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A Comprehensive Review of Economical Energy Storage Systems and Technologies

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***Abstract* – The fast development of renewable energy sources has led to an increased instability of the grid due to the intermittent nature of solar and wind power, while conventional electrochemical batteries are hampered by limitations such as resource scarcity, capacity degradation, thermal runaway hazards, and limited cycle life. For long duration energy storage, mechanical systems using gravity have been proposed as an alternative. The use of elevated masses to store gravitational potential energy, which is then released on demand through a controlled descent. This study provides an overview of gravity battery technologies namely pumped hydroelectric, solid mass towers, mine shaft storage, rail-based slope systems and buoyant ocean storage and discusses how they can be utilized in grid stabilization, industrial peak shaving and distributed energy management. Results show that gravity storage technologies can reach round-trip efficiencies of 70% to 85%, have operational lifetimes of over 30 to 50 years with marginal capacity degradation, and are increasingly cost-competitive for dispatch periods exceeding six hours. Moreover, the repurposing of abandoned mine shafts and obsolete industrial infrastructure supports circular economy principles and diminishes reliance on critical materials such as lithium and cobalt. There are challenges such as limits on structural load, high up-front capital costs, and mechanical fatigue on hoist cables and drive trains. However, the constant technical improvements in automated control, linear motor topologies and hybrid renewables integration are rendering it technically feasible. To summarize, gravity batteries present a sustainable and scalable path to grid resilience and deserve accelerated research, policy support, and industrial scale deployment.**

Keywords - **Gravity energy storage, Long-duration energy storage, Renewable energy integration, Mechanical energy storage, Circular economy, Grid stabilization, Mine shaft energy storage**

I. INTRODUCTION

The global energy landscape is undergoing a transformative shift toward renewable sources, with solar and wind capacity expanding at unprecedented rates to meet international net-zero targets. However, the inherent intermittency of these sources introduces significant challenges for grid stability, load balancing, and energy security, necessitating robust long-duration energy storage (LDES) solutions capable of bridging supply gaps extending from several hours to multiple days. Conventional electrochemical batteries—particularly lithium-ion systems—have dominated short-duration storage markets but face critical constraints, including the resource scarcity of lithium and cobalt, thermal runaway hazards, capacity degradation within 5–15 years, and economic limitations for discharge durations exceeding 4–6 hours. Furthermore, the environmental and geopolitical implications of mining critical minerals, combined with recycling challenges and fire-safety concerns, have intensified the search for sustainable, mechanical alternatives that circumvent chemical degradation entirely.
Gravity-based energy storage systems have emerged as a compelling mechanical alternative that stores energy by elevating large masses against gravitational force and recovering it through controlled descent to drive electric generators. Unlike electrochemical systems, gravity batteries operate without rare-earth materials, toxic electrolytes, or temperature-sensitive chemistries, offering operational lifespans exceeding 25–50 years with minimal capacity fade. Recent studies demonstrate that these systems achieve round-trip efficiencies ranging from 70% to 85% depending on the technology variant, with solid-mass tower systems and shaft-based configurations showing particular promise for modular, site-flexible deployment. The global gravity battery market is projected to expand substantially, driven by declining capital costs and increasing utility-scale deployments. Technologies under active development and commercialization span five principal categories: mature pumped-storage hydroelectricity (PSH), solid-mass tower and crane systems, shaft-based mine storage, rail-based inclined track systems, and emerging buoyant underwater configurations. Additionally, the repurposing of abandoned mine shafts and depleted industrial infrastructure for gravity storage aligns with circular economy principles, transforming liabilities into grid-scale assets while reducing reliance on virgin raw materials. This review systematically examines the principal gravity battery technologies and their working principles, including mechanical, structural, and thermodynamic characteristics. The study further explores value-added applications across grid-scale stabilization, industrial peak shaving, off-grid and remote community power, and residential energy management. A comparative techno-economic analysis is presented to evaluate efficiency, capital investment, site constraints, and lifecycle performance relative to electrochemical and hydrogen-based storage. Current challenges—including site specificity, mechanical wear in lifting systems, high upfront capital costs, and policy gaps—are critically discussed alongside future research directions involving automation, linear motor topologies, hybrid thermal-gravity integration, and digital twin optimization.

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By synthesizing recent advances across mechanical engineering, materials science, and power systems, this article aims to establish a comprehensive framework for understanding gravity batteries as a scalable, sustainable pathway toward grid resilience and deep decarbonization.

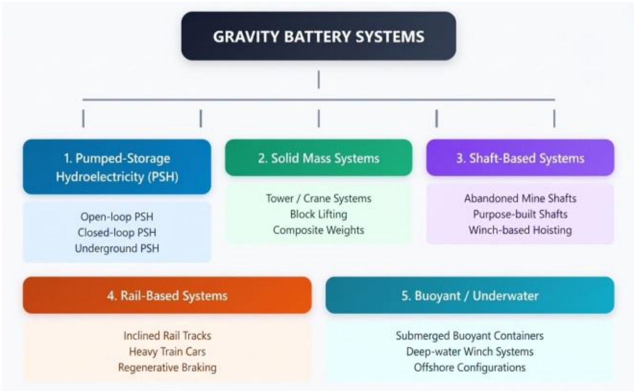

Figure 1. Classification of gravity battery technologies based on mass elevation mechanism and infrastructure type.

II. LITERATURE REVIEW

According to recent research, gravity-based energy storage has become a viable approach for promoting grid stability and long-duration energy storage while tackling the growing challenges of renewable energy intermittency. Together, the examined literature shows that the rapid expansion of solar and wind capacity globally has greatly increased the need for storage solutions capable of bridging supply gaps extending from several hours to multiple days. Researchers constantly stress that conventional electrochemical batteries—particularly lithium-ion systems—face increasing constraints related to material scarcity, thermal runaway hazards, capacity degradation within 5–15 years, and economic limitations for discharge durations exceeding 4–6 hours [1], [3], [21], [37]. As a result, gravity batteries have emerged as a crucial component of sustainable energy transition strategies designed to extend infrastructure lifecycles, reduce dependence on rare-earth minerals, and foster a circular energy economy [28], [32], [36].

