity Coverage						
	0 h	1–6 h	7–12 h	13–18 h	19–23 h	24 h	No Info
Number of Communities	71	1278	215	4	0	75	129 *

\* Note: Total communities in Table 1 is 1772 and in Table 2 is greater. The dataset from Table 2 dates from 2020 and Table 1 from 2021. Between the two years, some communities have been connected to the national grid and hence do not qualify as NIZ anymore.

**Table 2.** Number of Diesel Gensets in Colombian NIZ.

	Number of Diesel Gensets		
	1	2	3+
Number of Communities	1708	32	20

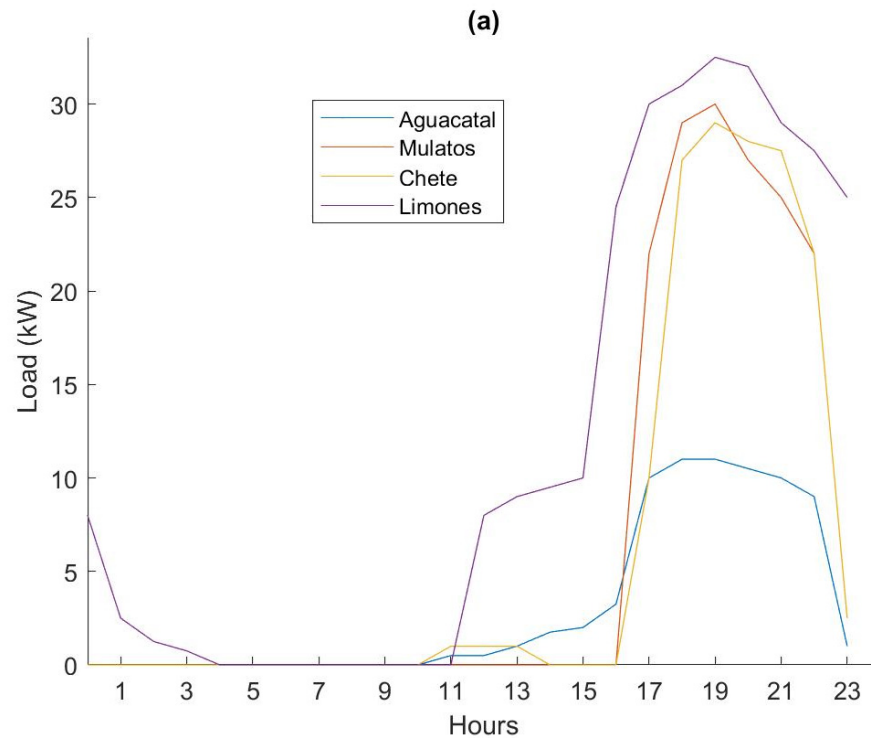
Table 3 and Figure 2 show installed power, population and typical daily load curves from four communities powered with a single diesel genset. They are all situated in the south-western part of Colombia, a region where there is the biggest “reservoir” of isolated communities in Colombia. Certain large communities possess their own airstrip but ultimately the last leg of the journey must be made by boat going upriver from the Pacific Ocean towards the Andean Mountain range. This makes the communities hard to access but being in semi-mountainous areas they present enough elevation differential near the village to host valuable resources for PHS. Colombia already relies heavily on hydro for its national grid electricity production [10].

**Table 3.** Population and installed power of four NZI communities in South-western Colombia.

Community	Aguacatal	Mulatos	Chete	Limones
Installed Power (kW)	25	40	98	118
Number of Households	150	112	167	350

The peak load of each community is always situated around the evening hours, especially when their electricity coverage is limited to those few hours. It can be observed by comparing Table 3 and Figure 2 that peak loads rarely reach the rated power of the installed genset, which means overconsumption as the generator is used in non-optimal conditions (see Section 2.3). Note that rapid ups and downs ramps are observed in the consumption and that fluctuation of the load is not important once the permanent regime

is established. The coverage hours are all situated in the evening. Local communities prefer to have access to power and lighting during these hours rather than during the daytime or before dawn. A sample size finer than hourly loads would be needed to implement them in a simulation environment. However, getting load profiles of small communities (installed power under 100 kW) is difficult because measurement and supervision tools for microgrids are not commonly installed. It is an objective of the IPSE to equip as many communities as possible for better transparency in the years to come [11].



**Figure 2.** Average daily loads for the months of August 2021 for the communities of Aguacatal, Mulatos, Chete, and Limones.

### 2.3. Diesel-Based Generation

As seen before, diesel gensets are the most widespread means of electricity generation in Colombian NIZs. Such generators supply power to a village or a community usually in a standalone mode, which means they need to regulate the frequency and voltage as well as provide reactive power to the local microgrid. The most common solution is to associate a diesel engine with a self-excited synchronous generator. The throttle is managed to control the intake of gasoline and henceforth the torque since the rotational speed remains constant at a frequency multiple of 50 or 60 Hz depending on location. The controller also manages the DC voltage on self-excited windings of the rotor that creates the magnetic flux and, in the process, maintains a constant voltage at the output of the generator. This is called an automatic voltage regulator (AVR) [12,13].

In the case of multiple diesel generators being connected simultaneously, whether their size varies or not, a droop control method is needed to share power between operating generators [14,15]. Further algorithms control the start and stop of additional generators in the rare cases where communities are large enough to host multiple generators without being connected to the utility grid, with the obvious exception being islands [16]. As seen in Table 2, this case is in a minority compared to single genset villages.

As seen in Figure 2, consumption sharply rises to a peak and stays there for the duration of coverage (larger villages see more fluctuation). The diesel generator thus should be designed for this peak of consumption. It is observed that the peak load is always far lower than the rated power of the genset. This causes the genset to operate in a degraded mode where the fuel consumption per kWh increases [17,18] as shown in Table 4.

**Table 4.** Efficiency and Fuel Consumption as a function of Fraction of Nominal Power.

Percentage of Nominal Power $P_n$ (%)	100	80	60	40	20
Efficiency (%)	38	37	36	30	22
Fuel Consumption (g/kWh <sub>electric</sub> )	230	235	240	280	400

Gensets are a simple solution requiring low to medium investment capabilities (CAPEX 450–750 USD/kW [19]), small infrastructures, and light transportation to the site. However, the reliability leans heavily on access to fuel, whether through a robust supply chain or low-enough prices, and the capacity of the operator to successfully maintain the generator. This induces high operational costs that have the other disadvantage to show great fluctuations. The yearly fixed OPEX is equal to 2–4% of CAPEX plus 0.3–0.5 USD/kWh of fuel [20]. This method of electricity generation also has a high carbon content (around 1200 g CO<sub>2</sub>/kWh [21]) which is problematic knowing the effort that must be put into mitigating climate change. Overall diesel costs per kWh of electricity in Colombian NIZs can be found in the Superintendencia de Servicios Públicos Domiciliarios (SSPD) costs report for early 2022. It is a public entity publishing data of private businesses providing public services such as electricity coverage in NIZs. Such costs amount to 0.4231 USD/kWh on average [22]. The scientific literature puts these costs in the 0.4–0.5 USD/kWh range for Colombian NIZs [23,24].

#### 2.4. Tolerances in Voltage and Frequency in Isolated Microgrids

Local and islanded microgrids are more unstable than regional continental grids [16]. This transpires in more frequency/voltage variations and interruption of coverages leading sometimes to blackouts. As a result, in small communities, such as in islands, a less strict grid code operates. The Comisión de Regulación de Energía y Gas (CREG), a public entity of the Colombian government regulating electricity prices and quality, tells us that in NIZs, a variation of  $\pm 1\%$  around the base frequency of 60 Hz is tolerated as well as  $\pm 10\%$  around base voltage of 220 V [25].

The traditional context of NIZ communities in Colombia is set. In the next section, hydro pumping and turbinning technical constraints are detailed in order to advance further discussion on how an isolated PHS can replace or join a diesel microgrid and for what benefits.

