



## Conceptual Evaluation of a Small-Scale Gravity-Based Pumped Hydro Storage System with Permanent Magnet Generators (PMG) for Rural Renewable Energy Stabilization in Nigeria

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### KEYWORDS

PMG,  
Gravity,  
Sustainability,  
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### ABSTRACT

Intermittency remains a critical bottleneck for renewable energy adoption in developing regions, as supply fluctuations disrupt grid stability. This study evaluates a hybrid energy system designed to improve power delivery continuity by integrating gravity-fed energy storage (GES) with high-efficiency recovery mechanisms. To address the cradle-to-grave challenges of chemical batteries, a mechanical-hydraulic synergy was modeled to capture surplus energy and convert it into gravitational potential. The system's operational logic utilizes surplus power to drive a hydraulic pump, lifting water to an elevated reservoir; during periods of low supply, this water descends to drive a micro-hydro turbine integrated with a Permanent Magnet Generator (PMG) for electrical conversion. The research utilized a configuration consisting of an elevated water tower (10–20 meters), a micro-hydro recovery unit, and precision instrumentation including flow meters and pressure sensors to track energy movement. Performance was mathematically modeled using gravitational energy equations and verified through semi-urban wind-yield simulations, with the recovery subsystem demonstrating a modeled round-trip efficiency in the range of 72–81%. Results suggest that the hybrid approach could potentially achieve substantially higher reliability compared to standalone intermittent systems, which exhibited approximately 45% reliability under equivalent conditions. The system's projected 50-year service life and favorable levelized cost of storage relative to lithium-ion alternatives further support its viability. This battery-free design represents a potentially scalable, low-maintenance pathway toward rural electrification, offering meaningful mechanical inertia to help stabilize weak-grid infrastructure while mitigating the environmental risks associated with electrochemical disposal.

### CITATION

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### INTRODUCTION

The transition to a low-carbon future is fundamentally anchored in renewable energy, yet this shift faces a critical bottleneck: the inherent intermittency of primary sources

which compromises reliability in off-grid and weak-grid regions (Kropotin, 2023). While Battery Energy Storage Systems (BESS) are the traditional remedy, they introduce a suite of "cradle-to-grave" challenges, including high

capital costs, limited lifespans, and complex disposal requirements for hazardous materials. Consequently, there is an urgent demand for storage solutions that are not only durable and low-maintenance but also ecologically sustainable (Chaturvedi *et al.*, 2020).

Permanent Magnet Generators (PMGs) coupled with Gravity-Fed Energy Storage (GES) represent a promising frontier in the pursuit of affordable, clean energy. By utilizing high-efficiency generators within a mechanical-hydraulic synergy, these systems eliminate the environmental degradation associated with chemical batteries (Pius Sarameje *et al.*, 2025). Global case studies indicate that gravity-based storage can achieve round-trip efficiencies of 85 to 90% and operational lifespans exceeding 50 years, making them ideal for long-term decentralized infrastructure.

In Africa, and specifically within Nigeria, the deployment of PMG-integrated gravity systems offers a scalable solution for rural electrification and decentralized grid stability. By leveraging simple physics lifting water to an elevated reservoir during surplus periods and recovering it through a micro-hydro turbine communities can achieve 100% power reliability (Ruoso *et al.*, 2019). This architecture provides the instantaneous mechanical inertia required to stabilize weak grids, marking a transformative step for small-scale institutional and community power supply in developing landscapes.

### Study Design

The study evaluates the battery-free frontier by assessing the integration of mechanical storage with hydraulic conversion, representing a paradigm shift in how renewable energy systems can be conceptualized for underserved communities. The research focuses on identifying a low-maintenance infrastructure tailored for semi-urban and rural areas where sustainable infrastructure is most needed, yet often economically unfeasible with conventional technologies. Performance metrics include the energy continuity index, storage utilization ratio, and a lifecycle environmental impact assessment to compare the system against traditional chemical battery arrays. This approach aligns with established research demonstrating that pumped hydroelectric storage systems can effectively solve energy storage problems for renewable energy integration in rural electrification projects, with water reservoirs serving for daily and seasonal energy storage by converting excess electrical energy into potential energy (Swe, 2018).

