

Modeling the Overall Efficiency of a PV + Pumping + Turbine System for the Electrification of a Medium-Sized City in a Mountainous Region of West Africa: Case Study of the City of Mamou in the Republic of Guinea

Abdou Karim Farota*, Moussa Ibra Ngom, Kadé Baïlo Bah

Laboratoire de Recherche en Sciences Appliquées (LaReSA), Institut Supérieur de Technologie (IST) de Mamou, Mamou, Guinea
Email: *abdoukfarota@netscape.net

How to cite this paper: Farota, A.K., Ngom, M.I. and Bah, K.B. (2026) Modeling the Overall Efficiency of a PV + Pumping + Turbine System for the Electrification of a Medium-Sized City in a Mountainous Region of West Africa: Case Study of the City of Mamou in the Republic of Guinea. *Energy and Power Engineering*, 18, 714-734. <https://doi.org/10.4236/epe.2026.1810033>

Received: June 26, 2026

Accepted: October 25, 2026

Published: October 28, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

West Africa faces a major structural energy deficit that hinders its economic and social development. According to the World Bank, the electrification rate in sub-Saharan Africa averages no more than 48%, with considerable disparities between urban areas (over 80%) and rural areas (less than 25%). In Guinea, the situation is particularly worrying: the national electrification rate is around 35%, and falls to less than 10% in rural and peri-urban areas. The interconnected national grid, managed by Electricité de Guinée (EDG), suffers from frequent power outages and limited reliability, with technical and non-technical losses that can reach 40% of the energy produced. Faced with these challenges, decentralized solutions based on renewable energies represent a promising alternative. The abundance of solar resources in the region (5 to 6 kWh/m²/day of global horizontal irradiance) offers considerable potential for the deployment of photovoltaic systems. However, the intermittent nature of solar production necessitates reliable, high-capacity storage systems to ensure a continuous power supply. Electrochemical batteries, while widely used for small-scale installations, have significant limitations in terms of lifespan, cost, and environmental impact when it comes to storing large quantities of energy on the scale of a village or small town. Pumped hydro storage (PHS), also known as a “hydroelectric battery”, is a proven large-scale energy storage solution capable of storing energy as gravitational potential energy. Micro-PHS plants, adapted for small power outputs (from a few tens to a few hundred kilowatts), offer a technically viable and economically competitive alternative for electri-

fying isolated areas with favorable terrain.

Keywords

PV, Micro-PHS, Micro-STEP, LPSP, LCOE, Guinea

1. Introduction and Context

1.1. Energy Context in West Africa

West Africa faces a major structural energy deficit that hinders its economic and social development. According to the World Bank, the electrification rate in sub-Saharan Africa averages no more than 48%, with considerable disparities between urban areas (over 80%) and rural areas (less than 25%). In Guinea, the situation is particularly worrying: the national electrification rate is around 35%, and falls to less than 10% in rural and peri-urban areas. The interconnected national grid, managed by Electricité de Guinée (EDG), suffers from frequent power outages and limited reliability, with technical and non-technical losses that can reach 40% of the energy produced.

Faced with these challenges, decentralized solutions based on renewable energies represent a promising alternative. The abundance of solar resources in the region (5 to 6 kWh/m²/day of global horizontal irradiance) offers considerable potential for the deployment of photovoltaic systems. However, the intermittent nature of solar production necessitates reliable, high-capacity storage systems to ensure a continuous power supply. Electrochemical batteries, while widely used for small-scale installations, have significant limitations in terms of lifespan, cost, and environmental impact when it comes to storing large quantities of energy on the scale of a village or small town.

Pumped hydro storage (PHS), also known as a “hydroelectric battery”, is a proven large-scale energy storage solution capable of storing energy as gravitational potential energy. Micro-PHS plants, adapted for small power outputs (from a few tens to a few hundred kilowatts), offer a technically viable and economically competitive alternative for electrifying isolated areas with favorable terrain.

1.2. The Problem of Electrification in Mountainous Areas

The mountainous areas of West Africa, such as the Mamou region in Guinea, present specific characteristics that make electrification particularly complex. The rugged terrain simultaneously offers advantages and constraints: on the one hand, the natural elevation changes favor the installation of pump-turbine systems with low civil engineering costs, and on the other hand, the topography makes it difficult to extend the conventional electrical grid and increases the construction costs of linear infrastructure (transmission lines, access roads).

Water management in mountainous areas is also a major challenge. Seasonal variations in rainfall, with an intense rainy season (June to October) followed by

a long dry season (November to May), impose constraints on the availability of water resources needed to operate a hydroelectric storage system. The system design must therefore incorporate optimal reservoir management to guarantee a continuous electricity supply throughout the year, even during the driest months. These specific characteristics necessitate a detailed model of the system's overall efficiency, taking into account all components of the energy chain and their interactions.

1.3. Case Study Presentation: Mamou, Guinea

The city of Mamou, capital of the Mamou region, is located in central Guinea, at the geographic coordinates 10.37 degrees North latitude and 12.09 degrees West longitude. With an estimated population of approximately 5000 inhabitants in 2024, providing a scalable pilot model for peri-urban electrification in the Mamou region in the mountainous region of Guinea (**Table 1**). The pilot model is situated at an average altitude of 820 meters, in a region characterized by plateaus, valleys, and hills offering significant elevation changes of 50 to 150 meters over short distances, which is particularly favorable for the installation of micro-wastewater treatment plants.

Based on a 5000-person settlement in Guinea (assuming an average household size of 6, yielding ~833 connections), the demand profile shifts from urban to peri-urban characteristics:

- Residential Demand: 833 households. Assuming a mix of MTP Tier 2 and Tier 3 consumers (lighting, phone charging, televisions, and fans; rare AC use).
 - *Average*: 1.8 kWh/household/day.
 - *Total Residential*: 1500 kWh/day.
- Commercial Demand: ~30 small enterprises (shops, bars, phone-charging kiosks) with basic refrigeration and lighting.
 - *Total Commercial*: 90 kWh/day.
- Productive Use of Energy (PUE): 1 grain mill (10 kWh/day) and 1 small cold-room for fisheries/agriculture (15 kWh/day).
 - *Total PUE*: 25 kWh/day.
- Public Services: 1 health center, 2 schools, 1 mosque, and 20 streetlights.
 - *Total Public*: 20 kWh/day.

1.3.1. Hourly Simulation over 8760 Hours and Climate Data Preprocessing

The hourly load curve was cross-referenced with meteorological data to generate a demand simulation covering the 8760 hours of a typical year. The solar irradiance profiles (global irradiance on an inclined plane) and ambient temperature profiles used were sourced directly from the PVGIS (Photovoltaic Geographical Information System) database (via the TMY—Typical Meteorological Year—tool). These hourly time series were not synthesized from monthly averages but represent realistic datasets generated by PVGIS, selected to reflect the most probable weather patterns for the Mamou region.