### 3. Pumped Hydro Generator

The PHS solution is preferred to chemical battery storage in Colombian NIZs for several reasons. Lithium-ion, sodium, or lead are the main technologies on market for static off-grid storage [26]. The depth of discharge of PHS is unaffected by usage conditions, unlike batteries that see it diminishing with temperature and repeated cycles [27,28]. Battery lifetime is greatly affected by working conditions for chemical batteries; increasing the working temperature from 20 °C to 30 °C cuts in half the total cycles a battery can provide [28–30]. PHS lifetimes exceed 20 years when batteries rarely go over 10 (when maximum cycles are not attained beforehand) [20]. As previously seen in Figure 1, NIZ communities are in Coastal or Amazonian regions with high humidity (>75%) and temperatures that do not drop below 25 °C year-round. These conditions are not ideally suited for chemical battery use. Furthermore, PHS systems do not heavily rely on critical minerals such as lithium and cobalt as batteries do [31,32].

In the specific case of the micro-PHS developed by STEPSol, reservoirs are closed cisterns made of geo-textiles and consequently, the water flows in a closed loop, preventing evaporation and further filling [33]. Being more low-tech storage than batteries, it is, therefore, easier for the local community to appropriate the technology of this micro-PHS and learn how to maintain it. Pumps, reservoirs, and valves are simple mechanical components compared to more complex power electronics bits. The community can

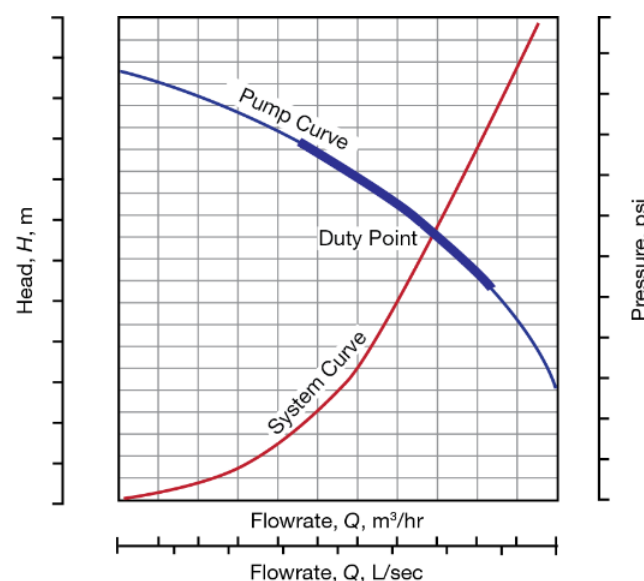
also get involved in the construction of the reservoir and trench for the pipe connecting the two reservoirs. Finally, experience from microgrid operators shows that batteries, coming in small modular blocks, can be prey to thieves when water reservoirs and heavy pumps/turbines are not. The low-tech philosophy is relevant for such installations. In the context of micro-PHS, reversible centrifugal pumps (or PATs) become a good solution, as common agricultural devices, sometimes recycled from former usage, can be installed. It also presents the advantage of using one machine for pumping and turbining, hence making the system simpler.

However, in an artificially closed loop circuit with fixed physical factors (roughness, shape, and length of the pipe, and altitude difference between the two ends of the system), a pump presents a single point of duty, as shown in Figure 3. This single point of duty is a function of the pump design (diameter of the wheel, number of stages, etc.), and the pump's operational characteristics (rotational velocity, the power drawn, etc.). Hence, the pump works at a unique flow and the storage can only absorb a constant power. This lack of flexibility could question the relevance of micro-PHS implementation to answer isolated communities' electrification issues.

There are several methods to change the point of duty, thus allowing for more flexible use of the pump.

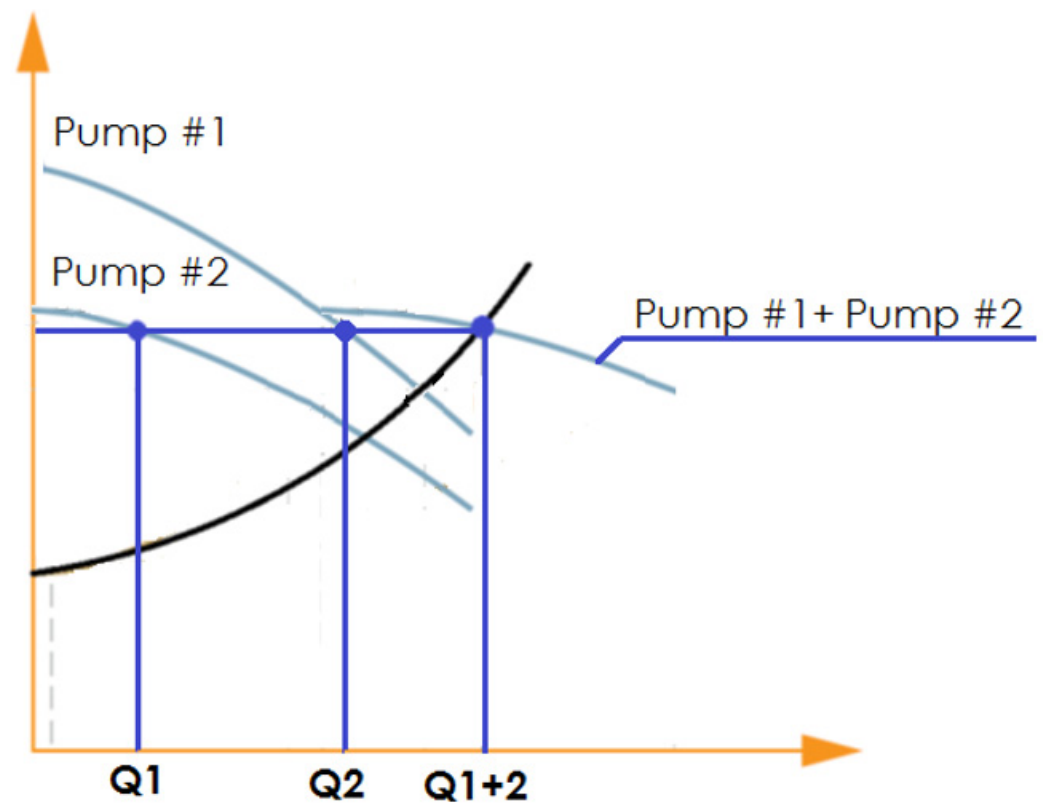
Two pumps running in parallel allow flexibility by powering one or both, see Figure 4. Hence, the system operates at three different flow rates (and hence power intakes). This, however, demands a start/stop strategy for all pumps in parallel and the purchase of multiple components. Too frequent start and stop cycles can also damage pumps over their lifetime [34] and certain pump manufacturers recommend a limit ranging from five per hour to one per day [35]. Mechanical constraints are less prevalent when a variable frequency drive (VFD) is used [29].

A variable frequency drive (VFD) is another efficient way to get flexibility, by controlling the frequency of the current fed to the motor of the pump. Hence, the rotational speed of the pump changes, modifying its operation curve, its power intake, its flow rate, and its efficiency. This allows the following maximum efficiency of the pump for different flow rates and improves the overall flexibility of the pump in the function of its usage, see Figure 5. In the context of PHS, this control allows the pump to track the variation of solar production for instance.



**Figure 3.** A basic pump curve plots pressure (or head) as a function of flow rate.





**Figure 4.** Pump curve plots pressure (or head) as a function of flow rate for two different pumps in parallel [30].

In the ever more particular case of a stable head, it can turn the pump into a variable power absorber for solar production, always adapting its power intake and pumping water as the sun goes. The same is possible in turbining mode, where the rotational speed of the electrical machine needs to be controlled by the variator to reach the desired power (i.e., the community load) respecting standard frequency and voltage. This solution is the most flexible and efficient one. Though it necessitates only one chain variator/motor/pump, it is the most expensive and high-tech solution, requiring power electronics with the same rating as electrical machines. This piece of power electronics presents efficiencies of over 90% at medium power ratings ( $10 < P < 100$  kW) and more than 95% at high power ratings ( $>100$  kW) [36].

A third solution relies on mechanical hydraulic control by way of valve throttling. The idea is to insert a valve after the pump exhaust and gradually close it to add friction.

