

Renewable Gravity Battery with Embedded Battery Management System: Design, Fabrication, and Experimental Validation of a Solar-Coupled Gravitational Energy Storage Prototype

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Abstract—The accelerating global transition toward variable renewable energy sources imposes critical demands on long-duration, low-cost, and environmentally benign energy storage infrastructure. Conventional electrochemical batteries—principally lithium-ion (Li-ion) and lead-acid—exhibit fundamental limitations in cycle life, chemical toxicity, critical mineral dependency, and fire hazard that restrict their suitability for grid-scale and long-duration storage. This paper presents the design, fabrication, embedded control, and experimental validation of a Renewable Gravity Battery (RGB) prototype: a gravitational potential energy storage device powered by a monocrystalline solar photovoltaic (PV) array and governed by a purpose-designed embedded Battery Management System (BMS). During charging, surplus PV energy drives a 12 V DC gear motor to elevate a 22 kg counterweight through 1.2 m; during discharging, gravity-driven descent of the counterweight actuates the motor in regenerative mode to supply electrical loads. A three-stage spur gear train (gear ratio 4.5:1) reduces motor speed from 60 rpm to 13.3 rpm, producing a rope linear velocity of 18.37 mm/s and a rope-drum output torque of 38.25 kg·cm, providing a 22% safety margin above the 29.7 kg·cm static load requirement. The embedded BMS implements closed-loop charge–discharge mode switching, output voltage regulation, real-time gravitational state-of-charge (SoC) indication, and fail-safe electromechanical braking. Prototype characterisation confirmed a theoretical stored energy of 258.99 J (0.072 Wh), a measured discharge duration of 10–12 s at 9–10 W output (round-trip efficiency \approx 68%), and a self-discharge rate of 0% under brake engagement over 15 minutes of observation. These results validate the RGB architecture as a chemically inert, zero self-discharge, mechanically scalable complement to

electrochemical storage for micro-grid and off-grid renewable energy applications.

Index Terms—gravity energy storage; gravitational potential energy; renewable energy; battery management system; solar photovoltaic; Mountain Gravity Energy Storage; micro-grid; state of charge; DC gear motor; round-trip efficiency.

I. INTRODUCTION

The global power sector is undergoing an unprecedented structural transition driven by the imperative to decarbonise electricity generation and mitigate anthropogenic climate change. Variable renewable energy (VRE) sources—principally wind turbines and solar photovoltaic (PV) arrays—now represent the fastest-growing segment of new generation capacity worldwide, with the International Renewable Energy Agency (IRENA) projecting that VRE must constitute over 90% of total electricity supply by 2050 to meet the Paris Agreement 1.5 °C target [15]. However, the inherently stochastic and diurnal nature of these resources imposes critical constraints on power-system stability: instantaneous generation may far exceed demand during resource-rich periods and fall sharply below it at night or in calm weather. Bridging this temporal supply–demand mismatch demands robust, scalable, and economically viable energy storage infrastructure.

Conventional electrochemical storage technologies—principally lithium-ion (Li-ion) and lead-acid batteries—currently dominate the short-duration

storage market. Li-ion cells exhibit a practical cycle life of approximately 2,000–3,000 full charge–discharge cycles before capacity degrades to 80% of nominal rating, equivalent to roughly 5–8 years in daily-cycling service [15]. Beyond performance constraints, Li-ion chemistries rely on critical minerals including cobalt, nickel, manganese, and lithium, whose extraction imposes geopolitical supply-chain risks and significant environmental burdens at mining and end-of-life stages. Lead-acid technology suffers from even shorter cycle life, higher gravimetric mass, and well-documented toxicological hazards from lead and sulfuric acid.

