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A Gravity-Based Energy Storage System Using Buoyancy-Assisted Mass Repositioning

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Abstract: Gravity-based energy storage systems store energy by elevating a mass and releasing it to generate power. A key limitation of such systems is the energy required to reset the mass to its elevated position after discharge. This paper proposes a novel canal-lift-assisted gravity battery that employs buoyancy and gravity-driven water transfer, inspired by ship canal lock mechanisms, to reduce the effective energy required for mass lifting. The system utilizes a two-chamber configuration in which a buoyant block is lifted by controlled water filling rather than direct mechanical hoisting. Water is transferred between chambers using gravity-fed channels and valves, while the mass drop phase generates electricity through a turbine. Analytical reasoning shows that although the system does not eliminate energy input, it significantly reduces peak mechanical lifting power and improves operational flexibility.

This design presents a hybrid approach combining principles of gravity batteries, buoyancy control, and pumped-hydro concepts, offering a viable pathway for low-cost and scalable energy storage.

I. INTRODUCTION

The rapid growth of renewable energy sources such as solar and wind has intensified the demand for efficient, reliable, and scalable energy storage technologies. Due to the intermittent nature of renewable generation, energy storage systems play a crucial role in maintaining grid stability, peak-load management, and energy reliability. While electrochemical batteries dominate short-term storage, their high material costs, degradation, and environmental concerns have motivated interest in alternative mechanical energy storage methods. Gravity-based energy storage, commonly referred to as gravity batteries, has emerged as a promising solution for large-scale energy storage. These systems store energy by elevating a mass using surplus electricity and release the stored energy by allowing the mass to descend and drive an electrical generator. Notable implementations include shaft-based systems and block-stacking concepts, which offer long operational lifetimes and minimal chemical degradation. However, a major limitation of gravity batteries lies in the energy and power required to reset the mass to its elevated position after discharge. Conventional approaches rely on cranes, winches, or high-power motors, resulting in high peak energy demand and mechanical complexity. To address this limitation, this paper proposes a canal-lift-assisted gravity battery that employs buoyancy and gravity-driven water transfer to reduce the effective energy required for mass resetting. Inspired by ship canal lock systems, the proposed design replaces direct mechanical lifting of a solid mass with controlled water filling in a two-chamber configuration. A buoyant block is lifted by flotation within a water-filled chamber, while water is transferred between chambers using gravity and controlled valves. The mass drop phase generates electrical power, and the reset phase is achieved through low-power water handling rather than direct lifting. It is important to emphasize that the proposed system does not violate the principle of energy conservation and does not generate free energy. Instead, it redistributes the lifting work from high-power mechanical lifting to low-power fluid handling, thereby reducing peak energy demand and mechanical stress. By combining principles of gravity energy storage, buoyancy-assisted lifting, and canal-lock mechanisms, the proposed system offers a novel hybrid approach to gravity-based energy storage. The remainder of this paper presents the system architecture, operating cycle, and working principle of the canal-lift gravity battery, followed by an energy analysis and discussion of advantages, limitations, and potential applications.

II. LITERATURE REVIEW

A. Gravity-Based Energy Storage Systems

Gravity-based energy storage systems store electrical energy by converting it into gravitational potential energy through the elevation of a mass. During discharge, the mass is allowed to descend, driving a generator to produce electricity. Due to their long service life, minimal material degradation, and use of conventional mechanical components, gravity batteries have attracted increasing research and industrial interest as an alternative to electrochemical storage technologies.

Several implementations of gravity batteries have been proposed in recent years. Shaft-based systems, such as those developed by Gravitricity, utilize deep vertical shafts where heavy weights are raised and lowered to store and release energy. These systems offer fast response times and high cycle durability. Similarly, block-stacking approaches, exemplified by Energy Vault, use cranes to lift and stack large composite blocks, releasing energy by lowering the blocks when required. Although effective at large scale, these systems rely heavily on high-power mechanical lifting equipment, resulting in significant energy consumption during the reset phase and increased mechanical complexity. A common limitation across gravity battery designs is the energy and power required to lift the mass back to its elevated position after discharge. Direct lifting using motors, cranes, or winches leads to high peak power demand and mechanical wear, which can reduce system efficiency and increase operational costs.

B. Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is the most widely deployed large-scale energy storage technology worldwide. PHES systems store energy by pumping water from a lower reservoir to a higher reservoir during periods of surplus electricity and releasing the stored energy by allowing water to flow back through turbines during peak demand.

