

Hybrid, Integrated System for the Production and Distribution of Photovoltaic (PV) Solar Energy and a Pumped Storage Hydroelectric Power (PSHP) for a Typical Locality in Benin: Study and Design

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Abstract Simultaneous access to electricity and drinking water remains a major challenge in rural areas of Benin. This work proposes the design of an integrated system combining solar and hydropower to effectively meet the energy and water needs of a typical community of 10,000 inhabitants. The methodology adopted is based on needs assessment, equipment sizing (solar panels, pump, tank, turbine, and alternator), and a techno-economic feasibility study. The results obtained demonstrate the feasibility of a system capable of producing an average of 1,976.98 kWh per day and supplying 2,668.88 m³ of water, thus guaranteeing energy and water self-sufficiency for rural populations. This innovative solution highlights the importance of an integrated approach to address the challenges of the energy transition and universal access to basic services in Benin.

Keywords: solar energy, hydropower, integrated systems, rural electrification, drinking water, pumped storage and pumped storage (PSPS)

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1. Introduction

Benin, by virtue of its geographical position, is in West Africa between the Tropic of Cancer and the equator (between 6°30' and 12°30' North latitude and 1° and 30°40' East longitude). It lies in the tropical zone and is particularly well sunny. As a result, temperatures are consistently high, with an annual average of 25°C across the country. Its population is approximately 14,400,000 inhabitants [1]. Access to energy and drinking water remains a major challenge and is still not a reality in rural areas of Benin. Access to drinking water in many localities in Benin remains a struggle. While studies such as those by IRENA (2022) and UNICEF highlight the country's strong solar potential as well as the persistent difficulties in accessing safe water, these resources remain largely underutilized. mainly due to the lack of technical solutions adapted to local realities. In West Africa, hydropower emerged as a strategic solution in the second half of the 20th century to support electrification and reduce dependence on fossil fuels [2]. In Benin, despite the absence of large dams comparable to those in Guinea, Ghana, or Cameroon, the hydropower potential remains

modest but not negligible, particularly on the Ouémé River and its tributaries [3]. Benin has primarily developed regional cooperation to benefit from hydropower produced in neighboring countries (Nigeria, Ghana) through electrical interconnections [4]. Today, faced with population growth and the impacts of climate change, hydropower is increasingly being considered as a complementary approach to decentralized renewable energies (solar, biomass, mini-grids) [5]. Unlike the European model based on large dams, African countries, including Benin, are exploring small and medium hydropower projects to limit environmental and social impacts, while supporting universal access to energy [6].

However, hydropower also presents major advantages in Africa and Benin: it is a renewable energy source, relatively predictable, and can be combined with storage capacity through reservoirs, while also being a low emitter of greenhouse gases [7]. Within the framework of international climate commitments, such as the 2015 Paris Agreement, many African countries have set themselves the objective of reducing their dependence on fossil fuels and increasing the share of renewable energy in their energy mix [4]. For Benin, where the electrification rate remains below the regional average, the use of local solutions such as small and medium-scale hydropower is

crucial, particularly for supplying electricity to remote rural areas [3]. Meeting national objectives for sustainable energy and energy security therefore requires, in addition to solar and biomass energy, revitalizing and developing the potential of small hydropower plants (SHPs) in river basins such as the Ouémé [5]. This article is structured around four main parts. Section 2 presents data based on a literature review, the state of the art, and the theoretical foundations of PV systems, turbines, and pumps. Methodologies for estimating photovoltaic power are described in Section 3. Section 4 presents the results and their validation. Finally, the conclusion is given, followed by limitations and future directions.

1.1. Literature Review

In the 21st century, sub-Saharan Africa, and Benin in particular, faces the dual challenge of universal access to electricity and the energy transition. In this context, pumped hydro storage (PHS) plants appear as a strategic option for strengthening energy security. Unlike in Europe, where PHS plants experienced rapid growth from the 1960s to the 1980s to support the development of nuclear and hydroelectric power, their deployment remains limited in Africa. However, with the recent rise of intermittent renewable energies such as solar and wind power, the relevance of PHS plants in the region is becoming increasingly evident [2]. In Benin, whose electricity mix relies heavily on imports and solar projects under development, the introduction of PHS plants could be a major lever for reducing external dependence, optimizing the use of local resources, and stabilizing the national grid [4]. Thus, Just as hydroelectricity shaped the French energy landscape in the 20th century, pumped storage hydroelectric plants (PSHPs) could play a structuring role in building a more resilient and sustainable energy system in Benin in the 21st century [3]. However, pumped storage hydroelectric plants offer considerable strategic advantages for Africa and Benin. They allow for the storage of surplus energy produced by intermittent sources such as solar and wind power, in order to release it during periods of high demand. This process, based on pumping water to an upper reservoir during periods of energy surplus and then using it to generate electricity during periods of deficit, is currently the most mature and efficient form of large-scale electricity storage [2]. The role of a hybrid power generation system in isolated developing regions is not simply to provide "energy power," but rather to serve as a tool for the social and economic development of rural areas. Within the framework of the commitments made by African countries through the Paris Agreement, the integration of energy storage solutions has become essential to securing the energy transition [4]. For Benin, whose electricity system remains highly interconnected with neighboring countries and vulnerable to production fluctuations, pumped hydro storage (PHS) offers a path to resilience and energy independence. Coupled with the rapidly developing solar power plants, these installations would not only stabilize the grid but also optimize the use of local renewable resources [3]. Thus, like the revival of small hydropower in Europe in the 2000s to meet climate directives, the implementation of pumped storage hydropower in Benin

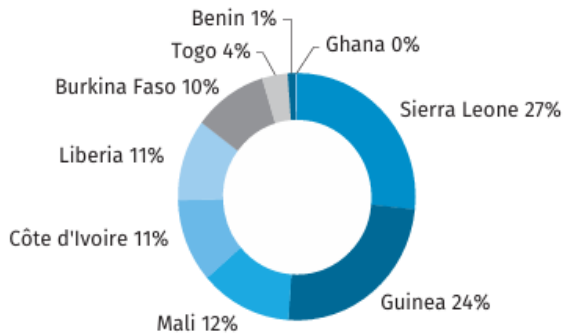
and West Africa could be a decisive lever for achieving the objectives of universal access to energy, while limiting greenhouse gas emissions and strengthening regional energy security [5].

Currently, there is a supply and demand imbalance for electricity in West African countries (Adeoye and Spataru, 2018). Furthermore, electricity demand is projected to increase fivefold by 2030 compared to 2013 levels (IRENA, 2015). Consequently, new large-scale power plants need to be developed, and existing infrastructure must be upgraded. The West African Power Pool (WAPP) was established in 1999 to coordinate these developments. WAPP's business plan envisions connecting In particular, photovoltaic (PV) energy is poised for growth, with a technical potential of approximately 100 PWh per year (Hermann et al., 2014) and is expected to cover a large share of future electricity supply (IRENA, 2015). Therefore, long-term changes in the potential of photovoltaic energy are relevant and are addressed in this study.