Several gravity storage technologies have been developed to recover and store electrical energy through mechanical elevation of mass, according to the literature. Pumped-storage hydroelectricity (PSH) remains the most dominant and commercially mature technology, accounting for over 95% of global grid-scale storage capacity; however, researchers note that its deployment is severely constrained by topographical requirements, long construction timelines, and environmental concerns [27], [30], [38]. In contrast, mechanical gravity systems—particularly solid-mass tower configurations and shaft-based storage—have been rapidly developing as modular alternatives that circumvent geographic limitations. Tong et al. [20], [21] provided comprehensive classifications and reviews of solid gravity energy storage technology, identifying tower-based block lifting and vertical shaft systems as promising pathways for commercial scalability. Morstyn et al. [34] and Botha and Kamper [33] demonstrated the technical feasibility of suspended-weight and dry gravity systems in abandoned mine shafts, while Hunt et al. [14] established underground gravity energy storage as a viable solution for long-term applications. Furthermore, Korski [8] and Siostrzonek [9] examined the practical functionality and implementation threats of mine-shaft energy storage, and Kula et al. [22] presented a detailed techno-economic case study of the Budryk mine shaft system in Poland. Hunt et al. [24] explored rail-based gravity concepts using electric truck hydropower for mountainous regions, while Hunt et al. [23] investigated buoyancy energy storage technology for coastal and offshore applications. Wu et al. [35] examined earth potential energy storage in rail transit systems, and Tarigheh [40] presented early prototype concepts for modular gravity power modules. Numerous studies conclude that site geology, shaft depth, discharge duration, and grid integration requirements significantly influence the selection of an appropriate gravity storage technology [20], [36].

Researchers further report that gravity storage systems can be successfully integrated into numerous value-added applications, including grid-scale stabilization, industrial peak shaving, remote off-grid power, and residential energy management. Bowoto et al. [25] and Al-Hilfi et al. [16] investigated the potential benefits and challenges of gravity energy storage in residential sectors, while Mondal et al. [19] developed a solar PV-driven hybrid gravity power module integrated with vanadium redox flow batteries for multi-storied buildings. Roushenas et al. [7] conducted a techno-economic analysis and multi-objective optimization of hybrid renewable plants integrated with gravitational energy storage, and Gao et al. [15] examined optimal dispatching strategies for wind-PV-mine pumped storage power stations. Krassakis et al. [11] presented a GIS-based assessment of hybrid pumped hydro storage using depleted lignite mines, and Yang et al. [31] proposed novel gravity energy storage operation modes specifically designed to accommodate renewable energy fluctuations.

Chaturvedi et al. [29] further explored electricity storage system architectures based on gravity battery principles for smart grid integration. These applications simultaneously increase infrastructure utilization and open up new economic opportunities while lessening the environmental impact of conventional battery manufacturing. Underground gravity storage has received special attention in recent studies as a viable strategy for creating closed-loop energy systems from abandoned industrial assets [14], [26]. In order to enhance gravity storage efficiency, structural reliability, and grid responsiveness, a number of studies also address the integration of advanced electromechanical systems with gravity storage infrastructure. Yan et al. [12] explored linear motor topologies for abandoned mine-type and mountain gravity energy storage, while Li et al. [6] analyzed flux switching linear machines for gravity storage applications. Tong et al. [10] investigated the inertial characteristics of gravity energy storage systems, and Emrani and Berrada [13] assessed structural behavior and flow characteristics through detailed modeling and experimental validation. Additionally, Emrani et al. [17] performed analytical and numerical analyses of energy loss mechanisms to assess round-trip efficiency, and Wang et al. [5] and Gao et al. [4] examined energy efficiency characteristics and sensitivity of transmission chain slope gravity storage systems using the Sobol method. These digital and electromechanical advancements optimize dispatch precision, reduce frictional losses, and improve overall system performance, thereby facilitating sustainable deployment of mechanical storage systems [1], [3], [10].

The literature notes a number of obstacles that still prevent the widespread adoption of gravity battery systems despite notable technological advancements. Major barriers to effective deployment still include site-specific constraints such as shaft depth and geomechanical conditions, high initial capital investment, mechanical wear in lifting and hoisting systems, and limited cycle speeds compared to electrochemical alternatives [8], [9], [33]. Schmidt et al. [26] highlighted the effects of cyclic loading on geomechanical performance in underground systems, while Menéndez et al. [27] identified efficiency limitations in underground pumped storage configurations. Furthermore, the shift toward commercial-scale gravity storage is hampered by the lack of standardized performance metrics, insufficient lifecycle assessment comparisons with chemical batteries, limited policy frameworks for long-duration energy storage, and the scarcity of industrial-scale demonstration facilities outside of pumped hydro [1], [3], [32].

Consequently, environmentally benign repurposing of industrial infrastructure for gravity storage remains a top research priority. Researchers advise more robust policy frameworks, dedicated capacity market remuneration mechanisms for long-duration energy storage, standardized infrastructure repurposing guidelines, investment in advanced electromechanical technologies, and increased interdisciplinary collaboration among geotechnical engineers, mechanical designers, and grid operators [2], [11], [39].

Overall, the reviewed literature shows that gravity battery systems reduce reliance on critical minerals, minimize chemical waste and thermal hazards associated with electrochemical disposal, lower long-term levelized costs for durations exceeding six hours, and promote sustainable industrial growth through infrastructure repurposing. To develop standardized efficiency benchmarks, improve hybrid system economics, validate geomechanical performance under cyclic loading, and create integrated circular business models that facilitate large-scale industrial deployment, more research is necessary.

The combined results of these studies offer a solid basis for further investigation into gravity energy storage technologies and their role in achieving sustainable resource management and a circular energy economy.