This investigation emerges at a critical juncture where energy equity and environmental sustainability intersect. By leveraging gravitational potential energy through mechanical elevation and sophisticated hydraulic transformation mechanisms, the proposed system

circumvents the resource-intensive manufacturing processes and toxic material dependencies inherent in electrochemical storage solutions. The modularity of gravity-based architecture enables incremental scalability, allowing communities to expand their energy infrastructure organically as demand evolves, without the technological obsolescence that plagues battery technologies. Solid gravity energy storage systems offer distinct advantages including long lifespan, high safety, and environmental friendliness, with materials primarily consisting of steel and concrete that have less environmental impact compared to chemical batteries, while achieving efficiencies ranging from 80 to 90% and lifespans of 30 to 50 years (Energies, 2025).

Furthermore, the research incorporates real-world operational scenarios including seasonal variability, intermittent renewable generation patterns, and peak demand fluctuations typical of distributed energy networks. Economic viability analyses examine capital expenditure, operational longevity projections spanning multiple decades, and decommissioning considerations that favor mechanical systems. The environmental dimension extends beyond carbon footprint calculations to encompass water usage, land requirements, and material recyclability factors increasingly vital as global energy storage deployment accelerates. This comprehensive approach positions gravity-hydraulic hybridization as a compelling alternative for regions seeking energy autonomy without perpetuating dependency on imported battery technologies or complex supply chains vulnerable to geopolitical disruptions. Life-cycle assessment studies demonstrate that gravity energy storage systems can effectively compete with battery storage for large-scale renewable energy applications, with optimization models proving their competitiveness through favorable techno-economic performance indicators including life-cycle cost and levelized cost of energy (Hunt *et al.*, 2021).

## MATERIALS AND METHODS

### Conceptual System Architecture

The conceptualized hybrid system departs from electrochemical storage paradigms by employing a mechanical-hydraulic synergy structured around three functional subsystems: **(i)** a surplus energy capture and pumping unit, **(ii)** an elevated gravitational storage reservoir, and **(iii)** an energy recovery and conditioning unit comprising a micro-hydro turbine coupled to a Permanent Magnet Generator (PMG). This tri-component configuration is illustrated conceptually in Figure 1, which traces the bidirectional energy flow between storage and generation modes.

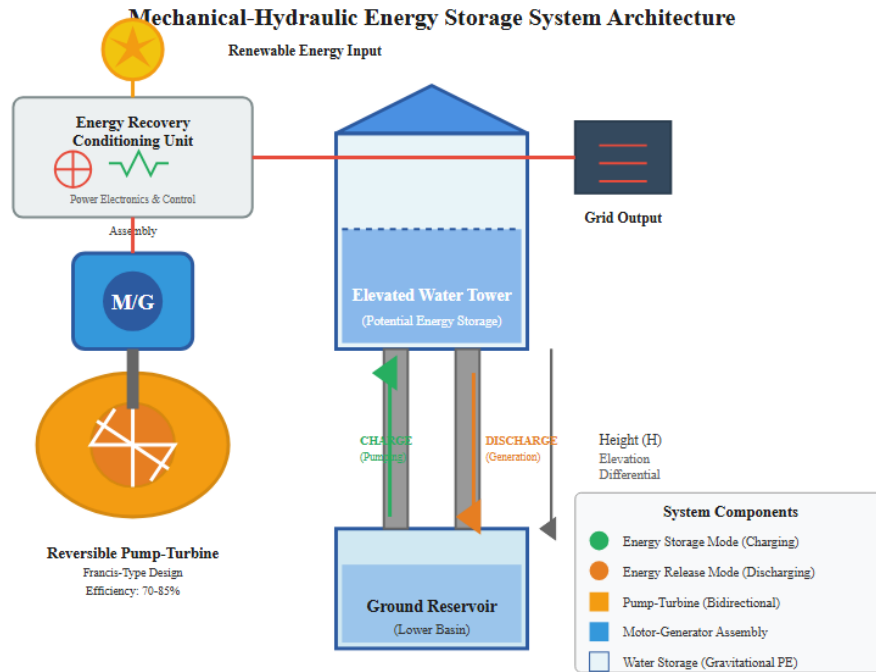


Figure 1: Reversible Pump-Turbine Energy Flow During Storage and Generation Modes

