Gravity Battery Energy Storage System: A Detailed Analysis

Saikat Mohanta
As an Independent Researcher
saikatmohantabkp@gmail.com

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Abstract

This paper presents a detailed analysis of a gravity-based energy storage system that employs a two-tank fluid configuration powered by solar pumping and discharged through a turbine–generator. A corrected mathematical framework is developed to model energy input, storage, and recovery, with emphasis on round-trip efficiency, hydrodynamic constraints, and realistic pipe sizing. The study highlights that renewable energy sources, while clean, often exhibit mismatched supply and demand curves and lack the inertia of conventional generation, creating stability challenges in grids with more than 70% renewable penetration. A representative case study for a continuous 100 kW output at a 50 m head shows that approximately $2.2 \times 10^4\,\mathrm{m}^3$ of fluid and large-diameter pipelines are required, highlighting scaling challenges but also confirming feasibility. Unlike mega dam-like structures, this approach is modular and practical for local communities, off-grid regions, or renewable-rich areas where continuous output, inertia, and eco-friendly operation are essential. The results show moderate efficiency (64%) but high sustainability, safety, and lifespan. Challenges remain in fluid handling, infrastructure cost, and land use, yet potential improvements include optimized flow control, higher heads, or denser working fluids. Overall, the system offers a non-hazardous, long-lasting, and environmentally sound option for long-duration renewable energy storage.

1 Introduction

Gravity-based energy storage stores electrical energy as gravitational potential energy by lifting mass (here: a working fluid) to an elevated reservoir. This work revisits the mathematical model presented in the provided manuscript, corrects derivations, recomputes system parameters for a representative case (100 kW continuous output), and produces an updated, publication-ready LaTeX document.

Renewable sources such as solar and wind are inherently variable and often produce supply and demand curves that are poorly aligned. In countries sourcing more than 70% of their electricity from renewables, the absence of mechanical inertia—normally provided by conventional rotating generators—presents a major challenge for grid stability. Gravity batteries directly address this gap by providing continuous output and inertial characteristics, without reliance on hazardous chemicals or large-scale dams.

2 System description

The system consists of two reservoirs separated by height Δh, a solar-powered DC pump that transfers fluid from the lower to the upper reservoir during solar hours, and a turbine/alternator that recovers electrical energy as fluid flows back down.

2.1 Notation

P_{sol}	instantaneous DC power available from solar panels (W)
$V_{\text{sol}}, I_{\text{sol}}$	solar array voltage and current (V, A)
P_{out}	required continuous AC output power (W)
$\eta_{\text{pump}},\ \eta_{\text{gen}}$	pump and generator (alternator+turbine) efficiencies
ρ	fluid density (kg m^{-3})
g	gravitational acceleration ($9.81\,\text{m}\,\text{s}^{-2}$)
Δh	vertical elevation difference between tanks (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Q	volumetric flow rate (m^3 s^{-1})
t_{day}	daylight (pump) duration (s)
$t_{\text{day,total}}$	total time of continuous operation (s)

3 Energy balance and efficiency

The solar panels produce an energy $E_{\text{sol}} = P_{\text{sol}}\,t_{\text{day}}$ during the charging window. A fraction of that electrical energy is consumed by the pump and converted to potential energy with pump efficiency η_{pump}. During discharge the turbine/alternator converts potential energy back to electrical energy with efficiency η_{gen}. Thus the round-trip electrical-to-electrical efficiency is

$$\eta_{\text{rt}} = \eta_{\text{pump}}\,\eta_{\text{gen}}. \tag{1}$$

To supply a required continuous electrical output P_{out} for $t_{\text{day,total}}$ seconds, the electrical energy delivered must be

$$E_{\text{out}} = P_{\text{out}}\,t_{\text{day,total}}. \tag{2}$$

The required potential energy that must be stored (at the top reservoir) to satisfy generation is the electrical output divided by the generator efficiency:

$$E_{\text{pot}} = \frac{E_{\text{out}}}{\eta_{\text{gen}}}. \tag{3}$$

The corresponding mass of fluid that must be elevated is therefore

$$M = \frac{E_{\text{pot}}}{g\,\Delta h} = \frac{E_{\text{out}}}{\eta_{\text{gen}}\,g\,\Delta h}. \tag{4}$$

