IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 5, Issue 4, May 2025

Impact Factor: 7.67

Gravity-Based Energy Storage for Wind Power: Addressing Renewable Intermittency with Sustainable Infrastructure

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Abstract: *The rapid growth of wind power has outpaced the ability of traditional grids to absorb its variability, making large-scale energy storage increasingly essential. Gravity-based energy storage (GBES) systems address this need by converting excess electricity into gravitational potential energy: for example, surplus power is used to hoist heavy masses (such as concrete blocks or water) to an elevated position and later release them to generate electricity. The most mature form of GBES is pumped hydro storage, which accounts for over 90% of global electricity storage, but emerging "solid" gravity systems (tower, rail or shaft designs) enable similar physics without large reservoirs. Recent commercial deployments demonstrate GBES viability: in 2023 China commissioned a 25 MW/100 MWh gravity system (Energy Vault's EVx™) adjacent to a wind farm, marking the first utility-scale, non-pumped-hydro GESS. Multiple projects totaling ~3.7 GWh are underway worldwide, and underground "gravity batteries" using sand in mine shafts have been proposed for ultra-long-duration storage. These implementations show high round-trip efficiency (80–90%), long lifetimes (30–50 years) and zero degradation. In summary, GBES offers a durable, low-maintenance complement to batteries for stabilizing wind-rich grids, though its low energy density and land requirements remain challenges to address.*

Keywords: traditional grids

I. INTRODUCTION

The integration of renewable energy sources like wind power into modern electricity grids presents a key challenge: their intermittent and variable nature. Wind energy generation is highly dependent on weather conditions, leading to periods of surplus generation followed by potential shortages. To ensure a reliable and continuous power supply, efficient energy storage solutions are essential[3][15].

Gravity-based energy storage, also known as gravitational potential energy storage, offers a promising solution to this challenge[1]. This method involves storing energy by lifting heavy masses using excess electricity (e.g., from wind turbines) during periods of low demand[9].

When energy is needed, the mass is allowed to descend, driving a generator to produce electricity. Unlike batteries, gravity storage systems can provide long-duration energy storage with minimal degradation over time and are environmentally friendly.

By coupling wind energy systems with gravity-based storage, surplus wind power can be effectively stored and dispatched as needed, enhancing grid stability and supporting a sustainable energy transition.

II. METHODOLOGY

Gravity-based energy storage is an innovative solution designed to address the intermittency of renewable energy sources like wind. It works by converting electrical energy into gravitational potential energy, which can be stored and later converted back into electricity when needed. Below is a step-by-step outline of the methodology:

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Energy Collection

Wind turbines generate electricity.

When energy production exceeds immediate demand (e.g., during windy periods), the surplus electricity is diverted to the gravity storage system instead of being wasted or curtailed.

Conversion to Potential Energy

The excess electricity powers motors or winches that **lift a heavy mass** (commonly made of concrete, steel, or earth) to a higher elevation.

This raised mass **stores energy as gravitational potential energy**, calculated using the formula:

$$\boldsymbol{E = m \times g \times h}$$

where:

E = energy stored (joules),

m = mass (kg),

g = acceleration due to gravity (9.81 m/s^2),

h = height (m).

Energy Storage

The lifted mass is securely held at its elevated position.

It can remain in this state indefinitely with minimal energy loss, making it ideal for long-duration energy storage[9].

Systems can be built vertically (e.g., in towers or mine shafts) or horizontally (e.g., on inclined tracks).

Energy Discharge (Conversion to Electrical Energy)

When power demand increases, the mass is gradually lowered.

As it descends, it drives a generator (via gears, pulleys, or hydraulic systems), converting potential energy back into electricity.

The generated electricity is fed into the grid to meet demand.

Repetition and Automation

The process is **fully reversible** and can cycle many times with low operational wear and minimal maintenance[10].

Modern systems use automated control systems and AI to manage charging and discharging based on grid needs.