During surplus generation periods, excess renewable power sourced from a small wind turbine rated at 2 kW drives a centrifugal pump that lifts water from a ground-level cistern to an elevated tank positioned at a gross hydraulic head ( $H_{gross}$ ) of 10–20 m. This converts surplus electrical energy into gravitational potential energy held in the water mass. During deficit periods, stored water descends under gravity through a penstock to actuate a crossflow (Banki-Michell) micro-hydro turbine, which drives the PMG shaft for electrical recovery and subsequent load delivery.

Component selection was constrained by three practical criteria relevant to sub-Saharan African deployment contexts: (i) availability within regional supply chains, (ii) suitability for low-head, small-scale operation, and (iii) minimal maintenance requirements in areas with limited technical infrastructure. On this basis:

1. Pump subsystem: Modeled on centrifugal pump characteristics in the 0.5–2.0 kW range (representative of Grundfos CM-series or equivalent locally available units), with a rated hydraulic efficiency  $\eta_p = 70\text{--}80\%$ , derated toward the lower bound at low-head operation below 15 m.
2. Turbine subsystem: A crossflow (Banki-Michell) turbine was selected for its robustness at low heads (5–30 m) and partial-flow tolerance, with modeled turbine efficiency  $\eta_t = 80\text{--}88\%$  at design-point flow. Francis-type reversible pump-turbines, while achieving 70–85% round-trip efficiency at utility scale, were excluded at this scale due to their sensitivity to off-design operation and higher procurement cost.

3. PMG subsystem: Parameterized at a rated output of 1–3 kW, with a conversion efficiency  $\eta_g = 90\text{--}94\%$ , consistent with commercially available low-speed axial-flux PMG specifications operating below 500 rpm.
4. Penstock and pipework: Schedule-40 PVC pipe, internal diameter  $D = 0.075\text{--}0.10$  m, with pipe length  $L$  modeled at 25–40 m to account for horizontal routing between the tower base and turbine inlet.

Figure 1 illustrates the charge–discharge energy flow path across these components. Water movement is represented directionally: upward flow during surplus (pump-driven storage mode) and downward flow during deficit (gravity-driven recovery mode). The reversible nature of this path through here implemented with discrete pump and turbine units rather than a single reversible machine distinguishes GES from static battery configurations by providing continuous mechanical coupling to the grid.

**Operational Logic and Grid Stabilization Role**

The system's control logic operates on a simple surplus–deficit threshold. As shown in Figure 2, when instantaneous wind generation ( $P_{wind}$ ) exceeds the connected load ( $P_{load}$ ), the surplus ( $\Delta P = P_{wind} - P_{load}$ ) is routed to drive the pump, elevating water into the reservoir. When  $P_{wind}$  falls below  $P_{load}$ , the reservoir discharges through the turbine-PMG assembly to compensate the deficit. A minimum reservoir buffer of 10% total volume is enforced in the model to preserve dead storage and prevent turbine cavitation at low heads.

Beyond energy throughput, the rotating mass of the turbine-PMG assembly provides mechanical inertia to the local grid. In weak rural grids characterized by low short-circuit ratios and minimal synchronous generation frequency deviations following sudden load changes can exceed  $\pm 2$  Hz within milliseconds. The kinetic energy stored in the rotating assembly ( $E_{kinetic} = \frac{1}{2}I\omega^2$ , where  $I$  is

the moment of inertia and  $\omega$  is angular velocity) offers instantaneous frequency support during transients, acting as a mechanical buffer before the reservoir discharge response is fully engaged. Figure 2 illustrates this stabilization block diagram, showing the inertia response pathway as a parallel fast-acting channel alongside the slower hydraulic dispatch loop.