Throttling the valve changes the system curve by adding a friction head and hence changing the functioning point of the pump (flow rate and power absorbed), see Figure 6. This rudimentary method can be used to regulate the flow rate and hence change power intake. This method generates major friction resulting in hydraulic losses, but it is purely mechanical and necessitates few electronic controls (thus presenting improved durability and decreased cost). It works the same in pumping and turbining modes and has been proven to be a robust solution over the years. The solution mandates, however, that the pump functions at higher heads due to the throttling of the valve and the choice of both components will be critical in the flexibility of the installation. This is the reason why, for grid-connected large industrial applications, a VFD is preferred.

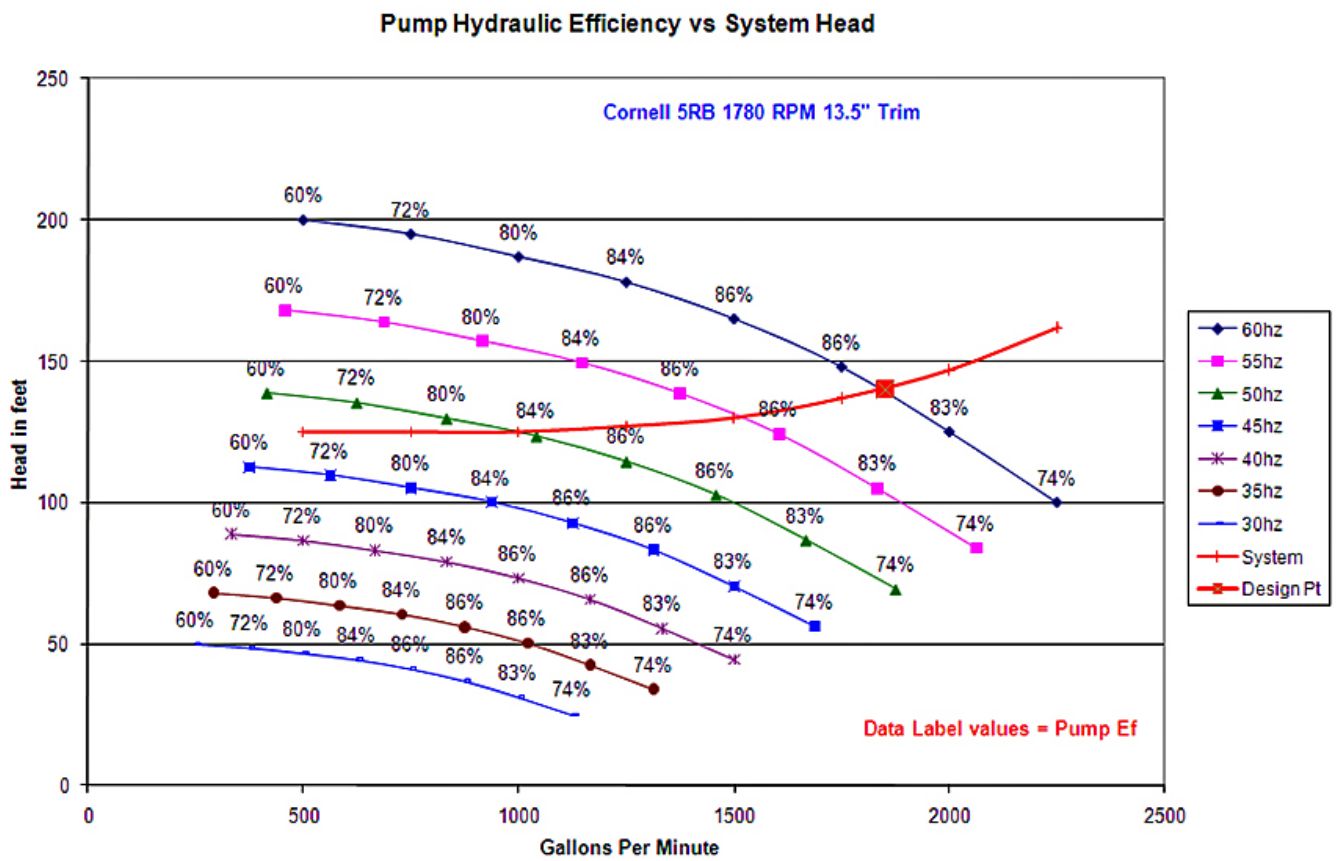


Figure 5. Variable frequency drive associated with a pump [31,32].

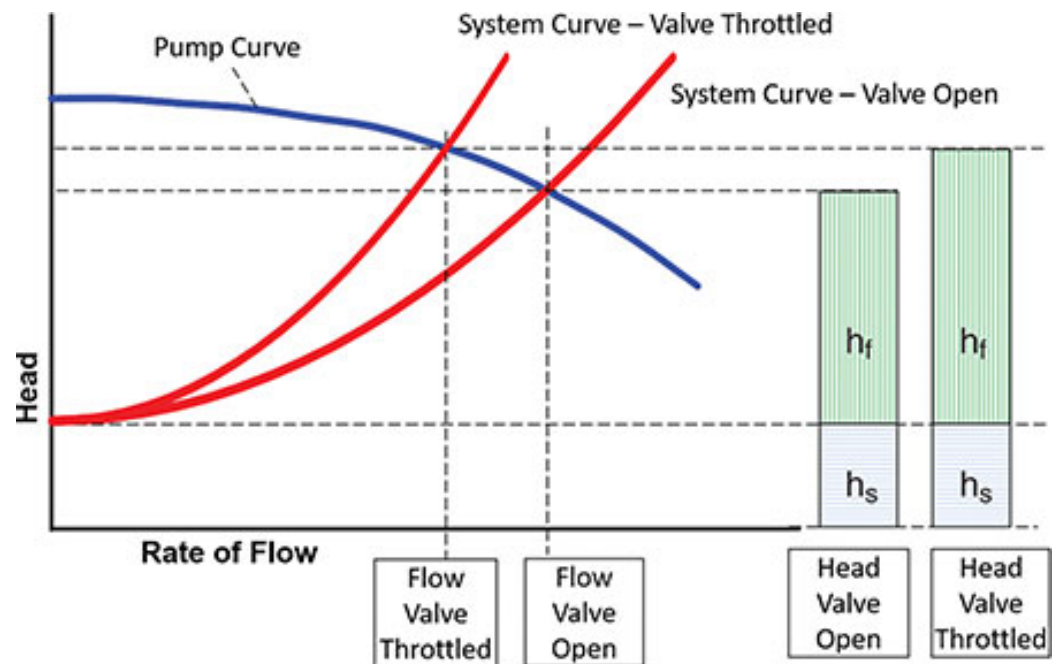


Figure 6. Pump curve and system curves showing static head ( $h_s$ ) and friction head ( $h_f$ ) [34].

Based on the presented advantages and disadvantages of the main existing PHS solutions, in this paper only one reversible centrifugal pump associated with one electrical machine is considered, hence limiting the options to throttling valves and VFDs. The

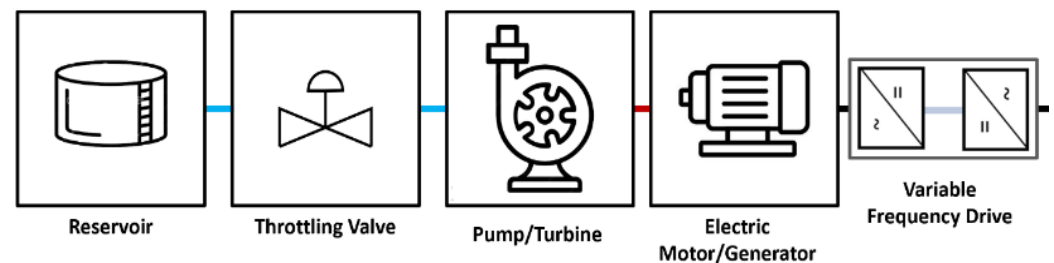


literature gives estimations for off-grid PV + PHS (eventually coupled with diesel and chemical batteries) using PATs with peak consumptions of villages under 100 kW. The prices for such systems ranges from 0.16 to 0.373 USD/kWh which means they are competitive with diesel-only systems, hence making the PHS storage an economically viable solution for our Colombian NIZs [37–39]

#### 4. Designing the PHS with Electrical Machines

In this section, technical solutions for the electrical machine of the PHS are explored. Pros and cons are discussed for each machine as a function of the configurations cited in Section 3.