The fundamental advantage of pumped hydro lies in its high efficiency, long lifetime, and mature technology base. However, its application is constrained by geographical requirements, large land use, and the need for significant elevation differences and water availability. Despite these limitations, pumped hydro demonstrates the effectiveness of using fluid handling instead of direct solid lifting for large-scale energy storage. The operating principles of pumped hydro systems highlight the potential of combining gravitational energy storage with controlled water movement, suggesting opportunities for hybrid storage concepts that adapt pumped hydro mechanisms to more compact or modular designs.

C. Buoyancy-Assisted and Fluid-Based Lifting Systems

Buoyancy-assisted lifting systems are widely used in marine engineering, underwater construction, and offshore operations to raise heavy objects with reduced mechanical effort. By exploiting the buoyant force generated by fluid displacement, these systems significantly reduce the effective weight of the lifted object, allowing controlled vertical motion with lower energy input compared to direct mechanical lifting. Ballast-controlled flotation systems, commonly employed in submarines and underwater vehicles, adjust object density through controlled fluid intake and discharge. Such systems demonstrate that buoyancy manipulation can serve as an effective method for vertical positioning without relying on high-power lifting mechanisms. Although buoyancy-based lifting does not eliminate energy input, it redistributes the required work from mechanical lifting to fluid handling, which can be achieved with higher efficiency and lower peak power. Despite their widespread use in marine and industrial applications, buoyancy-assisted lifting principles have received limited attention in the context of gravity-based energy storage systems.

D. Canal Lock and Gravity-Driven Water Transfer Mechanisms

Canal lock systems are a well-established engineering solution for elevating and lowering vessels between water bodies at different heights. In such systems, water is transferred between chambers through controlled gates, allowing vessels to rise or fall by flotation without direct mechanical lifting. The energy required for vessel elevation is primarily associated with water movement rather than lifting the vessel itself.

The efficiency and reliability of canal lock systems, which have been in continuous operation for over two centuries, demonstrate the effectiveness of gravity-driven water transfer for vertical motion control. These systems minimize mechanical complexity and reduce peak energy demand by leveraging gravity and controlled fluid flow. The canal lock principle provides a strong engineering analogy for lifting buoyant objects using water level manipulation rather than direct lifting.

E. Research Gap and Motivation

From the reviewed literature, it is evident that existing gravity battery systems predominantly rely on direct mechanical lifting of solid masses, resulting in high peak power requirements and mechanical complexity during the reset phase. Pumped hydro systems effectively use fluid handling for energy storage but are limited by geographical constraints. Buoyancy-assisted lifting and canal lock mechanisms- demonstrate energy-efficient methods for vertical motion but have not been systematically integrated into gravity-based energy storage designs.

There exists a research gap in the integration of canal-lock-inspired water transfer mechanisms with gravity battery systems to achieve low-energy mass resetting. The present work addresses this gap by proposing a canal-lift-assisted gravity battery that combines gravitational energy storage with buoyancy-assisted lifting through a two-chamber water transfer system.

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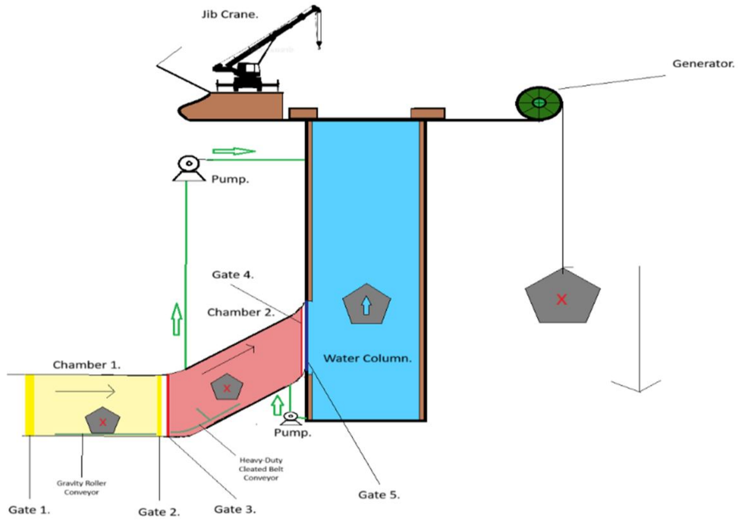
III. SYSTEM DESCRIPTION AND PROPOSED METHODOLOGY

