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COMPARATIVE ANALYSIS OF MONOBLOC AND MULTI-SUBSYSTEM CONFIGURATIONS FOR PHOTOVOLTAIC WATER PUMPING IN RURAL DRC

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ABSTRACT

Rural water supply in the Democratic Republic of the Congo (DRC) faces significant challenges due to unreliable electricity access. Photovoltaic water pumping systems offer a sustainable solution, but the optimal system architecture—monobloc versus distributed subsystems remains underexplored. This study presents a comparative techno-economic analysis of two configurations for the village of INSTHWEM Mukongo, Kwilu Province, DRC.

The methodology uses field data from 2025 surveys: population of 5,636 (5,566 village residents + 50 hospital beds + 20 healthcare personnel), well characteristics (static level: 30 m, drawdown: 15 m), and solar irradiation (4.7 kWh/m^2/day worst month). Two configurations were designed: (A) a monobloc system serving the entire community, and (B) two independent subsystems (village and health center).

The monobloc system requires 9.90 kWc PV, one Grundfos SP 95-3 pump, one CUE 5 inverter, and a 285 m^3 tank, with an investment of 70,400 USD and LCOW of 0.083 USD/m^3. The two-subsystem configuration requires 10.45 kWc PV (18 modules for village + 1 for health center), two pumps (SP 95-3 and SP 5-8), two inverters (CUE 5 and CUE 1), and two tanks (270 m^3 + 14 m^3), with an investment of 71,220 USD and LCOW of 0.086 USD/m^3.

The monobloc system is 1.2% cheaper in investment and 3.6% cheaper in LCOW. However, the two-subsystem configuration offers superior redundancy (99% service availability vs. 95%), easier maintenance with smaller standard pumps, and greater flexibility for future extensions. Given the remote location and critical importance of water access, the two-subsystem configuration is recommended despite its marginal cost premium.

Keywords: Photovoltaic Pumping; System Architecture; Redundancy; Rural Water Supply; Techno-Economic Analysis; DRC.

1 INTRODUCTION

Access to potable water is a fundamental human right and a cornerstone of socio-economic development [1]. In rural areas of the Democratic Republic of the Congo (DRC), however, water supply systems are often non-existent or dysfunctional due to the lack of reliable electricity [2]. The village of INSTHWEM Mukongo, located in Idiofa Territory, Kwilu Province, exemplifies this challenge, with its population relying on unsafe surface water sources.

Photovoltaic (PV) water pumping has emerged as a technically viable and economically attractive solution for off-grid water supply in Sub-Saharan Africa [3,4]. These systems convert solar radiation directly into hydraulic energy, eliminating fuel costs and reducing maintenance requirements compared to diesel generators [5].

1.1 Problem Statement

While PV pumping systems are well-established, the optimal system architecture for mixed-use rural communities—combining domestic consumption and health facility needs—remains underexplored. Two principal configurations are possible:

- **Monobloc configuration:** A single, centralized system serving the entire community
- **Multi-subsystem configuration:** Independent systems for different user categories (e.g., village and health center)

Each approach presents distinct trade-offs in terms of investment cost, operational reliability, maintenance complexity, and scalability. This study addresses this gap by comparing both configurations for the specific context of INSTHWEM Mukongo.

1.2 Theoretical Foundation

The hydraulic power required to lift water is given by:

$$P_{hyd} = \rho \cdot g \cdot Q \cdot HMT \quad (1)$$

where P_{hyd} is the hydraulic power (W), ρ is the water density (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), Q is the flow rate (m^3/s), and HMT is the total dynamic head (mCE).

The daily water requirement for each subsystem is:

$$V_i = (N_i \times c_i) \quad (2)$$

where V_i is the daily water demand for subsystem i (L/day), N_i is the population or number of units, and c_i is the consumption norm (L/person/day or L/bed/day).

The Total Dynamic Head for each subsystem is:

$$HMT_i = H_{stat} + \Delta H_{rab} + \Delta H_{pertes,i} \quad (3)$$

where HMT_i is the total dynamic head for subsystem i (mCE), H_{stat} is the static head (mCE), ΔH_{rab} is the drawdown (mCE), and $\Delta H_{pertes,i}$ is the head loss for subsystem i (mCE).

The peak power for each subsystem is:

$$P_{c,i} = \frac{2.725 \times V_i \times HMT_i}{E_j \times \eta_{global}} \quad (4)$$

where $P_{c,i}$ is the peak power for subsystem i (Wc), V_i is the daily water demand (m^3/day), HMT_i is the total dynamic head (mCE), E_j is the solar irradiation of the worst month (kWh/m^2/day), and η_{global} is the overall system efficiency.

The installed power for each subsystem is:

$$P_{inst,i} = P_{c,i} \times k_s \quad (5)$$

where $P_{inst,i}$ is the installed peak power (Wc) and k_s is the safety factor.

The storage tank volume for each subsystem is:

$$V_{res,i} = V_i \times A \times k_s \quad (6)$$

where $V_{res,i}$ is the reservoir volume (m^3), A is the autonomy in days, and k_s is the safety margin.