The electrical machine which can work in generator or motor mode is directly coupled to the reversible pump/turbine. No mechanical reduction or gearbox is used to change rotational speeds. Depending on the electrical machine and the configuration it is placed on, a variable frequency drive may be needed. A throttling valve is present between the reservoir and the pump, not only as an overall security device but in some cases as a regulator used in the machine control. A schematic gives an overall view of the system in Figure 7.



**Figure 7.** The main architecture of the pumping/turbining chain.

##### 4.1. Machine A: Asynchronous Machine (ASM)

The first electrical machine explored is the most widely used in the industry: the induction motor, also called the asynchronous motor (ASM).

###### 4.1.1. Machine A-1: ASM Directly Connected to the Grid

The ASM is inherently self-starting both in pumping and turbining mode, but the machine cannot generate its reactive current in generator mode [40–42]. An external source is needed (such as a capacity bank [40]). Current spikes in rotor bars can be solved with a simple “Star/Delta connection” [43]. It is overall a simple and robust machine produced in large series, presenting decent efficiencies (80–90% even for low-quality motors [44]) but lacking flexibility (only valve throttling is possible which induces greater losses than a VFD and demands oversizing the pump and henceforth the machine) and suffering sensitivity to voltage variations. It is a cheap solution but lacks the advanced capacities for a true standalone system to replace a diesel-based grid.

###### 4.1.2. Machine A-2: ASM with a VFD

The coupling of the ASM with a variable frequency drive allows for a wide range of rotational speeds for the motor. This AC/DC/AC static converter must be rated slightly above the machine’s nominal power. The efficiency of the converters is above 90% for a frequency change between 50 and 100% but degrades rapidly under that [45]. This solution provides great flexibility for an association with a pumping device (see Figure 5) and allows for a larger range of power drawn from the pumping mechanism (25% to 100% of machine nominal power [46]). This storage is more flexible and adaptable to sudden changes in sun irradiance [47].

Solution M-A-2 expands solution M-A-1 by offering improved flexibility in pumping mode. However, it shares the inherent lack of capacity to generate its reactive power in

turbining mode, making it hardly suitable for total independence from a diesel generator. The only way it can produce its reactive power is with the specific use of a four-quadrant VFD.

A slight variation is the doubly fed induction machine, which uses a VFD connected to the rotor and rated to a fraction of the machine's nominal power. This allows for flexibility around synchronism speed (can go hypersynchronous, i.e., above synchronism speed [48]) but requires slip rings which are heavy to maintain. This machine was developed mostly to handle rotor speed fluctuation, hence its use in wind turbines.

#### 4.2. Machine B: Synchronous Machine (SM)

The second electrical machine is the synchronous machine. It is very similar to the machines coupled with diesel gensets. The permanent magnet option (M-B-1) is first discussed and then the more complex self-excited option (M-B-2) is considered.

##### 4.2.1. Machine B-1: Synchronous Machine with Permanent Magnets (PMSM) Coupled with a VFD

The rotor is equipped with permanent magnets arranged in poles magnet and will rotate at the same speed as the stator rotating magnetic field [49]. The synchronous motor turns at the frequency of its input current, regardless of the applied load (up to 2–2.5 times full-load torque at which point it desynchronizes [39]). However, these motors are not self-starting. A solution to this problem is coupling with a four-quadrant VFD. Not only does it allow the motor to be gradually started, but it provides flexibility in generator mode. The four-quadrant VFD can take power generated at any frequency and inject it into the grid at the standard frequency [50]

A slight variation is the switched reluctance machine. Instead of permanent magnets, the rotor is a complex geometrical shape made from a ferromagnetic material and takes advantage of its natural magnetic reluctance. This machine requires high-tech frequency drives, and cannot produce its reactive power due to the rotor not being an actual magnet [51], but has the advantage to eliminate heat loss (no induction current in the rotor) and presents great efficiencies [52]. It is used in some recent electric car motors but would not be a good fit for the considered low-tech off-grid environment.

##### 4.2.2. Machine B-2: Self-excited Synchronous Machine (SESM) Coupled with a VFD

To follow a variable load in turbining mode, a self-excited synchronous machine can be used. This machine is similar to alternators used with gensets, with the addition of a VFD. The VFD is crucial in pumping mode since the motor cannot start on its own. In turbining mode, an AVR can be used along with a throttling valve. The valve regulates the flow and consequently the frequency at which the turbine spins. The AVR modulates the direct current fed to the rotor of the machine which modifies the magnetic field (unlike a PMSM that has a constant field) to match the output voltage. When using the AVR in turbining mode, the VFD is not needed. Using the VFD in turbining mode takes away the specificity of this machine and would equate to reverting to a PMSM.

This machine offers many similarities to the ones associated with diesel gensets, offering the same guarantees in turbining mode. It can generate its reactive power without a four-quadrant VFD; however, this expensive piece of hardware is only needed for start-up in pumping mode which is limited for such a high-tech device.

#### 4.3. Machine C: Variants (PMSM + SQ and SESM + SQ): Addition of a Squirrel Cage to Synchronous Machines, No VFD

The addition of an induction system to the rotor windings (also called a squirrel cage) allows the machine to start as an asynchronous motor. The same precautions for induced starting current should be taken as for ASM (through a  $*/\Delta$  system). This gives the advantage of being able to start the synchronous motor without a VFD and once near synchronism speed, to power the rotor magnetic field and lock it into synchronism speed. Once the regular regime is attained, slip is 0% and induced currents in the metal bars of the squirrel cage are null; therefore, it only acts as an additional inertia on the rotor when not

damping transient oscillations [53]. To change how much power this machine draws (and since a VFD is not present), a throttling valve needs to be used for power and frequency regulation in pumping mode (such as Machine A-1).

For the PMSM + SQ in generator mode, the prime mover needs to keep the rotational speed to regulate the frequency supplied to the load. The rotor magnetic field being constant (no variability of fields with magnets), transmitted power can be regulated only through one variable: mechanical power transferred through the turbine. This can affect the synchronism speed. Therefore, this type of machine is perfectly suited to inject at constant power when turbining [54]. This machine could be ideally suited for small communities that show a constant load, see Figure 2.

As for SESM + SQ, the squirrel cage eliminates the need for a VFD (only used for start-up in pumping mode previously). However, these machines are not standard and would require a custom build for every site. It is the trade-off for having no power electronics involved.

Table 5 proposes a summary of this section regarding the advantages and disadvantages of all presented machines.