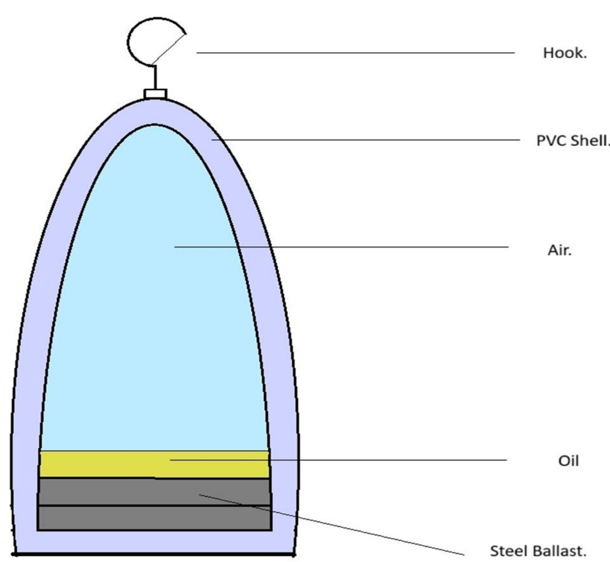


A. Overall System Architecture

The proposed system is a gravity-based energy storage unit that combines controlled gravitational descent, buoyancy-assisted lifting, and auxiliary crane-based positioning to reduce the effective energy required for mass resetting. The system is designed around a single gravity mass, a sealed vertical water column, and a mechanical power take-off (PTO) assembly consisting of a rope–pulley–gearbox–generator arrangement.

The overall architecture separates the energy generation phase, during which gravitational potential energy is converted into electrical energy, from the reset phase, during which buoyancy and auxiliary handling mechanisms are used to reposition the mass with reduced energy input.

B. Gravity Mass and Structural Arrangement



The gravity mass is a single, reusable block designed to operate in both air and water environments. Structurally, the mass consists of a rigid outer shell enclosing ballast material to achieve the required mass, along with a passive buoyancy volume that enables flotation within the water column. The buoyancy configuration is fixed and does not involve active control during operation.

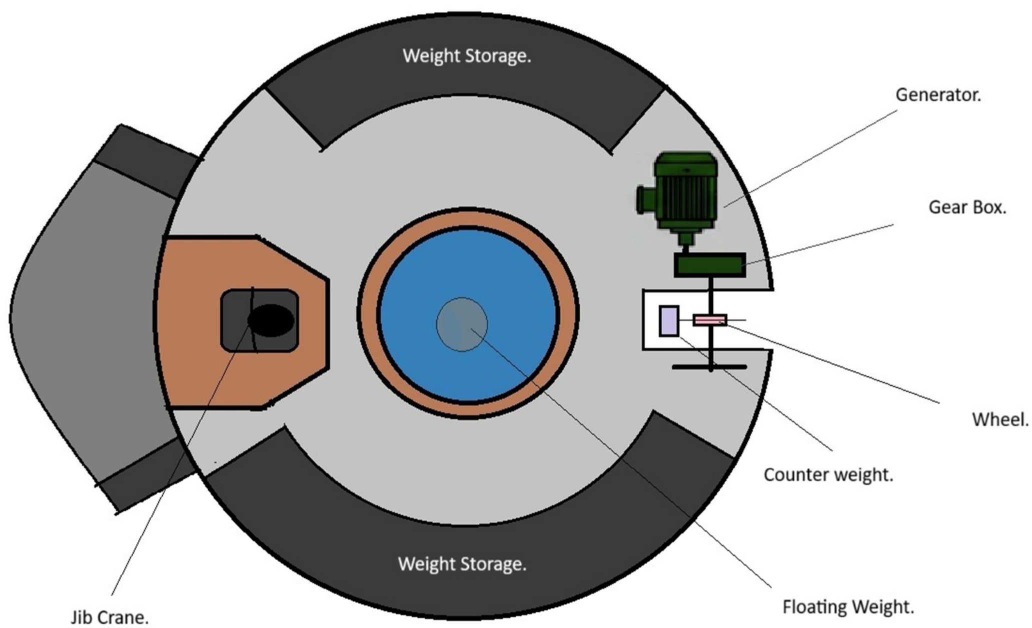
The mass is constrained to vertical motion using linear guide rails integrated within the water column. These guides suppress lateral oscillations, maintain alignment with the load cable, and protect the structural walls of the column from impact loads. The entire system is supported by a primary load-bearing structural frame that transfers mechanical loads to the foundation.