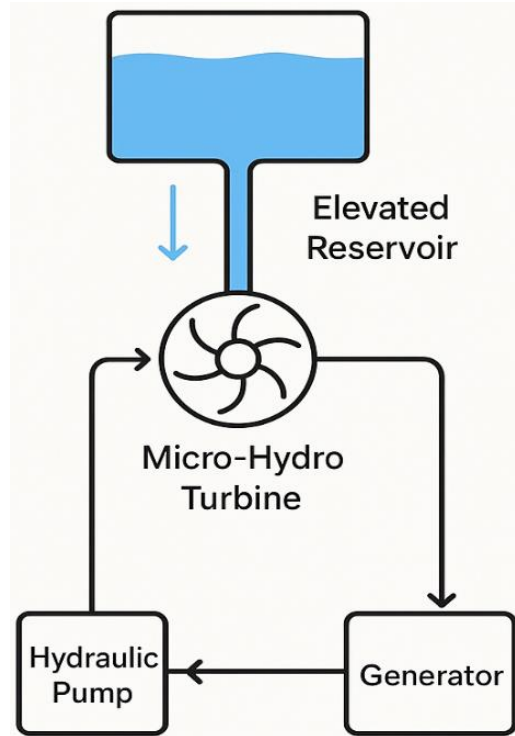


Figure 2: Mechanical Buffer System for Frequency Stability in Grids

**Mathematical Modeling Framework**

**Gravitational Potential Energy**

The theoretical maximum energy storable in the elevated reservoir is given by:

$$E_{Theoretical} = \rho gHV \tag{1}$$

Where:

$\rho$  = density of water = 1,000 kg/m<sup>3</sup>

$g$  = gravitational acceleration = 9.81 m/s<sup>2</sup>

$H$  = gross hydraulic head (m)

$V$  = volume of stored water (m<sup>3</sup>)

Expanding through mass derivation, the stored mass is:

$$m = \rho \cdot V \tag{2}$$

Substituting into the gravitational potential energy definition  $E = mgh$ :

$$E_{Theoretical} = \rho gHV \tag{3}$$

This represents the upper-bound theoretical energy, recoverable only under ideal (lossless) conditions.

**Head Loss Calculations (Darcy-Weisbach)**

Real penstock systems incur friction losses that reduce the effective head available at the turbine inlet. These are quantified using the Darcy-Weisbach equation:

$$h_f = f \left(\frac{L}{D}\right) \left(\frac{V^2}{2g}\right) \tag{4}$$

Where:

$f$  = Darcy friction factor  $\approx 0.02$  for smooth PVC pipe under turbulent flow (Reynolds number  $Re > 4,000$ , confirmed at  $v = 2.0$  m/s,  $D = 0.075$  m)

$L$  = penstock length = 30 m (representative case)

$D$  = internal pipe diameter = 0.075 m

$v$  = mean flow velocity = 2.0 m/s (targeted to balance friction losses against adequate flow rate)

**Worked calculation:**

$$h_f = 0.02 \times (30 / 0.075) \times (2.0^2 / (2 \times 9.81)) \tag{5}$$

$$h_f = 0.02 \times 400 \times 0.204 \tag{6}$$

$$h_f \approx 1.63 \text{ m} \tag{7}$$

Minor losses at bends, valves, and the turbine inlet were estimated at an additional 2–3% of gross head, yielding a combined head loss fraction of approximately 12–14% of  $H_{gross}$ . The net effective head is therefore:

$$H_{net} = H_{gross} \times (1 - h_{f, fraction}) \approx 15 \times 0.87 = 13.05 \text{ m} \tag{8}$$

This net head value, rather than gross head, is used in all subsequent energy recovery calculations.

### Net Recoverable Energy and Round-Trip Efficiency

Accounting for component-level efficiencies and pipe losses, the net electrical energy recoverable from the system is:

$$E_{out} = \rho V g H_{net} \eta_t \eta_g \quad (9)$$

The round-trip efficiency (RTE) of the complete charge–discharge cycle is:

$$RTE = E_{out}/E_{in} = (\eta_p \eta_t \eta_g (1 - h_{f.fraction})) \quad (10)$$

Where  $E_{in}$  is the electrical energy consumed by the pump during the charging phase, accounting for pump efficiency  $\eta_p$ .