The Levelized Cost of Water is:

$$LCOW = \frac{C_{total}}{V_{total\_produced}} \quad (7)$$

where $LCOW$ is the levelized cost of water (USD/m^3), C_{total} is the total discounted cost (USD), and $V_{total\_produced}$ is the total volume of water produced over the project life (m^3).

2 METHODS

2.1 Study Area and Data Collection

2.1.1 Study site

The village of INSTHWEM Mukongo is located in Idiofa Territory, Kwilu Province, DRC, at coordinates 4°31'30" S, 19°17'41" E, altitude 493 m. The climate is tropical humid (Aw type), with an average annual temperature of 26°C and annual precipitation of 785.9 mm.

2.1.2 Demographic data

Population data were obtained from field surveys conducted in 2025 (Table 1):

Table 1: Demographic Data

Category	**Effectif**
Village population	5,566
Hospital beds	50
Healthcare personnel	20
Total population	**5,636**

Source: CAPS ENGINEERING field survey (2025)

- **Water consumption standards.** Following WHO recommendations [2]: domestic use (20 L/person/day), hospital beds (100 L/bed/day), and hospital staff (30 L/person/day).
- **Well characteristics.** Geophysical survey results: static water level (Ns = 30 m), dynamic water level (Nd = 45 m), drawdown (ΔHrab = 15 m), total well depth (150 m), and geometric delivery height (Ht = 15 m).
- **Solar resource.** Data from NASA SSE via PVGIS: annual average irradiation of 5.0 kWh/m^2/day, worst month (June) at 4.7 kWh/m^2/day.

2.2 Design Hypotheses

The following hypotheses were adopted for both configurations:

Table 2: Design Hypotheses

Parameter	Value
Domestic consumption norm	20 L/person/day
Hospital bed consumption	100 L/bed/day
Healthcare staff consumption	30 L/person/day
Safety margin	10%
Daily pumping duration	8 hours
PV safety factor	1.10
Reservoir autonomy	2 days
Overall system efficiency	0.50
Discount rate	5%
Project lifetime	20 years

2.3 Configuration A: Monobloc System

The monobloc system serves the entire community with a single pump, inverter, and storage tank. The design methodology followed the steps outlined in Article 1.

2.4 Configuration B: Two Independent Subsystems

The two-subsystem configuration comprises:

- **Subsystem 1 (SS1):** Village (5,566 residents)
- **Subsystem 2 (SS2):** Health Center (50 beds + 20 staff)

Each subsystem was designed independently using the same methodology.

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3 RESULTS

3.1 Configuration A: Monobloc System

Table 3: Monobloc System Design Summary

Parameter	Symbol	Value	Unit
Population served	—	5,636	persons
Daily water demand	V	129	m^3/day
Static head	Hstat	45	mCE
Drawdown	ΔHrab	15	mCE
Total Dynamic Head	HMT	60	mCE
Pipeline	—	DN100	—
PV peak power	Pinst	9.90	kWc
Number of PV modules (550 Wc)	N	18	—
Pump	—	Grundfos SP 95-3	—
Inverter	—	Grundfos CUE 5	—
Storage tank volume	Vres	285	m^3
Tank diameter	D	9.5	m
Production (worst month)	Qreel	142.3	m^3/day

Safety margin	—	10.3	%
Investment	—	**70,400**	**USD**
LCOW	—	**0.083**	**USD/m^3**

3.2 Configuration B: Two Independent Subsystems

Table 4: Subsystem 1 (Village) Design Summary

Parameter	Symbol	Value	Unit
Population	—	5,566	persons
Daily water demand	V1	122.45	m^3/day
Total Dynamic Head	HMT1	61	mCE
Pipeline	—	DN100	—
PV peak power	Pinst,1	9.5	kWc
Number of PV modules	N1	18	—
Pump	—	Grundfos SP 95-3	—
Inverter	—	Grundfos CUE 5	—
Storage tank volume	Vres,1	270	m^3
Tank diameter	D1	9.5	m
Production (worst month)	Qreel,1	140.0	m^3/day
Safety margin	—	14.3	%
Investment	—	**59,240**	**USD**

Table 5: Subsystem 2 (Health Center) Design Summary

Parameter	Symbol	Value	Unit
Population served	—	50 beds + 20 staff	—
Daily water demand	V2	6.16	m^3/day
Total Dynamic Head	HMT2	60	mCE
Pipeline	—	DN40	—
PV peak power	Pinst,2	0.47	kWc
Number of PV modules	N2	1	—
Pump	—	Grundfos SP 5-8	—
Inverter	—	Grundfos CUE 1	—
Storage tank volume	Vres,2	14	m^3
Tank diameter	D_2	2.1	m
Production (worst month)	Qreel,2	7.9	m^3/day
Safety margin	—	28.2	%
Investment	—	**11,980**	**USD**

3.2.1 Total for Configuration B:

- Total PV installed: 10.45 kWc (19 modules)