**Table 5.** Overview of Machine capabilities requirements, advantages, and disadvantages.

Electrical Machine	M-A-1 ASM	M-A-2 ASM + VFD	M-B-1 PMSM + VFD	M-B-2 SESM + VFD	M-C-1 PMSM + SQ	M-C-2 SESM + SQ
<b>Comments</b>	No power electronics Overheating at low speeds	Overheating at low speeds	Rare earth concern (magnets)	Redundancy of power electronics with AVR and VFD	No power electronics Rare earth concern (magnets)	Small AC/DC converter for excitation system
<b>Market availability</b>	Mass production	Mass production	Mass production	A rare combination of common machines	Rarer product than ASM	Custom motor build
<b>Price range [50–53]</b>	Motor: 90–120 USD/kW	Motor: 90–120 USD/kW VFD: 50–70 USD/kW	Motor: 150–200 USD/kW VFD: 50–70 USD/kW	Motor: 150–200 USD/kW VFD: 50–70 USD/kW	Motor: 150–200 USD/kW	Motor: >150–200 USD/kW (since custom build)
<b>Frequency regulation</b>	Throttling valve (constant power output)	VFD	VFD	VFD	Throttling valve (constant power output)	Throttling valve
<b>Reactive power source</b>	No (unless capacity bank present)	Only with 4Q VFD	Yes	Yes	Yes	Yes
<b>Self-start mechanism</b>	Inherent (high start-up current)	Inherent + VFD allows lower start-up currents	Obligatory VFD	Obligatory VFD	Inherent (high start-up current)	Inherent (high start-up current)
<b>Efficiency range [47–49]</b>	IE1-IE4 70–90%	IE1-IE4 70–90%	IE3-IE5 85–95%	IE3-IE5 85–95%	IE3-IE5 85–95%	IE3-IE5 85–95%
<b>Power regulation mechanism; Power range (% of nominal power in each mode)</b>	Pumping: throttling valve; 25–100% Turbining: throttling valve; 100%	Pumping: VFD; 0–100% Turbining: VFD 25–100%	Pumping: VFD; 0–100% Turbining: VFD; 20–100%	Pumping: VFD; 0–100% Turbining: VFD or AVR + valve; 20–100%	Pumping: throttling valve; 25–100% Turbining: throttling valve; 100%	Pumping: throttling valve; 25–100% Turbining: throttling valve + AVR; 20–100%

## 5. Off-Grid Infrastructure for Communities in the Colombian Context

In the context of this paper, the considered composition of the microgrid is a DC power source (PV array), an AC consumption (village load), and a secondary power source in AC (diesel genset) all linked with inverters interfacing AC and DC. Chemical batteries place themselves on the DC side. It would be unwise to connect the PHS directly to the DC bus. Classic DC motors require brushes that cause sparking and are heavy to maintain. Brushless DC motors do not match the power rating required for this type of system. Both are also hardly reversible. Therefore, a PHS involving rotating machines using AC is considered, directly connected to the AC bus of the inverter, as shown in Figure 8.

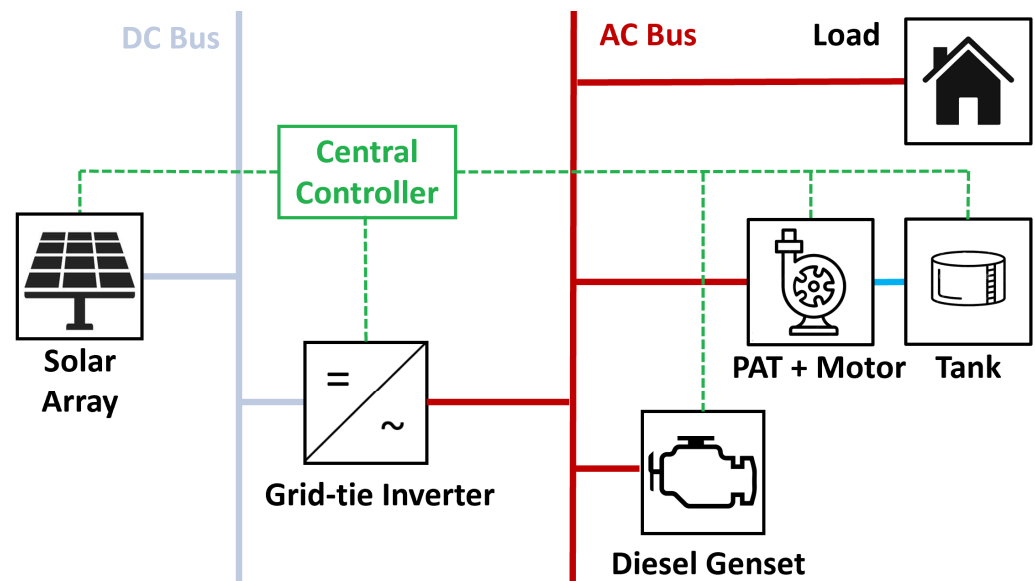


Figure 8. C1 configuration.

The following configurations present varying levels of diesel and renewable energy penetration, as well as communication complexity between the generators. The configurations are presented in descending order of comfort and technological complexity (then also affordability). Their technical benefits and disadvantages are discussed below [55].

### 5.1. Configuration 1 (C1): Diesel-Dominated Microgrid

In the first configuration, genset is the main energy contributor to the grid as shown in Figure 8.

In configuration C1, a centralized controller makes sure that the solar array and the PHS follow the grid imposed by the genset. This presents the advantages of:

- Only needing a grid-tie inverter. Power flows from the solar array to the AC bus, the genset being the grid master and grid former at all times.
- No need to tame solar production, the more is produced, the less diesel is consumed (up to a limit talked about afterward).
- If the load exceeds the genset's capacity + solar PV production, the PHS can switch to turbine mode and contribute to feeding the load.

However, it has these disadvantages:

- PV production needs to be curtailed to keep the genset master on the grid, if not it would lead to unacceptable operating conditions for the genset [55].
- There is always a genset running, which means, there is no moment where carbon is not emitted [56]. Additionally, a diesel shortage means no electricity.
- The PHS must be able to absorb the excess power produced by PV and its variations. This demands an accurate sizing of the PHS rotating machines and a strategy to control power intake.
- There is a risk that the PHS runs in pumping mode with the genset, but this can be removed through the general controller algorithms.

### 5.2. Configuration 2 (C2): Microgrid with an Automated Switch between All Generators

Configuration C2 proposed the widest electricity coverage. This configuration does not need the diesel generator to be constantly running and form the grid. This prevails with the inverter being a standalone grid-forming inverter, which is the gold standard for off-grid solar microgrids [55], with the associated costs. In practice, the grid-forming inverter is the central device of this microgrid. All power transits through it before being injected into the village load. This type of inverter was originally designed to function

alongside chemical batteries only and therefore will require a battery bank to handle power transitions between all other means of production (hence the presence of a battery in Figures 9 and 10). The PHS in this context is put forward as a substitute to both diesel and chemical batteries; consequently, the coupling of a PHS with grid-forming inverters (being a novel development led by STEPSol and Université de Corse) will look into reducing the capacity and usage of both diesel and chemical batteries while keeping the system functioning. Diesel not being the dominant producer, the PHS may provide most of the power when PV fails to produce enough (overcast or at night). A relevant choice of machinery discussed in Section 4 must be made (shown in Section 5.4).

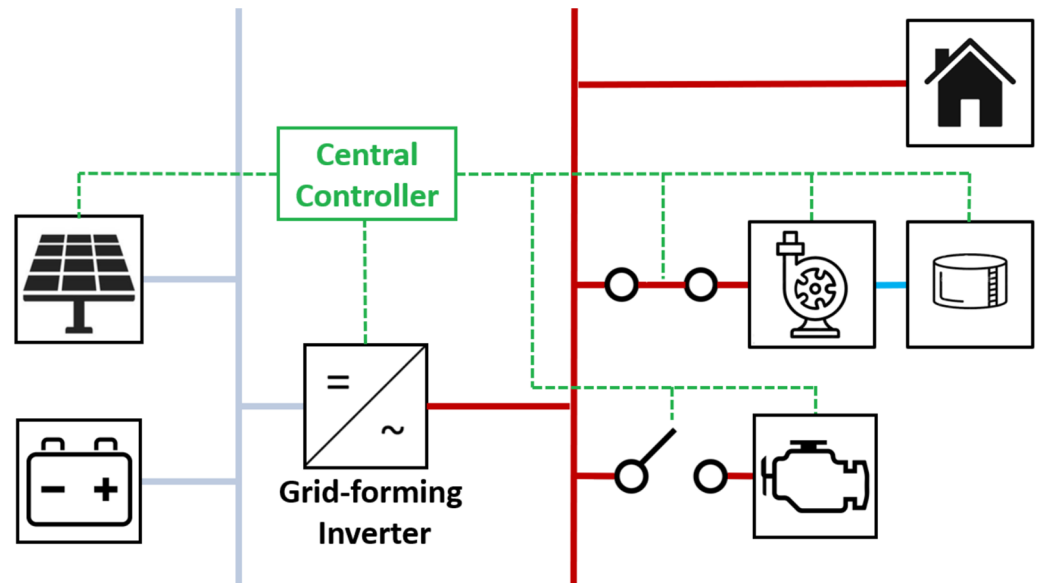


Figure 9. C2 configuration.