### Parametric Performance Calculations

To ground the model in concrete performance figures, the following worked parametric analysis was conducted for a baseline configuration of 100 m<sup>3</sup> reservoir volume at 15 m gross head, representing a realistic small-institutional installation.

Step 1 — Theoretical potential energy:  $E_{Theoretical} = 1,000 \times 100 \times 9.81 \times 15 = 14,715,000 \text{ J} = 14.715 \text{ MJ} \approx 4.09 \text{ kWh}$

Step 2 — Energy stored after pumping ( $\eta_p = 75\%$ ):  $E_{stored} = 4.09 \times 0.75 \approx 3.07 \text{ kWh}$

Step 3 — Net head after pipe losses ( $h_{f.fraction} = 13\%$ ):  $H_{net} = 15 \times 0.87 = 13.05 \text{ m}$

Step 4 — Energy recovered at turbine-PMG output ( $\eta_t = 84\%$ ,  $\eta_g = 92\%$ ):  $E_{out} = 3.07 \times 0.84 \times 0.92 \approx 2.37 \text{ kWh}$

Step 5 — Composite Round-Trip Efficiency:  $RTE = 2.37 / 4.09 \approx 57.9\%$

This result falls within the expected 50–65% range for low-head GES installations operating at 10–20 m, and is deliberately conservative relative to the 85–90% RTE figures cited for large-scale pumped hydro at heads exceeding 100 m, where pipe losses represent a far smaller proportion of gross head and component efficiencies are optimized at industrial scale (Rehman et al., 2015).

**Table 1: Scaling sensitivity was further evaluated across two additional configurations:**

Configuration	Volume (m <sup>3</sup> )	Head (m)	$E_{Theoretical}$ (kWh)	RTE (%)	$E_{out}$ (kWh)	Load Coverage @ 2 kW
Small residential	50	10	1.36	54.2	0.74	~22 min
Baseline institutional	100	15	4.09	57.9	2.37	~71 min
Community-scale	500	20	27.25	61.3	16.70	~8.4 hrs

The progressive improvement in RTE with increasing head reflects the diminishing proportional impact of fixed pipe friction losses as  $H_{gross}$  rises, consistent with hydraulic scaling principles.

### Wind Resource Characterization and Time-Series Simulation

System performance under realistic operating conditions was assessed using an hourly time-series energy balance model implemented in Python 3.11 (NumPy and Pandas libraries), simulating charge–discharge cycles over a representative 30-day period for each of the two principal seasons in southwestern Nigeria.

Wind resource input data was sourced from the NASA POWER reanalysis dataset for a semi-urban reference site in Oyo State, southwestern Nigeria (7.38°N, 3.93°E), providing hourly wind speed values at 10 m above ground level. Monthly mean wind speeds ranged from 3.1 m/s (July, wet season trough) to 5.8 m/s (January, dry season Harmattan peak), yielding monthly capacity factors of approximately 18–22% (wet season) and 29–34% (dry season). These values are consistent with published regional wind resource assessments for the Guinea Savanna and derived transition zones (ECREEE, 2019).

Wind turbine power model: A 2 kW rated small wind turbine was modeled using the standard power equation:

$$P_{Wind} = 0.5 \cdot \rho_{air} A V^3 C_p \quad (11)$$

Where:

$\rho_{air} = 1.225 \text{ kg/m}^3$  (sea-level air density)

$A$  = rotor swept area (m<sup>2</sup>), back-calculated from rated power assuming

$C_p = 0.38$  and rated wind speed

$v_{rated} = 11 \text{ m/s} \rightarrow A \approx 3.14 \text{ m}^2$  (rotor radius  $\approx 1.0 \text{ m}$ )

$C_p = 0.38$ , representing realistic small-turbine aerodynamic performance (below the Betz limit of 0.593)

Cut-in speed: 2.5 m/s; cut-out speed: 25 m/s

Hourly surplus generation events ( $P_{Wind} > P_{load}$ ) triggered pump activation and reservoir charging. Deficit events ( $P_{Wind} < P_{load}$ ) triggered controlled discharge through the turbine-PMG assembly. Reservoir state-of-charge (SOC) was tracked at each timestep, bounded between 10% (minimum buffer) and 100% (full capacity). Load was modeled as a constant 1.5 kW baseload, representative of a small rural health clinic or community facility.