Instantaneous mass flow rate during discharge satisfies

$$P_{\text{out}} = \dot{m}\,g\,\Delta h\,\eta_{\text{gen}} \quad \Rightarrow \quad \dot{m} = \frac{P_{\text{out}}}{g\,\Delta h\,\eta_{\text{gen}}}. \tag{5}$$

Volumetric flow rate is $Q = \dot{m}/\rho$.

If the pumping (charging) occurs during a shorter window t_{pump} (for example daytime hours) then the pump must transfer the total required volume $V_{\text{tot}} = Q\,t_{\text{day,total}}$ in time t_{pump}, giving a required pump volumetric flow rate

$$Q_{\text{pump}} = Q\frac{t_{\text{day,total}}}{t_{\text{pump}}}. \tag{6}$$

In the common case $t_{\text{day,total}} = 24\,\text{h}$ and $t_{\text{pump}} = 12\,\text{h}$, $Q_{\text{pump}} = 2Q$.

4 Hydrodynamic design and pipe sizing

Given a target mean velocity v in a pipe, the pipe cross-sectional area required is $A = Q/v$ and the pipe internal diameter is

$$D = \sqrt{\frac{4Q}{\pi v}}. \tag{7}$$

Reynolds number for a circular pipe of hydraulic diameter D is

$$\mathrm{Re} = \frac{\rho v D}{\mu}, \tag{8}$$

and flow is considered laminar (streamlined) when Re< 2000.

5 Representative numerical example

We recompute the numerical example from the supplied manuscript using corrected notation and arithmetic. The design specification is:

- Required continuous AC output: $P_{\mathrm{out}} = 100\,\mathrm{kW}$.
- Continuous operation time: $t_{\mathrm{day,total}} = 24\,\mathrm{h} = 86400\,\mathrm{s}$.
- Charging (pump) window: $t_{\mathrm{pump}} = 12\,\mathrm{h} = 43200\,\mathrm{s}$.
- Generator efficiency: $\eta_{\mathrm{gen}} = 0.8$.
- Pump efficiency: $\eta_{\mathrm{pump}} = 0.8$.
- Elevation difference: $\Delta h = 50\,\mathrm{m}$.
- Fluid density: $\rho = 1000\,\mathrm{kg\,m^{-3}}$ (water-like fluid).

Compute the required mass flow rate during discharge:

$$\dot{m} = \frac{P_{\mathrm{out}}}{g\,\Delta h\,\eta_{\mathrm{gen}}} = \frac{100 \times 10^3}{9.81 \times 50 \times 0.8} \tag{9}$$

$$\approx 254.84\,\mathrm{kg\,s^{-1}}. \tag{10}$$

The corresponding volumetric flow rate during discharge is

$$Q = \frac{\dot{m}}{\rho} \approx 0.254\,84\,\mathrm{m^3\,s^{-1}}. \tag{11}$$

Total elevated volume per 24-hour operating period is

$$V_{\mathrm{tot}} = Q\,t_{\mathrm{day,total}} \approx 22\,018\,\mathrm{m^3}. \tag{12}$$

If charging occurs during a 12-hour window then the pump must provide

$$Q_{\mathrm{pump}} = 2Q \approx 0.509\,68\,\mathrm{m^3\,s^{-1}}. \tag{13}$$

Assuming target mean velocities $v_{\mathrm{up}} = 0.1\,\mathrm{m\,s^{-1}}$ for the pump pipe and $v_{\mathrm{down}} = 0.2\,\mathrm{m\,s^{-1}}$ for the turbine pipe, the required internal diameters are

$$D_{\mathrm{pump}} = \sqrt{\frac{4Q_{\mathrm{pump}}}{\pi v_{\mathrm{up}}}} \approx 2.55\,\mathrm{m}, \tag{14}$$

$$D_{\mathrm{down}} = \sqrt{\frac{4Q}{\pi v_{\mathrm{down}}}} \approx 1.27\,\mathrm{m}. \tag{15}$$