III. GRAVITY BATTERY TECHNOLOGIES

In order to eliminate the environmental degradation associated with critical mineral extraction and conventional battery disposal, gravity-based storage technologies are essential for converting surplus renewable electricity into dispatchable mechanical potential energy. The selection of an optimal gravity storage architecture depends on site geology, existing infrastructure, required discharge duration, and economic constraints. Recent developments have significantly enhanced round-trip efficiency by incorporating advanced power electronics, automated multi-axis control algorithms, direct-drive linear machines, and repurposed industrial infrastructure. Pumped-storage hydroelectricity, solid mass tower systems, shaft-based storage, rail-based systems, and buoyant underwater configurations constitute the primary technological pathways.

Pumped-Storage Hydroelectricity (PSH): As the most commercially mature technique for grid-scale energy storage, pumped-storage hydroelectricity accounts for over 95% of global installed storage capacity. During periods of surplus generation, water is pumped from a lower reservoir to an elevated upper reservoir; during demand peaks, the stored water is discharged through hydraulic turbines to drive generators. Rehman et al. [38] categorized open-loop, closed-loop, and underground configurations as the principal variants. Dekka et al. [39] surveyed grid-scale technologies and confirmed PSH as the foundational benchmark, while Aneke and Wang [37] reviewed real-world grid operations. Round-trip efficiencies typically range from 70% to 85%. Underground pumped storage plants offer reduced surface land requirements but introduce geotechnical complexities. Furthermore, Yang et al. [31] formulated novel dispatch modes to mitigate renewable power fluctuations, Gao et al. [15] optimized wind-PV-mine pumped storage operations in mining basins, and Krassakis et al. [11] utilized GIS frameworks to validate hybrid storage feasibility in depleted lignite mines.

The primary advantages of PSH include multi-GWh storage capacities and extended operational lifespans exceeding 50 years. However, lengthy environmental assessments, protracted civil construction timelines, and strict geological and hydrological prerequisites limit widespread geographic expansion. Solid Mass Tower Systems (Lifted Weight Storage): Solid mass tower systems represent a modular alternative that functions independently of geographic elevation profiles by utilizing mechanical hoists or multi-arm cranes to lift engineered concrete blocks.

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Energy is stored during charging by elevating masses against gravity and recovered during controlled descent via motor-generator sets, achieving round-trip efficiencies between 75% and 85%. Tong et al. [20], [21] established comprehensive structural classifications for tower-based block lifting. Berrada et al. [36] developed fundamental design methodologies and techno-economic metrics, while Tarigheh [40] pioneered early modular gravity power module concepts. Recent research has concentrated on optimizing electromechanical conversion and load dynamics. Emrani et al. [17] provided numerical evaluations of mechanical and electrical loss mechanisms, and Emrani and Berrada [13] experimentally validated structural responses under continuous cyclic loading. Wang et al. [5] analyzed system efficiency dynamics, Gao et al. [4] conducted Sobol-based sensitivity analyses on transmission chain parameters, and Tong et al. [10] evaluated dynamic inertial responses. Furthermore, Li et al. [6] investigated flux-switching linear machines to eliminate mechanical transmission wear, while Kavoosi and Hagh [1] and Wang et al. [3] emphasized the scalability of solid gravity systems for long-duration applications.

Key benefits include modular scalability, zero operational water consumption, and operational lifespans exceeding 35 years. Challenges include structural wind loading on tall cranes, cable fatigue, and the requirement for sub-second automated block-handling control. Shaft-Based Gravity Storage: Shaft-based gravity storage repurposes vertical underground shafts (such as decommissioned mining assets) to hoist massive weights (ranging from 500 to 5,000 tonnes) via heavy-duty electric winches. Morstyn et al. [34] demonstrated the technical viability of suspended-weight systems in abandoned shafts, and Botha and Kamper [33] analyzed the physical capabilities of dry gravity configurations. Hunt et al. [14] established underground gravity storage as a competitive long-duration solution, while Kula et al. [22] provided a techno-economic case study of the Budryk mine shaft in Poland.

Yan et al. [12] analyzed linear motor topologies to replace conventional mechanical hoist ropes, Korski [8] evaluated mechanical payload dynamics, and Siostrzonek [9] detailed geotechnical threats and shaft liner integrity considerations. Tobór-Osadnik et al. [2] confirmed that utilizing existing shafts avoids extensive excavation CAPEX while delivering round-trip efficiencies between 75% and 88% with sub-second response times suitable for grid ancillary services. Major advantages include zero surface visual impact, brownfield infrastructure reuse, and direct proximity to established grid interconnections. Limitations include shaft structural deterioration, water ingress, and depth-dependent energy densities.

Rail-Based Gravity Storage: Rail-based gravity systems convert surplus electrical power into gravitational potential by driving heavily ballasted rail vehicles up an inclined grade; electrical energy is regenerated during descent via bidirectional regenerative braking systems. Wu et al. [35] optimized track vertical alignments to maximize kinetic-to-potential energy recovery in rail systems, while Hunt et al. [24] formulated electric truck and rail hydropower concepts for mountainous regions. Operating at gradients typically between 3% and 8%, rail-based systems offer linear scalability from 10 to 100+ MWh by simply adding train cars. While achieving round-trip efficiencies of approximately 75–82%, their primary constraints involve substantial land corridors and specific slope topography requirements.