C. Water Column and Buoyancy Lift Chamber

A sealed vertical water column serves as the primary buoyancy-assisted lifting chamber. Water is present only within this chamber, ensuring controlled interaction between the gravity mass and the fluid. When the mass enters the column, buoyant forces significantly reduce its effective weight, allowing it to rise to the water surface without direct mechanical lifting.

The water column includes provisions for controlled filling and drainage, facilitated by low-power pumps used exclusively during reset and preparation phases. These pumps do not participate in lifting the mass during energy generation and are employed only to manage water levels in the system.

D. Rope–Pulley–Gearbox–Generator Assembly



Energy conversion is achieved through a mechanical PTO assembly located at the top of the system. The gravity mass is connected via a load cable that passes through a sealed guide at the water–air interface and over a pulley or drum mounted on a shaft. The shaft is coupled to a planetary gearbox that matches the low-speed, high-torque motion of the falling mass to the operating speed of the generator. A controlled engagement clutch is incorporated between the gearbox and the generator to enable gradual torque transfer, preventing shock loading during start-up. Additionally, a fail-safe braking system is installed on the shaft to regulate descent speed, enable soft start and stop operation, and provide emergency shutdown capability.

E. Crane-Assisted Mass Positioning Mechanism

A jib crane is provided as an auxiliary handling device for mass positioning. The crane operates only when the gravity mass is fully buoyant at the water surface, where buoyancy substantially reduces the effective load. Under these conditions, the crane performs low-energy lateral positioning to align the mass with the generator rope attachment point.

The crane does not participate in vertical lifting during the energy generation phase and remains disengaged during controlled descent. Its role is limited to positioning, maintenance, and fault recovery, ensuring that the primary energy storage and generation mechanism remains gravity-driven.

F. Braking, Control, and Safety Provisions

System safety and controllability are ensured through the combined use of braking, controlled engagement, and mechanical guidance. The braking system provides speed regulation and emergency stopping capability, while the clutch allows smooth torque ramp-up during engagement. Sensors for position, speed, and water level are assumed to be integrated into the system, although they are not explicitly shown in schematic diagrams for clarity.

These measures ensure stable operation, prevent overspeed conditions, and protect mechanical components from excessive dynamic loads during repeated cycling.

G. Methodological Approach

The proposed methodology focuses on reducing peak mechanical lifting power by replacing direct solid lifting with buoyancy-assisted motion and controlled handling. Rather than maximizing energy density, the design prioritizes mechanical simplicity, operational safety, and long service life. Performance evaluation is carried out through analytical estimation of gravitational potential energy, mechanical losses, and auxiliary energy inputs, which are discussed in subsequent sections.

IV. WORKING PRINCIPLE

The proposed canal-lift assisted gravity battery operates through a cyclic process that combines buoyancy-assisted lifting, auxiliary positioning, and controlled gravitational descent to store and release energy. The system is designed such that the water column remains filled at a constant level during normal operation, and only the gravity mass undergoes vertical motion. A complete operating cycle is described below.

A. Buoyancy-Assisted Lifting Phase

After completing an energy generation cycle, the gravity mass reaches the bottom position and enters the sealed vertical water column. Due to its passive buoyancy configuration, the mass experiences an upward buoyant force that significantly reduces its effective weight and causes it to rise within the water column. This lifting process occurs without direct mechanical actuation and without emptying or refilling the water column.

The gravity mass is constrained to vertical motion by linear guide rails integrated into the column, ensuring stable alignment and preventing lateral oscillations. As the mass ascends, the surrounding water remains essentially stationary, and no net water transfer is required for the lifting process.

B. Surface Positioning Phase

When the gravity mass reaches the water surface, its effective weight is substantially reduced due to buoyancy. At this stage, a jib crane is employed as an auxiliary handling mechanism to perform **low-energy lateral positioning** of the mass. The crane operates only at the water surface and is used to align the mass with the rope–pulley interface of the power take-off assembly.

The crane does not participate in vertical lifting during the energy generation phase and remains disengaged during controlled descent. Its role is limited to positioning, maintenance, and fault recovery.

C. Engagement and Holding Phase

Once the gravity mass is correctly positioned, it is connected to the load cable of the power take-off system. A fail-safe braking mechanism holds the mass stationary while the crane is disengaged. During this phase, the controlled engagement clutch between the gearbox and the generator remains disengaged, preventing torque transmission.