The preprocessing of these input data relied on the following key assumptions:

- **Geometric parameters:** Irradiance was calculated for an optimal inclined plane set at a 12° tilt (corresponding to Mamou's latitude of approximately 10.37° N) and facing due south (0° azimuth) to maximize solar capture throughout the year.
- **Data cleaning:** Although PVGIS provides consistent TMY data, a validation filter was applied to remove potential outliers (such as non-zero nighttime irradiance values or inconsistent temperature jumps between consecutive hours).
- **Time synchronization:** PVGIS timestamps (typically in UTC+0 format) were strictly aligned with Guinea's local time zone (UTC+0)—without daylight saving adjustments—to ensure precise alignment between the user load curve (which depends on local time) and theoretical photovoltaic generation.

Region of Mamou has a humid tropical mountain climate (**Table 1**), with an average annual temperature of 25.3 degrees Celsius and approximately 1800 mm of annual rainfall. The average global horizontal solar irradiance is 5.1 kWh/m²/day, peaking at 5.9 kWh/m²/day in March, at the height of the dry season. The city has several permanent and seasonal streams in its immediate vicinity, providing the necessary water resources for initial filling and compensating for evaporation losses in the storage system's reservoirs.

Table 1. Geographic and climatic parameters of the pilot model.

Parameter	Value	Unit
Latitude/Longitude	10.37 N/12.09 O	degrees
Average Altitude	820	m
Population (2024)	~5000	residents
Average Temperature	25.3	°C
Annual Precipitation	1800	mm/year
Average GHI	5.1	kWh/m ² /day
Height difference available	50 - 150	m

1.3.2. Hydrological Feasibility and Annual Water Balance

The feasibility of the storage or hydroelectric generation component relies on a concise annual water balance that weighs natural inflows against unavoidable losses and the withdrawals required for system operation. The initial filling of the storage basin is scheduled for the end of the rainy season (October-November). It is achieved through a one-time withdrawal from the nearby watercourse, taking advantage of the high flood flows during this period to avoid impacting low-flow conditions later on.

The annual water balance (calculated based on a one-hectare water body) breaks down as follows:

- **Precipitation input:** The Mamou region, located in the upper Niger basin, receives approximately 1600 mm of rainfall per year. Across the basin's surface

area, this represents a gross inflow volume of 16,000 m³/year.

- Evaporation losses: Driven by the tropical climate and Harmattan winds during the dry season, evaporation is the primary source of loss. Estimated at around 1400 mm/year (based on typical data for the area), it results in a loss of 14,000 m³/year.
- Infiltration losses: Given the region's lateritic soils, an infiltration rate of 500 mm/year is assumed (presuming minor waterproofing measures are applied to the basin floor), representing a loss of 5000 m³/year.

Considering only these factors, the basin's natural water balance shows a deficit of 3000 m³/year (16,000 - 14,000 - 5000). This structural deficit is compounded by the water demand required for system operations (e.g., turbine operation or pumping)—estimated at 50,000 m³/year—which is concentrated during the dry season (November to May).

Consequently, a seasonal withdrawal volume of 53,000 m³/year must be drawn from the nearby watercourse. This withdrawal is strictly scheduled for the rainy season and the transition period, when the streamflow significantly exceeds the required ecological flow. This strategy ensures the long-term viability of the Mamou reservoir without compromising downstream water uses during periods of severe low flow.

1.4. Goals of the Report

This report aims to develop a comprehensive model of the overall efficiency of a hybrid system coupling a photovoltaic array, a pumping unit, and a turbine unit for the electrification of a medium-sized city in a mountainous region of West Africa. More specifically, the objectives are: first, to establish mathematical models for each component of the system (PV, pump, turbine, reservoirs); second, to evaluate the overall efficiency of the system in operation over an annual cycle; third, to analyze the sensitivity of the efficiency to the main design parameters (head, reservoir volumes, component power); and fourth, to propose an optimal sizing for the specific case of the city of Mamou in Guinea, integrating local constraints.

Particle Swarm Optimization (PSO) Configuration

The sizing of the hybrid system is formulated as a Mixed-Integer Nonlinear Programming (MINLP) problem, solved using the Particle Swarm Optimization (PSO) algorithm. The model configuration is structured as follows:

1) Decision variables

The decision vector $\mathbf{X} = [\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3]$ consists of the three key parameters to be sized:

- $\mathbf{x}_1$: Number of photovoltaic panels (discrete variable).
- $\mathbf{x}_2$: Usable volume of the hydrological storage basin in cubic meters (continuous variable).
- $\mathbf{x}_3$: Rated power of the inverter/converter in kW (continuous variable).

2) Variable bounds (Search space)

To avoid physically unfeasible solutions, each variable is constrained within a

range defined by the site limits:

- $x_1 \in [0, N_{\max}]$, where $N_{\max}$ corresponds to the maximum exploitable area available in Mamou.
- $x_2 \in [V_{\min}, V_{\max}]$, where $V_{\min}$ is the dead volume required for sedimentation and $V_{\max}$ is the maximum capacity permitted by local topography.
- $x_3 \in [P_{\text{dem,peak}}, P_{\text{grid_limit}}]$, bounded by the city's peak load and the maximum injection capacity permitted by grid standards.

3) Objective function

The objective is to minimize the Levelized Cost of Energy (LCOE), expressed in USD/kWh. The objective function $f(X)$ aggregates:

- The initial investment costs (CAPEX) for components x_1 , x_2 , and x_3 .
- The operating and maintenance costs (OPEX), discounted over the project's lifespan (e.g., 25 years).
- Replacement costs (standard inverter exchange in year 10).
- The total of these costs is divided by the total energy actually consumed by the city over the project's lifespan, as determined by the 8760-hour simulation.

4) Constraint management

As PSO is inherently an unconstrained algorithm, the handling of the system's physical and performance limits is managed via a quadratic penalty function. If a particle (a given configuration) violates any of the following constraints, a massive financial penalty is added to its LCOE, rendering it uncompetitive:

- Reliability constraint: The Loss of Power Supply Probability (LPSP), calculated over the 8760 hours, must be strictly less than or equal to a critical threshold (e.g., $LPSP \leq 0.01$, *i.e.*, a 1% failure rate).
- Hydrological constraint: The volume of water in the reservoir at any given hour t must never fall below the dead storage volume ($V(t) \geq V_{\min}$).

5) Convergence criterion and stability of the solution

The PSO algorithm is configured with decreasing inertia to favor global exploration at the beginning and local exploitation at the end. The solution is declared stable and converged based on a dual stopping criterion:

- Stagnation criterion (primary): The algorithm terminates if the objective function value of the global best solution (gbest) does not improve beyond a tolerance threshold ϵ (e.g., 10^{-5} USD/kWh) over a set number of consecutive iterations (e.g., 50 iterations).
- Safety criterion (secondary): A maximum number of iterations (e.g., 500) is imposed to ensure the calculation terminates even in the event of a complex search space, although, in practice, convergence via stagnation is reached well before this limit.