1.2. Solar Potential Estimation

Furthermore, it is worth noting the average solar irradiance exceeding 5 kWh/m²/day during the dry season, but these yields drop sharply during the rainy season, thus demonstrating the intermittency due to weather conditions [16]. This intermittent production is difficult to store, which complicates its continuous use for essential services such as lighting, water pumping, and domestic wastewater treatment. This observation highlights a structural and cyclical problem: the lack of systems capable of ensuring both reliable electricity production and efficient distribution of drinking water in rural areas, coupled with insufficient investment in the energy sector. Hence the following question: how can we design an integrated, sustainable, and realistic system, combining solar and hydropower, capable of effectively meeting the basic needs of rural populations for electricity and drinking water? This study aims to study and design a prototype of an integrated hybrid renewable energy system combining a small hydropower plant (SHP) with a pumped-storage hydropower station (PSH) and photovoltaic (PV) energy, intended to provide the population with both electricity and water. Beyond the ecological potential, a comparison based on a performance factor specific to the installation shows that hydroelectricity remains the most cost-effective form of energy production. The performance factor of small hydro installations is around 80-100. This performance factor is the ratio between the amount of energy produced by the installation over its entire lifespan and the energy required to set up the production equipment, including its supply. It is relatively higher than that of photovoltaic plants (3-5), solar thermal (20-50), and wind energy (10-30). It is necessary to implement multi-level supervision of the proposed PV/hydro/storage plant. [7]. Benin has only one hydroelectric power plant with an installed capacity of 0.5 MW. The potential capacity for small hydropower plants (SHPs) up to 30 MW is estimated at 95 MW, of which less than 1% has been developed. In addition, at least 5 MW of capacity for SHPs up to 10 MW has been identified, of which 10% has been developed. No recent activity has taken place in the

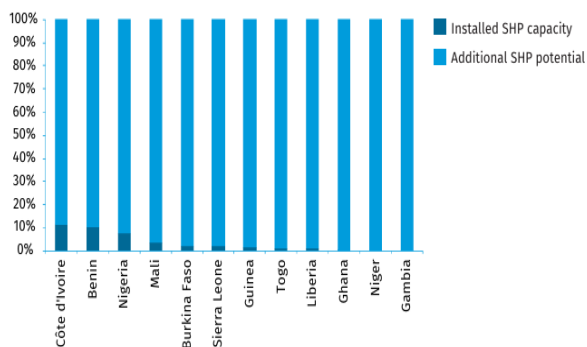
country's SHP sector, although an upgrade of the existing plant to increase its installed capacity to 1 MW has been considered [8].



Source: WSHDPDR 2022¹

Figure 1. Part de la capacité installée régionale des petites centrales hydroélectriques jusqu'à 10 MW par pays en Afrique de l'Ouest (%) [8].

Le Bénin a une capacité installée de petite centrale hydroélectrique de l'ordre de 10%.



Source: WSHDPDR 2022¹

Figure 2. Small-scale hydropower potential used by countries in West Africa (%) [8].

The difficulty of finding suitable sites for dams on rivers, including the associated environmental challenges, has led many analysts to assume that pumped hydro storage (PHS) has limited opportunities to support variable renewable energy production. Closed-loop, off-river PHS overcomes many of these obstacles. Small upper reservoirs (on the order of square kilometers) are typically located in hilly areas away from rivers, and water is circulated indefinitely between an upper and a lower reservoir. At the end of the 20th century, photovoltaic solar energy power (PV) has emerged as a strategic solution to address electrification challenges in sub-Saharan Africa. Unlike the large hydroelectric programs of the previous century, solar development has been characterized by a decentralized and gradual approach, driven by the decreasing cost of solar panels and international cooperation programs. [10].

In Benin, the first solar energy initiatives date back to the 1980s, with pilot projects for public lighting and powering pumping stations in rural areas [11]. However, it was from the 2010s onwards that photovoltaics experienced a real boom, notably thanks to the support of programs such as the National Renewable Energy Action Plan (PANER) and the Decentralized Rural Electrification Program (PERD). [12].

Today, PV technology represents an essential component of Benin's energy mix. Several grid-connected mini solar power plants have been developed, such as those in Illoulofin (25 MWp) and Parakou, while numerous stand-alone systems supply isolated rural areas. Solar energy thus offers a sustainable alternative to hydroelectric and fossil fuel constraints, while contributing to the carbon neutrality and universal access to electricity objectives set by the African Union's Agenda 2063 [13]. Thus, photovoltaic (PV) energy appears to be a promising technology in this region (West Africa), and developing a PV system would be profitable. Before investing in a PV system, three points must be considered using different resolutions of GHI (the sum of direct irradiance, DIR, and diffuse horizontal irradiance, DHI), which has a major impact on PV systems [15]. Figure XX shows the different irradiances across Africa.

While hydroelectricity marked the energy transition of the 20th century, photovoltaics is now emerging as the driving force behind Africa's 21st-century energy transition – a more modular, participatory, and environmentally friendly model. PV Installation Capacity: In an initial solar energy assessment, the National Environmental Atlas is consulted to obtain the average annual solar radiation (in hours), the average monthly solar irradiance (kWh/m^2), and the average temperature ($^{\circ}\text{C}$) of the site. The potential for solar energy production in Benin is higher in the northern part of the country, particularly in the departments of Atacora, Borgou, Donga, and Allibory. Annual photovoltaic production is estimated at 1560 kWh in the north, 1460 kWh in the center, and 1400 kWh in the south. Overall, the duration of sunshine in the best-case scenario is limited to between 1500 and 2000 hours per year. In the case of the city of Lokossa, a city in the Mono department of the West region, and more specifically in the city of hope, sunshine lasts between 1500 and 2000 hours on average per year, as shown in the following figure.

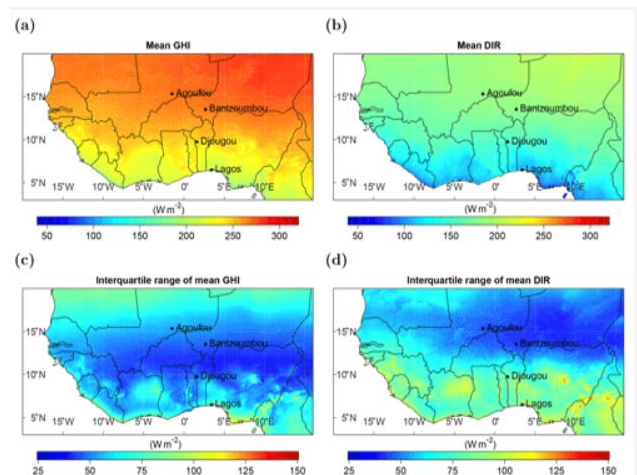


Figure 3. Mean (1983 -2017) global horizontal irradiance a) and direct horizontal irradiance b) with their respective temporal interquartile ranges given in panels c) and d). [15]

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hours on average per year, as shown in the following figure.

