Experimental Analysis and Fabrication of Gravity Batteries for Tall Buildings

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Abstract— **In this work, the use of gravity battery for the purpose of alternative energy storage for residential and tall buildings has been explored, keeping in view the disadvantages of traditional lithium-ion batteries. The energy storage principle is based on lifting a mass by the help of electricity, along with the assistance of solar power, and then releasing the energy upon the descent of the mass. A small-scale prototype has been developed, and its components include mechanical components such as the gear, cable and drum, and the truss structure, along with the electrical components. Experimental analysis was performed by measuring the parameters during operation. The efficiency of the system was between 48% and 51%. This shows the successful recovery of energy while also indicating the loss of efficiency due to friction, mechanical losses, and non-optimized component efficiencies. This is comparable to the results of similar studies, where efficiencies were in a range of 50% and 75%. The structural analysis verified the safety of the structure under loading conditions. Although gravity batteries have lower energy density, they provide benefits like long life, minimal environmental impact, and scalability, making them a promising solution for sustainable energy storage.**

Index Terms— **Energy storage, Gravity battery, Renewable energy, Sustainable infrastructure, tall buildings.**

I. INTRODUCTION

The global energy landscape is shifting from fossil-fuel-based centralized power generation to decentralized grids that focus on renewable sources. While solar and wind power lead this change, their natural variability is the biggest challenge for reliable power around the clock. To address this issue, Energy Storage Systems (ESS) have emerged as a key solution for modern power systems. However, current leaders like Lithium-ion batteries face criticism due to their significant ecological impact, limited availability of resources such as lithium and cobalt, and notable fire risks problems that are especially concerning in dense urban residential areas. Pumped Hydroelectric Storage (PHS) currently makes up most of the global storage capacity, but its use is limited to mountainous regions with plenty of water. In contrast, modern cities are characterized by tall buildings. These structures require large investments but are often not fully utilized for energy management. Gravitational Energy Storage Systems (GESS) provide a mechanical solution by using the height of these buildings to store energy as potential energy. Unlike chemical storage, gravity batteries do not self-discharge over time, do not use hazardous chemicals, and can last as long as the buildings themselves. This research examines the practical feasibility of integrating GESS into urban residential settings. By creating a scaled prototype, the study goes beyond theoretical models to tackle real-world issues like mechanical friction, transmission losses, and structural stability. The main goal is to confirm a system that can easily fit into lift shafts or external frames of tall buildings, providing a self-sufficient, sustainable power backup to meet urban energy needs and support renewable supply.

II.LITERATURE SURVEY

A.C. Ruoso et al. (2025) conducted a detailed study on storing gravitational energy for small-scale industrial and residential use. Their research suggested a system that uses a vertically suspended mass in a 12-meter shaft, achieving a theoretical efficiency of 90%. A key finding was that GESS lasts longer than electrochemical batteries, with a possible operational lifespan of over 50 years. This study sets a standard for the mechanical longevity of solid-mass gravity systems.

The integration of gravity batteries with other renewable sources, particularly wind power, was the main focus of Miss Lahure S. K. et al. (2025). They achieved experimental efficiencies ranging from 50% to 75% by creating a prototype that made use of a vertical tower and a concrete mass. According to their research, the efficiency of the gear train and motor-generator set is the main obstacle to energy recovery. This emphasizes that in order to reduce energy dissipation during the conversion of potential energy to electricity, the transmission assembly must be precisely engineered.

A techno-economic feasibility study of gravity batteries in residential settings was conducted by Purdue University's C. L. Jarausch et al. The study noted that the initial capital expenditure for residential-scale systems is currently higher than traditional storage, even though it acknowledged the significant environmental benefits, such as the absence of toxic materials found in lithium batteries. However, the study found that the lack of degradation in mechanical storage media makes the Levelized Cost of Storage (LCOS) extremely competitive over long-term cycles.