2. State of the Art of Solar Micro-Wastewater Treatment Plants

2.1. Principle of Pumped-Storage Hydroelectricity

Pumped hydro storage (PHS) is a large-scale electrical energy storage technology

based on the principle of gravitational potential energy. The system consists of two reservoirs located at different altitudes, connected by a penstock. When the available electrical energy exceeds demand (PV production surplus), water is pumped from the lower reservoir to the upper reservoir, converting the electrical energy into potential energy. When demand exceeds production (PV deficit), water is released from the upper reservoir through a turbine that drives an electric generator, releasing the stored energy as electricity. The energy stored in such a system is directly proportional to the mass of water displaced, the height of the fall, and the acceleration due to gravity, according to the following fundamental relationship [1] (Equation (1)):

$$E = \rho * g * V * H = \rho * g * V * (h_{\text{SUP}} - h_{\text{inf}}) \quad (1)$$

where ρ represents the density of water (1000 kg/m³), g the acceleration due to gravity (9.81 m/s²), V the volume of water stored in the upper reservoir (m³), and H the gross head (m). For a head of 80 meters and a volume of 5000 m³, the theoretically stored potential energy is approximately 3924 MJ, or about 1090 kWh. Large conventional pumped storage plants, with capacities ranging from 100 MW to several GW, represent more than 94% of the world's stationary storage capacity, with cycle efficiencies ranging from 70% to 85%.

2.2. Micro-STEP: Concepts and Scales

The concept of micro-PHS (or micro-pumped hydro storage) refers to small-scale pumped-storage hydroelectric systems, typically between 10 kW and 10 MW, suitable for decentralized applications and isolated mini-grids. Unlike large conventional pumped hydro storage plants that require massive investments (several hundred million euros) and large-scale, dedicated sites, micro-PHS utilize modest natural elevation differences (20 to 200 meters) and reduced storage volumes (500 to 50,000 m³), making them suitable for rural and peri-urban electrification.

Micro-wastewater treatment plants (MWTPs) are categorized into several configurations: the two-reservoir system (conventional), the single-reservoir system with a stream (open-loop), and the underground system (abandoned mine pumped storage, or PHS). For the mountainous regions of West Africa, the two-reservoir configuration is the most suitable because it does not depend on a minimum stream flow and minimizes environmental impact. The key components of a MWTP include: a centrifugal or vertical-axis pump (from 20 to 500 kW), a Francis or Pelton turbine depending on the head, a synchronous or asynchronous generator, control valves, and a supervisory control and data acquisition (SCADA) system for the automatic management of storage and discharge.

2.3. Experiences in Africa and around the World

Several micro-pumped pumped storage (PSP) pilot projects have been completed or are under development worldwide, demonstrating the technical viability of this technology for isolated sites. In Switzerland, the Gondo project (Valais) has

demonstrated cycle efficiencies of 72% with a capacity of 0.9 MW and a head of 267 meters. In Austria, the Gerlos plant (500 kW) has been operating for several years with an overall efficiency of 74%. In Spain, the El Hierro project in the Canary Islands combines an 11.3 MW wind farm with an 11.3 MW PSP and a 380,000 m³ reservoir, supplying up to 80% of the island's electricity.

In Africa, projects are still in their early stages but show promise. The Bokhol project in Senegal (2019) combined a 20 MWp solar power plant with 18 MWh battery storage. Morocco is deploying several pumped storage hydroelectric (PSH) sites in the Atlas Mountains, such as the Afourer complex (464 MW), although these are large-scale. In East Africa, the Kidatu project in Tanzania utilizes a topographic profile similar to that of Mamou. However, to our knowledge, there is still no detailed study specifically modeling the overall efficiency of a PV system coupled with a micro-PSH for the electrification of a medium-sized city in a mountainous area of West Africa, which is the originality of this report.

3. Data from the Mamou Site

3.1. Geographic and Topographic Data

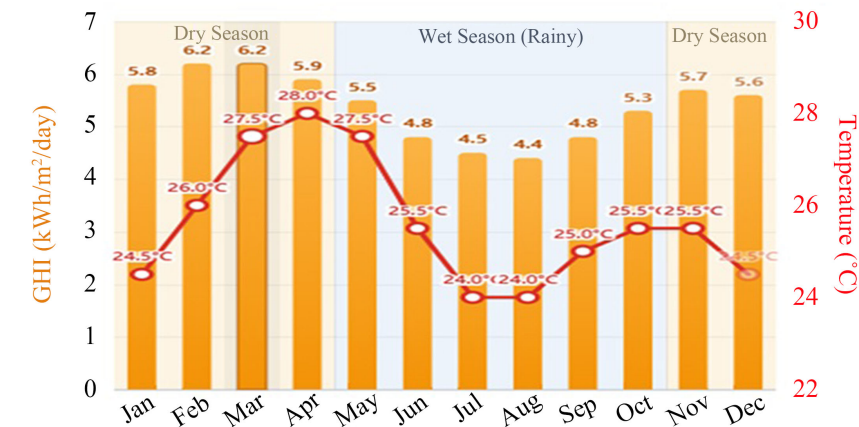
The Mamou region is characterized by a mountainous plateau-type relief belonging to the Guinean Dorsal range, with altitudes varying between 700 and 1100 meters. Topographical investigations have identified a potential site located approximately 5 km northeast of the city center, with a natural elevation difference of 80 meters between two plateaus separated by a slope of 15% to 25%. This site offers several advantages: proximity to the target village, the availability of two natural basins that could be developed into reservoirs, access to a surface water resource (a seasonal stream 500 meters from the lower site), and low geological risks (no active seismic zone, stable bedrock of the granite type).

The upper and lower reservoirs are sized with a usable volume of 5000 m³ each, representing a theoretical potential energy of 1090 kWh per complete emptying cycle. The surface area of the upper reservoir is estimated at 1500 m² (approximately 40 m × 38 m), and that of the lower reservoir at 2000 m² (approximately 50 m × 40 m). The usable depth is 3.3 meters for the upper reservoir and 2.5 meters for the lower reservoir, with a free head of 0.5 meters. The annual evaporation volume is estimated at 3500 m³/year for the upper reservoir and 4200 m³/year for the lower reservoir, representing an energy loss of approximately 1.5% per year.

3.2. Solar Resource

Solar irradiance data were obtained from the European Commission's PVGIS database and from *in-situ* measurements carried out by the Guinean National Energy Directorate. The average annual global horizontal solar irradiance (GHI) is 5.1 kWh/m²/day, with marked seasonal variability: the dry season (November to May) shows high values of 5.1 to 5.9 kWh/m²/day, while the rainy season (June to October) records lower values of 4.2 to 5.3 kWh/m²/day due to cloud cover associated with rainfall (Figure 1). The average monthly ambient temperature varies

between 23 and 27 degrees Celsius, with a peak in April (27.5 degrees Celsius) and a minimum in August (23.5 degrees Celsius) (**Table 2**).