Remark: These diameters are orders of magnitude larger than the millimetre-scale values stated in the original manuscript and are consistent with the large daily volumes ($2.2 \times 10^4\,\mathrm{m}^3$) required to deliver 100 kW continuously at 50 m elevation. The earlier numbers in the manuscript appear to have been a units/decimal-point error.

6 Power requirements

The pump electrical power required (steady-state) to produce the pump volumetric flow Q_{pump} against gravity is

$$P_{\mathrm{pump}} = \frac{\rho\, g\, \Delta h\, Q_{\mathrm{pump}}}{\eta_{\mathrm{pump}}}. \tag{16}$$

Using the numbers above,

$$P_{\mathrm{pump}} = \frac{1000 \times 9.81 \times 50 \times 0.5096839959}{0.8} \tag{17}$$

$$\approx 312\,500\,\mathrm{W} \;=\; 312.5\,\mathrm{kW}. \tag{18}$$

This implies the solar array must supply roughly 312.5 kW during pumping hours (neglecting other losses and parasitics) to meet the 24-hour, 100 kW continuous demand.

7 Comparison with lead-acid battery

A short qualitative comparison (improved clarity and units) is provided in Table 1.

Table 1: High-level comparison (qualitative).

Parameter	Gravity storage	Lead–acid battery
Lifespan	Long (20+ years)	Short (5–7 years)
Round-trip efficiency	Moderate (depends on efficiencies)	Typically higher (70–85
Environmental impact	Low (inert fluid)	High (toxic lead, recycling needed)
Maintenance	Low	Higher (electrolyte management)
Scalability	Good for large scale	Limited by chemistry and footprint

8 Discussion and practical notes

- The large tank volumes and pipe diameters are the principal engineering challenge for low-head (50 m) gravity storage when targeting continuous moderate powers (100 kW). Raising the head (making Δh larger) drastically reduces required volume and pipe size.
- Using denser working fluids reduces required volume proportionally, but introduces material, cost and pump/turbine compatibility considerations.
- The pump power requirement during charging (here, 312.5 kW) is larger than the continuous output because charging is compressed into fewer hours. If the pumping window is widened (longer pumping time), the instantaneous pump power requirement reduces.
- The round-trip efficiency here is $\eta_{\mathrm{rt}} = 0.64$ ($0.8{\times}0.8$), consistent with the original manuscript; improving component efficiencies improves both energy and power economics.

Practical deployment

The system is especially suited for regions where conventional grid access is limited, where renewable penetration is high, or where local communities need continuous, low-impact energy. Unlike mega-structures such as hydroelectric dams, the modular tank-and-pump configuration can be scaled to match local demand and geography, powered by solar, wind, or even limited grid availability for pumping. This makes it attractive for rural electrification, islanded grids, and community-level microgrids.

Advantages

Key benefits include:

- Provision of inertia and stabilizing continuous output to complement renewables,
- Minimal ecological impact and no toxic or hazardous materials,
- Long operational lifespan with low maintenance,
- Compatibility with variable renewable inputs.

Challenges and potential improvements

Despite these advantages, challenges include the large fluid volumes and infrastructure requirements at low elevation heads, capital costs of large tanks and pipelines, and the need for site-specific geographic suitability. Potential improvements involve:

- Increasing elevation head to reduce volume requirements,
- Employing denser working fluids to lower tank sizes,
- Integrating AI-based flow and pump control for higher round-trip efficiency,
- Developing hybrid models that combine gravity storage with electrochemical batteries for flexibility.

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Independent researcher: Saikat Mohanta. ! Lets work together for a better future !