The idea of "Energy Mountain," a large-scale gravity storage solution that entails transporting sand or gravel to various elevations, was first presented by Julian D. Hunt et al. (2018). Their mathematical modeling served as the basis for determining energy density in solid-mass systems, despite their emphasis on massive geographical features. They contended that gravity-based systems could offer a crucial "middle-ground" storage option, filling the void between long-term high-capacity pumped hydro storage and short-term high-power flywheels.

Underground Gravity Energy Storage (UGES) using abandoned mines was investigated by Thomas Blaschke and Julian D. Hunt in 2023. According to their research, the cost of infrastructure is greatly decreased by using already-existing vertical shafts. Because lift shafts in skyscrapers can function as "artificial mines," providing the required vertical displacement without requiring additional land use, this paper is especially pertinent to urban settings. The "dual-use" infrastructure model put forth in this project is supported by their findings.

A comparison of recently developed gravity storage systems and conventional Pumped Hydro Storage (PHS) was presented by Zhening Kang et al. (2022). The study discovered that although PHS is more developed, gravity batteries are not limited by water availability and have a significantly smaller environmental impact on nearby ecosystems. According to their analysis, the most practical mechanical storage solution for arid or densely populated areas where water-based storage is not feasible due to geography is solid-weight gravity batteries.

III. METHODOLOGY

A multi-stage engineering approach was used to develop the gravity battery system, with an emphasis on autonomous power management, effective energy conversion, and structural stability. The approach combines electromechanical synchronization, finite element validation, and mechanical design.

A. Structural Design and Material Selection

The whole point of the structural framework was to hold up the suspended mass and keep everything steady, especially during high-torque lifts. The frame itself stands 1.4 meters tall, built from 1-inch mild steel square tubes. Mild steel was an easy choice, it's got a Young's Modulus around 200 GPa and strong yield strength, so it barely flexes even when loaded up. To make sure the frame stays stable when everything's moving fast, the designers went with an H-frame for the base. They welded cross-bracing right in the middle, which helps absorb the twisting force that comes from the motor's spinning. Up top, there's a CNC-machined platform where the transmission unit sits. That keeps the drive shaft and the load lined up perfectly, so you don't lose energy to any extra friction. It's a clean, purpose-driven setup.

B. Electromechanical Transmission and Kinematics

The energy conversion unit sits right at the heart of the GESS. It's basically made to handle both charging and discharging—switching between storing power and sending it back out. For charging, the lifting subsystem uses a tough 12V 7A DC motor to pull most of the weight. But motors alone aren't enough you need more torque for the heavy lifting, so there's a worm gear reduction system in play. Not only does this setup give you the extra torque, but the worm gear has a neat bonus: it locks itself. So, if the power cuts out, the mass won't fall suddenly. The worm gear handles that like a built-in brake. On the flip side, when it's time to recover energy, the system converts the stored potential energy into rotation using a 100W DC generator hooked up to the descending mass. The team dialed in the gear ratio with kinematic equations to keep the generator spinning at its most efficient speed—even when the descent is slow. That way, you squeeze out the most energy every time.

C. Power Management and Solar Integration

This setup runs on its own, constantly cycling energy thanks to renewable sources. At the heart of it, there's a 10W monocrystalline solar panel grabbing sunlight and turning it into power. A big 20A PWM solar charge controller keeps the panel's output steady, making sure a 12V lead-acid battery gets charged safely. To keep things organized, there's a custom DPDT switch in the mix. This bit of circuitry separates the motor and generator so they don't mess each other up. It stops the generator's back-EMF from causing problems with the solar charging gear, especially while the battery is being drained.

D. Computational Modeling and FEA Validation

Before the physical construction, a Digital Twin of the system was created using SolidWorks 2024.

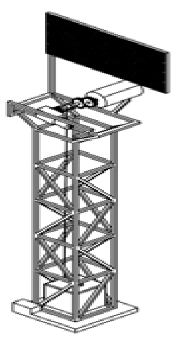

Fig 1. 3D model using SolidWorks 2024 version.