Annual Avg. GHI: **5.4 kWh/m²/day**. Peak GHI: **6.2 kWh/m²/day (Feb)**. Lowest GHI: **4.4 kWh/m²/day (Aug)**. Annual Avg. Temp: 25.6°C. Temp Range: **24.0°C - 28.0°C**.

Figure 1. Global horizontal solar irradiance (GHI) and average monthly temperatures in Mamou.

Table 2. Monthly climate data for Mamou.

Month	GHI (kWh/m²/J)	Average T (°C)	Humidite (%)	Rainfall (mm)
Jan	5.8	24.5	35	2
Feb	6.2	26.0	32	5
Mars	6.2	27.5	38	25
April	5.9	28.0	50	90
May	5.5	27.5	65	180
Jun	4.8	25.5	78	280
July	4.5	24.0	85	350
Aug	4.4	24.0	88	380
Sept	4.8	25.0	82	300
Oct	5.3	25.5	72	150
Nov	5.7	25.5	55	30
Dec	5.6	24.5	38	8

3.3. Water Resources

The availability of water resources is a determining factor for the viability of the hydraulic storage system. The selected site benefits from its proximity to a seasonal stream, the “Bafing de Mamou”, whose catchment area covers approximately 120 km². The average annual flow of this stream is estimated at 1.2 m³/s, with surface runoff concentrated during the rainy season (June to October, representing 85% of the total volume). The system’s annual water deficit, primarily due to evaporation (estimated at 1600 mm/year for the region) and losses through in-

filtration (estimated at 5% of the annual cycle volume), is compensated by direct rainfall on the reservoir surfaces and by controlled withdrawals from the nearby stream during the wet season. Hydraulic modeling shows that the system can operate in a closed cycle (without continuous external input) during the dry season thanks to a sufficient reserve volume in the reservoirs.

3.4. Electricity Consumption Profile

The electricity consumption of the city of Mamou was estimated based on surveys conducted with households and businesses, and on the average per capita consumption in rural and peri-urban Guinea (approximately 120 kWh/year per capita, excluding productive uses).

This study focuses on electrifying a targeted peri-urban settlement within the Mamou administrative district, serving a fixed population of 5000 inhabitants. All demand projections, system sizing, and financial analyses are strictly scoped to this 5000-person catchment area, excluding the broader 130,000 inhabitants of the greater Mamou urban center.

The daily load profile is typical of semi-urban African areas, with a morning peak from 6:00 to 9:00 AM (lighting, meal preparation) and an evening peak from 6:00 to 10:00 PM (lighting, televisions, mobile phone charging). Baseline demand between these two peaks remains relatively low (approximately 30% of the peak). This profile is particularly suited to PV-STEP coupling, as the surplus of solar production in the middle of the day (10 am to 4 pm) corresponds to the optimal window for pumping.

4. Mathematical Modeling of the System

4.1. Photovoltaic Production Model

The photovoltaic field's output is modeled in three successive steps: calculation of the irradiance in the plane of the panel (POA), conversion to DC power using the single-diode model, and conversion to AC power by the inverter. The irradiance in the plane of the panel, inclined at the optimal angle (10 degrees for Mamou, *i.e.*, the latitude), is calculated from the global horizontal irradiance (GHI) using the Hay-Davies model [2]-[4] (Equation (2)).

$$G_{\text{POA}} = G_{bn} * R_b + G_{\text{diff}} * (1 + \cos(\beta)) / 2 + \rho_s * G(1 - \cos(\beta)) / 2 \quad (2)$$

where G_{bn} is the normal direct irradiance, R_b the ratio of the direct irradiance on an inclined plane to the horizontal direct irradiance, G_{diff} the horizontal diffuse irradiance, β the tilt angle, and ρ_s the ground albedo (0.2 for natural ground). The PV module's output power is then calculated taking into account the cell temperature, which affects the efficiency of crystalline silicon cells. The cell temperature T_c is determined by the nominal operating cell temperature (NOCT) model [5] (Equation (3)):

$$T_c = T_{\text{amb}} + (\text{NOCT} - 20) / 80 * G_{\text{POA}} \quad (3)$$

with NOCT = 45 degrees C (nominal operating temperature of the cell). The cell efficiency as a function of temperature is then [6] (Equation (4)):

$$\xi_{PV}(t) = \xi_{STC} * [1 + \Gamma * (T_C - 25)] \quad (4)$$

where $\xi_{STC} = 18.5\%$ is the module efficiency under standard conditions (STC), and $\Gamma = -0.0045/C$ is the power temperature coefficient. The DC power produced by the total surface area PV array is then (Equation (5)):

$$P_{PV,DC}(t) = \xi_{PV}(T_C) * A_{PV} * G_{POA}(t) \quad (5)$$

With a panel surface area (A_{PV}) of 2700 m² (peak power of 500 kWp), the estimated annual production is 842 MWh/year, representing a capacity factor of 19.2%. Daily production varies from 1.8 MWh/day in August to 3.2 MWh/day in March.

4.2. Pumping Model

The pumping model represents the conversion of electrical energy (surplus PV) into hydraulic potential energy. The hydraulic power absorbed by the pump is related to the electrical power by the pump efficiency and the pressure losses in the hydraulic circuit. The pumped volumetric flow rate $Q_p(t)$ is determined by [7] (Equation (6)):

$$Q_p(t) = \xi_p * P_{pump,e}(t) / (\rho * g * H_{man}) \quad (6)$$

where ξ_p is the pump efficiency (varies from 0.65 to 0.85 depending on the operating point), $P_{pump,e}(t)$ is the electrical power consumed by the pump, ρ is the density of water, g is the acceleration due to gravity, and H_{man} is the total dynamic head (net head + head losses). The head losses in the pumping pipe, estimated using the Darcy-Weisbach formula [8]-[10], are on the order of 5% to 8% of the gross head, representing a significant energy loss that depends directly on the length and diameter of the pipe. For the chosen design (DN 200 steel pipe, 350 m long), the head losses are estimated at 6.2 m, bringing the total dynamic head to 86.2 meters for a gross head of 80 meters.

4.3. Turbine Model

The turbine model represents the conversion of hydraulic potential energy into electrical energy during periods of PV deficit. The electrical power produced by the turbine is [11] (Equation (7)):

$$P_{turb,e}(t) = \xi_t * \xi_g * \rho * g * Q_t(t) * H_{man} \quad (7)$$

where ξ_t is the turbine efficiency (0.80 to 0.90 for a Francis turbine adapted to the head range) [12], ξ_g is the electrical generator efficiency (0.90 to 0.95 for a synchronous generator), and $Q_t(t)$ is the turbine flow rate. The maximum turbine flow rate is limited by the turbine's nominal capacity and the water availability in the upper reservoir. The water volume in the upper reservoir varies according to the continuity equation (Equation (8)):

$$V_{\text{sup}}(t + dt) = V_{\text{sup}}(t) + [Q_p(t) - Q_t(t) - Q_{\text{evap}}(t) - Q_{\text{inf}}(t)] * dt \quad (8)$$

where Q_{evap} is the evaporation rate (a function of the free surface area, temperature, and relative humidity), and Q_{inf} is the seepage loss rate. The volume must remain between the dead volume (10% of the usable volume, *i.e.*, 500 m³) and the maximum volume (5000 m³). The electric generator converts the mechanical energy of the turbine into electrical energy, with an efficiency that varies from 88% to 95% depending on the load.