This sequence ensures that the transition of load from the crane to the power take-off system occurs smoothly and without shock loading.

D. Controlled Descent and Energy Generation Phase

Following crane disengagement, the controlled engagement clutch is gradually activated, and the braking system is progressively released. The gravity mass then descends under gravitational force in a regulated manner. As the mass moves downward, it pulls the load cable over the pulley or drum, causing rotation of the shaft.

The rotational motion is transmitted through the planetary gearbox, which matches the low-speed, high-torque input to the operating speed of the generator. Electrical power is produced as the generator converts the mechanical energy of descent into electrical energy. Descent speed and generator loading are regulated by the coordinated action of the brake and clutch, ensuring stable operation and preventing overspeed conditions.

E. Stop and Reset Phase

At the completion of the descent, the braking system is reapplied to bring the gravity mass to a controlled stop at the lower position. The generator is unloaded, and the clutch is disengaged. The system is then ready to begin the next operating cycle, starting again with buoyancy-assisted lifting of the gravity mass. Throughout the entire cycle, the water column remains filled and does not undergo cyclic emptying or refilling. Pumps, if present, are used only for initial filling, minor water-level correction, or maintenance operations and do not participate in the energy generation or lifting process.

V. ENERGY AND MECHANICAL ANALYSIS

A. Gravitational Potential Energy Storage

The energy stored and released by the proposed system is governed by the gravitational potential energy of the gravity mass. For a mass $m$descending through a vertical height h, the theoretical maximum energy available per cycle is given by:

$$E_g = mgh$$

where $g$is the acceleration due to gravity. This expression represents the upper bound of extractable energy and assumes ideal conditions without losses. In practice, the usable energy is reduced due to mechanical, electrical, and hydrodynamic losses.

B. Mechanical Power During Controlled Descent

During the energy generation phase, the gravity mass descends at a controlled velocity v. The instantaneous mechanical power available at the shaft is expressed as:

$$P_m = mgv$$

The descent velocity is regulated by the braking system and controlled engagement clutch to ensure stable operation and to match generator operating conditions. Unlike free-fall systems, the proposed design intentionally limits acceleration to reduce dynamic loading, improve component life, and maintain predictable power output.

C. Generator Power Output and Transmission Losses

The mechanical power produced during descent is transmitted through a pulley, gearbox, and generator assembly. The net electrical power output $P_e$is given by:

$$P_e = \eta_{\mathrm{mech}}\, \eta_{\mathrm{gear}}\, \eta_{\mathrm{gen}}\, mgv$$

where:

- η_{mech}represents losses due to rope friction and bearings,
- $\eta_{\mathrm{gear}}$is the gearbox efficiency,
- $\eta_{\mathrm{gen}}$is the generator efficiency.

Typical industrial values for combined efficiency range between 70–85%, depending on component selection and operating conditions.

D. Effect of Buoyancy on Reset Energy

Buoyancy plays a critical role in reducing the energy required for mass repositioning. When the gravity mass enters the water column, the buoyant force $F_b$acting on the mass is given by:

$$F_b = \rho_w g V$$

where $\rho_w$is the density of water and $V$is the displaced volume of the mass. The effective weight of the mass in water becomes:

$$W_{\text{eff}} = mg - F_b$$

As a result, the energy required for crane-assisted positioning at the water surface is significantly lower than that required for lifting the same mass in air. Importantly, this reduction in reset energy does not increase the net energy output of the system; it merely reduces auxiliary energy input during repositioning.

E. Auxiliary Energy Consumption

Auxiliary energy inputs in the proposed system include:

1) Crane operation during buoyant positioning,
2) Control electronics and sensors,
3) Brake actuation and clutch engagement,
4) Minor pumping for water-level correction or maintenance.

These energy inputs are not part of the energy storage mechanism and are minimized through system design. The crane operates only when the mass is buoyant, and pumps do not participate in the lifting or generation cycle. Consequently, auxiliary energy consumption remains a small fraction of the energy generated per cycle.

F. Overall Energy Balance and Efficiency

The net energy recovered per cycle is always less than the gravitational potential energy mghdue to unavoidable losses. The overall round-trip efficiency of the system depends on:

1) Mechanical transmission efficiency,
2) Gene

VI. CONTROL AND SAFETY CONSIDERATIONS

The proposed gravity battery system incorporates multiple control and safety features to ensure stable operation, controlled energy conversion, and protection of mechanical components. Given the large mass involved and the gravitational nature of the system, controlled motion and fail-safe operation are essential design requirements.