1.3. Pumped Storage Hydroelectric Power

Pumped storage hydroelectric plants (PSHPs) are a specific type of hydroelectric facility where electrical energy is stored as the mechanical (potential) energy of water. The operation of a PSHP is based on a simple concept. (See the following figure) During periods of low demand and high availability of electrical energy, water is pumped, via the pump-motor unit, from a low-altitude water source (or reservoir) and stored in a high-altitude water reservoir.

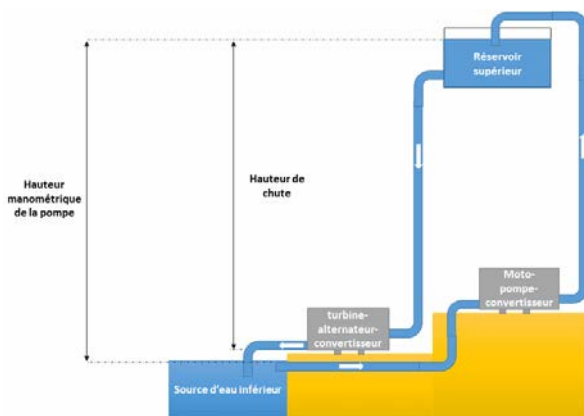


Figure 4. Pumped hydro energy transfer station (PHES) [16]

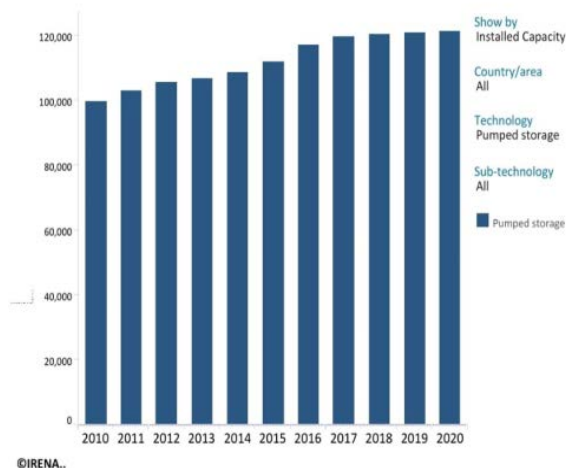


Figure 5. Change in global installed pumped storage capacity (MW) between 2010 and 2020

Pumped hydro storage requires a large, inclined area for the upper and lower reservoirs. The amount of energy stored depends on the amount of water discharged from the upper reservoir and the difference in elevation between the upper and lower reservoirs. The efficiency factor of small hydroelectric installations is in the order of 80-100. This efficiency factor is the ratio between the amount of energy produced by the installation during its entire life and the energy required for the installation of the production equipment, including its power supply. The originality of this study lies in the fact that the hybrid source consists solely of electrical generators powered by renewable energy. The advantage of this solution is that it

avoids polluting and environmentally destructive energy sources, which have caused a radical change in the climate through the enormous and direct production of CO₂. The variation in global installed pumped storage capacity over the last decade, according to IRENA data, is shown in the figure.

Other studies confirm this. The results show that solar PV with pumped-storage hydroelectricity (PSH) remains the optimal system configuration for rural and urban cases, even when the construction costs of lower and upper reservoirs are taken into account. 14of a hybrid power generation system (HPGS) is to supply energy to various loads while maintaining the quality of the supplied power. HPGS are often associated with electricity production in remote areas and can take the form of: a single renewable energy source with or without a generator (in our case, without a generator). In this case, a storage system is essential to always meet consumer demand; or two or more renewable energy sources with or without a generator, operating with a storage system. [20].

1.4. Objective of the Work

To achieve this, a conceptual study of a hybrid photovoltaic/pumped hydro storage system will be conducted. Specifically, this will involve estimating the actual needs of the target population, sizing the essential technical equipment required for the system (solar panels, pump, alternator, turbine, storage tanks, converters, and controllers), evaluating the system's techno-economic feasibility, and finally, proposing a management model adapted to local conditions. The study will define the overall architecture, energy flows, and interactions between the subsystems (PV, pumping, storage tanks, turbine, generator). It will also establish calculation relationships (power, flow rate, head, efficiency, usable volume) adapted to local conditions (sunlight, topography, energy requirements).

2. Methods and Material of Size Equipment

The methodology adopted combines an experimental, digital and participatory approach. The literature review on integrated solar and hydropower generation and distribution systems is based on scientific, adaptability, and design considerations. Procedures were followed to: (1) identify articles, (2) review, compare, and analyze articles, and (3) identify current literature and research gaps. Frameworks were established to identify appropriate articles based on the theme of our study. Initially, major online databases were selected, namely ScienceDirect, Wiley Online Library, IEEE Xplore, Springer, Taylor & Francis, IET, and Energies (MDPI). To ensure the breadth and depth of the exploration, established academic databases were also used, including Google Scholar and Web of Science Clari. This progressive, rigorous, and structured approach, based on specific defined objectives, serves as a guiding principle for the development of the upcoming sections. Each stage of the work follows a logic of analysis, design, and adaptation to the technical and social realities of Benin, particularly its rural areas.

2.1. Site Localisation

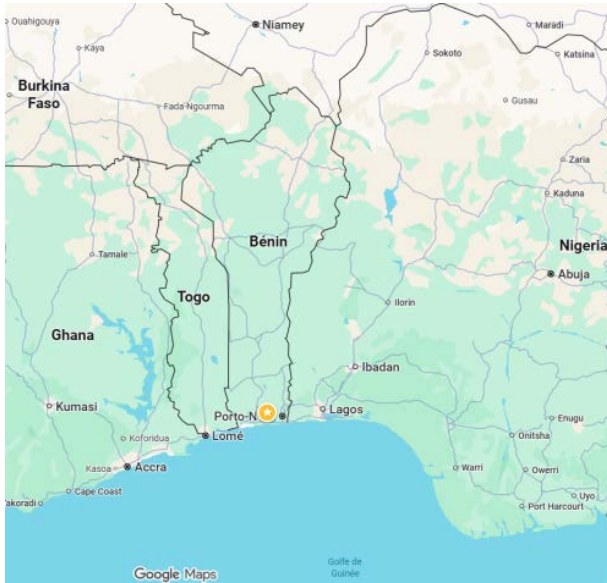


Figure 6. Location of the locality in Lokossa, Benin and of the vacant area on the roof of the locality site

3. Results and Discussion

3.1. Proposed Block Diagram

The proposed system consists of a photovoltaic solar power plant, an intermittent renewable energy source, and an energy storage system. Here, the small hydropower plant will be connected to the electrical grid to make it more reliable and resilient. The following figure, an integrated conceptual structure for solar and hydropower production and distribution, describes the suggested configuration of renewable energy resources. This system is a self-contained solution designed to simultaneously meet the basic electricity and drinking water needs of a rural population. It relies on the combined use of solar energy and the gravitational force of water to ensure a stable and sustainable energy supply. Electricity produced by solar panels is used to power an electric pump that raises water from an underground source to a reservoir located at a higher elevation, such as a water tower or reservoir. This water is then partially purified for human consumption and used downstream to generate electricity via a hydraulic turbine coupled to an alternator.