4.4. Overall System Performance

The overall efficiency of the Micro-STEP system, defined as the ratio between the electrical energy delivered by the turbine and the electrical energy consumed by the pump over a complete cycle, is the product of the individual efficiencies of each component of the energy chain (**Figure 2**). The round-trip efficiency is expressed as (Equation (9)):

$$\xi_{\text{global}} = \xi_{\text{inverter}} * \xi_{\text{pump}} * \xi_{\text{hyd}} * \xi_{\text{turbine}} * \xi_{\text{generator}} \quad (9)$$

where ξ_{inverter} is the inverter efficiency during pumping (CC to AC conversion via the pump speed control), ξ_{hyd} is the hydraulic efficiency of the circuit (accounting for linear and singular head losses in the pipe), ξ_{turbine} is the turbine efficiency, and $\xi_{\text{generator}}$ is the electric generator efficiency. For the nominal values used in this study, we obtain a nominal cycle efficiency of (**Table 3**).

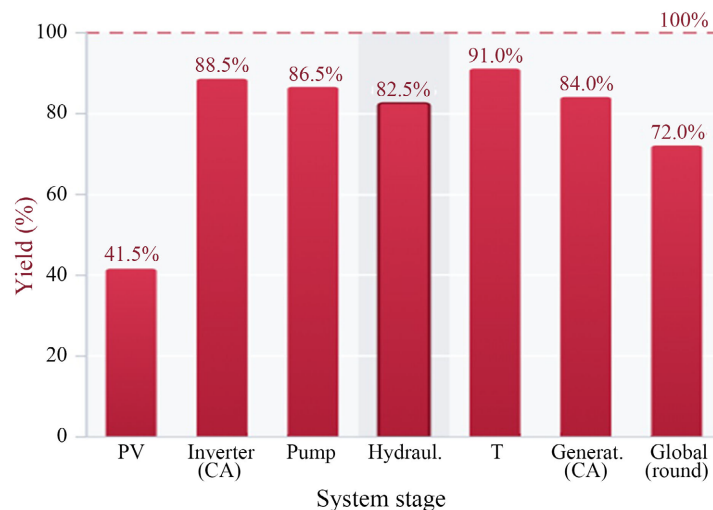


Figure 2. Decomposition of the yields of the system components.

Table 3. Micro-STEP system component yields.

Component	Nominal yield	Operational Range	Main losses
PV Field	18.5%	15% - 20%	Temperature, reflexion, mismatch
Inverter (CA/CC)	96.5%	93% - 98%	Commutation, harmonics
Centrifugal pump	82%	65% - 85%	Friction, recirculation
Hydraulic circuit	92%	88% - 95%	Pressure losses, leaks

Continued

Francis Turbine	87%	75% - 90%	Cavitation, friction
Generator	93%	88% - 95%	Copper losses, ventilation
Overall performance	59.8%	48% - 70%	Cumulative losses

4.5. Performance Indicators

Two main indicators are used to assess the overall performance of the electrification system. The first is the LPSP (Loss of Power Supply Probability), which measures the probability of power supply failure over the simulation period. It is defined as the ratio of the energy not supplied on demand to the total energy demanded [13] (Equation (10)).

$$\text{LPSP} = E_{\text{not provided}} / E_{\text{total requested}} \quad (10)$$

A LPSP of 0% means that all demand is met, while an LPSP of 5% indicates that 5% of the requested energy could not be supplied. For reliable electrification in isolated areas, the target is generally an LPSP of less than 5%, which corresponds to a maximum of approximately 18 days of outages per year.

The second indicator is the LCOE (Levelized Cost of Energy) [14], which represents the average cost of producing one kilowatt-hour of electricity over the entire lifespan of the system. It is calculated by discounting all costs (initial investment, operation, maintenance, replacement) and dividing them by the total energy produced (Equation (11)):

$$\text{LCOE} = \left[I_0 + \sum \left(C_t / (1+r)^t \right) \right] / \sum \left(E_t / (1+r)^t \right) \quad (11)$$

where I_0 is the initial investment, C_t the annual operating and maintenance costs, r the discount rate (8% in West Africa), and E_t the annual energy actually supplied. The LCOE allows us to compare the economic competitiveness of the PV-MicroSTEP system (Figure 3) with alternatives such as diesel (generator sets) or extending the national grid.

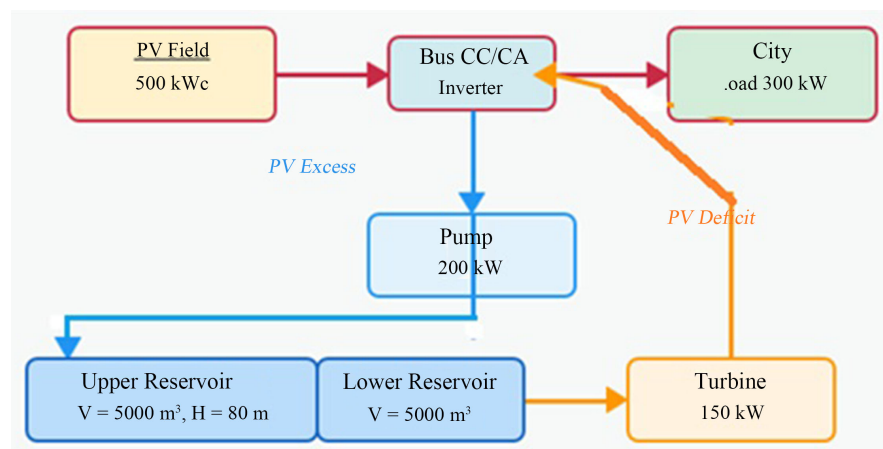


Figure 3. System architecture diagram for Micro-STEP PV for Mamou.

5. Sizing and Simulation Results

5.1. Sizing Methodology

The system is sized using a time-domain simulation approach with an hourly time step, over a full year of 8760 hours. The method is based on minimizing the LCOE under a maximum LPSP constraint of 5%, by varying the following design parameters: the PV array power (from 200 to 1000 kWp), the reservoir volume (from 2000 to 10,000 m³), the pump power (from 100 to 400 kW), the turbine power (from 50 to 300 kW), and the head (fixed at 80 m based on the site topography). The search algorithm uses a particle swarm optimization (PSO) method with 50 particles over 200 iterations, with a detailed hourly simulation model for each set of parameters [15].