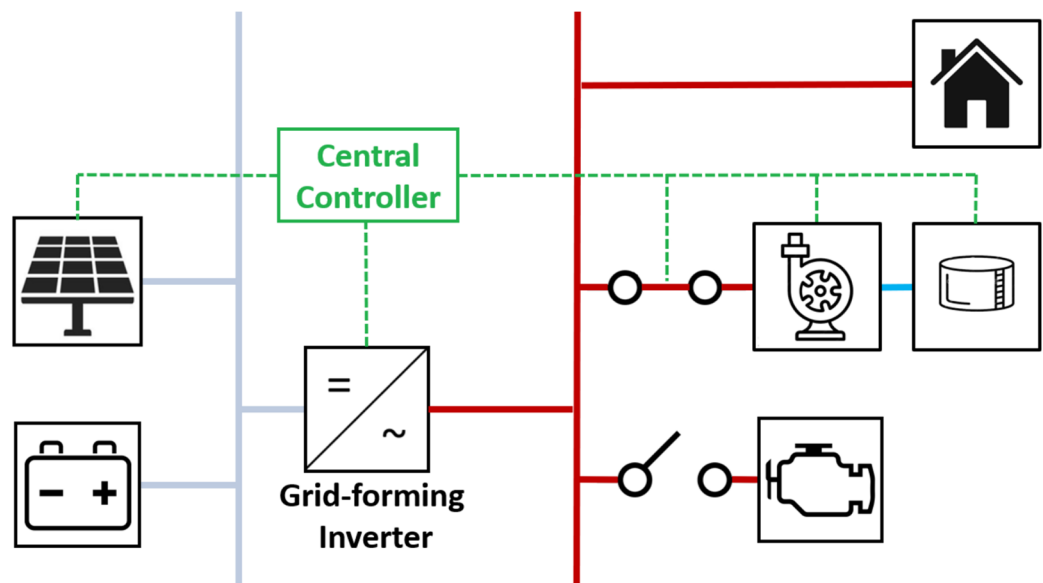


Figure 10. C3 configuration.

In C2, PHS in pumping mode serves as a power absorber to balance the load and the solar production. Diesel is used as a last resort when solar and/or PHS fail to meet the load. Constant control and communication between the mean of production are mandatory to provide smooth transitions and assure 24 h coverage. This means a full power and energy management system (PMS/EMS) which can be costly [57].

This configuration presents the following advantages:

- A total of 24 h of electricity coverage with PHS and diesel that can take over on the run thanks to the PMS/EMS [55].

Disadvantages are compiled of:

- Necessity to have a standalone grid-forming inverter (more expensive than a grid-tie, also needing a small battery bank);
- Necessity to develop a specific set of PMS/EMS which (depending on the number of variables) can be more or less expensive but mainly needs to be dedicated to each site-specific equipment rating.
- Necessity to have a variable pumping system to maximize its use compared to chemical batteries [56];
- The PHS must be able to absorb the excess power produced by PV and its variations.

### 5.3. Configuration 3 (C3): Microgrid with an Automated Switch between All Renewable Means of Production. Diesel Only as a Backup Solution

Configuration C3 disconnects by default the diesel generator. It is used only as a backup when solar PV or PHS cannot meet the load and is started manually. This means electricity will be unavailable until the genset starts. The PHS still runs in variable power in pumping mode to balance solar production and daily load. This configuration demands a simpler management system due to diesel being out of the equation but requires the same type of grid-forming inverter to function.

This configuration shows the following advantages:

- Diesel is only used as a backup (for overcast days and long nights);
- Simpler management system and control strategy.

Additionally, it shows these inconveniences:

- Necessity to have a standalone grid-forming inverter (more expensive than a grid-tie);
- Necessity to have a variable speed pumping system (to absorb changes in PV production while keeping the load supplied);
- Black-out occurs when the PHS reservoir is empty. In this case, a manual black start can be made with the genset, as most Colombian communities used to do before having storage systems added to their energy mix;
- A full 24 h uninterrupted electricity coverage is not possible by default. It can be a problem if the community has health facilities or other critical loads that cannot afford to be unsupplied.

### 5.4. Comparing Configurations

Three configurations for a solar PV/PHS/diesel microgrid for NIZ Colombian communities are compared. The first one can only pretend to reduce diesel consumption (C1) and the other two can reduce more significantly the role of diesel generation with limited use of chemical battery storage. In summary, it can be said:

C1 would be an easy and quick solution to reduce diesel consumption in large off-grid communities where the solar-installed power and PHS-rated power available dwarf the size of diesel. However as seen in Section 2, such communities are few in number and would not represent an interesting developing market. Most communities have < 100 kW of installed power and maximum loads further inferior to this value.

C2 is a more capital-intensive configuration and offers the closest solution to being linked to a national main grid. It demands that PV and PHS potential be high compared to the local consumptions and diesel power rating. It also requires communication between all generators. This can be achieved in smaller communities with critical loads (such as refrigeration for food and medicine). As seen in Section 2, the vast majority of communities have installed power < 100 kW and coverage < 8 h. This solution would greatly benefit them in attaining a level of comfort similar to those of urban areas of the country.



C3 seems to be a middle-ground solution where few electricity shortages and cuts are tolerable. It would be particularly suited for communities without critical loads and has the advantage to be possibly installed regardless of genset proximity since it is not part of the communication scheme and is used only for emergencies. This configuration concerns almost all communities in Colombian NIZs. They do not have critical loads (having no 24 h coverage) and would greatly benefit economically and socially from a doubling or tripling of their coverage and energy consumption.

Possibilities offered using each electrical machine are summed up in Table 6:

**Table 6.** Compatibility of Electrical Machines with off-grid configurations.

	C1	C2	C3
ASM	Yes	No	No
ASM + VFD	Yes	Only with 4Q VFD	Only with 4Q VFD
PMSM + VFD	Yes	Yes	Yes
SESM + VFD	Yes	Yes	Yes
PMSM + SQ	Yes (constant load)	Yes (constant load)	Yes (constant load)
SESM + SQ	Yes	Yes	Yes

In conclusion, C1 being a minor progress from a 100% diesel generation, configurations C2 and C3 will be further investigated. C2 for its potential to bring diesel on-the-fly and not having a temporary loss of power (comfortable solution) and C3 for its independence from diesel and overall robustness and simplicity. These two configurations also fit with the current needs in Colombian NIZs and would consequently make the most impact on communities with low electricity coverage.

It is worth mentioning here that the SESM + SQ machine is the only viable one without the use of a VFD. However, this machine is custom and seldom made. Its use could be a direction to investigate in the future. These control strategies and technological choices will drive future simulations and studies alongside the chosen electrical machines.

## 6. Conclusions

Based on the observations of electricity generation in Colombian non-interconnected zones, together with the typical load profiles, and the necessity to be a credible alternative to gensets (both in service and price range), this paper investigated the relevance of the pump-hydro storage (PHS) solution. The idea was to list the main design principles of a microgrid that would rely, depending on a set of scenarios, on a PHS system, coupled with local PV production, some additional storage facility, and a reminiscent genset. This was conducted to produce a decision-making tool helping the choice of specific systems to match energy needs in certain off-grid conditions.

The evaluation was conducted in three phases. First, the Colombian context was set, then the main design principles of a PHS system were discussed, and finally, everything was put together to sketch off-grid infrastructures, selected to represent typical configurations that best fit different village conditions in Colombian NIZs. The analyses showed that the use of a permanent magnet synchronous machine with a variable frequency drive (VFD) or squirrel cage, as well as the asynchronous machine with a four-quadrant VFD were the technical solutions to be further investigated in the implementation of an off-grid PV + PHS microgrid. These solutions are the ones most likely to improve electricity coverage in the majority of Colombian NIZs.