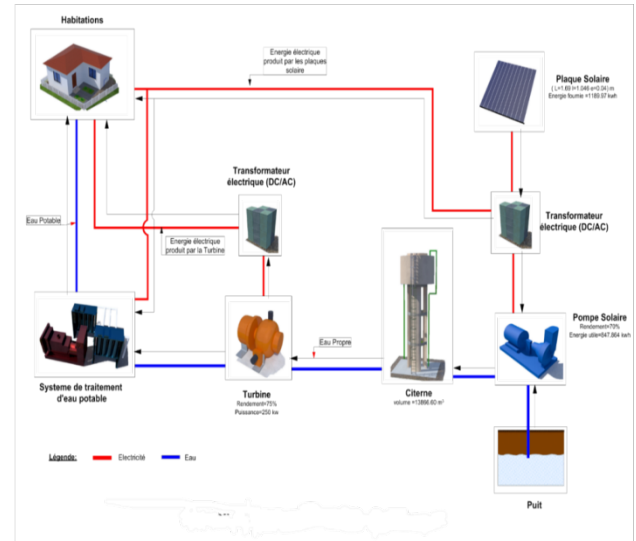


Figure 7. General overview of the integrated solar and hydroelectric power production and distribution system

3.2. Synopsis of the PV/STEP Microgrid Sizing Method

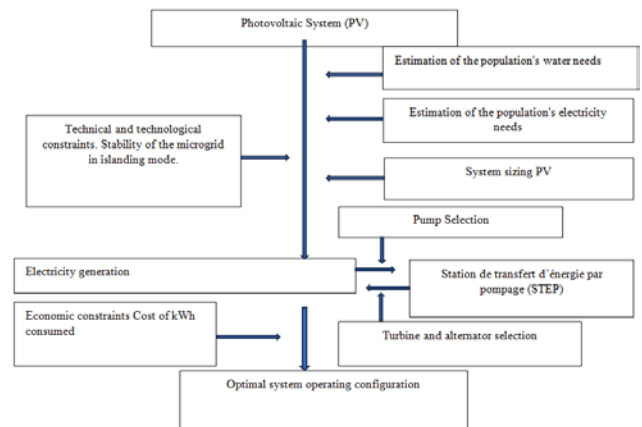


Figure 8. Synopsis of the PV/STEP microgrid sizing method

3.3. Estimation of the Storage Capacity of the Upper Water Tank

The required capacity of the upper water reservoir is described by the following equation.

$$C_r = \frac{n_h \cdot E_L \cdot 3.6 \cdot 10^6}{\eta_{TUR} \cdot \rho \cdot g \cdot h_{tur}} \quad (1) \quad [19]$$

Where the installation capacity of the upper tank in m^3 , n_h is the number of days the upper tank can operate autonomously. E_L (kWh) is the number of days the upper tank can operate autonomously. η_{tur} (%) is the overall efficiency of the turbomachine ($\eta_{tur} = \eta_{gen} \cdot \eta_{hyd}$). The industry has adopted the term "days of autonomy" as a means of specifying the size of a storage system based on the specific needs of the site; this is defined as the number

of days the storage system can power the site's loads without any support from the PV generation source. Considering the space dedicated to the installation of the upper tank, approximately 2000 m^3 , 1 A day's autonomy is ensured in this study. Thanks to the previous formula, we can preliminarily estimate the capacity of the upper water reservoir at $Cr = 1279 \text{ m}^3$.

• Drinking water needs

Before proceeding with equipment sizing, it is important to estimate the drinking water and electricity needs of the target population. The system covers a rural area of Benin, with approximately 10,000 inhabitants.

Water is the system's priority. According to WHO recommendations, a person needs at least 30 liters of drinking water per day for basic needs (drinking, cooking, hygiene).[1]

Therefore, for 10000 people:

Total need = Number of inhabitants $\times$ water requirement per person

Total need = 10 000 inhabitants $\times$ 30 liters

Total need = 300 000 liters/jour

Total need = $300 \text{ m}^3/\text{day}$

3.4. Different Systems Modules Sizing

The sizing of the different modules is preceded by the formulation of the population's needs for drinking water and electricity.

3.4.1. Nomenclatures (SI units)

- ρ : water density ($\approx 1000 \text{ kg} / \text{m}^3$)
- g : acceleration due to gravity ($9,81 \text{ m} / \text{s}^2$)
- $Q(t)$: turbine flow [m^3/s]
- $H(t)$: net height of fall [m]
- η_{turb} : turbine hydraulic efficiency (0–1)
- $\omega_{\text{turb}}(t)$: angular velocity of the turbine [rad/s]
- $n_{\text{turb}}(t)$: turbine rotation speed [tr/min] (rpm);
 $\omega = \frac{2\pi n}{60}$: rotation frequency
- i_g : turbine mechanical gear ratio $\rightarrow$ alternator (transmitted power = unchanged, but changed speed)
- $\omega_{\text{gen}}(t) = i_g \cdot \omega_{\text{turb}}(t)$: alternator angular speed [rad/s]
- $n_{\text{gen}}(t)$: alternator speed [tr/min]
- $T_{\text{mec}}(t)$: mechanical torque supplied to the shaft [$\text{N}\cdot\text{m}$]
- $P_{\text{mec}}(t)$: mechanical power available at the alternator [W]
- η_{gen} : generator efficiency /alternator (0–1)
- N : number of effective turns (per phase) of stator/rotor (according to architecture)
- Φ : magnetic flux per turn [Wb] (RMS value or amplitude according to convention)
- $E_{\text{ind}}(t)$: induced voltage (electromotive force) [V]

— dépend de N , Φ , ω

- $P_{\text{elec}}(t)$: active electrical power delivered to the grid [W]
- E_{elec} : electrical energy produced over an interval [J] or [kWh]
- pf : power factor ($\cos\phi$), if we want to calculate active power from voltage and current.

3.4.2. Estimation of Energy Needs

The system provides two sources of electricity: solar energy during the day, and hydroelectric energy at night (using water stored at a higher elevation). The needs are estimated considering the rural lifestyle.

The day:

- Charging phones: 2 telephones per household, 10 Wh/day each
- Lamp charging/torches: 3 torches per household, 15 Wh/dayeach
- Water purification: approximately 1 kWh to treat 1 m^3 water

According to INStaD, the average household size in Benin is approximately 5 to 6 peoples [2]. Let's take 6 people for this project, so we have:

$$N = \frac{Z}{W}$$

With: N the total number of households; Z: size of the community; W: the number of people per household

$$N = \frac{10000}{6} = 1\,666,66 \text{ households}$$

For what follows, we consider 1 667 households.