- Interference Analysis: The 3D model enabled accurate routing of the load-carrying cables and ensured that the diameter of the drum was optimized to avoid "cable overlapping," which can cause non-linear discharge rates.
- Finite Element Analysis (FEA): The structural frame was subjected to static load simulations. A high-density tetrahedral mesh was applied to the joints and support brackets. Simulating a 6kg load with a dynamic safety factor, the stress distribution was analyzed to ensure that the maximum Von-Mises stresses remained well below the proportional

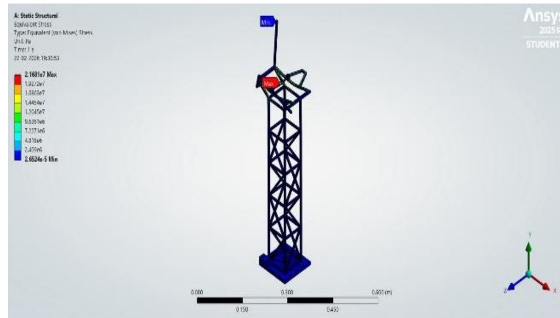

Fig 2. FEA using ANSYS student version R2

This figure should show the stress distribution on the MS frame under full load, highlighting the safety margin.

IV. RESULTS AND ANALYSIS

The evaluation of the gravity battery prototype was conducted through different trial tests and structural validation through FEA. The following data shows the core findings of the research:

A. Experimental Performance and Efficiency Mapping

The prototype was subjected to five distinct trials to determine the operational efficiency of the system. In each trial, a 6 kg mass was elevated to a maximum height and dropped in order to get the input and ouput power with the help of voltage and current readings using necessary reading devices.

Fig 3. Fabricated model of the gravity battery

- Charging Phase Analysis: During the lifting cycle, the 12V DC motor consumed a power input between 30.75 W and 35.38 W. The slight variation in power was related to the starting torque which is required to overcome the static friction of the worm gear and the inertia of the suspended mass.
- Discharging Phase Analysis: Upon descent, the generator's output was in the range between 15.04 W and 17.67 W.
- Efficiency Results: The Round-Trip Efficiency (RTE) was calculated as follows:

$$\eta = \left(\frac{p_{out}}{P_{in}}\right) \times 10$$

The experimental results yielded an average efficiency between the range 48% to 51%. While this is lower than theoretical values, it represents a significant achievement for a small-scale prototype

Table 1: Motor Input data

Sl. No.	Voltage (V)	Current (A)	Power (W)
1	12.3	2.5	30.75
2	12.1	2.92	35.33
3	12.1	2.77	33.51
4	12.2	2.90	35.38
5	12.1	2.82	34.12

Table 2: Generator Output data

Sl. No.	Voltage (V)	Current (A)	Power (W)
1	37.6	0.4	15.04
2	31	0.57	17.67
3	37	0.45	16.65
4	21.2	0.82	17.38
5	21.8	0.77	16.78

B. Structural Validation (FEA)

To ensure the safety of the 1.4m Mild Steel frame, Finite Element Analysis (FEA) was performed using SolidWorks Simulation.

- Stress Analysis: Under a static load of 6kg, the maximum Von-Mises Stress recorded was 21.68 MPa. This stress concentration was localized at the primary support joints and the shaft bearing joints. The stress recorded was far below the yield strength of mild steel which is 250 Mpa.
- Factor of Safety (FoS): With a yield strength of 250 MPa for Mild Steel, the Factor of Safety was calculated as:

$$FoS = \frac{\sigma_{yield}}{\sigma_{\max}} = \frac{250}{21.68} \approx 11.53$$

This high FoS confirms that the structure can safely handle significant load upgrades (up to 50 kg) without reaching the plastic deformation zone.