The energy management strategy is based on predefined rules: when PV production exceeds demand, the excess is directed to the pump (storage mode); when PV production is less than demand, the turbine is activated to compensate for the deficit (de-storage mode); if the upper reservoir is full and the PV excess persists, the energy is dissipated in a ballast resistor (curtailment); if the reservoir is empty and the deficit persists, the demand is not met (failure, accounted for in the LPSP).

5.2. Scenarios Studied

Three sizing scenarios were studied to evaluate the impact of different configurations on system performance. Scenario 1 represents a conservative configuration with significant PV oversizing to minimize the need for storage. Scenario 2 corresponds to the optimal configuration identified by the PSO algorithm, balancing PV and storage investment costs. Scenario 3 explores a configuration with high hydro storage, better suited to prolonged periods of low sunlight (rainy season) (Table 4).

Table 4. Sizing results for the three scenarios studied.

Parameter	Scenario 1 (Conservative)	Scenario 2 (Optimal)	Scenario 3 (Strong Storage)
PV Power (kWc)	800	500	400
Tank Volume (m ³)	3000	5000	8000
Pump Power (kW)	250	200	300
Turbine Power (kW)	100	150	200
Drop height (m)	80	80	80
PV Production (MWh/an)	1347	842	674
Energy pumped (MWh/an)	412	298	265
Turbine Energy (MWh/an)	256	185	164
Overall performance (%)	62.1	62.1	61.9
LPSP (%)	1.8	3.4	4.2
LCOE (EUR/kWh)	0.28	0.22	0.25
Investment	2.45	1.68	2.10

5.3. Overall Performance Analysis

Analysis of the simulation results shows that the overall system efficiency varies between 48% and 70% depending on operating conditions, with a nominal value of 62% under optimal conditions. The main causes of efficiency degradation are identified as follows: losses in the inverter (3.5% in pumping mode), mechanical and hydraulic losses of the pump (18% at partial load), head losses in the pipe (8%), losses at partial load of the turbine (13% to 25%), and losses in the generator (7%). Pumping efficiency is particularly sensitive to the operating point: pump efficiency drops to 65% when the flow rate is reduced to 40% of the nominal flow rate, corresponding to periods of low solar surplus (morning and late afternoon). Using a variable frequency drive (VFD) on the pump allows for maintaining an efficiency greater than 75% over an extended operating range of 50% to 100% of the nominal flow rate.

The overall monthly efficiency varies between 54% (in August, during the rainy season) and 67% (in March, during the dry season). This variation is mainly explained by the reduction in solar irradiance during the rainy season, which leads to shorter pumping periods and lower pumping rates, thus moving the pump away from its optimal efficiency point. During the dry season, the abundance of excess solar energy allows the pump to operate near its nominal point for 5 to 6 hours per day, thereby maximizing pumping efficiency.

5.4. Daily Energy Balance

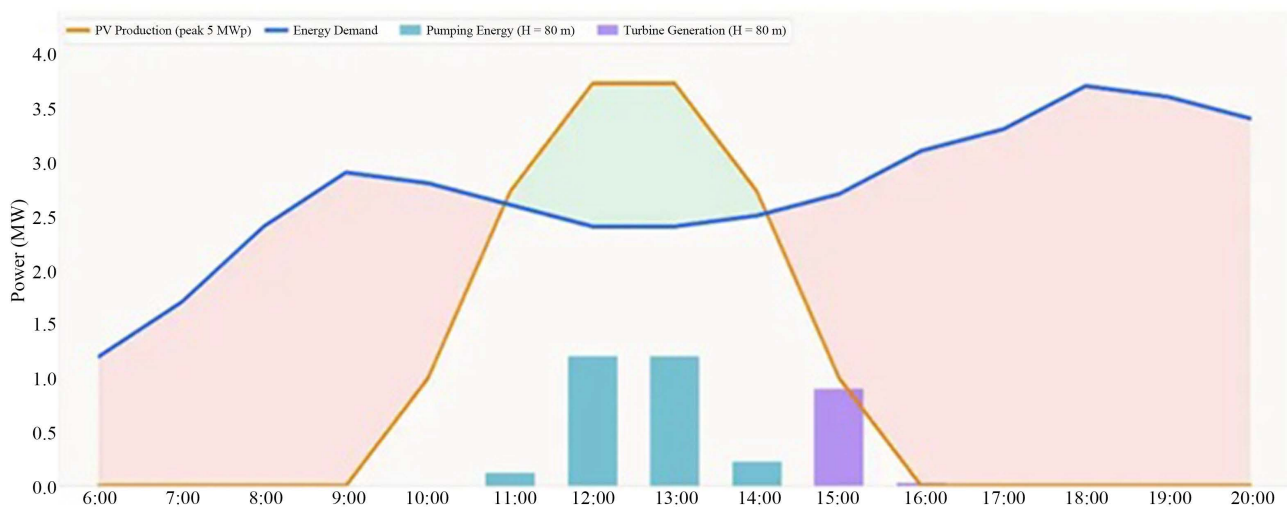


Figure 4. Typical daily energy balance (dry season on March)—hourly power profiles.

The analysis of the typical daily energy balance, illustrated in **Figure 3** and **Figure 4**, shows the system's operating mode during a dry season day (March). From 6:00 to 10:00, PV production increases rapidly and exceeds the demand at 7:00. The surplus is directed to the pump, which operates at full capacity from 8:00 to 14:00. The upper reservoir reaches its maximum level around 15:00, and the remaining surplus is dissipated in the ballast heater. From 16:00 to 18:00, PV production

decreases and demand increases (beginning of the evening peak), and the system switches to mixed mode. From 18:00 to 22:00, the turbine is fully activated to compensate for the PV deficit, using the water stored during the day. The upper reservoir gradually empties and reaches its minimum level around 22:00. The daily cycle efficiency for this typical day is 64%, higher than the annual average because the conditions are optimal (strong sunshine, pump at nominal point) (**Figure 4** and **Figure 5**).

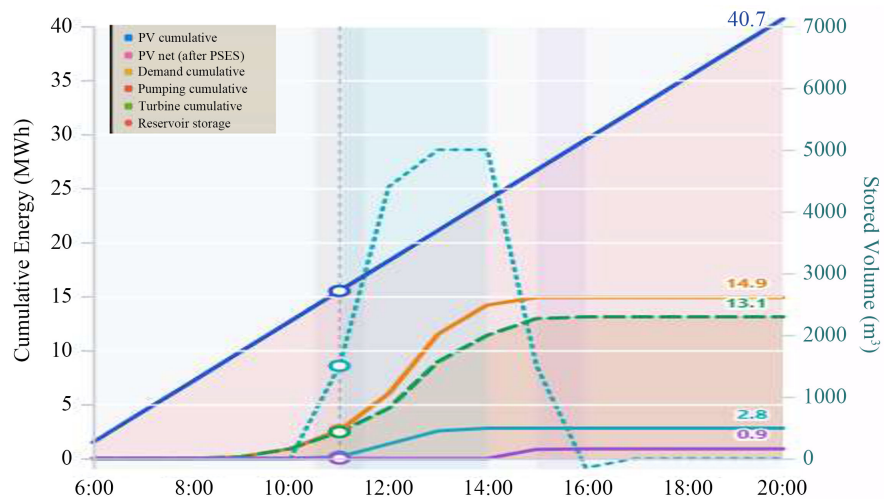


Figure 5. Typical daily energy balance (dry season on March)—cumulative energy and reservoir storage.