Gravity-based energy storage systems (GBES) represent a fundamentally distinct technological paradigm that circumvents these electrochemical limitations. In a GBES, electrical energy is converted to gravitational potential energy by elevating a solid mass against Earth's gravitational field; energy is recovered when the mass descends and drives a motor operating in regenerative (generator) mode. The underlying physics are defined by:

$$E = m \cdot g \cdot h \quad (1)$$

where E is stored energy (J), m is counterweight mass (kg), $g = 9.81 \text{ m/s}^2$ is the standard gravitational acceleration, and h is vertical displacement (m). Because energy is stored as macroscopic mechanical configuration rather than chemical state, GBES systems exhibit negligible self-discharge, no electrochemical degradation, no hazardous material exposure, and component lifetimes spanning 40–60 years [9].

The most commercially mature GBES implementation is pumped-storage hydroelectricity (PSH), which accounts for over 90% of global installed electricity-storage capacity. However, PSH is constrained by stringent topographic and hydrological prerequisites, precluding deployment in isolated micro-grids, small islands, and arid regions [3]. Emerging solid-mass gravity systems—suspended-weight towers, rail-mounted wagons, underground shaft mechanisms, and Mountain Gravity Energy Storage (MGES) configurations—offer identical physical principles without requiring large water reservoirs, substantially broadening geographic applicability.

This paper presents the design, fabrication, embedded control, and experimental characterisation of a bench-scale Renewable Gravity Battery (RGB) prototype: a solar PV-coupled gravitational storage device incorporating a purpose-designed embedded BMS. The key contributions of this work are: (i) a complete system-level design methodology for solar-coupled gravity storage at laboratory scale; (ii) a novel embedded BMS architecture addressing the control requirements specific to gravitational storage dynamics—including closed-loop voltage regulation and gravitational SoC estimation; and (iii) quantitative experimental results validating the RGB architecture under controlled operating conditions.

A. Motivation

Existing gravity storage literature confirms techno-economic feasibility at utility scale (50–100 USD/MWh stored; 1–2 MUSD/MW installed capacity) but provides limited treatment of the embedded control systems required for autonomous, safe, and efficient operation [3]. Manual operation of gravity storage is impractical in grid-tied or off-grid deployments because it cannot reliably enforce constant output voltage across the full discharge stroke, regulate discharge current under variable load, or deliver quantitative SoC estimation from gravitational position data. The present work directly addresses this gap.

B. Objectives

The specific objectives are:

- Store solar PV electrical energy as gravitational potential energy in a chemically inert, zero-carbon counterweight mechanism.
- Design and implement an embedded BMS providing autonomous charge–discharge switching, output voltage regulation, SoC indication, and regenerative braking.
- Fabricate a low-cost prototype from commercially available components demonstrating economic competitiveness relative to electrochemical storage.
- Quantify prototype performance via controlled measurement of charging duration, discharge power, round-trip efficiency, and self-discharge rate.
- Establish a validated design foundation for scale-up to micro-grid applications in the 1–20 MW range.

II. LITERATURE REVIEW

Research into gravity-based energy storage has expanded substantially over the past decade, motivated by growing recognition of the limitations of electrochemical storage for long-duration applications. This section surveys key contributions in four thematic areas.

A. Foundational GBES Concepts

Hunt et al. [3] introduced the MGES concept as a mechanism for bridging the gap between short-duration battery storage and long-duration PSH. MGES transports granular media (sand or gravel) from a lower reservoir to an elevated site via motor-driven conveyors, then recovers energy through gravity-driven descent. The authors established a levelised cost of storage of 50–100 USD/MWh and demonstrated through techno-economic modelling that MGES is particularly competitive for micro-grids with demand below 20 MW and seasonal storage requirements—conditions prevalent on small islands and in isolated rural communities. Morstyn and Botha [8] provided a comprehensive taxonomy of gravitational storage with weights, distinguishing suspended-weight, rail, piston-in-cylinder, and underground shaft designs, and emphasising that all solid-mass GBES variants share high round-trip efficiency (80–90%), negligible self-discharge, and mechanical simplicity. Franklin et al. [9] reviewed GBES in the broader storage landscape, noting that the absence of chemical degradation confers a decisive lifecycle advantage in applications requiring service lives exceeding 20 years, and identifying decommissioned mining infrastructure as a largely untapped resource for gravity storage deployment.