C. Theoretical Scaling for Building Integration

A theoretical analysis was performed for a medium-rise building (30 meters height) with a 2,000 kg mass.

- Energy storage capacity (E_p) :

$$E_P = m \times g \times h = 2000 \times 9.81 \times 30 = 588600\ Joules$$

This equates to approximately 0.163 kWh per cycle. For a skyscraper of 100 meters with a 20-ton mass, this storage capacity scales to 5.45 kWh.

- Theoretical Efficiency Improvement: In a large-scale system, the scaling reduces the impact of surface friction. By using a high-efficiency planetary gearbox ($\eta \approx 96\%$), the projected total system efficiency rises to 72.9%.
- Discharge Profile: To provide a steady 1 kW backup for a residential unit, the 20-ton mass would have a controlled descend rate of:

$$v = \frac{P}{m \times g} = \frac{1000}{20000 \times 9.81} \approx 0.005\ m/s$$

C. Reasons for loss of efficiency in prototype

1. Use of worm gear: Worm gears involve sliding contact between teeth, which creates high friction and heat losses, reducing overall efficiency compared to other gear types.
2. Small size of the project: In small-scale systems, frictional and mechanical losses form a larger percentage of the total energy, leading to lower overall efficiency.
3. Slip in drum can cause losses: Any slipping between the cable and drum reduces effective energy transfer, leading to loss of stored energy and decreased output efficiency.
4. Use of non-specific components: Using general-purpose components that are not optimized for the system can lead to mismatched performance, causing higher energy losses during conversion.

These results indicate that while the prototype successfully demonstrates the working principle of gravity-based energy storage, practically it requiers a significantly higher lifting heights and larger masses to achieve meaningful energy output and improved efficiency. Therefore, scaling up the system with greater structural height and heavier storage masses would enhance energy storage capacity and make gravity battery systems more viable for real-world applications.

V. APPLICATIONS

The versatile nature of the Gravity Battery System (GESS) allows for its implementation across different sectors where traditional chemical storage is either too expensive, dangerous, or geographically restricted. Based on the experimental analysis, the following applications have been identified:

A. Residential Peak Shaving and Load Leveling

In modern urban environments, electricity tariffs are often dynamic, with higher costs during the peak hours which is in evening and lower costs during off-peak periods.

- Mechanism: The GESS can be integrated into high-rise residential complexes to lift heavy weights using excess solar energy or low-cost off-peak grid electricity.
- Impact: During peak demand, the descent of the mass at a controlled rate provides enough power to common utilities (lighting, sensors, or security systems), effectively shaving the peak load and reducing the building's overall electricity expenditure.

B. Emergency Power Backup for High-Rise Safety Systems

Traditional backup systems, such as Diesel Generators suffer from initial delays during startup and require constant fuel maintenance.

- Mechanism: Because a gravity battery has zero self-discharge, it can remain in a fully charged state for longer period of time without energy loss.
- Impact: In the event of a fire or grid failure, the GESS can provide instant, high-torque mechanical energy to operate emergency fire-fighting pumps or critical evacuation lifts, ensuring a safe secondary power source that is not dependent on any chemical reactions.

C. Sustainable Off-Grid Infrastructure and Disaster Relief

In remote areas or post-disaster zones where the availability for lithium-ion batteries or fuel is not there, the GESS offers a strong solution.

- Mechanism: Since the storage medium is simply a dense mass made up of concrete or waste materials, it can be sourced locally.
- Impact: Combined with the integrated solar panel and charge controller demonstrated in this prototype, the system provides a robust power hub which can be used for charging devices used for communication and medical equipment in environments where electronic infrastructure has been compromised.

D. Integration with Elevator Counterweight Systems

One of the most promising large scale application is the modification of the already existing elevator shafts.