Phones:

$$B_T = N \cdot N_T \cdot P_T \quad (2)$$

With: B_T the energy required to charge phones; N_T the number of telephones per household; P_T the power of a phone

$$B_T = 1\,667 \times 2 \times 10 = 33\,340 \text{ Wh} = \mathbf{33,34 \text{ kWh}}$$

Torches:

$$B_t = N \cdot N_{to} \cdot P_{to}$$

With: B_t the energy requirement for charging the torches; N_{to} the number of torches per house h; P_{to} the power of a torch

Numerical Application: $B_t = 1\,667 \times 3 \times 15 = 75\,015 \text{ Wh} = \mathbf{75,015 \text{ kWh}}$

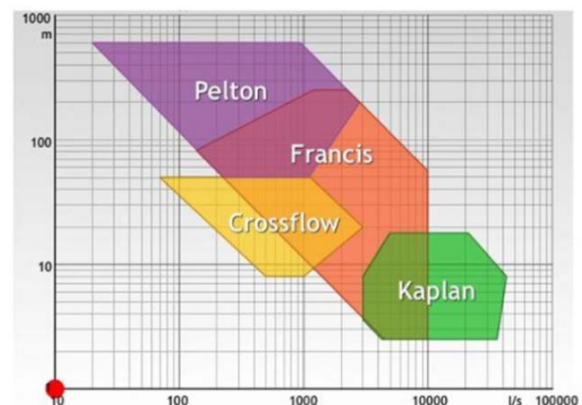


Figure 9. Types of hydraulic turbines

Turbine and alternator sizing

The turbine is selected using the turbine classification shown in Figure 9. For a nominal flow rate $Q = 0.03 \text{ m}^3/\text{s}$, the only possibility is to use a Pelton turbine.

After choosing the type of turbine, it is necessary to determine the maximum power that the turbomachine can generate. This generating power P_{gen} is obtained using the formula:

$$P_{gen} = \eta_{gen} * P_{mec} \quad (3)$$

Where η_{gen} is the generator's output and

P_{mec} (kW) the mechanical power of the generator shaft. The mechanical power is calculated as follows.

$$P_{mec} = \eta_{hyd} * P_{hyd} \quad (4)$$

Where η_{hyd} is the hydraulic efficiency and P_{hyd} (kW) Hydraulic power. Power P_{hyd} is calculated according to the formula:

$$P_{hyd} = \frac{\rho g Q h}{1000} \quad (5)$$

Where $\rho = 1000 \text{ kg/m}^3$ is the density of water and $g = 9.81 \text{ m/s}^2$ is the acceleration due to gravity. $Q = 0.03 \text{ m}^3/\text{s}$ is the nominal flow rate and $h = 15 \text{ m}$ is the height of the fall.

Efficiencies η_{gen} and η_{hyd} are determined using charts according to the type of turbine

Choice

1. Available hydraulic power

$$P_{hyd}(t) = \rho g Q(t) H(t) [\text{W}] \quad (6)$$

2. Mechanical output of the turbine

Actions to take

Operating microgrids presents several technical and technological challenges: the stability of the microgrid must be guaranteed in islanded mode or when connected to the grid to avoid power supply/demand imbalances, and the storage elements and the grid must also be protected against power surges from various sources (load connection to the common power bus, variations in power produced by renewable energy storage systems, machine startup, etc.). To achieve this, it is necessary to adopt a control strategy that provides effective control of power flows and an energy management strategy to ensure continuous power supply to loads and reduce system costs.

Real water and electricity needs of residents

A study of living conditions in rural Benin, specifically regarding water and electricity needs, is conducted, supplemented by National Institute of Statistical Analysis data (INSAE, World Bank, etc.). The objective is to quantify the average demand for electricity (kWh/day) and drinking water (liters/day/inhabitant) prior to system sizing.

Determining the appropriate equipment for pumping, storing and purifying water.

Technical research is being conducted to identify the most suitable types of solar pumps, hydroelectric turbines, reservoirs, and water treatment systems. adapted to rural areas (cost, availability, easy maintenance). The technical characteristics of each piece of equipment are sized to select those that meet the technical and local constraints (electricity shortage, limited resources, simple maintenance).

Sizing of the main equipment (solar panels, pump, turbine, alternator and tank)

The sizing of solar panels is based on the average solar radiation of the region (in kWh/m²/j). Pump power sizing is calculated based on the head and daily flow rate. Sizing the water reservoir or water tower for electricity and domestic use.

Project costs studies and technical feasibility

A simplified economic analysis is conducted based on average equipment prices on the local or regional market. Installation and maintenance costs, as well as component lifespan, are evaluated to assess the project's profitability and long-term viability. Technical feasibility is analyzed according to topography, available water sources, and the quality of local infrastructure.

It take into account:

- Of the level of user training,
- Of the availability of local technicians,
- And of the community's financial capacity for maintenance.

Le but est d'éviter l'abandon du système par manque de suivi ou d'expertise.

Water purification:

According to the International Atomic Energy Agency (IAEA) and IRENA, purifying 1 m³ of water requires on average about 1 kWh, especially in rural areas using simple methods such as filtration or chlorination. [3]

$$300 \text{ m}^3 \times 1 \text{ kWh} = 300 \text{ kWh}$$

Total need of day = 33,34 + 75,015 + 300 = 408,355 kWh / day

❖ Night:

Household room lighting: 3 x 10W LED bulbs per household providing 5 hours of light.

Night total need = 1 667 × (3 × 10 × 5) = 250,05 kWh/night so **250kWh/night**.

The use of LED bulbs for nighttime lighting is a recognized solution due to its low energy consumption and long lifespan, as confirmed by World Bank reports on domestic solar systems. [4]

Pumped hydro storage and electricity production: Pumped storage

Turbine

The energy produced over a 5-hour night period is the energy needed for lighting. This amount of energy must be supplied by the turbine.

Type de turbine

For a head of between 10 and 300 meters in a rural installation, the Francis turbine is recommended due to its efficiency, its adaptability, its cost and its efficiency of up to 90%.

Table 1. Size of Turbine

Designation	Formulas	Results	Units and observations
Water flow rate (Q)	$Q = \frac{P}{\eta \times \rho \times g \times H}$	0,1235	m ³ /s
Specific speed	$N_s = n \times \sqrt{P/H^{1,25}}$	70,8 ∈ [60;300]	Perfect for a medium-speed Francis turbine
Turbine diameter	$D = \frac{60 \times V_u}{\pi \times n}$	0,376	m

Table 2. Summary of Needs Estimates

Category	Detaill	Formula used	Result	Unit
Total population	Target population	Direct data	10.000	Residents
Average household size	National average according to INStaD	Direct data	6	People/household
Number of households	N = Z / W	10000/6	1 667	Household
Water requirement	Per person	30 liters / day / personn	300 000	Litres/day
	Total need	10 000 × 30	300	m ³ /day
Electricity requirement (day)	Energy for water purification	300m ³ × 1kWh	300	kWh/day
	Charging phones	1 667 × 2 × 10 Wh	33,34	kWh/day
	Torches charging	1 667 × 3 × 15 Wh	75,015	kWh/day
Total day	Phones + Torches + Purification	33,34 + 75,015 + 300	408,355	kWh/day
Electricity requirements (night)	LED lighting: 3 bulbs 10W × 5h	1 667 × 3 × 10 × 5	250	kWh/night