## 7. Perspective of Future Research

Numerical simulations will be carried in future works to differentiate the machines and the different levels of comfort in each configuration. Power outages will be quantified using SAIDI and SAIFI indicators and compared to current microgrid failures in Colombian NIZs. Following these numerical models, physical experimentation will be made to test such systems in real off-grid conditions and at scale.

The PAGLIA ORBA platform located in Ajaccio and belonging to Université de Corse contains a 15 kW PHS as well as several chemical battery storage options and can switch to “off-grid mode”, thus allowing for an experiment at scale and in exact field conditions as isolated communities. All future results, both numerical and experimental, will be published in following papers.

**Author Contributions:** Conceptualization, N.G., L.G. and V.D.; methodology, N.G., C.C., L.G., V.D. and T.L.M.; formal analysis, N.G., C.C. and V.D. investigation, N.G.; resources, N.G. and T.L.M.; data curation, N.G. and T.L.M.; writing—original draft preparation, N.G.; writing—reviewing and editing, C.C., V.D. and T.L.M.; visualization, N.G.; supervision, C.C., L.G. and V.D.; project administration, C.C. and T.L.M.; funding acquisition, C.C. and T.L.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors would like to acknowledge the Association Nationale Recherche Technologie (ANRT) for the French CIFRE fellowship funding (n°20201721).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank Jean-Laurent Vellutini, regional delegate of ANRT to Corsica, and Didier Pierrat-Agostini, president and founder of STEPSol.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. IEA. *World Energy Outlook 2022*; IEA: Paris, France, 2022; p. 524.
2. Sandia Labs. DOE Global Energy Storage Database. Available online: <https://sandia.gov/ess-ssl/gesdb/public/projects.html> (accessed on 18 January 2022).
3. Nikolaidis, P.; Poullikkas, A. A comparative review of electrical energy storage systems for better sustainability. *J. Power Technol.* **2017**, *97*, 27.
4. Mongird, K.; Viswanathan, V.; Alam, J.; Vartanian, C.; Sprenkle, V.; Baxter, R. *2020 Grid Energy Storage Technology Cost and Performance Assessment*; Technical Report; United States Department of Energy: Washington, DC, USA, 2020; p. 20.
5. Salevid, K. Market Requirements for Pumped Storage Profitability. 2013. Available online: <https://uu.diva-portal.org/smash/get/diva2:661286/FULLTEXT01.pdf> (accessed on 1 December 2022).
6. Lazard. *Levelized Cost of Storage—Version 2.0.*; Lazard: Hamilton, Bermuda, 2016.
7. Stocks, M.; Stocks, R.; Lu, B.; Cheng, C.; Blakers, A. Global Atlas of Closed-Loop Pumped Hydro Energy Storage. *Joule* **2021**, *5*, 270–284. [[CrossRef](#)]
8. IPSE. Caracterización ZNI. Available online: <https://aspree.org/pdf/Presentaci%C3%B3n%20de%20Pedro%20Bejarano%20IPSE%20Colombia.pdf> (accessed on 1 December 2022).
9. IPSE. Oportunidades Actuales En El Campo De Las Energías Renovables En Colombia. 2015. Available online: <https://www.mzv.cz/file/1638464/ipse.pdf> (accessed on 1 December 2022).
10. Hydropower Colombia, Hydropower Potential and Production in Colombia. Available online: <https://www.hydropower.org/country-profiles/colombia> (accessed on 1 December 2022).
11. IPSE. Objetivos Y Funciones Del IPSE. 2022. Available online: <https://ipse.gov.co/mapa-del-sito/ipse/direccionamiento-estrategico/objetivos-y-funciones/> (accessed on 1 December 2022).
12. Tuckey, A.; Round, S. Round. Grid-Forming Inverters for Grid-Connected Microgrids: Developing “good citizens” to ensure the continued flow of stable, reliable power. *IEEE Electr. Mag.* **2022**, *10*, 39–51. [[CrossRef](#)]
13. Zaleskis, G.; Rankis, I.; Prieditis, M. Self-Excitation System for Synchronous Generator. *Electr. Control Commun. Eng.* **2013**, *4*, 32–37. [[CrossRef](#)]
14. Tayab, U.B.; Roslan, M.A.B.; Hwai, L.J.; Kashif, M. A review of droop control techniques for microgrid. *Renew. Sustain. Energy Rev.* **2017**, *76*, 717–727. [[CrossRef](#)]

15. Barklund, E.; Pogaku, N.; Prodanovic, M.; Hernandez-Aramburo, C.; Green, T.C. Green, Energy Management in Autonomous Microgrid Using Stability-Constrained Droop Control of Inverters. *IEEE Trans. Power Electron.* **2008**, *23*, 2346–2352. [CrossRef]
16. Notton, G.; Duchaud, J.; Nivet, M.; Voyant, C.; Chalvatzis, K.; Fouilloy, A. The electrical energy situation of French islands and focus on the Corsican situation. *Renew. Energy* **2019**, *135*, 1157–1165. [CrossRef]
17. International Finance Corporation (World Bank). *The Dirty Footprint of the Broken Grid*; International Finance Corporation: Washington, DC, USA, 2019.
18. Multon, B.; Moine, G.; Aubry, J.; Haessig, P.; Jaouen, C.; Thiaux, Y.; Ahmed, H.B. *Ressources Énergétiques Et Solutions Pour L'alimentation En Électricité Des Populations Isolées*; HAL: Belfort, France, 2011; p. 13.
19. Rockefeller Foundation. Comparing Costs of an Integrated Approach Versus Pure Grid Extension. 2020. Available online: <https://www.rockefellerfoundation.org/wp-content/uploads/2020/12/EE-Download-Opportunity-Datasheet-Detailed-Cost-Models-and-Benchmarks.pdf> (accessed on 15 November 2022).
20. European Union. *Sustainable Energy Handbook Module 6.1 Simplified Financial Models*; European Union: Maastricht, The Netherlands, 2016.
21. Jakhvani, A.Q.; Othman, A.-K.; Rigit, A.R.H.; Samo, S.R. Estimation of carbon footprints from diesel generator emissions. In Proceedings of the 2012 International Conference on Green and Ubiquitous Technology, Bandung, Indonesia, 7–8 July 2012; pp. 78–81. [CrossRef]
22. SSPD. Boletín Tarifario ZNI I. 2022. Available online: [https://www.superservicios.gov.co/sites/default/files/inline-files/Boleti%CC%81n\\_Tarifario\\_Energi%CC%81a\\_ZNI\\_I\\_Trim\\_2022.pdf](https://www.superservicios.gov.co/sites/default/files/inline-files/Boleti%CC%81n_Tarifario_Energi%CC%81a_ZNI_I_Trim_2022.pdf) (accessed on 15 November 2022).
23. Vides-Prado, A.; Camargo, E.O.; Vides-Prado, C.; Orozco, I.H.; Chenlo, F.; Candelo, J.E.; Sarmiento, A.B. Techno-economic feasibility analysis of photovoltaic systems in remote areas for indigenous communities in the Colombian Guajira. *Renew. Sustain. Energy Rev.* **2018**, *82*, 4245–4255. [CrossRef]
24. Rodríguez-Urrego, D.; Rodríguez-Urrego, L. Photovoltaic energy in Colombia: Current status, inventory, policies and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *92*, 160–170. [CrossRef]
25. CREG. RESOLUCIÓN No. 091 (26 OCT. 2007). 2009. Available online: <http://apolo.creg.gov.co/Publicac.nsf/Indice01/Resolucion-2007-Creg091-2007> (accessed on 15 November 2022).
26. IRENA. *Electricity Storage and Renewables: Costs and Markets to 2030*; IRENA: Abu Dhabi, United Arab Emirates, 2017; p. 132.
27. Wu, W.; Wang, S.; Wu, W.; Chen, K.; Hong, S.; Lai, Y. A critical review of battery thermal performance and liquid based battery thermal management. *Energy Convers. Manag.* **2019**, *182*, 262–281. [CrossRef]
28. Spitthoff, L.; Shearing, P.; Burheim, O. Temperature, Ageing and Thermal Management of Lithium-Ion Batteries. *Energies* **2021**, *14*, 1248. [CrossRef]
29. Hoppecke. Installation, Commissioning and Operating Instructions for Vented Stationary Lead-Acid Batteries. 2013. Available online: [https://www.hoppecke.com/fileadmin/Redakteur/Hoppecke-Main/Products-Import/v1\\_manual\\_en.pdf](https://www.hoppecke.com/fileadmin/Redakteur/Hoppecke-Main/Products-Import/v1_manual_en.pdf) (accessed on 15 November 2022).
30. Dufo-López, R.; Cortés-Arcos, T.; Artal-Sevil, J.; Bernal-Agustín, J. Comparison of Lead-Acid and Li-Ion Batteries Lifetime Prediction Models in Stand-Alone Photovoltaic Systems. *Appl. Sci.* **2021**, *11*, 1099. [CrossRef]
31. McManus, M. Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Appl. Energy* **2012**, *93*, 288–295. [CrossRef]
32. Santillán-Saldivar, J.; Gaugler, T.; Helbig, C.; Rathgeber, A.; Sonnemann, G.; Thorenz, A.; Tuma, A. Design of an end Point Indicator for Mineral Resource Supply Risks in Life Cycle Sustainability Assessment. *J. Ind. Ecol.* **2020**, *25*, 1051–1062. Available online: <https://onlinelibrary.wiley.com/doi/epdf/10.1111/jiec.13094> (accessed on 15 November 2022). [CrossRef]
33. STEPSOL: An Innovative Hydraulic Storage Solution. 2018. Available online: <https://www.youtube.com/watch?v=sIuzsryMkMQ&t=1s> (accessed on 15 November 2022).
34. Savin, O.; Badina, C.; Drommi, J.-L.; Baroth, J.; Charbonnier, S.; Bérenguer, C. Influence of Starts and Stops on the Aging of Hydroelectric Generator Stators by Thermal Cycling: Empirical Study and Accelerated Lifetime Model. In Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021), Angers, France, 19–23 September 2021; pp. 3214–3221. [CrossRef]
35. KSB. Multitec/Multitec-RO Pompe Multicellulaire Haute Pression Notice De Service/Montage. Available online: <https://live-commerce-proxy-e2e-sales.ksb.com/rest/v2/ksb/users/anonymous/odata/disfile?application=PDF&documentType=YTO&documentNumber=1777.8&documentPart=FR&documentVersion=17&checksum=fb82bfe25a0f33f103f23bcbcb461fe42204aa6280bb9da9979b7116589ac846&salesOrg=1010&extension=PDF&mimetype=application%2Fpdf> (accessed on 15 November 2022).
36. Waide, P.; Brunner, C.U. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*; IEA Energy Papers; OECD Publishing: Paris, France, 2011. [CrossRef]
37. Shirinda, K.; Kusakana, K.; Koko, S.P. Techno-economic analysis of a standalone solar PV with groundwater pumped-hydro-storage system. In Proceedings of the 2019 International Conference on the Domestic Use of Energy (DUE), Wellington, South Africa, 25–27 March 2019; p. 6.
38. Javed, M.S.; Ma, T.; Jurasz, J.; Canales, F.A.; Lin, S.; Ahmed, S.; Zhang, Y. Economic analysis and optimization of a renewable energy based power supply system with different energy storages for a remote island. *Renew. Energy* **2020**, *164*, 1376–1394. [CrossRef]
39. Javed, M.S.; Ma, T.; Jurasz, J.; Mikulik, J. A hybrid method for scenario-based techno-economic-environmental analysis of off-grid renewable energy systems. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110725. [CrossRef]
40. Greacen, C.; Engel, R.; Quetchenbach, T. A Guidebook on Grid Interconnection and Islanded Operation of Mini-Grid Power Systems Up to 200 Kw. p. 80. Available online: <https://www.osti.gov/servlets/purl/1171616> (accessed on 1 December 2022).