5.5. Sensitivity Analysis

Table 5. Sensitivity analysis of key system parameters.

Parameter varies	Variation	Performance impact	LCOE Impact	LPSP Impact
Drop height	−20 m (60 m)	−4.1 pts	+12%	+2.8 pts
Drop height	+20 m (100 m)	+3.2 pts	−8%	−1.5 pts
Tank Volume	−2000 m ³	−0.5 pts	−3%	+5.2 pts
Tank Volume	+3000 m ³	+0.2 pts	+9%	−1.1 pts
PV Power	−100 kWc	+1.3 pts	+4%	+3.5 pts
Pump efficiency	−5 pts (77%)	−3.8 pts	+7%	+1.2 pts
Pump cost	+20%	-	+5%	-
PV cost	−15%	-	−6%	-

A sensitivity analysis was conducted to assess the impact of key parameters on the overall efficiency and LCOE of the system. The five most influential parameters are: head, reservoir volume, installed PV capacity, pump efficiency, and component price. The results show that head is the most sensitive parameter: an increase of 20 meters (from 80 to 100 m) improves overall efficiency by 3.2 percentage points (from 62% to 65.2%) and reduces the LCOE by 8% (from €0.22 to

€0.20/kWh), because the potential energy stored is directly proportional to the head. The volume of the reservoirs has a non-linear impact: below 3000 m³, the LPSP increases rapidly (>10%), while above 7000 m³, the marginal gain in LPSP is negligible and oversizing increases the LCOE (**Table 5**).

6. Economic Analysis

6.1. Investment Costs

The total investment cost of the Micro-STEP PV system for the optimal scenario (scenario 2) is estimated at €1.68 million, representing a specific cost of €3.36/Wp for the PV array and €1125/kW for the installed hydro storage capacity. A detailed breakdown of costs by component shows that the photovoltaic array represents the largest share (34.2%), followed by hydraulic structures (reservoirs and civil engineering works, 27.1%), electromechanical equipment (pump, turbine, generator, 24.4%), and auxiliary equipment (inverters, control system, distribution lines, 10.9%) (**Table 6**).

Table 6. Investment cost breakdown—optimal scenario.

Component	Cost (EUR)	Part (%)	Observations
PV Field (500 kWc)	575,000	34.2	Moduls, structures, DC Wiring
Upper reservoir	185,000	11.0	Civil engineering, waterproofing
Lower reservoir	165,000	9.8	Civil engineering, waterproofing
Forced driving	105,000	6.3	DN 200 steel, 350 m
Pump + motor	190,000	11.3	200 kW, variator VFD
Turbine + generator	220,000	13.1	150 kW, Francis
Inverters	85,000	5.1	2 × 250 kVA, couplers
Control System (SCADA)	42,000	2.5	Automation, sensors, telecom
Distribution Lines	55,000	3.3	MT + BT, 8 km
Studies and engineering	38,000	2.3	Feasibility study, BAT (Building Authorization), supervision
Contingency (5%)	20,000	1.2	Unexpected
Total	1,680,000	100	

6.2. Operating and Maintenance Costs

Annual operating and maintenance (O&M) costs are estimated at €33,600/year, representing 2% of the initial investment. This estimate is based on international benchmarks for similar installations in Africa. The main expenditure items include: preventive maintenance of electromechanical equipment (pump, turbine, generator) estimated at €12,000/year, including regular replacements of seals, bearings, and oil; corrective maintenance provisioned at €8000/year for unplanned repairs; daily operations (operating personnel, monitoring) estimated at €6000/year for two full-time operators; and maintenance of the PV array (module

cleaning, bypass diode replacement) estimated at €3600/year. The major replacement of the pump and turbine is provisioned at 50% of their initial value over a 15-year cycle, representing an annualized cost of €4000/year included in the O&M.

6.3. LCOE Analysis

The LCOE of the optimal scenario is calculated over a 25-year lifespan (consistent with the lifespan of the PV modules), with a discount rate of 8%. The total discounted investment (initial investment + major replacements) amounts to €1.93 million. The discounted operating costs over 25 years represent €0.36 million. The total discounted energy supplied over the lifespan is 10,310 MWh. The resulting LCOE is (Equation (12))

$$\text{LCOE} = (1930000 + 360000) / 10310000 = 0.22 \text{ EUR/kWh} \quad (12)$$

This cost is competitive compared to off-grid generation alternatives in West Africa. The cost of diesel, which varies depending on the price of a barrel of oil and transport costs to remote areas, is generally between €0.25 and €0.45/kWh, with an upward trend linked to the volatility of oil prices and increasing logistical costs. Extending Guinea's national grid to Mamou, while desirable in the long term, requires an estimated investment of €8 - 12 million for 50 km of medium-voltage line and a substation, and does not guarantee sufficient reliability given the current performance of EDG (Electricity of Guinea). The PV-MicroSTEP system therefore presents an economically attractive and technically reliable solution for the medium-term electrification of the city of Mamou.

6.4. Comparison with Alternatives

The multi-criteria comparison highlights the advantages of the PV-MicroSTEP system (**Table 7**). Although the LCOE of the PV-battery system is higher than that of the PV-MicroSTEP system, lithium-ion batteries offer a faster response to demand fluctuations and do not require specific topographic conditions.

Table 7. Multi-criteria comparison of electrification options for Mamou.

Criteria	PV + Micro-STEP	PV + Batteries Li-ion	Diesel Group	National Network (EDG)
LCOE (EUR/kWh)	0.22	0.30 - 0.40	0.25 - 0.45	0.15 - 0.20
Lifetime (years)	25 - 50	10 - 15	10 - 15	30 - 40
Reliability	High (>95%)	Midle	Low	Variable
Impact CO ₂ (g/kWh)	15 - 25	30 - 50	600 - 900	50 - 150
Investment cost	Midle	High	Low	Very High
Implementation time	18 - 24 month	6 - 12 month	1 - 3 month	3 - 5 years
Autonomy	days	Hours	days (if fuel)	N/A
Local Maintenance	Possible	Difficult	Necessary	EDG

However, for storage capacities exceeding 500 kWh and storage durations of several hours, the micro-pumped hydro storage (MPHS) system becomes significantly more economically advantageous. While diesel generators have a lower initial investment cost, they present prohibitive long-term operating costs (dependence on imported fuel, frequent maintenance) and a considerable environmental impact. Extending the national grid, although potentially offering a lower level of cost of energy (LCOE), remains uncertain in terms of timelines and reliability, and represents a considerably higher investment.