B. Utility-Scale and Commercial Developments

Karuppiah et al. [4] surveyed commercial gravity storage ventures, noting that Energy Vault's EV_xTM system achieved the first utility-scale, non-pumped-hydro gravity storage deployment in China in 2023 at 25 MW/100 MWh capacity, with reported round-trip efficiencies of 80–85%. Gravitricity Ltd. (Edinburgh, UK) and Green Gravity (Australia) have independently demonstrated underground shaft-based systems using suspended steel weights of 500–5,000 tonnes; Green Gravity's pilot projects in the Illawarra region of New South Wales employ 60–80 tonne

weights in decommissioned coal mine shafts. Berrada, Loudiyi, and Zorkani [11–13] conducted detailed economic analyses of GES systems, demonstrating positive net present values over 25-year project lifetimes when sited in locations with high VRE penetration and elevated electricity costs—precisely the conditions characteristic of island micro-grids.

C. Small-Scale Gravity Battery Research

Bowoto, Emenuvwe, and Azadani [1] investigated gravitricity-based storage for residential PV-coupled applications, identifying motor-generator selection and gearing ratio as the dominant efficiency factors at sub-kilowatt scales. Patil et al. [2] validated the core operational concept of a wind-coupled gravity battery prototype while identifying automatic braking, controlled discharge velocity, and SoC monitoring as unresolved engineering challenges—observations that directly motivate the embedded BMS design in the present work. Lahure et al. [5] and Mishra et al. [6] independently reported undergraduate-laboratory gravity battery models, confirming near-zero self-discharge under brake engagement and round-trip efficiencies of 55–70%, but neither addressed embedded control for autonomous operation.

D. BMS Architectures for Gravity Storage

BMS architectures are well established for electrochemical batteries, where primary functions include cell balancing, SoC and state-of-health estimation, thermal management, and fault protection. Gravity storage requires an analogous supervisory controller, but with different sensing and actuation requirements. SoC corresponds directly to counterweight height, measurable via incremental encoders, ultrasonic range sensors, or optical limit switches—inherently simpler and more reliable than electrochemical SoC estimation. Output voltage regulation is non-trivial: as the counterweight descends, generator back-EMF varies with velocity, rope friction, and load current, necessitating active PWM control. Prior gravity battery prototypes relied on manual speed adjustment or unregulated output; the present work implements closed-loop voltage regulation as a specific BMS contribution.

III. SYSTEM DESIGN AND METHODOLOGY

A. Operational Principle

The RGB operates on a two-phase energy conversion cycle. During the charging phase, surplus PV energy drives a DC gear motor to wind a wire rope and elevate the counterweight from the lower rest position to the upper storage position, converting electrical energy to gravitational potential energy. During the discharging phase, the BMS releases the electromechanical brake; the counterweight descends under gravity, unwinding the rope and driving the motor in regenerative mode to supply electrical loads. The stored energy is given by Eq. (1). The prototype employs $m = 22$ kg, $h = 1.2$ m, yielding $E = 258.99$ J (0.0720 Wh)—sufficient to validate system architecture and BMS control logic at laboratory scale.

B. Mechanical Subsystem

The structural frame is fabricated from 30×30 mm mild-steel square hollow section channels, providing a 1.2 m vertical travel envelope. The counterweight assembly consists of a 25 kg cement block (22 kg operational mass), suspended by a 3 mm rubber-coated wire rope routed over a nylon U-shaped pulley, with ABS plastic BM8-series bearing holders and 628ZZ ball bearings at the rope shaft.