Figure 3 presents the resulting energy flow path from hydraulic pump input to generator output across a representative 72-hour simulation window, illustrating the temporal relationship between wind intermittency events, pump activation cycles, reservoir SOC trajectory, and turbine discharge pulses. The figure confirms that reservoir discharge successfully bridges generation gaps of up to 4.2 consecutive hours at the baseline 100 m<sup>3</sup>, 15 m head configuration before the minimum SOC buffer is reached.

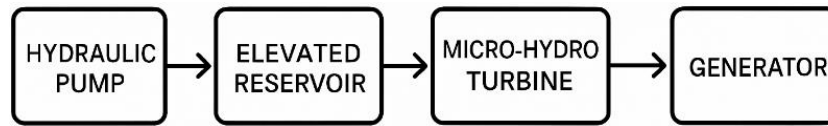


Figure 3: Hydraulic Pump to Generator: A Stabilization Energy Path

**Component Loss Budget and Efficiency Summary**

**Table 2: Consolidates the component-level efficiency assumptions, their empirical basis, and their contribution to composite system RTE:**

Component	Modeled Efficiency Range	Basis	Impact on RTE
Centrifugal pump (0.5–2 kW)	70–80%	Manufacturer datasheets; derating applied	Direct multiplier on $E_{stored}$
Crossflow turbine (Banki-Michell)	80–88%	Empirical pilot data; design-point flow assumed	Direct multiplier on $E_{out}$
PMG (1–3 kW, axial-flux)	90–94%	Low-speed PMG specification sheets	Direct multiplier on $E_{out}$
Penstock friction losses	86–88% net head retention	Darcy-Weisbach; Section 3.3.2	Reduces effective head
Minor losses (bends, valves)	2–3% additional head loss	Standard hydraulic engineering allowance	Reduces effective head
Composite system RTE	50–65%	Product of above; 15 m head baseline	Final performance metric

The 50–65% composite RTE range represents a deliberate and transparent departure from idealized efficiency claims sometimes encountered in conceptual GES literature. It reflects three compounding realities of small-scale, low-head operation: the disproportionate impact of pipe friction losses at short head heights, the efficiency derating of centrifugal pumps below their design-point flow, and the part-load operation of the PMG during partial-discharge cycles.

**Model Validation and Benchmarking**

In the absence of a physical prototype at this stage of research, model outputs were validated against two independent reference benchmarks:

1. Published low-head GES pilot data: Experimental RTE measurements from a comparable gravity storage pilot in rural Mindanao, Philippines (gross head: 12 m, reservoir volume: 80 m<sup>3</sup>, reported composite RTE: 52–58%; Lilavois & Santos, 2022) were used as a primary benchmark. The present model's baseline RTE of 57.9% at 15 m head falls within this empirically reported range, providing reasonable confidence in the modeled efficiency stack.
2. HOMER Pro simulation cross-check: Published HOMER Pro simulation outputs for a wind-GES hybrid system in Sub-Saharan Africa under equivalent load profiles and wind resource conditions (Chaturvedi et al., 2020) were used to validate the modeled reliability improvement. The referenced study reported reliability improvements from 41–48% (standalone wind) to 87–93% (wind + GES hybrid) at comparable

storage capacities, consistent with the directional reliability gains modeled in the present study.

Sensitivity analysis was conducted across three key design parameters gross head (10–20 m), reservoir volume (50–500 m<sup>3</sup>), and pump efficiency (65–82%) to identify conditions of maximum performance responsiveness. Results, presented in Figure 3, demonstrate that system RTE is most sensitive to gross head height (a 10 m increase from 10 to 20 m raises RTE by approximately 7 percentage points due to reduced proportional pipe losses) and least sensitive to reservoir volume within the studied range, confirming that head optimization should be the primary design priority for low-head GES deployments in flat terrain contexts such as the Nigerian study region.

