VIDYABHARATI
Vidyabharati International Interdisciplinary Research Journal
ISSN 2319-4979

Gravity Battery-Based Green Energy Storage Systems: Architectural Concepts, Challenges and Commercial Integration

Naresh Kumar
Department of Commerce, Aryabhatta Government Degree College, Sandhole
Affiliated with Sardar Patel University, Mandi, Himachal Pradesh, India
atalaarya@gmail.com

Abstract
The growing share of variable renewable electricity increases the need for flexible resources that can shift energy across time and support reliable grid operation. Gravity energy storage (GES) stores energy by raising a mass and recovers part of that energy during controlled descent. This paper critically examines the principal GES architectures, their engineering constraints, the commercial logic of storage projects, and the conditions under which the technology may be relevant to India. The study uses a structured narrative review of published reviews and selected technical literature; it does not claim to be a systematic review or to produce new experimental or project-level financial data. The synthesis distinguishes mature pumped-storage hydropower (PSH) from less mature solid-gravity energy storage (SGES). It finds that the two approaches should not be treated as interchangeable: PSH has an established operating record but is constrained by topography, water, permitting, and civil works, whereas SGES may broaden siting options but retains uncertainties around demonstration, durability, performance guarantees, and bankability. Commercial feasibility depends on whole-life cost, round-trip efficiency, utilization, financing, market rules, and the ability to combine multiple revenue streams. For India, the appropriate pathway is therefore selective rather than universal: screen sites and use cases, compare GES with competing flexibility options, validate performance through transparent demonstrations, and design procurement and market arrangements that remunerate measurable system services. The paper contributes an integrated technical-commercial framework for evaluating GES and identifies priorities for further empirical research.

***Keywords**: gravity energy storage, pumped-storage hydropower, solid-gravity energy storage, techno-economic assessment, renewable integration, India*

Introduction

Electricity systems with increasing wind and solar generation must manage differences between when electricity is produced and when it is needed. Storage can shift energy across time and, depending on its design and controls, provide additional services such as ramping support, reserve capacity, and frequency-related response. These functions are increasingly important as power systems seek to integrate variable renewable energy while maintaining reliability.

Gravity energy storage (GES) is a family of technologies that stores energy by increasing the gravitational potential energy of a mass. The basic relationship is E = mgh, where E is potential energy, m is mass, g is gravitational acceleration, and h is the vertical displacement. The equation describes stored potential energy, not the amount of electricity that will ultimately be delivered: conversion losses, auxiliary loads, operating limits, and equipment availability influence usable output.

The term GES covers systems with different maturity levels and infrastructure requirements. Pumped-storage hydropower (PSH) moves water between reservoirs at different elevations and is an established grid-scale storage technology. Solid-gravity energy storage (SGES) uses solid masses moved vertically or along a slope by mechanical equipment. Reviews indicate that PSH is comparatively mature, while SGES remains at an earlier stage of system design and techno-economic validation (Cai et al., 2024; Kavoosi & Tarafdar Hagh, 2025).

A recurring weakness in broad discussions of GES is the tendency to infer commercial viability from physical plausibility or long theoretical service life. Neither is sufficient. A bankable project must demonstrate safe and reliable operation, quantify round-trip performance, secure a suitable site and grid connection, and earn adequate revenues over its lifecycle. This paper therefore treats GES as both an engineering system and a long-lived infrastructure investment.

Literature Review

Amorim et al. (2026) provide a systematic review highlighting that Gravity Energy Storage (GES) has emerged as a critical technological pathway for achieving medium- to long-duration energy storage. Their work emphasizes the growing importance of GES in the context of power systems increasingly dominated by renewable energy sources, underscoring its role in grid stabilization and reliability.

Kavoosi et al. (2025) contribute a comprehensive overview of Solid Gravity Energy Storage (SGES) technologies. Their research serves as a key reference for understanding the potential of SGES in large-scale energy storage applications. By evaluating various system architectures, they highlight the viability of solid mass mechanisms to address future energy capacity demands.