Buoyant / Underwater Gravity Storage: Buoyant energy storage leverages hydrostatic pressure and buoyancy forces in deep water bodies by utilizing electrical winches to pull buoyant containers down to the seabed during charging, releasing them to drive generator winches during discharge. Hunt et al. [23] demonstrated the applicability of buoyancy storage for offshore wind integration, island power grids, and offshore hydrogen compression. With round-trip efficiencies around 70–82%, the technology requires no land footprint and integrates directly with offshore marine renewables. However, deep-water anchoring complexities, cable biofouling, and maritime corrosion currently limit deployments to early prototype stages. Underground Caverns and Multi-Vector Hybrid Configurations: Combining mechanical gravity storage with thermal or electrochemical systems within underground caverns provides flexible, multi-vector energy management. Matos et al. [30] detailed reservoir identification criteria for large-scale underground cavities, while Schmidt et al. [26] analyzed rock mass fatigue under cyclic loading. Mondal et al. [19] engineered hybrid gravity-flow battery modules for multi-story residential structures, Bowoto et al. [25] designed decentralized micro-gravity units for residential PV self-consumption, and Chaturvedi et al. [29] investigated smart-grid gravity battery interfaces.

Synthesis and Technology Comparison: As summarized in Table I, no single gravity storage topology addresses all grid constraints universally. PSH provides cost-effective bulk storage where topography permits, whereas solid mass towers offer modularity for distributed networks. Shaft-based installations maximize circular economy value by repurposing depleted mining assets, while rail and buoyant configurations target specialized terrain and offshore niches. Future developments must combine advanced power electronics, linear direct-drive machines, and automated grid-forming controllers to fully optimize round-trip efficiency and dispatch economics.

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Table 1. Comparative Analysis of Gravity Battery Technologies

Parameter	Pumped-Storage Hydroelectricity (PSH)	Solid Mass Tower Systems	Shaft-Based Gravity Storage	Rail-Based Gravity Storage	Buoyant / Underwater Storage
Operating Principle	Gravitational potential via water pumping between dual reservoirs	Vertical block hoisting using tower cranes and winch arrays	Suspended heavy mass hoisting in vertical underground shafts	Electric train car elevation on natural inclined tracks	Submersion and controlled ascent of buoyant containers
Primary Materials	Water, rock mass, concrete, steel penstocks	High-density concrete blocks, steel framing, hoist cables	Heavy ballast (steel/dense scrap/slag), hoist ropes	Steel rails, reinforced chassis, concrete ballast cars	Buoyant composite tanks, high-tensile mooring lines
Round-Trip Efficiency (RTE)	70% – 85%	75% – 85%	75% – 88%	75% – 82%	70% – 82%
Energy Storage Capacity	GWh-scale (Bulk grid storage)	5 – 80 MWh (Modular scalability)	1 – 25 MWh per shaft installation	10 – 100+ MWh (Linear scaling)	Multi-MWh to GWh potential
Site Constraints	Very High (Requires specific topography & water access)	Low (Terrain-agnostic, modular footprint)	Moderate–High (Requires deep vertical shafts/mines)	Moderate (Requires continuous 3%–8% slope)	Moderate (Requires deep water bodies/offshore access)
Capital Expenditure (CAPEX)	High upfront investment	Moderate	Low to Moderate (If repurposing existing mine shafts)	Moderate	Moderate to High (Marine infrastructure)
Environmental Footprint	Moderate–High (Reservoir land inundation & ecological impact)	Very Low (Compact surface footprint, non-toxic)	Negligible (Subsurface industrial asset repurposing)	Low–Moderate (Linear land corridor requirement)	Very Low (Minimal surface disruption)
Operational Lifespan	50+ Years	35–50 Years	30–50 Years	30–40 Years	25–35 Years
Commercial Maturity	Commercially mature (>95% global capacity)	Commercial pilot / Early utility-scale	Demonstration / Pilot phase	Pilot testing / Semi-commercial	Emerging / Laboratory & prototype R&D
Key Grid Applications	Baseload shifting, long-duration bulk balancing	Fast-response peak shaving, industrial microgrids	Grid frequency regulation, brownfield asset reuse	Mountainous terrain balancing, long-duration shifting	Offshore wind balancing, island microgrid stability
Key Literature References	Rehman et al. [38], Menéndez et al. [27]	Tong et al. [20], [21], Emrani et al. [17]	Morstyn et al. [34], Hunt et al. [14], Kula et al. [22]	Wu et al. [35], Hunt et al. [24]	Hunt et al. [23]

IV. APPLICATIONS AND VALUE CREATION OPPORTUNITIES

Gravity battery systems promote resource conservation, environmental sustainability, and economic growth while providing substantial opportunities to transform surplus renewable electricity into dispatchable grid services and industrial value. Recovered gravitational potential can be utilized across consumer, commercial, and industrial sectors rather than curtailing excess generation as waste. This strategy aligns with the core principles of a circular economy by extending infrastructure life cycles, reducing dependence on virgin raw materials, and eliminating the ecological footprint and chemical degradation associated with electrochemical battery disposal. Advances in mechanical design, electrical drivetrains, and geotechnical integration have significantly expanded the scope of gravity storage across diverse operational scales [1], [3], [21]. Grid-Scale Energy Storage and Renewable Integration: The deployment of gravity batteries for utility-scale load shifting, peak shaving, and frequency regulation represents one of the most vital applications of mechanical energy storage. Mature PSH configurations continue to serve as the benchmark for grid balancing and bulk power management, as documented by Rehman et al. [38] and Dekka et al. [39].

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Yang et al. [31] formulated dynamic operation modes specifically tailored to accommodate high-penetration renewable fluctuations, while Gao et al. [15] optimized dispatch strategies for wind–PV–mine hybrid stations. Hunt et al. [14] established underground gravity storage as a competitive long-duration alternative for grid-scale stability, and Roushenas et al. [7] validated the economic feasibility of hybrid renewable plants integrated with gravitational storage through multi-objective optimization. Furthermore, Tong et al. [20], [21] demonstrated that modular solid-mass tower systems provide flexible grid services without topographic limitations, and Berrada et al. [36] validated their lifecycle economic viability. These utility-scale installations effectively buffer intermittent solar and wind generation across 6- to 24-hour discharge windows while supplying rotational inertia and rapid ancillary response to stabilize grid frequency [10], [37].

