GRAVITATIONAL ENERGY STORAGE BY REPURPOSING THE INFRASTRUCTURE OF DECOMMISSIONED UNDERGROUND AND OPEN-PIT MINES

SORIN MIHAI RADU[1], OLGA GANE (SZEGEDI)[2], AURELIAN HORIA NICOLA[3]

Abstract: Decarbonized electricity systems require long-duration energy storage (LDES) to balance variable renewable energy (VRE). Gravitational technologies can meet this need by reusing the shafts, voids, pits, roads, and grid interconnections of decommissioned underground and open-pit mines. This paper surveys three main classes of mine-repurposed gravitational storage systems: (i) underground pumped-storage hydropower (UPSH) that uses underground workings or open pits as reservoirs; (ii) underground gravity energy storage (UGES) that hoists and lowers granular solids in shafts; and (iii) rail-based gravity storage (RBGS) that moves heavy mass cars on mine slopes and haul roads. We synthesize technical principles, siting criteria, environmental and geotechnical risks, and economics, and we review emblematic projects and studies from Australia (Kidston), Germany (Prosper-Haniel), Finland (Pyhäsalmi), the UK (Gravitricity), and the United States (ARES Nevada). We conclude with design guidelines and policy recommendations for integrating mine-repurposed gravitational storage into regional net-zero strategies.

Keywords: energy storage, decommissioned mines, pumped-storage hydropower, net-zero strategies

1. INTRODUCTION

Power systems with high penetrations of wind and solar require storage capable of daily, weekly, and seasonal balancing, fast frequency response, and firm capacity. Among available LDES options, pumped-storage hydropower (PSH) remains the most

[1] *Professor Ph.D. Eng., University of Petrosani, sorin_mihai_radu@yahoo.com*
[2] *PhD. Student Eng., University of Petrosani,olgaignat@gmail.com*
[3] *Lecturer Ph.D. Eng., University of Petrosani*

proven at multi-GW scale but faces geographic and permitting constraints for new surface sites. Repurposing legacy mines partially overcomes these constraints by leveraging existing excavations, shafts, pits, grid connections, and industrial land use.

Two gravitational alternatives complement classical PSH: (a) UGES, which stores energy by lifting sand or aggregate in mine shafts and generates by lowering it through regenerative hoists; and (b) RBGS, which stores energy by raising weighted railcars on graded alignments and regenerates during downhill motion.

These concepts share the core physics of gravitational potential energy while fitting different mine geometries and hydrological contexts [1], [2].

Mine repurposing also offers socio-economic benefits-sustaining industrial skills and infrastructure in regions affected by mine closures-provided that geotechnical stability, water management, and acid mine drainage (AMD) risks are carefully managed

2. TECHNOLOGY PRINCIPLES AND CONFIGURATIONS

2.1. Underground Pumped-Storage Hydropower (UPSH)

UPSH variants place one reservoir underground—within mine workings, caverns, or a deep pit-and the other at surface or in a nearby pit, enabling heads of hundreds of meters with reduced visual footprint compared to new surface PSH.

Feasibility depends on available head (depth difference between reservoirs), reservoir volumes in galleries/pits, hydraulic conveyance (tunnels/shafts), lining tightness, and mine hydrogeology. Studies of Germany's Prosper-Haniel colliery estimate ~200–350 MW with ~4 h cycles using ~600,000 m^3 lower storage between 600–1000 m depth, contingent on water level management and alternative underground structures if flooding resumes post-closure [3].

A recent review formalizes a multidisciplinary workflow-3D geological modeling, rock mass classification, hydrogeology, and mine records-to screen abandoned coal mines for UPSH, with Prosper-Haniel as a reference case [4].

Open-pit configurations can pair pits (upper/lower), as in Australia's **Kidston** project (250 MW/2,000 MWh), the first PSH to reuse an abandoned gold mine; design employs two pits as reservoirs, a powerhouse cavern, and a 275 kV grid connection [5].

Geomechanical coupling is non-trivial. For example, slope stability in a repurposed open-pit can be sensitive to reservoir level fluctuations; numerical analyses at the Fushun West open-pit indicate zones requiring reinforcement and seepage control across operating levels.

2.2. Underground Gravity Energy Storage (UGES)

UGES proposes lifting sand/aggregate to the surface when electricity is cheap and lowering it through a mine shaft to generate via motor-generator hoists when prices are high. Unlike batteries, granular media exhibit effectively zero self-discharge, enabling ultra-long storage durations.

The IIASA-led assessment estimates global technical potential of ~7–70 TWh, with indicative capital intensity of ~1–10 USD/kWh for energy capacity and ~2,000 USD/kW for power blocks, contingent on shaft geometry and automation [6].

Key plant components include the shaft and hoist system, upper and lower stockpiles, conveyors or autonomous trucks, and controls. Efficiency is projected at 60–80% depending on frictional losses, hoist control, and material handling.

UGES is particularly suited where deep shafts exist but hydrologic reuse for PSH is constrained.

2.3. Rail-Based Gravity Storage (RBGS)

RBGS systems (e.g., **Advanced Rail Energy Storage, ARES**) move heavy mass cars on steel rails over grades of several percent. During charging, traction motors lift cars uphill; during discharge, regenerative braking converts potential energy to electricity.