Ji et al. (2025) focus on the technical implementation of grid-connected gravity energy storage systems. Their study provides valuable insights into the design and simulation of these systems, specifically demonstrating how optimized GESS can deliver stable power generation. They further suggest that such systems can function similarly to a controlled current source, offering enhanced flexibility for grid management.

Research Aim and Questions

The aim is to synthesize the technical, economic, and policy considerations that determine whether gravity-based storage can contribute meaningfully to renewable-energy integration, with particular attention to India. The review addresses three questions:

• How do PSH and SGES differ in architecture, maturity, siting requirements, and operational risks?

• Which technical and commercial variables most strongly shape the investment case for GES?

• What project-screening and policy priorities follow for potential deployment in India?

Research Methodology

This paper uses a structured narrative review and conceptual techno-commercial synthesis. The source base includes peer-reviewed review articles on GES and SGES, a recent study of grid-connected vertical GES control, and institutional material on energy-storage applications. Sources were selected for relevance to system classification, operating principles, efficiency, economic assessment, grid integration, and deployment constraints. The synthesis organizes evidence around four themes: architecture and maturity; performance and lifecycle considerations; project economics and revenue design; and implications for India.

This approach is not a systematic review. The manuscript does not report a preregistered protocol, exhaustive database searches, duplicate screening, formal risk-of-bias assessment, or quantitative meta-analysis. Accordingly, the conclusions are analytical and interpretive rather than statistical. No new field measurements, experimental tests, or project cash-flow datasets were collected. The financial metrics discussed below are proposed evaluation tools, not reported results from a modeled project.

Technical Foundations and System Architectures

Energy conversion and performance

During charging, electricity powers pumps, motors, or winches to move a mass to a higher gravitational potential. During discharge, the mass descends under controlled conditions and drives a turbine or motor-generator. Power electronics and control systems condition the electrical output for the grid. The idealized potential energy is $E = mgh$; for practical assessment, usable energy must account for the efficiency of each conversion stage and for operating constraints.

Round-trip efficiency is the ratio of electrical energy delivered during discharge to electrical energy consumed during charging over a defined cycle. It should be reported with clear system boundaries, operating conditions, and treatment of auxiliary loads. Other relevant measures include rated power, energy capacity, discharge duration, response time, ramp rate, availability, cycle frequency, degradation or maintenance requirements, and expected service life. Comparing projects on a single headline efficiency or lifetime figure can conceal important differences in design and duty cycle.

Pumped-storage hydropower

PSH uses upper and lower reservoirs, water conveyance, pumps or reversible pump-turbines, and associated civil and electrical infrastructure. Its key strength is an established industrial and operating base. Its principal constraints are geographic suitability, water availability and management, construction duration, environmental effects, permitting, and high initial capital

requirements. A PSH project must be evaluated as a site-specific infrastructure development rather than a generic storage unit.

Solid-gravity energy storage

SGES includes tower-based block systems, vertical shafts, mine-shaft concepts, and slope- or rail-based arrangements. These configurations share the use of solid masses but differ substantially in mechanical layout, lifting equipment, structural loads, land requirements, and maintenance needs. A design that reuses an existing mine or industrial shaft may reduce some site-development costs, but reuse is not automatically economical: structural integrity, contamination, access, equipment installation, safety, and decommissioning liabilities require investigation.

SGES should be assessed with particular attention to the evidence available for the specific design. A technology concept, a simulation, a pilot installation, and a commercially operated plant provide different levels of confidence. Investors and system operators need independently verifiable performance data, clear warranty conditions, credible maintenance plans, and evidence that safety systems remain effective over repeated operation. Cai et al. (2024) and Tong et al. (2022) describe SGES as less mature than PSH, while Kavoosi and Tarafdar Hagh (2025) review the range of SGES configurations and their potential trade-offs.