Off-Grid and Remote Community Storage: Gravity storage systems deliver critical value to island nations, remote mining outposts, agricultural hubs, and mountainous settlements where grid interconnections are absent and reliance on diesel generators is high. Hunt et al. [23] demonstrated that buoyancy energy storage systems are ideally suited for island microgrids and coastal renewable integration, while Hunt et al. [24] proposed electric truck hydropower topologies for flexible, terrain-following storage in alpine regions. Bowoto et al. [25] evaluated gravitricity systems combining decentralized solar generation with gravity storage for remote residential clusters. Mondal et al. [19] engineered hybrid gravity modules integrated with vanadium redox flow batteries to support multi-story buildings in weak-grid environments. Additionally, Krassakis et al. [11] verified through GIS modeling that depleted lignite mines can be repurposed into localized hybrid storage hubs. These decentralized configurations displace costly diesel fuel imports, integrate localized renewable assets, and provide uninterrupted backup power for critical infrastructure [14], [23].

Industrial and Commercial Peak Shaving: Repurposed industrial infrastructure and modular gravity towers have gained strong traction as non-chemical storage assets for energy-intensive facilities, including manufacturing plants, data centers, metal refineries, and active mining complexes. Kula et al. [22] provided techno-economic proof of electric energy storage feasibility within the Budryk mine shaft, while Siostrzonek [9] analyzed structural and operational parameters governing industrial mine shaft storage. Tobór-Osadnik et al. [2] demonstrated how gravity storage integrates into industrial energy management frameworks across post-mining regions. Korski [8] evaluated mechanical weight-hoisting functionality in industrial shafts, and Schmidt et al. [26] assessed geomechanical stability and cyclic loading dynamics in closed mines. Matos et al. [30] established criteria for selecting suitable underground cavities for large-scale industrial storage. Deploying gravity batteries in industrial facilities reduces expensive grid peak-demand surcharges, ensures clean backup power, and protects voltage-sensitive manufacturing machinery [7], [34].
Residential Energy Storage and Multi-Story Buildings: Compact tower, elevator-shaft, and micro-hoist gravity mechanisms offer a non-hazardous alternative for residential energy management, particularly when paired with rooftop photovoltaic (PV) arrays. Al-Hilfi et al. [16] investigated the performance benefits and design constraints of residential gravity systems, while Bowoto et al. [25] demonstrated solar-paired gravitricity units for household self-consumption. Mondal et al. [19] validated multi-story building gravity installations, and Chaturvedi et al. [29] explored gravity battery integration within smart residential microgrids. Sized typically between 5 kWh and 50 kWh, residential gravity units maximize solar self-consumption and provide domestic resilience while completely eliminating the fire hazards, thermal runaway risks, and capacity degradation inherent to residential lithium-ion packs [16], [25].

Repurposed Industrial Infrastructure Applications: The conversion of decommissioned mine shafts, quarries, depleted oil wells, and vertical industrial cavities into gravity energy storage assets represents an exemplary circular economy application. Morstyn et al. [34] and Botha and Kamper [33] validated the mechanical and economic viability of suspending heavy payloads in abandoned mine shafts. Hunt et al. [14] confirmed that underground gravity storage transforms environmental liabilities into revenue-generating grid assets. Yan et al. [12] analyzed linear motor topologies to streamline hoisting in abandoned shafts, while Korski [8] and Siostrzonek [9] addressed shaft liner integrity and hoist mechanics. Krassakis et al. [11] applied GIS spatial modeling to repurpose the Kardia lignite mine into a hybrid storage facility, and Menéndez et al. [27] evaluated underground hydraulic efficiencies. Repurposing these assets avoids substantial excavation and civil engineering capital expenditure while rejuvenating local economies in post-mining regions [2], [30].

Economic and Environmental Sustainability Benefits: Deploying gravity battery systems across utility, commercial, and decentralized sectors delivers clear environmental and economic advantages. Repurposing brownfield industrial assets minimizes the embodied carbon and virgin mineral demand associated with battery cell manufacturing [1], [3]. Gravity batteries operate without rare-earth materials, toxic chemical electrolytes, or critical minerals such as lithium, cobalt, and nickel, thereby eliminating hazardous waste streams and battery recycling bottlenecks [14], [36]. Furthermore, gravity systems offer operational lifespans of 30 to 50+ years with negligible capacity fade, significantly outperforming the 5- to 15-year replacement cycles of electrochemical batteries [21], [38]. Techno-economic analyses by Kula et al. [22], Roushenas et al. [7], and Berrada et al. [36] show that gravity storage achieves highly competitive Levelized Cost of Storage (LCOS) for durations exceeding 6 hours.

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When combined with efficiency loss modeling by Emrani et al. [17] and sensitivity evaluations by Wang et al. [5] and Gao et al. [4], gravity batteries emerge as a durable, environmentally benign foundation for long-duration energy storage [18], [28], [32], [40].

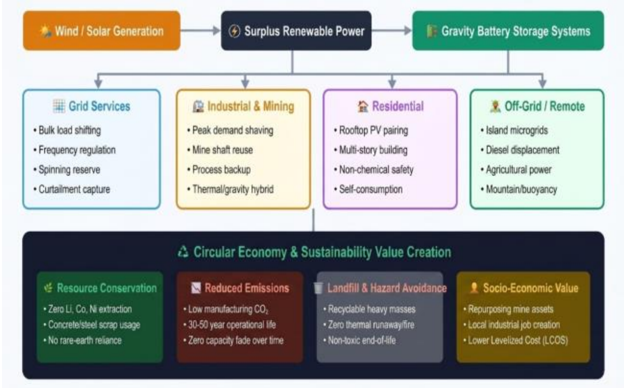

Figure 2. Unified global gravity battery framework illustrating energy flow from renewable generation through mechanical storage to grid, industrial, residential, and remote applications, with integrated circular economy and sustainability benefits.