Average mechanical power (P)

$$P = \frac{\text{Energy}}{\text{Time}}$$

$$\text{Numerical Application: } P = \frac{250}{5} = 50 \text{ kW}$$

P = 50kW (Average mechanical power); $\eta = 0,75$ (Turbine efficiency); H = 55m (Net fall height)

The specific speed (dimensionless) ensures that the turbine type is well suited to the head and flow rate. For this, its value must be within the range [60; 300].n: The rotational speed in tr/min, for values n = 500 tr/min, $N_s = 23,6$; Too low for a Francis turbine, n = 1000 tr/min, $N_s = 47,2 \notin [60;300]$; slow for a Francis turbine; P: The average mechanical power in kW (50kW); H: La hauteur nette (55m)

For **n = 1500 tr/min**

V_u : Peripheral speed

$V_u = \varnothing \sqrt{2gH}$ où $\varnothing = 0,9$ (optimal hydraulic efficiency coefficient)

$$V_u = 0,9 \times \sqrt{2 \times 9,81 \times 55} = 29,56 \text{ m/s}$$

Number of rotor poles

$$P = \frac{c \times f}{n}$$

With:

c: The number of poles per pair

P_p : The number of poles; f: The frequency (50 Hz); n:

The rotational speed in tr/s

$$A.N: P_p = \frac{2 \times 50}{25}$$

$$P_p = 4 \text{ poles}$$

Alternator

Once the turbine transforms the water's potential energy into mechanical energy, an alternator is needed to convert this mechanical energy into usable electricity. The choice of alternator therefore depends on the mechanical power supplied by the turbine, the rotational speed, and the electrical frequency of the local grid.

Electrical power supplied by the alternator

Electrical Power

$$= \text{Alternator efficiency} \times \text{Mechanical Power}$$

Numerical Application: Electrical Power = $0,95 \times 50$

Electrical Power = 47,5kW ; That make
Electrical Power = 48kW

Torque to be transmitted to the alternator

$$C = \frac{\text{Mechanical Power}}{\omega} \text{ and } \omega = \frac{2\pi N}{60}$$

$$C = \frac{30P}{\pi N} \quad (7)$$

With: C: the torque to be transmitted to the alternator.

N: the turbine rotation frequency; P: the average mechanical power

Numerical Application:

$$C = \frac{30 \times 50000}{\pi \times 1500}$$

$$C = 318,30 \text{ N.m}$$

Nominal current (coupling with the turbine)

The alternator receives a mechanical power of 50kW at 1500rpm, which it converts into electricity.

$$I = \frac{P}{\sqrt{3}U.\cos\phi} \quad (8)$$

With: U: Output voltage (in three-phase 230/400 V)

$\cos\phi$: Power factor ($\cos\phi = 0,8$)

$$\text{AN: } I = \frac{50000}{\sqrt{3} \times 400 \times 0,8}$$

$$I = 90,21\text{A}$$

Alternator type choice

For our system:

- **Type:** Three-phase synchronous alternator
 - **Cooling:** À air naturel ou ventilé
 - **Assembly:** En ligne avec la turbine
 - **Estimated Efficiency:** 95 %
 - **IP Protection:** suitable for rural areas (IP55 minimum)
 - **Winding material:** copper for better performance
- Alternator synchronous speed

$$f = \frac{P_p \times n}{c}$$

With: c: The number of poles per pair; P_p The number of poles; f: Frequency; n: The rotational speed in tr/s

$$f = \frac{4 \times 25}{2}$$

$$f = 50\text{Hz}$$

Table 3. Summary of Francis Turbine and Alternator Characteristics

Parameters	Values
Turbine type	Francis
Mechanical power	50kW
Electrical Power	48kW
Flow	0,1235 m ³ /s
Fall height	55 m
Rotation speed	1500 tr/min
Specific speed	70,8 tr/min
Turbine efficiency	75%
Alternator efficiency	95%
Turbine diameter	0,376 m
Rated current	90,21 A
Output voltage	In three-phase 230 / 400 V
Number of poles	4
Alternator frequency	50Hz

Tank sizing

Tank volume

$$V = \frac{E}{\rho.g.H.\eta}$$

With: E: Energy to be produced by night; g: Gravitational acceleration ($g = 9,81\text{m}^2/\text{s}$); H: Net fall height; ρ : Water density; η : System efficiency

Numerical Application:

$$V = \frac{250 \times 3600000}{1000 \times 9,81 \times 55 \times 0,75}$$

$$V = 2224,07\text{m}^3$$

Pour des raisons de sécurité, ajoutons une marge de 20%.

$$V_{total} = 2224,07 + (0,2 \times 2224,07)$$

$$V_{total} = 2668,88\text{m}^3$$

Physical dimensions of the tank

We're starting with a vertical cylindrical shape

$$V = \pi \times R^2 \times h$$

$$R = \sqrt{\frac{V}{\pi \times h}}$$

For a height of 15 meters, we have:

$$R = \sqrt{\frac{2668,88}{\pi \times 15}}$$

$$R = 7,52\text{ m}; \text{ so, the diameter } D = 15,04\text{ m}$$

Choice of construction material for the cistern

To construct a cistern capable of storing over 2,668.88 m³ of water at a height of 55 meters, the material used must be strong, durable, and readily available in Benin, especially in rural areas. After analyzing the technical, economic, and environmental constraints, reinforced concrete was selected as the most suitable material.

Table 4. Summary of Cistern Characteristics

Elements	Values
Usable volume	2 224,07 m ³
Safety margin (20%)	444,814 m ³
Tank volume	2 668,88 m ³
Internal height of the cistern	15 m
Drop height (structure)	55 m
Diameter of the tank	15,04 m
building material	Reinforced concrete

Pump Sizing and Pump Selection

The pump is selected using the pump classification based on nominal flow rate and head shown in the following figure. For a nominal flow rate $Q = 0.03\text{ m}^3/\text{s} = 30\text{ l/s}$ and a gross/net head $h = 15\text{ m}$, the only option is to use a centrifugal volute pump. It can also be seen from the following figure that the pump's operating point (indicating the flow rate it can deliver for a given head) is less than 5 kW.

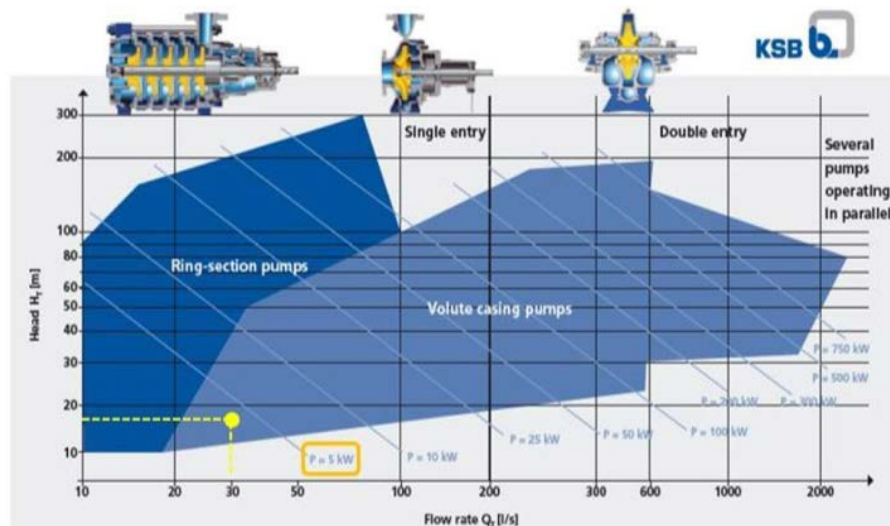


Figure 10. Pump types according to nominal flow rate and net head

Pump flow rate required

$$\text{Flow rate } Q = \frac{\text{WaterVolume}}{\text{Pumpingtime}}$$

$$\text{Flow rate } Q = \frac{2668,88}{3600 \times 7}$$

$$\text{Flow rate } Q = 0,1059 \text{ m}^3/\text{s}$$

Hydraulic Power (P_h)