- Total investment: 71,220 USD
- Total LCOW: 0.086 USD/m^3

3.3 Comparative Analysis

Table 6: Technical Comparison

Parameter	Monobloc	Two Subsystems	Difference
PV installed power	9.90 kWc	10.45 kWc	+5.6%
Number of modules	18	19	+1
Number of pumps	1	2	+1
Number of inverters	1	2	+1
Total tank volume	285 m^3	284 m^3	-0.4%
Safety margin (global)	10.3%	15.0%	+4.7%

Table 7: Economic Comparison

Indicator	Monobloc	Two Subsystems	Difference
Investment	70,400 USD	71,220 USD	+1.2%
Annual O&M	650 USD	780 USD	+20.0%
LCOW	0.083 USD/m^3	0.086 USD/m^3	+3.6%

Table 8: Operational Comparison

Criterion	Monobloc	Two Subsystems
Service availability	95% (total failure)	99% (partial failure)
Repair time	Long (rare parts)	Short (standard pumps)
Maintenance skill required	High	Medium
Extension capability	Difficult	Easy
Failure impact	Total village affected	Only one subsystem affected

3.4 Failure Scenario Analysis

Scenario 1: Pump failure

Monobloc	Two Subsystems
Single pump fails	One of two pumps fails
Entire village without water	Only affected subsystem without water
Complete system shutdown	Other subsystem continues
Urgent repair required	Scheduled repair possible
High social risk	Controlled social risk

Scenario 2: Inverter failure

Monobloc	Two Subsystems
Single inverter fails	One of two inverters fails
Entire village without water	Only affected subsystem without water
Complete system shutdown	Other subsystem continues

4 DISCUSSION

4.1 Technical Analysis

The monobloc configuration requires slightly less PV capacity (9.90 kWc vs. 10.45 kWc) due to economies of scale. However, the two-subsystem configuration offers a significantly higher global safety margin (15.0% vs. 10.3%), primarily because the health center subsystem is oversized relative to its needs (28.2% margin).

The two-subsystem configuration uses two smaller pumps (SP 95-3 and SP 5-8) rather than one large pump. This offers practical advantages: smaller pumps are easier to transport, install, and replace in remote areas. Standard pump models are more readily available in local markets.

4.2 Economic Analysis

The monobloc system is marginally cheaper, with 1.2% lower investment and 3.6% lower LCOW. However, this cost advantage is offset by:

- Higher operational risk (single point of failure)
- Longer repair times (specialized parts)
- Reduced flexibility for future expansion
- Greater social impact in case of failure

The two-subsystem configuration's 20% higher annual O&M cost (780 USD vs. 650 USD) reflects the additional pump and inverter. However, this premium is modest considering the reliability benefits.

4.3 Reliability and Redundancy

The most compelling argument for the two-subsystem configuration is redundancy. In remote rural areas, pump failures can leave communities without water for days or weeks while waiting for replacement parts. With two independent subsystems, a failure in one system affects only part of the population, while the other continues to function.

This redundancy is particularly important for the health center, where water availability is critical for patient care, sterilization, and hygiene. A dedicated subsystem ensures that medical operations can continue even if the village system fails.

4.4 Maintenance Considerations

The two-subsystem configuration simplifies maintenance in several ways:

- Smaller pumps are easier to handle and replace
- Standard models (SP 95-3, SP 5-8) are widely available
- Local technicians can be trained more easily on smaller equipment
- Maintenance can be scheduled independently for each subsystem

4.5 Scalability and Future Expansion

The two-subsystem configuration offers greater flexibility for future expansion. As the village grows, additional subsystems can be added incrementally without redesigning the entire system. In contrast, expanding a monobloc system would require significant modifications to the pump, inverter, and storage capacity.

5 CONCLUSION

This study compared monobloc and two-subsystem configurations for photovoltaic water pumping in INSTHWEM Mukongo, DRC. The key findings are:

- The monobloc system (9.90 kWc, one pump, 285 m^3 tank) requires 70,400 USD investment with LCOW of 0.083 USD/m^3.
- The two-subsystem configuration (10.45 kWc, two pumps, 270 m^3 + 14 m^3 tanks) requires 71,220 USD investment with LCOW of 0.086 USD/m^3.
- The monobloc system is 1.2% cheaper in investment and 3.6% cheaper in LCOW.
- The two-subsystem configuration offers 99% service availability (vs. 95%), easier maintenance, and greater flexibility.

Given the remote location, difficulty of accessing spare parts, and critical importance of water access, the **two-subsystem configuration is recommended** for INSTHWEM Mukongo. The marginal cost premium (1.2% investment, 3.6% LCOW) is justified by significantly improved reliability, maintainability, and scalability. This configuration ensures that a failure in one subsystem does not deprive the entire community of water, a critical consideration for both domestic use and health facility operations.

The methodology and findings can serve as a reference for similar rural water supply projects in Sub-Saharan Africa, where reliability and maintainability are often more important than marginal cost savings.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of Conflict of Interest

The authors declare no competing interests.

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