V. COMPARATIVE ANALYSIS

In terms of round-trip efficiency, discharge duration, capital expenditure (CAPEX), environmental footprint, and geographical siting flexibility, gravity battery systems exhibit distinct operational trade-offs compared to conventional electrochemical and chemical energy storage alternatives. Selecting an optimal storage technology depends on the target discharge duration, capacity requirements, site geomechanics, and lifecycle economic objectives. Electrochemical batteries—predominantly lithium-ion systems—dominate short-duration applications (<4 hours); however, mechanical gravity energy storage systems (GESS) are increasingly cost-competitive for long-duration energy storage (LDES) exceeding 6 to 24 hours [1], [3], [37]. While pumped-storage hydroelectricity (PSH) remains the established benchmark for multi-GWh bulk grid storage, it is inherently constrained by topography and water availability [27], [30], [38]. Conversely, solid-mass and shaft-based gravity systems provide modular, terrain-agnostic alternatives that bridge the operational gap between fast-ramping electrochemical packs and bulk PSH [17], [20], [34].

Table II. Techno-Economic Comparison of Gravity Batteries with Alternative Storage Technologies

Parameter	Lithium-Ion Battery (BESS)	Pumped-Storage Hydro (PSH)	Solid-Mass Gravity Storage (GESS)	Hydrogen Energy Storage (H_2)
Round-Trip Efficiency (RTE)	85% – 95% [37], [39]	70% – 85% [27], [38]	75% – 85% [17], [21]	30% – 45% [37]
Discharge Duration	1 – 4 Hours [37]	6 – 24+ Hours [27], [38]	4 – 24+ Hours [20], [21]	Days to Weeks / Seasonal [37]
Operational Lifespan	5 – 15 Years [1], [3]	50+ Years [30], [38]	30 – 50 Years [1], [21]	15 – 25 Years [37]
Capacity Degradation	High (2\%–5\% annual fade) [3], [37]	Very Low (Turbine cavitation) [27]	Negligible (Zero chemical fade) [1], [17]	Low (Fuel cell / electrolyzer aging) [37]
Critical Material Scarcity	High (Li, Co, Ni) [3], [28]	Low (Water, civil aggregate) [38]	Very Low (Recycled steel, slag, concrete) [20], [21]	Moderate (Platinum, iridium catalysts) [37]
Fire / Chemical Hazard	High (Thermal runaway risks) [3], [28]	None [38]	None (Non-chemical, non-flammable) [20], [33]	Moderate–High (High-pressure H_2 flammability) [37]
Geographic Siting Flexibility	High (Footprint-limited) [37]	Very Low (Requires dual reservoirs & head) [30], [38]	High (Modular towers or brownfield shafts) [20], [21]	High (Requires cavern/pipeline infrastructure) [37]
Levelized Cost for >6h Storage	High (Due to periodic cell replacement) [3]	Low to Moderate [38]	Low to Moderate (Long cycle life) [7], [36]	High (Electrolyzer& round-trip penalty) [37]

Chemical alternatives such as green hydrogen accommodate multi-day or seasonal balancing, but suffer from low round-trip efficiency (30\%–45\%) and significant system complexity [37], [39]. Solid-mass gravity storage delivers competitive round-trip efficiencies (75\%–85\%), moderate capital expenditure, negligible capacity degradation over 30 to 50+ years, and zero thermal runaway hazards [1], [17], [21]. As synthesized in Table II, no single storage medium satisfies all grid demands universally. Lithium-ion batteries deliver high power density and rapid sub-second response for short durations, but face critical material scarcity and cycle aging constraints [3], [28], [37]. PSH delivers large-scale volumetric storage with low levelized costs over decades, yet requires specific geological elevation differentials and lengthy permitting horizons [27], [30], [38]. Solid-mass gravity storage delivers comparable round-trip efficiencies without geographic limitations, utilizing recyclable civil materials (concrete, scrap metal, rock aggregate) while completely eliminating fire hazards [17], [20], [21], [33]. Consequently, mechanical gravity storage occupies an optimal techno-economic niche for mid-to-long duration balancing where electrochemical degradation and PSH geographic limitations make alternative systems impractical [1], [36].

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Beyond cross-technology comparisons, individual gravity storage applications exhibit varying performance profiles in terms of resource conservation, economic return, commercial readiness, and sustainability value. Grid-scale installations leverage mechanical inertia and multi-MWh capacity to buffer variable renewables and maintain grid frequency [10], [14], [31], [38]. Industrial peak shaving exploits existing mining assets and high cycle endurance to eliminate peak electricity demand surcharges [8], [9], [22]. Off-grid and island microgrids leverage low-maintenance mechanical assemblies to displace expensive diesel fuel imports [23], [24], [25]. Residential micro-gravity installations offer safety and lifecycle longevity advantages over home chemical batteries, although they require higher initial capital per unit of capacity [16], [19], [29]. Finally, decommissioned mine-shaft repurposing offers substantial circular economy value by transforming legacy industrial liabilities into revenue-generating grid storage assets [11], [12], [26], [34].

Table III. Comparative Evaluation of Gravity Battery Application Domains

Application Domain	Resource Conservation	Economic Value	Commercial Readiness	Overall Sustainability
Grid-Scale Storage & Ancillary Services	Very High [7], [15], [38]	Very High [7], [36]	High (Commercializing) [1], [3]	Excellent [21], [38]
Industrial & Mining Peak Shaving	High [2], [22]	Very High [9], [26]	High [8], [30]	High [14], [34]
Off-Grid & Remote Island Microgrids	High [19], [24]	High [23], [25]	Moderate (Early Demos) [11], [19]	Very High [23], [24]
Residential & Multi-Story Buildings	Moderate [16], [25]	Moderate [19], [29]	Moderate (Prototype Stage) [16], [25]	High [19], [25]
Decommissioned Mine-Shaft Repurposing	Very High [11], [26]	High [8], [9]	High (Active Pilot Plants) [12], [34]	Excellent [14], [27]

The multi-criteria evaluation in Table III reveals that grid-scale balancing and mine-shaft repurposing achieve the highest combined resource conservation and sustainability ratings, largely driven by the avoidance of critical mineral extraction and the direct reuse of brownfield civil infrastructure [14], [26], [38]. Industrial peak shaving provides immediate economic viability through peak demand tariff mitigation and uninterruptible operational support [2], [9], [22]. Off-grid and island systems offer high environmental value by displacing polluting diesel generation with mechanical potential energy [23], [24], [25]. While decentralized residential units remain constrained by higher specific costs at small capacities, their complete safety from thermal hazards and 30+ year lifespan sustain active research interest [16], [19].