$$P_h = \rho \cdot g \cdot Q \cdot \text{HMT}$$

With: HMT: Total Manometric Head

HMT

= Drilling Depth

+Height net between the ground and the basis of the cistern

+Height of the cistern

$$\text{HMT} = 51 + 55 + 15$$

$$\text{HMT} = 121 \text{ m}$$

$$P_h = 1000 \times 9,81 \times 0,1059 \times 121$$

$$P_h = 125704,359 \text{ W} = 125,704 \text{ kW}$$

Electric Power consumed (P_e)

$$P_e = \frac{P_h}{\eta}$$

$$P_e = \frac{125,704}{0,75}$$

$$P_e = 167,60 \text{ kW}$$

Required Energy over 7 hours

$$E = P_e \times t$$

$$E = 167,60 \times 7$$

$$E = 1173,23 \text{ kWh}$$

Inlet diameter (suction)

$$D = \sqrt{\frac{4 \times Q}{\pi \times V}}$$

$V = 2 \text{ m/s}$: the average suction speed of a **Multistage centrifugal pump**

$$D = \sqrt{\frac{4 \times 0,1059}{\pi \times 2}}$$

$$D = 0,259 \text{ m, soit } D = 259 \text{ mm}$$

Outlet diameter (Repression)

$$D = \sqrt{\frac{4 \times Q}{\pi \times V}}$$

$V = 3 \text{ m/s}$: the average discharge velocity of a **Multistage centrifugal pump**

$$\text{Numerical Application: } D = \sqrt{\frac{4 \times 0,1059}{\pi \times 3}}$$

$$D = 0,212 \text{ m, that is } D = 212 \text{ mm}$$

Pump Type

The system requires a capable of working with high discharge heads and high flow rates and high flow rates. The most suitable type in this case is the submersible **multistage centrifugal pump**.

Table 5. Summary of pump characteristics

Elements	Values
Pump Type	Multi stage centrifugal pump
Required rate flow	0,1059 m³/s
Efficiency	75%
Total Manometric Head	121 m
Hydraulic Power	125,704 kW
Electric Power absorbed	167,60 kW
Required Energy on 7 hours	1 173,23 kWh
Inlet diameter	259 mm
Outlet diameter	212 mm

Sizing Solar panels

Total required Energy

Potential Energy to be supplied to the pu: $E = 1 173,23 \text{ kWh}$

Daily electricity requirement: Daily requirement = 408,355 kWh

$$\text{Required Energy} = 1 173,23 + 408,355$$

$$\text{Required Energy} = 1 581,585 \text{ kWh}$$

Like Any system, there are losses (in cables, inverters, due to dust, etc.). We consider a margin of **25 %**, to cover them then we have:

$$\text{Total required Energy} = 1 581,585 + (0.25 \times 1 581,585)$$

$$\text{Total required Energy} = 1 976,981 \text{ kWh}$$

Real energy to be produced by the panels (E_p)

$$E_p = \frac{\text{Total required Energy}}{\eta_p}$$

With: η_p : Efficiency of the entire regulator, cable, and loss system, $\eta_p = 80\%$

Numerical Application:

$$E_p = \frac{1976,981}{0,8}$$

$$E_p = 2471,226 \text{ kWh}$$

Peak Power of the panels

$$P_c = \frac{E_p}{\text{Fullsun hour}}$$

Numerical Application:

$$P_c = \frac{2471,226}{5,5}$$

$$P_c = 449,313 \text{ kWc soit } P_c = 450 \text{ kWc}$$

Panels type

For this solar installation, monocrystalline panels were chosen due to their excellent performance in Benin's climatic conditions. These panels offer high efficiency, generally exceeding 18%, which maximizes the energy production even with available reduced surface area. Furthermore, their efficiency is less affected by the high temperatures common in many parts of the country. Thanks to their durability and long-term stability, monocrystalline panels represent a reliable and high-performance solution for optimized solar energy production.

Solar panels choice

We choose standard panel:

Unit Power: 450Wc; Average size: 1,95 m² (approximately 2m × 1m) Thickness: ~35mm

$$N_p = \frac{\text{Total Peak Power}}{P_c}$$

With: N_p : Number of solar panels; P_c : The peak power of each panel

$$N_p = \frac{450}{0,45}$$

$$N_p = 1\,000 \text{ panels}$$

The choice fell on a SunPowerMaxeon 450Wp monocrystalline solar panel, IBC type, for its high efficiency (22.6%) and reliability. Its standard dimensions are 2000 × 1000 × 35 mm, allowing for compact and efficient installation.

Table 6. Summary of Solar Panel Characteristics

Elements	Values
Total required Energy (with losses)	1 976,981 kWh
Peak power of each panel	450Wc
Panel type	Monocrystalline
Number of panels	1 000
Panel models	SunPower Maxeon
Orientation	Southward
Tilt	15°
Length	2 m
Width	1 m
Epaisseur	35mm

Orientation and tilt

To capture maximum sunlight, the panels will be oriented towards the south with an inclination of approximately 10 to 15°, which corresponds well to the latitude of Benin.

Sizing the Drinking Water Treatment System

Within the framework of this project to design an integrated solar and hydroelectric power generation and distribution system, the supply of drinking water is a crucial component. Water is pumped from a borehole using solar energy, stored in a tank at a height, and then released by gravity to power a turbine. Immediately after passing through the turbine, some of this water is redirected to a treatment plant before being distributed to the population.

Daily Consumption. According to WHO recommendations, a person should have at least 30 liters of drinking water per day. [5]

Total need = Number of inhabitants × water requirement per person

Total needs = 10 000 habitants × 30 liters

Total needs = 300 000 liters/day

Total needs = 300m³/jour

But to power the turbine and meet all the needs, pumping and storage are required. 2668,88 m³/water day

3.5. Implications of the Results

Several positive implications can be noted.

The energy stored as hydropower can produce approximately 250 kWh over 5 hours at night, which covers domestic lighting as well as essential public needs (street lighting, health centers, etc.).

3.5.1. Continuous Access to Drinking Water

The system can pump and treat 2668.88 m³ of water per day, well beyond the average daily needs of the population, with a margin for unforeseen events or periods of high demand.