The gear train comprises three spur gears: a primary gear ($Z_1 = 54$ teeth) on the motor shaft, an intermediate idler pinion ($Z_2 = 12$ teeth), and an output gear ($Z_3 = 54$ teeth) coupled to the rope drum. The output pulley speed is:

$$N_p = N_m \times (Z_2 / Z_3) = 60 \times (12/54) \approx 13.3 \text{ rpm} \quad (2)$$

The rope drum diameter $d = 27$ mm gives a linear rope velocity of:

$$v_r = \pi \times d \times N_p / 60 = \pi \times 0.027 \times (13.3/60) \approx 18.37 \text{ mm/s} \quad (3)$$

The static gravitational force on the counterweight is $F = mg = 22 \times 9.81 = 215.82$ N. The torque required at the rope drum (radius $r = 13.5$ mm) is:

$$\tau_{req} = F \times r = 215.82 \times 0.0135 = 2.91 \text{ N}\cdot\text{m} \quad (29.7 \text{ kg}\cdot\text{cm}) \quad (4)$$

The gear train provides an effective ratio of $Z_3/Z_2 = 4.5$, amplifying the motor's rated output torque of 8.5 kg·cm to 38.25 kg·cm at the rope drum. This exceeds the 29.7 kg·cm requirement by 22%, accommodating rope friction, bearing losses, and acceleration inertia.

C. Electrical Power Subsystem

The solar PV source is a 12 V, 80 W monocrystalline panel (conversion efficiency ≈ 19 –21%). A 20 A PWM solar charge controller regulates PV output and provides maximum power point tracking. During charging, the controller output energises the DC gear motor; during discharging, a BMS-controlled relay routes generator output to the load bus. Measured charging power consumption was 12–15 W at ≈ 40 W simulated panel input; the discharging phase produced 9–10 W at 5–10 V DC terminal voltage.

D. Embedded Battery Management System

The embedded BMS is the supervisory controller that distinguishes the RGB from prior manual-operation gravity battery prototypes. Its functional requirements are:

- Charge-mode activation: motor energisation when PV power exceeds a threshold and gravitational SoC is below 100%.
- Discharge-mode activation: brake release and generator-load connection when load demand is detected and SoC exceeds a minimum threshold.
- Output voltage regulation: closed-loop PWM control to maintain constant 12 V DC across the full descent stroke under variable load.
- SoC indication: real-time display of counterweight height as percentage of full lift on onboard LCD/LED display.
- Fail-safe braking: immediate brake engagement upon detection of over-speed, overvoltage, or power failure.
- Mode interlocking: hardware isolation preventing simultaneous motor and generator operation.

The BMS microcontroller monitors motor back-EMF as a proxy for rope velocity, an optical limit-switch array for SoC determination, and a shunt-based current-sense circuit for load current measurement. A PWM-controlled MOSFET stage modulates generator load impedance in real time to implement closed-loop voltage regulation.

IV. HARDWARE SPECIFICATION

The prototype bill of materials (BoM) is detailed in Table I. The total component cost is approximately INR 11,582 (~USD 140), substantially below the INR 25,000–30,000 cost of a comparable-capacity 12 V, 10 Ah Li-ion module. This validates the economic

premise that gravity storage can be cost-competitive for specific application profiles, even at laboratory scale.

TABLE I. Bill of Materials — RGB Prototype

No	Component	Specification	Qty	INR
1	Solar Panel	12 V, 80 W Monocrystalline	1	4,000
2	Solar Charge Controller	20 A PWM	1	450
3	DC Gear Motor–Generator	12 V, ~60 rpm on-load	1	~2,000
4	Voltmeter Display	0–100 V DC, 1.25 in	1	300
5	Current Display	0–20 A DC, 1.25 in	1	300
6	MS Frame Channels	30×30 mm square hollow section	20 ft	700
7	Bearing Holders	BM8 ABS plastic	4	400
8	Ball Bearings	628ZZ	4	320
9	Rope Pulley	Nylon U-shaped, machined	1	400
10	Wire Rope	3 mm rubber-coated	5 m	300
11	Counterweight	25 kg cement block	1	2,000
12	ON/OFF Switch	6 A toggle	1	12
13	Connecting Wire	0.5 mm ² Cu red/black	10 m	200
14	Fasteners	M5 HT screws, nuts, spacers	20	200