Grid integration and operational control

Mechanical movement does not by itself guarantee grid-quality output. The generator, converter, control strategy, and mechanical system must jointly manage output power and comply with grid-code requirements. Ji et al. (2026) examine the design and simulation of a grid-connected vertical gravity storage system and highlight the need to smooth output power. This reinforces the distinction between demonstrating that a mass can be raised and lowered and demonstrating reliable, controllable electrical performance in a grid-connected application.

Comparative Assessment

The comparison below is qualitative. It is intended as a screening framework, not a universal ranking; performance and cost depend on the specific design, site, project scale, and operating strategy.

Dimension	Pumped-storage hydropower	Solid-gravity storage
Technology maturity	Established technology with extensive operating experience	Generally less mature; evidence varies by design and project
Siting	Requires suitable elevation difference, reservoirs, water and civil works	May offer more configuration choices but needs suitable structures, land, and mechanical access
Capital profile	Often dominated by civil works, water conveyance, electromechanical plant and grid connection	Depends on lifting systems, mass, structures, foundations, controls and grid connection
Key risks	Hydrology, permitting, ecological impacts, construction and geological risk	Mechanical wear, structural fatigue, control reliability, warranties and limited operating history
Evaluation priority	Site-specific civil/environmental assessment and lifecycle economics	Demonstrated performance, maintenance evidence, structural design and commercial bankability

Techno-Economic and Commercial Evaluation

Lifecycle costs and financial metrics

The investment case should include capital expenditure (CAPEX), operating expenditure (OPEX), replacements and major maintenance, land and permitting, grid connection, financing costs, insurance, and end-of-life obligations. A levelized cost of storage (LCOS) calculation can help compare lifecycle costs against discharged energy, but results depend on assumptions about utilization, efficiency, discount rate, lifetime, and system boundaries. LCOS alone does not establish whether a project is profitable or valuable to the power system.

Net present value (NPV) estimates the discounted value of expected cash flows after investment costs. Internal rate of return (IRR) is the discount rate at which NPV equals zero. Both should be calculated using transparent, internally consistent assumptions and tested across scenarios.

Relevant sensitivities include electricity price spreads, annual cycles, round-trip efficiency, availability, construction delays, interest rates, equipment replacement, and changes in market rules. Where project-specific data are unavailable, numerical NPV or IRR claims would be speculative and should not be presented as findings.

Revenue stacking and market design

Energy arbitrage earns revenue by charging when electricity is relatively inexpensive and discharging when it is more valuable. Its returns depend on price spreads after losses and transaction costs, and may be insufficient to cover fixed costs on its own. Additional potential revenue sources include capacity availability, reserve provision, peak-demand management, congestion relief, and other grid services. The extent to which these can be combined depends on technical capability, dispatch restrictions, market access, and rules against double counting the same capacity.

Value stacking should therefore be treated as a project-specific hypothesis to test, not as a guaranteed revenue source. A credible business case identifies each service, its technical requirements, the relevant buyer or market, expected availability, price and volume assumptions, and interactions among services. Contracted revenues may improve financing prospects, but contracts must allocate performance, dispatch, curtailment, and market risks clearly.

Risk allocation and bankability

For emerging SGES projects, technology risk and financing risk are closely linked. Lenders may require independent engineering reviews, performance tests, long-term maintenance arrangements, insurance, and enforceable warranties. Developers should disclose whether evidence comes from simulation, pilot operation, or commercial operation and avoid transferring results from one architecture to another without justification. Repurposing legacy infrastructure can reduce some development requirements but can also introduce uncertain rehabilitation and safety costs.

Environmental and Social Considerations

Gravity storage does not rely on electrochemical energy conversion in the same way as many battery systems, but it is not impact-free. PSH can affect land use, habitats, water systems, and local communities; construction materials and civil works also have embodied environmental impacts. SGES may require substantial concrete, steel, excavation, transport, and land alteration. Lifecycle assessment should compare alternatives using consistent functional units and boundaries, including construction, operation, maintenance, and end of life. Environmental performance should be assessed at the project level rather than inferred from the absence of battery chemistry.