3.5.2. Sustainable and Self-reliant Approach

Using local resources (sun and groundwater) avoids dependence on external sources of fuel or energy.

3.5.3. Low Environmental Impact

Unlike thermal generators, this system does not produce greenhouse gases or noise pollution.

Reservations and limitations to consider:

Despite these positive results, it is important to remain cautious regarding certain points:

Sunlight dependence: Even though the site benefits from an average of 5.5 hours of full sun per day, prolonged periods of cloud cover or rain could reduce the performance of the solar system.

High initial cost: Installing all the equipment (solar panels, pump, turbine, tank, treatment system) requires a significant initial investment.

3.6. Estimation of the System Component Costs

Cost estimation is an essential step in the project's

feasibility study, as it allows for determining the actual financial requirements for implementing the system. In the context of our project to provide drinking water and electricity to a rural population of 10,000 inhabitants, it is crucial to identify and assess the price of the various necessary equipment. The approach adopted here is based on the technical choices we validated during the sizing process: 450 Wp photovoltaic panels, submersible solar pump suited to the required flow rate, reinforced concrete tank, hydraulic turbine, water purification system, etc. To ensure a realistic and up-to-date evaluation, prices were checked on well-known platforms for technical equipment sales, notably Amazon and Alibaba. These sources provide a representative view of costs on an international scale, allowing for a coherent estimate, even though adjustments may be necessary depending on local conditions or purchasing policies.

The main expense items are: solar panels, the submersible pump, the hydraulic turbine, the storage tank, the purification system, as well as electrical and control accessories.

All components were chosen for their resistance to climate variations and ease of maintenance, a crucial factor for an isolated village.

3.6.1. Annual Maintenance Cost

The annual maintenance and operation cost ranges between USD 52,000 and USD 93,000, depending on the level of service, the frequency of filter replacement, and staff salaries. These costs are reasonable for infrastructure of this scale, and can be supported by grant programs, NGOs, or public-private partnerships.

3.6.2. Return on Investment (ROI)

The return on investment (ROI) analysis allows assessing the economic profitability of the "Design of an Integrated Solar and Hydraulic Energy Production and Distribution System" project intended for a rural municipality of 10,000 inhabitants. This analysis is based on investment costs, potential annual revenues, operating costs, and the payback period of the initial capital.

Table 7. Summary of the Estimated Cost of Components

Component	Quantity	Unit Cost (USD)	Total (USD)
Solar panels	1000	120	120 000
Solar Pump	1 kit	25 000	25 000
Turbine + Generator	1 unité	15 000	15 000
Reinforced concrete tank	2669 m ³	200/m ³	537 776
Water treatment system	1 unité	35 000	35 000
Solar support structure	1 000	15	15 000
Labor + installation	-	-	30 000
Training + local management	-	-	5 000
Distribution network	-	-	50 000
Total (excl. tax)	-	-	827 776

Table 8. Basic data

Serial number	Description	Cost	Unit
1	Capital Expenditure (CAPEX)	828 776	USD
2	Daily energy production ($E_{\text{day} + \text{night}}$)	658,355	kWh/day
3	Annual energy production (E_{annual})	240299,575	kWh/year
4	Electricity selling price per kWh	0,146 [29]	USD/kWh
5	Annual electricity revenue (R_{elec})	35083,654	USD/year
6	Estimated volume of drinking water sold per day $V_{\text{water}} / \text{day}$	300	m ³
7	Estimated volume of drinking water sold per year $V_{\text{water}} / \text{year}$	109500	m ³
8	Estimated selling price of water	0,55 [29]	USD/m ³
9	Annual water revenue (R_{water})	60225	USD/year
10	Total annual revenue ($R_{\text{Total}} = R_{\text{water}} + R_{\text{elec}}$)	95308,654	USD/year

Table 9. Estimate

Serial number	Description	Cost	Unit
1	Annual Operating Expenditure (OPEX=2%*CAPEX)	16575,52	USD/year
2	Annual net profit ($B_{\text{Net}} = R_{\text{Total}} - \text{OPEX}$)	78733,134	USD/year
3	Investment Payback Period ($\text{Payback} = \frac{\text{CAPEX}}{B_{\text{Net}}}$) [30]	10,52	year
4	Rate of return (simple) $\text{ROI} = \left(\frac{B_{\text{Net}}}{\text{CAPEX}} \right) * 100$ [30]	9,50	%

3.6.3. Interpretation

The results show that the system is cost-effective in the long term:

- It recoups the initial investment in 10.52 years, well

before the end of the equipment's useful life (estimated at 20–25 years). [31]

- It has an annual ROI of 9.50%, which is reasonable for a project with a strong social component.
- It does not take into account potential subsidies or

indirect savings (public health, education, local development), which could improve the actual ROI.

4. Conclusion

The results obtained through the design phase show that the system effectively meets the two essential needs of the 10,000 inhabitants: access to electricity and drinking water. Thanks to the combination of a solar power plant and a pumped-storage hydroelectricity system (PSH), the village has an autonomous, renewable, and environmentally friendly solution. Faced with the persistent challenges of access to electricity and drinking water in rural areas of Benin, this study proposed an integrated and sustainable solution: the Pumped Storage Power Plant (PSPP). Through a methodical approach, we analyzed the actual needs of a community of 10,000 inhabitants, sized the necessary equipment (solar panels, pump, tank, turbine), evaluated the technical and economic aspects, and then proposed a realistic management model adapted to local realities. This proposed methodological approach links applied research, training, and sustainable development. By combining solar photovoltaic energy and gravity-fed hydro storage, this study offers an innovative and replicable solution for rural African areas with limited access to energy. The results of this pilot project will serve as a basis for larger-scale applications and the establishment of an African research network on hybrid PV-PHV systems. The results obtained show that a well-designed PHV system can guarantee both a regular electricity supply, particularly during nighttime hours, and sufficient daily drinking water production to meet the needs of the entire target population are essential. This solution is distinguished by its ability to store solar energy in the form of water, to operate autonomously without fuel, and to minimize its environmental impact. Other studies confirm the results and show that solar PV with pumped-storage hydropower (PSH) remains the optimal system configuration for both rural and urban areas, even when the construction costs of lower and upper reservoirs are considered [14].

This system thus forms a complete energy chain, from production to distribution, relying on local renewable resources, requiring no fuel, and with a low environmental impact. It constitutes a viable and replicable alternative to the challenges of rural electrification and access to drinking water, while promoting local development and community self-sufficiency. A realistic, functional, and sustainable system meets the essential needs of rural communities while utilizing local resources and abundant but underutilized solar energy. This project therefore demonstrates the feasibility and relevance of such a system for sustainably improving the living conditions of rural populations, while leveraging local resources. It also opens interesting prospects for replication. This solution has been implemented in other localities facing the same challenges. However, its success depends heavily on the quality of implementation, ongoing maintenance, and the active involvement of the beneficiary communities. Further studies are needed to systematically compare PV-STEP vs. PV-batteries (Li-ion) and to methodically compare pumped hydro storage, electric batteries on the

one hand, and green hydrogen on the other.

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