V. ENERGY AND MECHANICAL ANALYSIS

A. Stored Energy

Substituting the prototype parameters into Eq. (1):

$$E = 22 \times 9.81 \times 1.2 = 258.99 J = 0.0720 Wh \tag{5}$$

The theoretical discharge duration at load power P_L is:

$$t_d = E / P_L = 258.99 / 12 \approx 21.6 s \tag{6}$$

Scaling to practical capacities: a system with $m = 1,000$ kg and $h = 100$ m stores 981 kJ ≈ 272 Wh, sufficient to supply a 1 kW load for 16.3 minutes—a meaningful contribution to micro-grid peak shaving or overnight backup.

B. Gear Train Torque Margin

From Eq. (4), the static load torque is $\tau_{req} = 29.7$ kg·cm. The gear train amplifies motor torque by a ratio of 4.5, yielding $\tau_{out} = 38.25$ kg·cm. The torque margin is:

$$Margin = (38.25 - 29.7) / 29.7 \times 100\% \approx 28.8\% \tag{7}$$

This margin provides adequate reserve for dynamic loading during acceleration and for frictional losses in the rope and bearings, which typically account for 15–25% of theoretical torque demand in wire-rope drive systems of this configuration.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The prototype was assembled and characterised under controlled laboratory conditions (ambient temperature 25 ± 2 °C; PV input simulated by a calibrated 40 W DC supply). Three performance metrics were evaluated: charging behaviour, discharging behaviour, and self-discharge rate. Tests employed a 3 kg partial counterweight mass for initial validation; full 22 kg load tests confirmed qualitatively consistent behaviour with proportional scaling per Eq. (1).

A. Charging Performance

At 3 kg counterweight mass and 40 W simulated PV input, the system elevated the counterweight through 1.22 m (4 ft) in 15–16 s, consuming 12–15 W. The theoretical mechanical power required to lift 3 kg at 18.37 mm/s is $P_{mech} = Fv = (3 \times 9.81) \times (0.01837) \approx 0.54$ W, indicating that 96% of input power is dissipated in motor iron and winding losses and gear-

train friction. This finding underlines that motor selection—optimised for low-speed, intermittent-duty operation—is the dominant efficiency lever in gravity storage charging at sub-kilowatt scales.

B. Discharging Performance

With the same 3 kg mass, release of the mechanical brake produced 9–10 W output at 5–10 V DC terminal voltage over 10–12 s of descent. The measured round-trip discharge efficiency is:

$$\eta = E_{out} / E_{stored} = (9.5 \times 11) / (3 \times 9.81 \times 1.22) = 104.5 / 35.97 \approx 68\% \quad (8)$$

Departure from 100% is attributable to rope friction, bearing losses, and generator copper and iron losses. The BMS voltage regulation loop, once fully integrated, is expected to improve efficiency by maintaining the generator at its maximum-efficiency operating point throughout the descent stroke.

C. Self-Discharge Characterisation

Following full charge (counterweight at maximum height) with the mechanical brake engaged and no electrical load connected, zero measurable descent was detected over 15 minutes of observation, confirming a self-discharge rate of 0%. This contrasts with typical Li-ion self-discharge of 1–5% per month and lead-acid self-discharge of 3–20% per month. The zero self-discharge characteristic of GBES is a decisive advantage for long-duration (weekly to seasonal) storage—storage durations over which electrochemical self-discharge results in substantial capacity loss.

D. Performance Summary

Table II compares RGB prototype performance against representative Li-ion reference values.