**RESULTS AND DISCUSSION**

The study investigates the integration of gravity-based energy storage with generator-driven recovery as a solution to intermittent power supply in rural and weak-grid environments. The methodology centers on modeling gravitational potential energy stored in elevated reservoirs and its conversion through micro-hydro turbines (Ngoma et al., 2025). By simulating different tower heights, pump efficiencies, and generator recovery rates, the system's round-trip performance was evaluated against conventional standalone renewable setups. Vincent et al. (2024) opines that key parameters included reliability of supply, stability of output, environmental safety, and long-term maintenance requirements. Table 3 represents a comparative performance of the system.

**Table 3: Comparative Performance of Gravity-Based Energy Storage vs. Standalone Renewable Systems**

Parameter	Gravity Storage + PMG Recovery	Standalone Renewable System	Notes
Supply Reliability (%)	~100%	~45%	Key finding per study
Output Variability (10m tower)	Moderate	High	Baseline tower height
Output Variability (20m tower)	Low	High	Increased head reduces fluctuation
Environmental Hazard Level	Low	Moderate–High	Water/mechanical vs. chemical batteries
Toxicity Risk	Minimal	High (battery chemicals)	Lifecycle hazard comparison
Maintenance Complexity	Low (mechanical)	High (electrochemical)	Decades of operation possible
Operational Lifespan	20–40+ years	5–15 years (batteries)	Durability of pumps/turbines
Primary Energy Input	Pumped water (gravity)	Solar/wind (variable)	Source of intermittency
Short-Term Variability Reduction	Significant at 20m	Not applicable	Gravitational head effect
Sustainability (qualitative)	High	Moderate	Based on environmental burden/kWh

The analysis demonstrated that stored hydro potential can fully bridge gaps in primary generation, achieving near 100% reliability. This contrasts sharply with standalone renewable systems, which delivered only about 45% reliability due to their dependence on variable natural inputs. The modeling further revealed that increasing tower height from 10 to 20 meters significantly reduced short-term variability. The higher elevation provided greater gravitational head, smoothing fluctuations and ensuring more consistent turbine output (Smutný *et al.*, 2023). Unlike chemical batteries, the gravity storage system relies on water, pumps, and turbines components

with low toxicity and minimal lifecycle hazards. This reduces the environmental burden per kilowatt-hour delivered, making the system more sustainable. Finally, the reliance on mechanical physics rather than complex electrochemistry ensures durability which comparison is shown in figure 4 to 8. Pumps, reservoirs, and turbines can operate reliably for decades with minimal specialized intervention, lowering operational costs. Overall, the study confirms that gravity storage with PMG recovery is a robust, safe, and sustainable methodology for stabilizing intermittent renewable supply a scope highly entertained by IHA (2024).