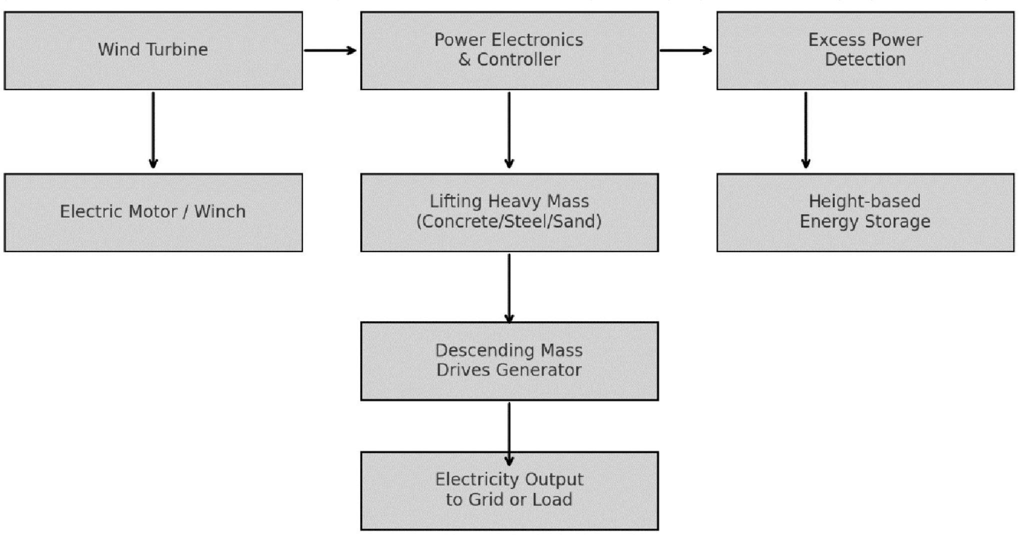

Fig. 1. Block Diagram of wind energy integrated gravity-based energy storage system

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Applications & Benefits

- **Wind Energy Integration**: Stores excess energy generated during high wind periods.
- **Grid Stability**: Provides dispatchable power when wind generation drops.
- **Sustainability**: No chemical degradation, minimal land impact, and recyclable materials.

III. COMPPONENT REQUIRED

- Gear Dynamo Motor
- Wind Mill Components
- Micro Switch
- 60rpm Geared Motor
- PCB Board
- 6 pin Toggle Switch
- LEDs
- 10 core wire:
- 9v Battery
- Servo motor
- Push Button

IV. CIRCUIT DIAGRAM

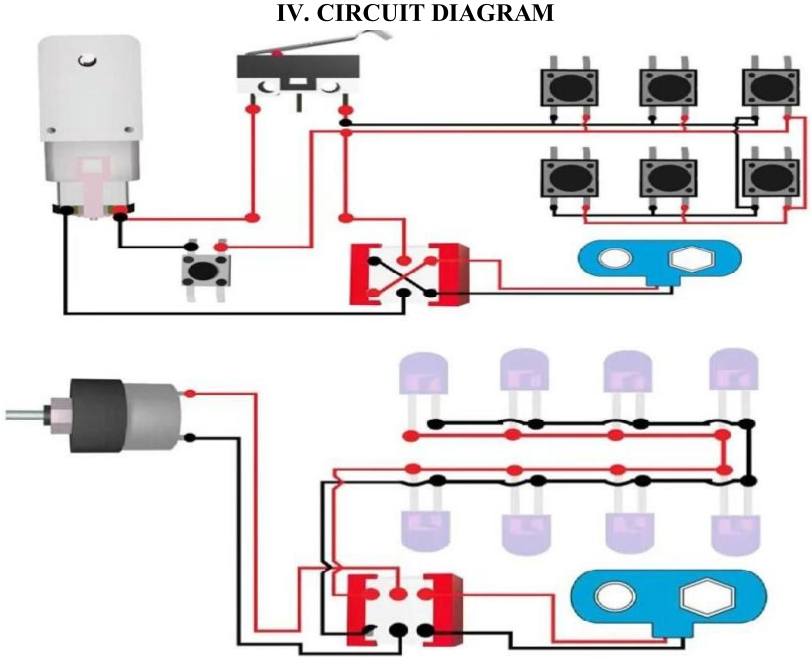

Fig.2. Connection Diagram of the Project

V. WORKING

Gravity-based energy storage systems (GBESS) operate by converting surplus electrical energy, often from renewable sources like solar or wind, into gravitational potential energy. This is achieved by using the excess electricity to elevate a heavy mass—such as concrete blocks or steel weights—to a higher position. The energy used in lifting is stored as potential energy. When there is a demand for electricity, the mass is allowed to descend, and its downward motion drives a generator, converting the stored potential energy back into electrical energy. This method offers a sustainable and efficient solution for energy storage, with advantages including long operational lifespan, minimal environmental impact, and scalability to various energy demands. Innovative implementations, such as tower-based systems and the use of abandoned mine shafts, demonstrate the versatility and potential of GBESS in addressing the intermittency challenges of renewable energy sources[9].

VI. RESULT

Recent advancements in gravity-based energy storage systems (GBESS) have demonstrated their potential as effective solutions for large-scale, long-duration energy storage, particularly in complementing renewable energy sources[10].

- **India's Baud Resources Initiative**: An Indian startup, Baud Resources, has developed a sand- based gravity energy storage system using locally available materials like sand and industrial waste. Their upcoming 100 MWh pilot plant aims for a levelized cost of storage around INR
- 2.5 ($0.03)/kWh, showcasing a cost-effective and environmentally friendly alternative to traditional storage methods.
- **China's Rudong Project**: The world's first 26 MW gravity energy storage facility in Rudong, Jiangsu Province, successfully completed its initial charge-discharge tests in May 2024[4]. Utilizing gravity blocks made from recycled materials, the system is expected to achieve a storage capacity of 100 MWh upon full operation, offering a lifespan of up to 50 years without degradation[12].
- **Energy Vault's Global Deployments**: Swiss company Energy Vault has been at the forefront of GBESS technology[5], with its EVx system demonstrating round-trip efficiencies above 75%. Notably, a 25 MW/100 MWh EVx system near Shanghai began commissioning in 2023, marking a significant step towards commercial-scale, non-pumped hydro gravity energy storage solutions[11].