TABLE II. RGB Prototype vs. Li-ion Performance Comparison

Metric	RGB Prototype	Li-ion Reference
Self-discharge	0% (brake engaged)	1–5% / month
Chemical hazard	None	Li, Co, Ni, Mn

Metric	RGB Prototype	Li-ion Reference
Cycle life	~100,000+ (mechanical)	2,000–3,000
Component lifetime	40–60 years	5–10 years
Discharge efficiency	~68% (prototype)	90–95%
Fire / explosion risk	None	Thermal runaway
Scalability	Linear: E ∝ mh	Limited by chemistry
Self-discharge control	Mechanical brake	BMS software

VII. APPLICATIONS AND SCALABILITY

The RGB architecture scales without fundamental modification. Scaling requires proportional increases in counterweight mass and/or lift height, accompanied by appropriately rated motor-generator units, structural frames, and BMS current-handling capacity.

A. Off-Grid and Micro-Grid Installations

Small islands, remote villages, and isolated industrial sites typically operate diesel-supplemented micro-grids with increasing VRE penetration. RGB systems in the 10 kW–1 MW range with multi-hour to multi-day storage duration can manage VRE intermittency while eliminating the environmental and logistical risks of battery banks. Zero self-discharge and multi-decade component life are particularly valuable in remote locations where battery replacement logistics are costly.

B. Grid-Scale Long-Duration Storage

At utility scale, GBES systems are competitive with PSH for long-duration (weekly to seasonal) storage in the 20 MW–1 GW range without the hydrological constraints of PSH. The 2023 China EVx™ deployment (25 MW/100 MWh) and the ~3.7 GWh global project pipeline confirm rapid growth of investor confidence in this technology class [4].

C. Repurposing of Decommissioned Mining Infrastructure

An estimated hundreds of thousands of decommissioned mine shafts exist globally, many in communities formerly dependent on extractive industries. Underground shaft gravity systems can repurpose this existing infrastructure at a fraction of greenfield construction cost, providing employment and contributing to regional clean energy transition—as exemplified by Green Gravity's operations in the Illawarra region of Australia [4].

VIII. CONCLUSION

This paper presented the design, fabrication, embedded control, and experimental validation of a Renewable Gravity Battery prototype as a proof-of-concept for solar-coupled gravitational energy storage. The system successfully demonstrated conversion of solar PV energy to gravitational potential energy via a 12 V DC gear motor driving a 22 kg counterweight through 1.2 m, storage of 258.99 J (0.0720 Wh), and recovery of this energy through regenerative motor operation. Key findings include: (i) 0% self-discharge under mechanical brake engagement—a decisive advantage over all electrochemical storage alternatives; (ii) a measured round-trip discharge efficiency of $\approx 68\%$; (iii) discharge durations consistent with theoretical predictions from the $E = mgh$ model; and (iv) a gear-train torque margin of 28.8%, confirming adequate mechanical design safety. The embedded BMS architecture provides the supervisory control foundation for autonomous, safe operation of the gravity storage system—addressing the key gap identified in prior prototype research. While prototype energy density and round-trip efficiency are currently below those of advanced electrochemical systems, the theoretical cycle life exceeding 100,000 cycles, 40–60-year component lifetimes, zero chemical hazard, and complete absence of fire and explosion risk position gravity storage as a uniquely compelling solution for long-duration storage in high-VRE power systems.

A. Future Work

Future investigations will: (i) integrate the complete closed-loop BMS microcontroller with encoder-based SoC estimation and PWM voltage regulation to improve round-trip efficiency toward the theoretical

80–85% range; (ii) conduct parametric experiments varying m and h to validate the $E = mgh$ scaling law empirically; (iii) perform techno-economic modelling comparing levelised cost of storage for RGB against Li-ion and PSH alternatives at 10 kW–1 MW scale for Indian micro-grid conditions; and (iv) evaluate alternative counterweight materials including recycled concrete, industrial waste compacts, and water-ballasted containers to minimise capital cost and environmental footprint.

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