RBGS avoids water use and underground works, can be sited on mine spoil slopes and haul roads, and targets grid regulation to multi-hour services. ARES documents a 50 MW Nevada “GravityLine” concept and earlier demonstrations, with stated round-trip efficiency near ~85–90% (machine-level) and ~40-year service life.

3. CASE STUDIES AND DEMONSTRATORS

3.1. Kidston (Queensland, Australia): Open-Pit PSH

The Kidston Pumped Storage Hydro Project repurposes two mine pits (upper Wises dam and lower Eldridge pit) to deliver 250 MW for ~8 h (2,000 MWh). Supported by public finance (e.g., NAIF loan), it integrates with a solar hub via a 186 km transmission line. Recent construction reports highlight tunnel design, dewatering, geotechnical management, and model testing for turbines; commissioning is scheduled mid-2020s [7].

External assessments emphasize the project’s significance as Australia’s first new PSH in >40 years and the first to reutilize a mine site globally, with expected economic and system benefits [8].

3.2. Prosper-Haniel (North Rhine-Westphalia, Germany): UPSH Concept

The Ruhr district’s last hard-coal mine was extensively studied for an underground PSH concept using existing galleries as lower reservoirs and an upper surface lake; installed capacity estimates ranged from ~200 to 350 MW with several hours’ duration, but feasibility depends on long-term mine water management. The program yielded hydraulic modeling, geological screening, and techno-economic analyses, positioning UPSH as a landscape-friendly alternative in flat regions [9].

3.3 Gravitricity (UK/EU): Shaft-Weight Gravity Storage

Gravitricity's 2021 Port of Leith (Edinburgh) demonstrator validated a 250 kW rig with two 25-t weights, sub-second response, and smooth sequential discharge—de-risking controls and mechanical systems for mine-shaft deployments. Subsequent plans include a full-scale project in a 530-m auxiliary shaft at Pyhäsalmi (Finland), leveraging ABB hoist expertise [10].

3.4 Underground Gravity Energy Storage (UGES): Conceptual Global Potential

The Energies feature article and IIASA briefing quantify UGES potential at 7–70 TWh and outline cost ranges and workforce transition benefits by reusing grid connections and shafts. News and professional summaries echo these findings, with emphasis on zero self-discharge and seasonal storage capability [11].

3.5 ARES Nevada (USA): Rail-Based Gravity

ARES is developing a GravityLine near Pahrump, Nevada, using weighted cars on a grade to provide fast grid services (e.g., 50 MW for short-duration frequency regulation), with public presentations detailing manufacturing, patents, and siting flexibility—including siting along mine infrastructure [12].

4. SITING, ENGINEERING, AND OPERATIONAL CONSIDERATIONS

4.1 Geotechnical & Hydrogeological Issues

PSH and PSH in pits: Key risks include slope stability under cyclic reservoir level changes, seepage into fractured rock, uplift/lining integrity, and interaction with mine water rebound.

Work at Fushun and Prosper-Haniel illustrates the need for coupled stability–hydraulics modeling, targeted grouting, and long-term monitoring of pore pressures and phreatic surfaces [13].

UGES. Shaft condition and hoisting systems dictate power density. Larger diameters and depths linearly increase storable energy (mass × head).

Automation (stackers/conveyors/AGVs) and dust control are crucial for efficiency and O&M. Indicative round-trip efficiency ranges 60–80% depending on friction and handling [14].

RBGS. Track geometry, braking systems, and wheel-rail adhesion control dispatch quality and losses. Systems can be modular along mine benches and haul roads, reducing earthworks relative to greenfield alignments [15].

4.2 Environmental & Water Quality Management

Mine reuse must avoid exacerbating **acid mine drainage (AMD)** and metal mobilization. AMD forms when sulfide minerals oxidize, generating acidic, metal-rich waters that harm ecosystems and infrastructure; comprehensive monitoring, prevention, and treatment (passive wetlands, active neutralization, or hybrid/zero-liquid-discharge schemes) are required [16].

For PSH in sulfide-bearing pits or galleries, lining, hydraulic isolation from contaminated zones, and controlled water chemistry are essential; recent case studies and reviews highlight variable AMD severity and the need for site-specific mitigation with life-cycle assessment of treatment options [17], [18].

UGES and RBGS minimize water interactions but pose dust, noise, and visual considerations that can be mitigated via enclosures, filtration, and low-profile design compared to large surface dams [19].

CONCLUSIONS

Repurposing decommissioned mines for gravitational energy storage can unlock substantial long-duration, low-degradation capacity with reduced land-use conflict and opportunities for just transition in mining regions.

PSH/UPSH delivers bulk energy and capacity, UGES enables ultra-long seasonal storage without self-discharge, and RBGS offers fast, flexible ancillary services without water dependency.

Real-world progress-from Kidston's construction to Gravitricity's demonstrator and the ARES Nevada GravityLine-demonstrates technical viability. The next steps are disciplined hydro-geotechnical design and AMD risk management, standardized valuation in capacity markets, and supportive permitting and finance to scale deployment across suitable mine districts worldwide.

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