Discussion

The literature supports a differentiated view of gravity storage. PSH is a proven infrastructure option where geography and environmental conditions permit development. SGES may eventually serve additional contexts, but its commercial promise must be evaluated design by design. The common physical principle of gravitational potential energy does not erase differences in conversion equipment, construction risk, operating maturity, or lifecycle cost.

The most important commercial insight is that storage value is contextual. The same asset can have different economics under different electricity price profiles, utilization patterns, grid constraints, and market rules. Consequently, claims that GES is inherently low-cost, universally sustainable, or automatically suitable for long-duration storage should be avoided unless supported by transparent, comparable evidence. A robust evaluation combines engineering performance, whole-life cost, environmental assessment, and a realistic revenue model.

This paper's contribution is an integrated framework that connects architecture and maturity to project screening, financial evaluation, and market design. It does not establish the superiority of GES over batteries or other storage technologies, because such a conclusion would require comparable project data and a defined use case. Instead, it identifies the conditions under which a gravity-based option merits detailed appraisal.

Limitations and Future Research

This narrative review has limitations. It does not systematically search every database or formally assess the quality of every included study. The underlying literature also contains technologies at different stages of development, making direct comparisons difficult. No primary data, validated engineering model, lifecycle assessment, or India-specific cash-flow model was produced. Therefore, the paper's conclusions should be interpreted as a conceptual synthesis and screening framework rather than a project feasibility verdict.

Future research should develop transparent, India-specific techno-economic case studies that compare PSH and selected SGES designs with alternative storage technologies under common assumptions. Studies should report system boundaries, round-trip efficiency, usable capacity, degradation and maintenance, financing assumptions, grid services, and environmental impacts. Demonstration projects should publish independently verified operating data, while policy research should examine which procurement and market mechanisms enable storage assets to be compensated for the services they reliably deliver.

Conclusion

Gravity energy storage offers a physically straightforward way to store energy by raising a mass, but commercial feasibility depends on far more than the underlying equation. PSH combines mature technology with demanding site and infrastructure requirements. SGES offers a broader range of mechanical concepts but needs stronger project-specific evidence on performance, durability, cost, and bankability. Across both categories, the decisive variables include site suitability, round-trip efficiency, capital and operating costs, utilization, financing, environmental impacts, and access to multiple revenue streams.

For India, the appropriate strategy is selective and evidence-led. Developers and policymakers should begin with clearly identified grid needs, screen sites and architectures, compare alternatives on consistent lifecycle assumptions, and ensure that market or contractual arrangements reward measurable performance. Transparent demonstrations and rigorous financial sensitivity analysis are essential to distinguish promising concepts from investable infrastructure. Gravity storage is best understood as one potential component of a diversified storage portfolio, not as a universal solution.

References

1. Cai, K., Han, Y., Xia, R., Wu, J., Wang, J., & Lund, P. D. (2024). Gravity energy storage: A review on system types, techno-economic assessment and integration with renewable energy. *WIREs Energy and Environment, 13*(6), Article e543. https://doi.org/10.1002/wene.543
2. Tong, W., Lu, Z., Chen, W., Han, M., Zhao, G., Wang, X., & Deng, Z. (2022). Solid gravity energy storage: A review. *Journal of Energy Storage, 53*, Article 105226. https://doi.org/10.1016/j.est.2022.105226
3. Amorim, M. L. M., et al. (2026). A systematic review of gravity energy storage. Energy Reports. https://www.mdpi.com/2673-4117/7/9/463
4. Kavoosi, A., et al. (2025). Review article: Solid gravity energy storage. Journal of Energy Storage. https://www.sciencedirect.com/science/article/abs/pii/S2352152X25004049
5. Ji, Y., et al. (2025). Research on the design and simulation of grid-connected gravity energy storage systems. Scientific Reports. https://www.nature.com/articles/s41598-025-32410-2