7. Conclusion and Recommendations

7.1. Summary of Results

This report presents a detailed model of the overall efficiency of a hybrid PV-MicroSTEP system for the electrification of the city of Mamou in Guinea. The model integrates the main system components: the photovoltaic array, the inverter, the centrifugal pump, the hydraulic circuit, the Francis turbine, and the electric generator. The system's nominal overall efficiency is 62%, with monthly variations between 54% (rainy season) and 67% (dry season). The optimal sizing identifies a 500 kWp PV array coupled with 5000 m³ reservoirs, a 200 kW pump, and a 150 kW turbine, for an investment of €1.68 million. This system allows us to achieve an LPSP of 3.4% and an LCOE of 0.22 EUR/kWh, which is competitive compared to the alternatives (diesel: 0.25 - 0.45 EUR/kWh, PV-battery: 0.30 - 0.40 EUR/kWh).

7.2. Key Success Factors

The successful deployment of a micro-wastewater treatment plant (MWTP) in Mamou depends on several key factors. First, the availability of a suitable topographical site with sufficient elevation and the possibility of creating two reservoirs at minimal civil engineering costs. Second, the sustainable management of water resources, requiring a thorough understanding of the local hydrological cycle and consultation with users upstream and downstream of the site. Third, the training of a competent local team for the operation and maintenance of the system, including preventive maintenance of electromechanical equipment and optimal management of reservoir filling. Fourth, the institutional integration of the project within the Guinean regulatory framework, including obtaining environmental permits and aligning with the national rural electrification policy.

7.3. Recommendations

Based on the results obtained, the following recommendations are made for the remainder of the project. First, it is recommended to conduct a detailed topographic and geotechnical survey of the identified site to confirm technical feasibility and refine the civil engineering cost estimate. Second, a water resource measurement campaign (river flow, piezometric levels, water quality) should be carried out over at least one complete hydrological cycle to calibrate the hydraulic model. Third, it would be advisable to equip the site with a meteorological station

to refine the solar irradiance and temperature data. Fourth, an environmental and social impact assessment should be conducted in accordance with Guinean regulations and international standards (IFC Performance Standards). Fifth, the establishment of a suitable financing mechanism, combining subsidies, microcredit and community participation, should be studied to ensure the financial viability of the project.

7.4. Research Perspectives

Several research avenues could be explored to improve the performance of micro-pumped hydro storage (PPS) systems in the African context. Integrating hybrid systems combining PPS and short-term lithium-ion batteries would allow for combining the advantages of both technologies: PPS for large-scale storage (daily cycles) and batteries for rapid regulation and short-term peak demand. Using reversible pump-turbines, which operate alternately in pumping and turbine modes, could reduce investment costs by eliminating the need for two separate machines. Applying artificial intelligence (machine learning) techniques for forecasting PV production and demand would allow for optimizing storage management strategies in real time. Finally, the development of low-power pumps and turbines specifically designed for micro-STEP applications in Africa (robustness, ease of maintenance, local manufacturing) would help to reduce costs and improve operational reliability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Le, L. (2026) Water Power Equation: Calculating Hydroelectric Energy Generation Potential. *Green Energy*. <https://www.smartreability.com/water-power-equation>
- [2] Rynoson, M., Ma Lu, S., Munkhammar, J. and Campana, P.E. (2025) Evaluation of Reverse Transposition and Separation Methods for Global Tilted Irradiance: Insights from High-Latitude Data. *Solar Energy*, **297**, Article 113597. <https://doi.org/10.1016/j.solener.2025.113597>
- [3] Lave, M., Hayes, W., Pohl, A. and Hansen, C.W. (2015) Evaluation of Global Horizontal Irradiance to Plane-of-Array Irradiance Models at Locations across the United States. *IEEE Journal of Photovoltaics*, **5**, 597-606. <https://doi.org/10.1109/jphotov.2015.2392938>
- [4] Pereira, S., Canhoto, P. and Salgado, R. (2024) Prediction of Global Solar Irradiance on Parallel Rows of Tilted Surfaces Including the Effect of Direct and Anisotropic Diffuse Shading. *Energies*, **17**, Article 3444. <https://doi.org/10.3390/en17143444>
- [5] Gilman, P., Dobos, A., Diorio, N., Freeman, J., Janzou, S. and Ryberg, D. (2018) SAM Photovoltaic Model Technical Reference Update. National Renewable Energy Laboratory Report NREL/TP-6A20-67399.
- [6] Sun, V., Asanakham, A., Deethayat, T. and Kiatsiriroat, T. (2021) Evaluation of Nominal Operating Cell Temperature (NOCT) of Glazed Photovoltaic Thermal Module. *Case Studies in Thermal Engineering*, **28**, Article 101361.

- <https://doi.org/10.1016/j.csite.2021.101361>
- [7] Skorek, G. (2018) Study of Losses and Energy Efficiency of Hydrostatic Drives with Hydraulic Cylinder. *Polish Maritime Research*, **25**, 114-128.
<https://doi.org/10.2478/pomr-2018-0138>
 - [8] Jones, G.M. (2006) Pumping Station Design. 3rd Edition, Butterworth-Heinemann.
 - [9] Chaudhry, M.H. (2013) Applied Hydraulic Transients. 3rd Edition, Springer.
 - [10] McKeon, B.J., Zagarola, M.V. and Smits, A.J. (2005) A New Friction Factor Relationship for Fully Developed Pipe Flow. *Journal of Fluid Mechanics*, **538**, 429-443.
<https://doi.org/10.1017/s0022112005005501>
 - [11] Andreica, A.M. (2009) Optimisation énergétique de chaînes de conversion hydroliennes-modélisation, commandes et réalisations expérimentales. Thèse de doctorat, Institut National Polytechnique de Grenoble, NPG.
 - [12] Guo, P.C., Wang, Z.N. and Luo, X.Q. (2017) Characteristic Analysis of the Efficiency Hill Chart of Francis Turbine for Different Water Heads. *Advances in Mechanical Engineering*, **9**.
 - [13] Khatib, T., Ibrahim, I.A. and Mohamed, A. (2016) A Review on Sizing Methodologies of Photovoltaic Array and Storage Battery in a Standalone Photovoltaic System. *Energy Conversion and Management*, **120**, 430-448.
<https://doi.org/10.1016/j.enconman.2016.05.011>
 - [14] Kabeyi, M.J.B. and Olanrewaju, O.A. (2023) The Levelized Cost of Energy and Modifications for Use in Electricity Generation Planning. *Energy Reports*, **9**, 495-534.
<https://doi.org/10.1016/j.egy.2023.06.036>
 - [15] Tang, K.Z. and Meng, C.J. (2024) Particle Swarm Optimization Algorithm Using Velocity Pausing and Adaptive Strategy. *Symmetry*, **16**, Article 661.
<https://doi.org/10.3390/sym16060661>