A. Descent Speed Regulation

The descent speed of the gravity mass during the energy generation phase is regulated through a coordinated braking and clutch engagement strategy. A fail-safe braking system is used to control acceleration, maintain a predefined descent velocity, and bring the mass to a controlled stop at the lower position. This prevents excessive dynamic loading on the rope, pulley, gearbox, and generator.

Unlike free-fall systems, the proposed design operates under controlled descent conditions, enabling predictable power output and reducing mechanical wear.

B. Controlled Engagement and Torque Limiting

A controlled engagement clutch is integrated between the gearbox and the generator to allow gradual transfer of torque during start-up. This mechanism prevents shock loading when the gravity mass transitions from a stationary state to active descent. Torque limiting further protects the drivetrain from overload conditions caused by sudden changes in load or speed.

The combination of controlled engagement and torque limiting enhances system reliability and extends component service life.

C. Braking System and Fail-Safe Operation

The braking system is designed to be fail-safe, meaning it defaults to an engaged state in the event of power loss or control system failure. This ensures that the gravity mass remains securely held under abnormal conditions. The brake serves multiple functions, including holding the mass during rope attachment, regulating descent speed, enabling soft start and stop operation, and providing emergency stopping capability. Such fail-safe braking strategies are standard practice in elevator, crane, and hoisting systems and are directly applicable to the proposed design.

D. Position, Speed, and Water-Level Monitoring

Although not explicitly shown in the schematic diagrams, the system is assumed to incorporate standard sensor instrumentation for monitoring critical parameters. These include position sensors for tracking mass location, speed sensors for descent velocity, and water-level sensors for the buoyancy chamber.

Sensor feedback is used to coordinate brake release, clutch engagement, and generator loading, ensuring synchronized operation and preventing unsafe operating conditions.

E. Crane Interlock and Operational Isolation

The crane-assisted positioning mechanism is interlocked with the power take-off system to prevent simultaneous operation. Energy generation is permitted only when the crane is fully disengaged and clear of the gravity mass. This interlock eliminates the risk of unintended load sharing between the crane and the generator system and reinforces the separation between auxiliary handling and energy conversion functions.

F. Emergency and Maintenance Considerations

Emergency stop functionality is provided through manual and automated braking activation. In maintenance scenarios, the system can be locked in a safe state using mechanical stops and braking devices. The water column may be drained only during maintenance or inspection activities and does not require cyclic emptying during normal operation.

These provisions ensure safe access for inspection, servicing, and fault recovery without compromising system integrity.

VII. ADVANTAGES AND LIMITATIONS

A. Advantages

The proposed canal-lift assisted gravity battery offers several advantages compared to conventional gravity-based and mechanical lifting energy storage systems.

1) Reduced Reset Energy Requirement: By utilizing buoyancy-assisted lifting within a permanently filled water column, the system significantly reduces the effective weight of the gravity mass during the reset phase. This minimizes auxiliary energy consumption for repositioning and avoids the need for high-power lifting motors or winches.
2) Controlled and Safe Operation: The integration of a fail-safe braking system and controlled engagement clutch enables smooth start-up, regulated descent, and safe shutdown of the gravity mass. This controlled operation reduces mechanical shock, improves system reliability, and enhances operational safety.
3) Mechanical Simplicity and Longevity: The system relies primarily on well-established mechanical components such as pulleys, gearboxes, brakes, and generators. Unlike electrochemical batteries, there is no material degradation associated with charge–discharge cycles, resulting in potentially long service life and low lifecycle replacement requirements.
4) Modular and Scalable Design: The proposed architecture is modular, allowing multiple units to be installed in parallel to increase total storage capacity and power output. Scaling can be achieved by adjusting the mass, drop height, or number of modules without altering the fundamental operating principle.
5) Separation of Energy Generation and Handling Functions: By isolating energy generation from auxiliary handling mechanisms such as the crane, the system maintains a clear distinction between power conversion and positioning tasks. This separation simplifies control logic and reduces the risk of unintended energy losses or unsafe interactions.

B. Limitations

Despite its advantages, the proposed system also has inherent limitations that must be acknowledged.