To optimize round-trip efficiency and maximize commercial adoption across the supply chain, future gravity battery deployments must integrate advanced linear motor drives, automated multi-vector dispatch algorithms, circular material formulations, and updated capacity market policy frameworks that properly remunerate long-duration mechanical storage [3], [10], [32].

VI. CHALLENGES AND FUTURE SCOPE

Challenges

The establishment of a commercial-scale gravity energy storage ecosystem is subject to several interconnected technical, geomechanical, economic, and regulatory hurdles despite notable recent advancements in mechanical topologies.

Mechanical Drivetrain, Loss Mechanisms, and Synchronization Dynamics

A primary technical bottleneck lies in the electromechanical complexity required for precision multi-ton mass hoisting and controlled regenerative descent. Emrani et al. [17] quantified key parasitic loss mechanisms—including motor-generator conversion inefficiencies, cable bending hysteresis, winch drum friction, and aerodynamic drag—demonstrating that total round-trip efficiency is heavily influenced by mechanical transmission design. Emrani and Berrada [13] established through experimental validation that structural deflection and dynamic cable vibration demand sophisticated damping systems to avoid structural fatigue over multi-decade lifecycles. Furthermore, Tong et al. [10] investigated inertial characteristics that govern dynamic response times, while Wang et al. [5] and Gao et al. [4] utilized Sobol sensitivity methods to prove that transmission chain friction on inclined rail tracks significantly penalizes system efficiency. In dry gravity systems, Botha and Kamper [33] identified payload mass-to-volume limitations, and Siostrzonek [9] emphasized that mechanical wear on hoist ropes, wire sheaves, and high-torque gearboxes imposes severe operational and maintenance (O&M) burdens. Additionally, although direct-drive linear systems achieve fast ramp rates, conventional mechanical winch systems exhibit slower response profiles compared to electrochemical batteries, creating challenges for sub-second primary frequency response [17], [34].

Geotechnical Uncertainties and Site Specificity

The reliance of subterranean gravity systems on site-specific geological conditions introduces project risk and constrains wide-scale replication [8], [11]. Converting decommissioned mine shafts requires thorough structural verification; Morstyn et al. [34] and Korski [8] demonstrated that degraded shaft liners, variable shaft verticality, and legacy mining cavities pose severe operational constraints. Schmidt et al. [26] showed that multi-year cyclic mechanical loading induces cyclic fatigue and micro-fracturing in surrounding rock masses. In underground pumped-storage schemes, Menéndez et al. [27] identified head losses and complex underground hydraulic turbulence, while Matos et al. [30] noted that standardized screening criteria for converting depleted reservoirs remain nascent. Manual underground surveys remain labor-intensive and costly, and continuous structural health monitoring of deep shafts demands high upfront capital expenditure [9], [14].

Capital Cost and Market Competitiveness

Economic viability presents a significant barrier to commercialization, particularly for non-utility developers. Solid-mass tower cranes and deep shaft conversions require substantial upfront capital expenditure (CAPEX) for heavy civil structures, high-capacity hoists, and power conversion systems [36]. Kula et al. [22] highlighted extended capital amortization timelines in mine-shaft installations, while Roushenas et al. [7] demonstrated that financial returns are heavily sensitive to wholesale electricity arbitrage spreads and capacity market price signals. Furthermore, the rapid cost reduction and mature supply chains of lithium-ion batteries continue to undercut mechanical systems in short-duration (<4 hour) markets [1], [3], [37]. At the decentralized scale, Al-Hilfi et al. [16] revealed that residential gravity storage currently exhibits extended payback horizons of 8 to 14 years, hindering distributed adoption.

Policy, Regulatory, and Market Design Gaps

Regulatory frameworks in most jurisdictions are designed for either conventional thermal generation or short-duration electrochemical storage, lacking clear definitions and valuation for mechanical long-duration energy storage (LDES) [1], [3]. Market barriers are compounded by the lack of dedicated capacity remuneration mechanisms, standardized grid-code certification for gravity batteries, and clear liability guidelines for repurposing decommissioned mine infrastructure [28], [32]. Fyke [32] observed that gravity storage has historically experienced cyclical investment interest due to early-stage demonstration risks, and O'Neill [18] noted that institutional investor conservatism toward novel mechanical platforms limits project bankability. Consequently, national energy storage roadmaps frequently underrepresent gravity storage relative to chemical batteries and green hydrogen [37], [39].

Environmental and Spatial Footprint Constraints

While gravity storage eliminates toxic chemical hazards, physical spatial constraints remain technology-dependent. Surface rail systems (such as ARES) require extensive dedicated land corridors and continuous 3% to 8% gradients that often conflict with regional zoning and environmental conservation [24], [35]. In underground systems, water ingress, mine water drainage contamination, methane outgassing, and local ground subsidence require strict environmental monitoring [26], [27].

Future Scope

Addressing these technical and regulatory challenges requires focused interdisciplinary research across electromechanical engineering, materials science, advanced automation, and energy policy.