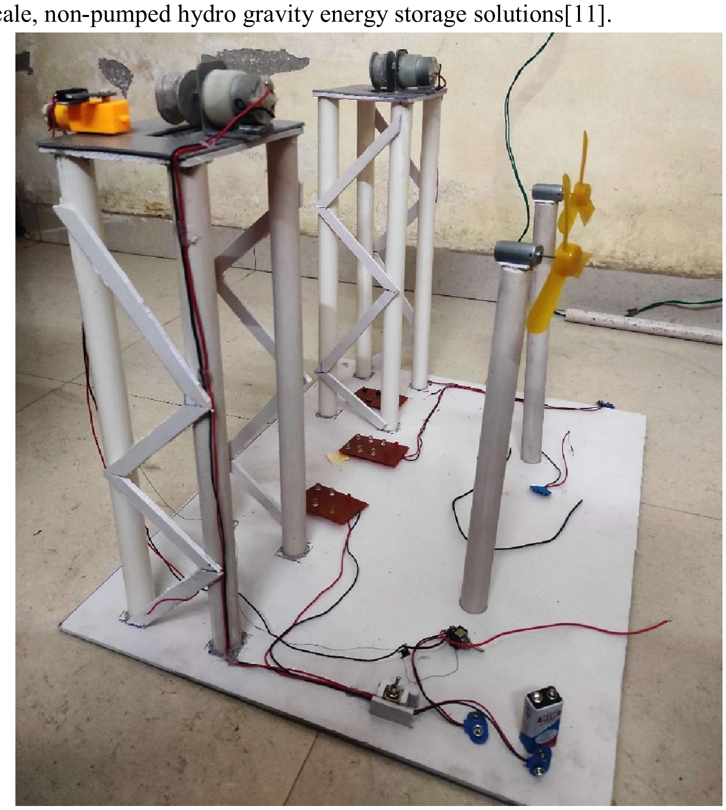

Fig. 3. Final Working Model

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VII. CONCLUSION

Gravity-based energy storage offers several compelling advantages for renewable integration. By relying on simple physics and robust materials (steel, concrete, water), GBES systems achieve extremely long lifetimes and deep discharge with virtually no degradation. They can store energy for days or weeks with very low self-discharge, making them well-suited to buffer wind variability and shifting excess generation to peak demand periods. However, key limitations include low power/energy density (thus large physical footprints) and high upfront costs for infrastructure. GBES deployments also face siting constraints – pumped hydro needs terrain, while tower systems require space or specialized sites (e.g. disused mine shafts[9]). As a result, gravity storage is likely to complement rather than replace other storage technologies[14]. Its strengths – long duration capability, environmental sustainability, and material abundance – make it a valuable component of a diversified energy portfolio, especially for wind and solar plants. In practice, pilot projects have confirmed the technical feasibility of GBES[3], but scaling up will depend on cost reductions and supportive policies. Overall, gravity storage emerges as a promising long-duration solution[15], balancing its renewable integration benefits against the practical challenges of construction and investment.

VIII. FUTURE SCOPE

Future research and development on gravity energy storage should focus on the following areas:

- **Technical innovation.** Improve design and efficiency by exploring new lifting mechanisms, materials and configurations. For example, enhancing mechanical reliability and automation (e.g. advanced computer controls) can optimize round-trip performance, while hybrid systems (combining gravity with batteries or pumped hydro) may leverage complementary strengths. Underground approaches (e.g. sand-filled mine shafts)[9] merit further study for seasonal or multi-day storage.
- **Economic analysis.** Conduct life-cycle cost and market studies to assess GBES competitiveness. Investigate using low-cost or recycled materials (like mine waste or construction debris) to lower capital expenditure. Analyze business models (utility versus merchant) and valuation of ancillary services (frequency regulation, load shifting) that gravity systems can provide[10].
- **Policy and regulatory support.** Develop incentives and standards that recognize long-duration storage value. As the U.S. DOE notes, advancing storage technologies is key to unlocking 24/7 renewable power[4]. Policies could include energy storage mandates, procurement targets for long-duration solutions, or co-location subsidies (e.g. pairing GBES with wind farms)[12]. Pilot programs in China and elsewhere illustrate how government-backed demonstration projects can accelerate deployment. International collaboration and knowledge-sharing will also be important.
- **Grid integration studies.** Model and simulate large-scale GBES impact on grids with high wind penetration. Examine operational strategies (intelligent dispatch, hybrid configurations) to maximize flexibility and economic return[15]. Assess environmental and social factors (land use, community acceptance) in project siting.

Together, these efforts will clarify the role of gravity storage in future energy systems. By addressing technical and economic barriers through innovation and supportive policy, gravity-based systems could become a mainstream solution for bridging the gap between variable wind generation and continuous demand.

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