1) Low Energy Density: Gravity-based energy storage systems inherently exhibit lower energy density compared to electrochemical batteries. Large masses and vertical structures are required to store meaningful amounts of energy, which may limit applicability in space-constrained environments.
2) Infrastructure Requirements: The system requires substantial structural support, a vertical water column, and mechanical housing. These civil and structural requirements may increase initial capital cost and limit deployment to industrial or utility-scale installations.
3) Dependence on Water Availability: Although the water column is not cyclically emptied, the system still requires a stable water volume. In arid regions or locations with limited water access, additional considerations such as water sourcing and evaporation control may be necessary.
4) Limited Suitability for Small-Scale Applications: Due to the involvement of heavy masses, cranes, and large mechanical components, the proposed design is more suitable for grid-scale or industrial energy storage rather than small or portable applications.

5) Unmodeled Dynamic Effects: The present analysis does not include detailed transient effects such as fluid–structure interaction, rope elasticity, or control system dynamics. These factors may influence performance and will require further investigation through numerical modeling and experimental validation.

VIII. APPLICATIONS

The proposed canal-lift assisted gravity battery is intended for applications where long service life, mechanical robustness, and safe large-scale energy storage are prioritized over high energy density. Potential application areas include the following.

1) Grid-Scale Energy Storage: The system can be deployed as a grid-support energy storage solution for balancing intermittent renewable energy sources such as solar and wind. Its ability to deliver controlled power output and withstand frequent cycling makes it suitable for peak shaving, load leveling, and grid stabilization.
2) Industrial Facilities and Process Plants: Energy-intensive industrial installations with available vertical space, such as chemical plants, steel plants, and mining facilities, can integrate the proposed system for energy recovery and backup power applications. The mechanical nature of the system aligns well with industrial environments where heavy equipment and cranes are already present.
3) Renewable Energy Integration Sites: At renewable energy generation sites, the proposed gravity battery can store excess energy during periods of low demand and release it when generation drops. The system's independence from electrochemical storage makes it attractive for locations requiring long operational lifetimes with minimal degradation.
4) Remote and Harsh Environments: Due to its reliance on mechanical components rather than sensitive chemical systems, the proposed design is well-suited for remote or harsh environments where maintenance access is limited and environmental conditions may be challenging for conventional batteries.
5) Infrastructure-Integrated Energy Storage: The gravity battery concept can be integrated into existing infrastructure such as tall industrial buildings, shafts, or purpose-built towers. This integration enables energy storage without requiring large land areas, making it suitable for industrial zones with constrained footprints.

IX. CONCLUSION

This study presented a conceptual design and analytical assessment of a canal-lift assisted gravity battery that combines controlled gravitational descent with buoyancy-assisted mass repositioning. The proposed system employs a single gravity mass, a permanently filled water column, and a mechanically controlled power take-off assembly to store and release energy in a safe and regulated manner.

Unlike conventional gravity-based storage systems that rely on direct mechanical lifting, the proposed approach reduces auxiliary energy input by utilizing buoyant forces to assist mass lifting during the reset phase. The inclusion of controlled engagement mechanisms, fail-safe braking, and guide rails ensures stable operation, predictable power output, and mechanical safety throughout repeated operating cycles. Importantly, the system adheres strictly to energy conservation principles and does not depend on cyclic emptying of the water column or pumped-hydro behavior.

Analytical evaluation demonstrates that the energy output of the system is governed by the gravitational potential energy of the mass, while auxiliary energy consumption is minimized through buoyancy-assisted handling and limited crane usage at the water surface. Although the system exhibits lower energy density compared to electrochemical storage technologies, it offers advantages in terms of durability, scalability, mechanical simplicity, and long service life.

Overall, the proposed canal-lift assisted gravity battery represents a mechanically robust and conceptually sound approach to large-scale energy storage, particularly suited for industrial and grid-support applications where long-term reliability and safety are critical considerations.

X. FUTURE SCOPE

The present study establishes the conceptual framework and analytical feasibility of a canal-lift assisted gravity battery. Several aspects of the proposed system offer scope for further investigation and development.

Future work may include detailed numerical modeling of fluid–structure interaction within the water column to better understand hydrodynamic effects on buoyancy-assisted lifting and descent stability. Advanced simulations incorporating rope elasticity, transient braking behavior, and control-system dynamics could further refine performance predictions.

Experimental validation through a scaled laboratory prototype is another important direction. Such a prototype would enable measurement of actual mechanical losses, auxiliary energy consumption, and system response under varying operating conditions. Results from experimental testing would help validate analytical assumptions and guide optimization of component sizing.