- Mechanism: By replacing standard elevator counterweights with an active gravity battery weights, the vertical motion of passengers can be matched with energy storage cycles.
- Impact: This reduces the net energy consumption of the building's vertical transportation system, effectively turning the internal movement in the building into a massive energy harvesting network.

VI. FUTURE SCOPE AND STRATEGIC ROADMAP

The current research serves as a foundational proof-of-concept for small scale gravitational energy storage. To change this technology from a laboratory prototype to a proper urban utility, several key areas of development are proposed:

A. Optimization of Energy Density through Advanced Materials

The energy capacity of the system is linearly proportional to the mass. Future works should move beyond standard weights to explore high density composite materials.

- Material Research: material wastage can be reduced by using iron slag, recycled lead, or high-density concrete which can help increase the mass to volume ratio.

- Impact: Higher density allows for greater energy storage within the restricted area of residential lift shafts or structural columns, maximizing energy of urban real estate.

B. Implementation of High Efficiency Transmission systems

As identified in the results, mechanical efficiency plays a crucial role with lead to efficiency loss.

- Planetary Gearsets: Replacing the worm gear with multi stage planetary gearboxes can elevate transmission efficiency from 50% to over 90%.

- Magnetic Braking: Future designs could accommodate regenerative magnetic braking (eddy current brakes) to control descent rate without the heat loss associated with mechanical friction, further boosting the Round-Trip Efficiency.

C. Smart Grid Integration and AI-Driven Dispatch

To maximize the economic viability of gravity batteries, the system must have grid awareness.

- Automated Control: Integrating IoT-enabled micro-controllers would allow the system to automatically charge when solar production peaks and discharge when grid value exceed a certain threshold.
- Predictive Analytics: Using Machine Learning to predict building occupancy and different energy demand patterns will allow the system to optimize and ensure backup power is always available.

D. Hybrid Energy Storage Systems (HESS)

The future of urban storage lies in developing a hybrid system by combining the high-power density of supercapacitors or small lithium buffers with the high energy capacity and zero-discharge nature of gravity batteries.

- Mechanism: Short-term voltage fluctuations can be handled by a small battery, while long duration-based load support is provided by the descending mass. This approach extends the lifespan of chemical batteries by reducing their cycle frequency.

E. Architectural Integration (Active Infrastructure)

Future urban planning could see an active infrastructure system, where the skyscraper structure can be designed to house several independent GESS units.

- Vertical Urbanism: By utilizing the unused spaces in building cores or hollow pillar structures, gravity batteries can provide a decentralized storage network across a city, reducing the burden on the main power grid and increasing urban resilience against natural disasters.

VII. CONCLUSION

The project of interest was mainly centered on the experimental analysis and development of a gravity battery energy system for tall buildings as a form of alternative energy storage. In this respect, the project was successful in the development of a prototype that demonstrated the viability of storing excess energy in the form of gravitational potential energy through the lifting of a mass via electrical energy, with a portion of the energy being harnessed upon the descent of the mass via a generator. In this respect, the project has several mechanical components as well as the electrical components for successful.

The experimental results have also confirmed that electrical energy is obtainable during the discharge phase, validating the working principle of the system on a small scale. Moreover, the system's efficiency was in the range of 48% to 51%, which is comparable to the efficiency obtained in a study with the title "GRAVITY BATTERY PROJECT" ([2] in the bibliography) reported the efficiency of the system ranging from 50% to 75%. The variation in efficiency might be due to the design of the system, the size of the system, and the mechanical losses of the system.

The structural analysis carried out using ANSYS also confirmed the safety and stability of the supporting frame, as the maximum Von Mises stress is much lower than the yield strength of the material. Even though gravity batteries have less energy density than the traditional lithium-ion batteries, they have several advantages, such as longer operational life, less impact on the environment, less degradation, and the availability of locally used materials.

With the improvement in mechanical efficiency and scaling in terms of mass and height, gravity battery systems have a great potential to be used as a clean, sustainable, and long-term energy storage solution.

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