41. Ekanayake, J. Induction generators for small hydro schemes. *Power Eng.* **2002**, *16*, 61–67. [[CrossRef](#)]
42. Chilipi, R.; Sumaiti, A.A.; Singh, B. Control of Self-Excited Induction Generator-based Micro-Hydro Power Generation System Feeding Single-Phase and Three-Phase Loads. In Proceedings of the 2020 IEEE Industry Applications Society Annual Meeting, Detroit, MI, USA, 10–16 October 2020; pp. 1–8. [[CrossRef](#)]
43. Evans, P. Star Delta Starters Explained. Available online: <https://theengineeringmindset.com/star-delta-starters/> (accessed on 1 December 2022).
44. Laughton, M.A.; Warne, D.J. Motors and Actuators. In *Electrical Engineer's Reference Book*; Elsevier: Amsterdam, The Netherlands, 2003; pp. 20-1–20-44. [[CrossRef](#)]
45. Sellers, D. Variable Frequency Drive System Efficiency—Part 1. Available online: <https://av8rdas.wordpress.com/2010/12/18/variable-frequency-drive-system-efficiency/> (accessed on 1 December 2022).
46. Le Mao, T. Intégration De Micro-STEP Solaire Dans Un Contexte Insulaire. Ph.D. Thesis, Université Grenoble Alpes, Grenoble, France, 2020.
47. Capelo, B.; Pérez-Sánchez, M.; Fernandes, J.F.; Ramos, H.M.; López-Jiménez, P.A.; Branco, P.C. Electrical behaviour of the pump working as turbine in off grid operation. *Appl. Energy* **2017**, *208*, 302–311. [[CrossRef](#)]
48. Nag, S.; Lee, K.Y. DFIM-Based Variable Speed Operation of Pump-Turbines for Efficiency Improvement. *IFAC-PapersOnLine* **2018**, *51*, 708–713. [[CrossRef](#)]
49. Belhadji, L. Optimisation Du Contrôle Commande D'un Système Hydraulique Réversible À Vitesse Variable. Ph.D. Thesis, Université Grenoble Alpes, Grenoble, France, 2013; p. 198.
50. Reljić, D.; Čorba, Z.; Dumnić, B. Application of permanent magnet synchronous generators within small-scale hydropower systems. *J. Process. Energy Agric.* **2010**, *14*, 4.
51. Maroufian, S. Generator Applications of Synchronous Reluctance Machines (SynRM). Available online: <https://users.encs.concordia.ca/~peer/ppts/Sarah.pdf> (accessed on 1 December 2022).
52. ABB. IE5 Synchronous Reluctance Motors, News. Available online: <https://new.abb.com/news/detail/80775/ie5-synchronous-reluctance-motors> (accessed on 9 February 2022).
53. Bidgoli, M.A.; Yang, W.; Ahmadian, A. DFIM versus synchronous machine for variable speed pumped storage hydropower plants: A comparative evaluation of technical performance. *Renew. Energy* **2020**, *159*, 72–86. [[CrossRef](#)]
54. Krishna, V.B.M.; Sandeep, V.; Murthy, S.S. Experimental Study on Three Phase Permanent Magnet Synchronous Generator for Pico Hydro Isolated Systems. In Proceedings of the 2021 International Conference on Sustainable Energy and Future Electric Transportation (SEFET), Hyderabad, India, 21–23 January 2021; pp. 1–4. [[CrossRef](#)]
55. Salas, V.; Suponthana, W.; Salas, R. Overview of the off-grid photovoltaic diesel batteries systems with AC loads. *Appl. Energy* **2015**, *157*, 195–216. [[CrossRef](#)]
56. Shezan, S.; Julai, S.; Kibria, M.; Ullah, K.; Saidur, R.; Chong, W.; Akikur, R. Performance analysis of an off-grid wind-PV (photovoltaic)-diesel-battery hybrid energy system feasible for remote areas. *J. Clean. Prod.* **2016**, *125*, 121–132. [[CrossRef](#)]
57. Habib, M.; Ladjici, A.A.; Khoucha, F. Frequency Control in Off-Grid Hybrid Diesel/PV/Battery Power System. In Proceedings of the 4th International Conference on Electrical Engineering and Control Technologies (CEECT 2022), Shanghai, China, 16–18 December 2022; p. 7.