Further scope exists in system optimization and scaling, including the use of multiple gravity masses, alternative structural configurations, and improved gearbox and generator selection to enhance power output and operational efficiency. Integration with automated control systems and advanced sensing could also improve reliability and operational flexibility.

Finally, long-term studies focusing on durability, maintenance requirements, and lifecycle assessment would support evaluation of the proposed system as a viable large-scale energy storage solution for industrial and grid-support applications.

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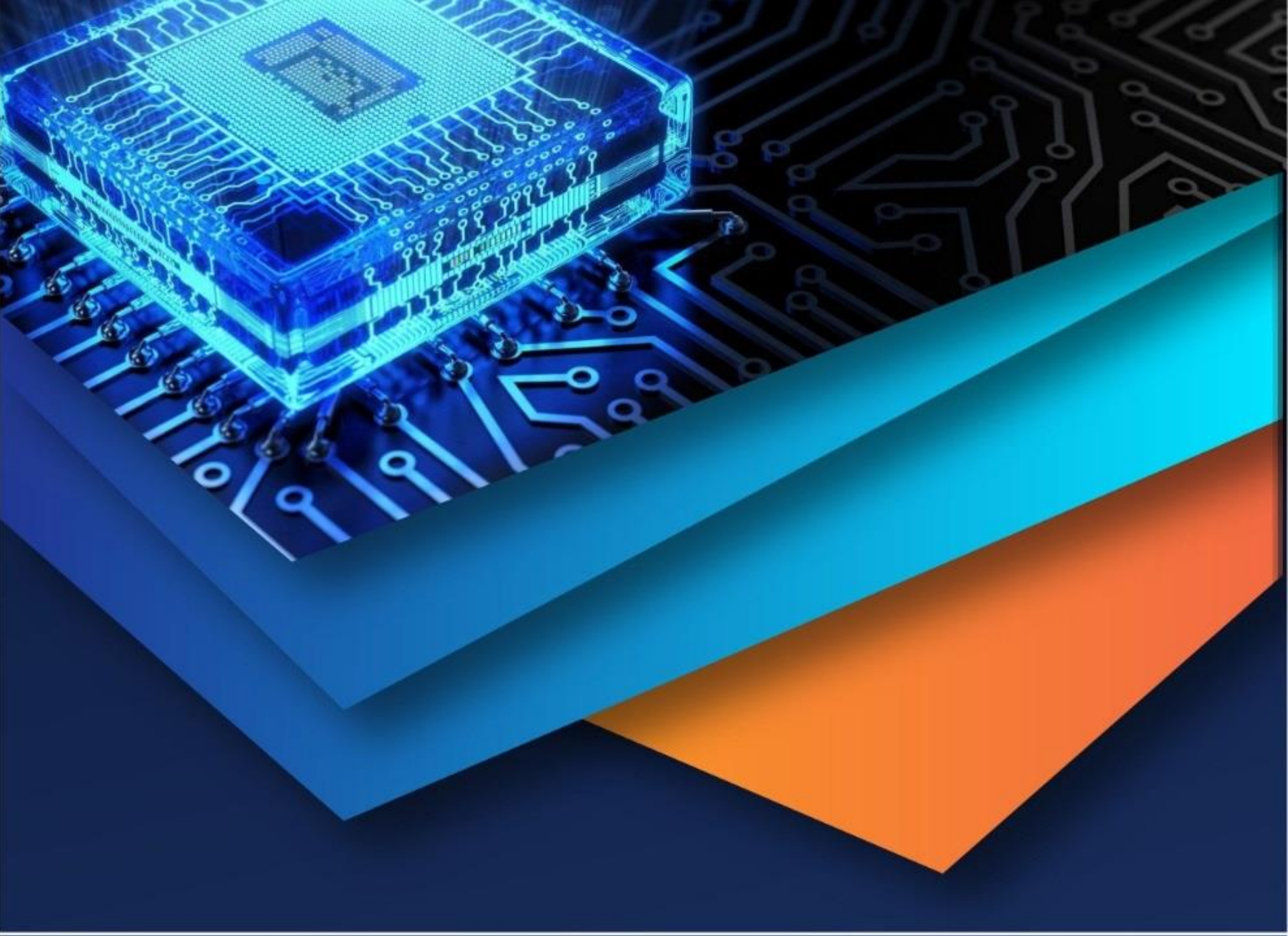

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