Integration of Industry 4.0, AI, and Digital Twins

The integration of Internet of Things (IoT) sensor networks, machine learning algorithms, and digital twin models will transform gravity storage dispatch and maintenance [10], [12], [13]. High-frequency sensor arrays combined with predictive algorithms can model dynamic cable tension, detect micro-cracks in hoistingcomponents, and optimize acceleration/deceleration profiles to minimize drivetrain fatigue [4], [5]. AI-driven multi-vector controllers can optimize real-time dispatch schedules between energy arbitrage, spinning reserve, and frequency containment markets based on predictive weather and pricing forecasts [10], [13].

Direct-Drive Linear Machines and Frictionless Topologies

To bypass the mechanical wear and frictional losses of cables, gearboxes, and winches, direct-drive linear electric machines represent a high-efficiency alternative. Yan et al. [12] and Li et al. [6] demonstrated that permanent magnet and flux-switching linear machines (FSLMs) can convert gravitational potential directly into electricity without mechanical transmission linkages. Combining linear motors with electromagnetic guiding systems eliminates physical cable contact, significantly elevating round-trip efficiency above 85% while minimizing lifecycle maintenance costs [6], [12].

Advanced High-Density and Circular Materials

Future material research should focus on formulating low-cost, ultra-dense composite masses using industrial by-products. Replacing standard virgin concrete aggregates with mining tailings, iron ore slag, and recycled demolition aggregate can increase block density while substantially lowering embodied carbon [20], [21]. In hydraulic and buoyancy configurations, developing eco-friendly, high-density working fluids and biofouling-resistant marine composites will expand the operational limits of deep-water and cavern systems [23], [36].

Multi-Vector and Hybrid Energy Storage Architecture
Hybridizing gravity batteries with complementary storage media creates versatile multi-timescale assets [19], [25]. Coupling high-inertia gravity modules with fast-responding supercapacitors or vanadium redox flow batteries (VRFBs) bridges the gap between millisecond frequency response and multi-day energy storage [19]. Furthermore, integrating gravity storage with underground compressed air energy storage (CAES) or geothermal energy in depleted mines—as explored by Schmidt et al. [26] and Krassakis et al. [11]—allows simultaneous mechanical, thermal, and pneumatic energy management.

Geographic Expansion via Advanced Subterranean and Offshore Siting
Expanding GIS-based geological screening frameworks will unlock thousands of viable sites in depleted oil wells, deep-sea trenches, and decommissioned deep-shaft coal mines [11], [14], [30]. Offshore buoyant systems represent a major growth vector for pairing directly with floating offshore wind farms and marine hydrogen production hubs [23].

Policy Harmonization and Standardized Performance Metrics
Accelerating commercial deployment requires reforming electricity market structures to provide long-term revenue certainty. Policymakers must establish clear LDES procurement targets, create capacity market mechanisms that remunerate mechanical inertia and 8+ hour duration, and develop standardized techno-economic benchmarking protocols that recognize the 40+ year, non-degrading lifecycle value of gravity storage assets [1], [3], [38].

VI. CONCLUSIONS

Rapid renewable energy expansion, escalating decarbonization targets, and the increasing electrification of global energy demand have made the intermittency of solar and wind power a central challenge for grid security and power quality. While lithium-ion batteries dominate short-duration storage, their reliance on critical minerals, thermal runaway risks, capacity degradation, and high replacement costs limit their economic feasibility for multi-hour discharge horizons. Consequently, gravity-based energy storage systems (GESS) have emerged as a viable, sustainable mechanical alternative capable of delivering long-duration grid resilience while conserving critical mineral resources [1], [3], [28], [37], [38], [39].

This review systematically examined the primary gravity storage architectures—pumped-storage hydroelectricity (PSH), solid-mass tower cranes, shaft-based underground storage, rail-based inclined systems, and deep-water buoyant configurations. While PSH remains the commercially dominant baseline for multi-GWh bulk storage, solid-mass tower and shaft-based systems provide modular, terrain-agnostic alternatives that operate independently of natural hydrologic resources. Rail-based configurations deliver linear terrain-following scalability in mountainous regions, while buoyant underwater systems offer emerging opportunities for offshore wind integration. Each topology exhibits distinct techno-economic trade-offs governed by site geomechanics, structural loading, round-trip efficiency, discharge duration, and capital expenditure [14], [20], [21], [23], [24], [27], [31], [34], [35], [38], [40].

Furthermore, gravity battery systems present extensive value creation opportunities across multiple sectors. Utility-scale load shifting, industrial peak demand shaving, remote off-grid electrification, non-hazardous residential storage, and brownfield asset repurposing represent high-impact deployment domains. Transforming decommissioned mine shafts, quarries, and depleted industrial infrastructure into operational gravity batteries directly aligns with circular economy principles—converting legacy liabilities into productive grid assets while stimulating economic redevelopment in post-industrial communities [2], [7], [11], [15], [16], [19], [22], [25], [26], [29].

Despite these advantages, widespread commercial scaling faces notable engineering and regulatory hurdles. Mechanical wear in cables and winches, drivetrain friction, structural fatigue under continuous cyclic loading, site-specific geotechnical risks in deep shafts, and high initial capital expenditure present ongoing technical challenges. In addition, existing electricity market structures often fail to adequately monetize the long-duration capacity, mechanical inertia, and 40+ year non-degrading operational lifespan offered by mechanical storage. Overcoming these barriers requires coordinated advances in high-capacity direct-drive drivetrains, standardized geotechnical screening protocols, and reformed capacity market mechanisms [4], [5], [8], [9], [13], [17], [18], [22], [32], [33], [36].

The future of gravity energy storage will be driven by the integration of Industry 4.0 paradigms—including artificial intelligence, digital twin monitoring, flux-switching linear motor drives, and advanced high-density composite masses formulated from industrial by-products. These advancements will optimize real-time dispatch precision, eliminate cable wear, and significantly reduce lifecycle levelized costs. When combined with dedicated long-duration energy storage policies and circular engineering practices, gravity batteries will play a critical role in establishing a resilient, low-carbon, and circular energy economy [1], [3], [6], [10], [12], [13], [19], [23], [30], [38].

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