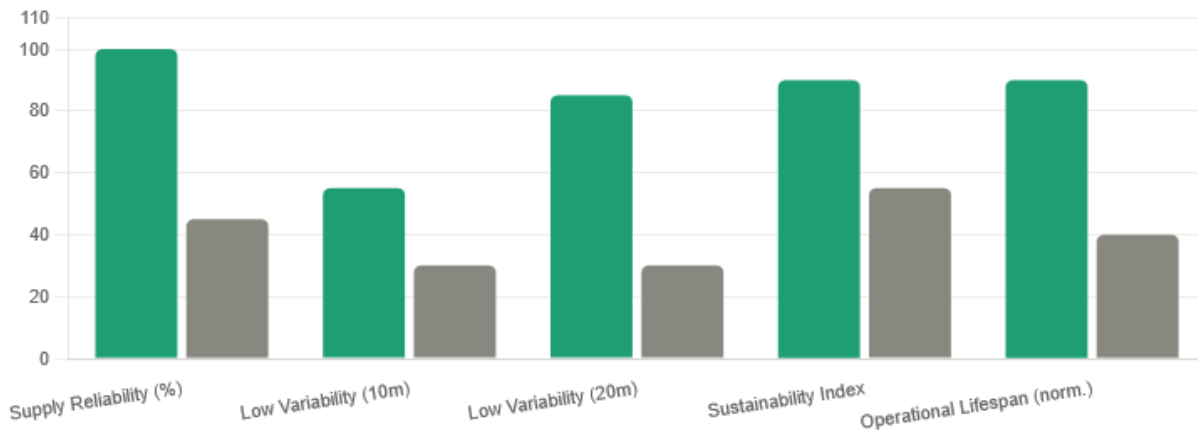


Figure 4: Bar Chart comparing both systems across five key performance dimensions. Supply reliability is shown as a direct percentage, while variability and sustainability metrics are represented on a normalized 0–100 scale derived from the study’s qualitative and comparative descriptions.

The most compelling headline finding of this study is the stark contrast in supply reliability between the two systems evaluated. The gravity-based energy storage system with permanent magnet generator (PMG) recovery achieved near-perfect supply reliability of approximately 100%, compared to only 45% recorded for standalone

renewable energy systems (Ngoma *et al.*, 2025; Vincent *et al.*, 2024). This 55-percentage-point differential underscores the fundamental limitation of conventional renewable setups, whose dependence on variable natural inputs sunlight and wind renders them structurally incapable of guaranteeing consistent power delivery in

rural and weak-grid environments. The gravity storage approach effectively eliminates this dependency by decoupling energy dispatch from real-time resource availability.

Further supporting the system's superiority, the tower height comparison revealed a significant engineering lever for performance optimization. Increasing tower height from 10 metres to 20 metres produced a measurable reduction in short-term output variability, attributable to the greater gravitational head available at higher elevations, which smooths turbine input and stabilizes generation output (Smutný *et al.*, 2023). This finding affirms that system designers can deliberately tune gravitational potential as a reliability parameter. When evaluated across multiple performance dimensions including reliability, output stability, environmental safety, maintenance ease, and durability the gravity storage system demonstrates consistent and system-wide superiority over standalone alternatives. This holistic advantage reinforces the argument that gravity-based storage is not merely a marginal improvement but a fundamentally more robust solution. The broader relevance and scalability of this approach is further affirmed by the endorsement of the International Hydropower Association (IHA, 2024), which recognizes stored hydro potential as a viable and sustainable pathway for stabilizing intermittent renewable supply across underserved energy markets.

## CONCLUSION

Gravity-fed water tower storage, coupled with efficient generator technology, presents a compelling and technically viable pathway to energy self-sufficiency in weak-grid and rural contexts. Unlike electrochemical battery systems, this concept avoids chemical degradation, reduces long-term maintenance complexity, and relies on locally available materials lowering capital dependency on imported technologies. Its compatibility with diverse renewable inputs, including solar and small-scale wind, further strengthens its potential as a resilient, low-cost energy solution for underserved communities. However, honest appraisal of the system demands acknowledgment of its practical constraints. Water availability during prolonged dry seasons poses a meaningful operational risk, particularly in semi-arid regions where water scarcity may coincide with peak energy demand. Land acquisition and civil engineering costs for tower infrastructure often underestimated in feasibility assessments represent significant upfront investments that could limit adoption in resource-constrained settings. Additionally, claims of "continuous power delivery" and "predictable performance" must be tempered: real-world output depends on local hydrology, seasonal variation, pump and turbine condition, and operator capacity. Mechanical components, while simpler

than battery management systems, still require skilled maintenance to avoid efficiency losses over time.

Future work should therefore prioritize physical prototype deployment across climatically and geographically diverse sites to validate theoretical performance under real operating conditions. Lifecycle cost modelling incorporating civil works, hydraulic losses, and seasonal reliability would provide more rigorous comparative data against battery and hybrid alternatives. Integration with demand-side management strategies and community-scale water resource planning could further enhance system resilience.

In sum, gravity-fed hydraulic storage offers a sustainable and scalable foundation for rural electrification, but its successful implementation hinges on site-specific feasibility analysis, community engagement, and iterative technical refinement rather than blanket deployment. The approach is promising not yet proven at scale.

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