# MODULAR GRAVITY-ENERGY STORAGE SYSTEMS FOR POST-MINING REGENERATION: A TECHNICAL AND SYMBOLIC APPROACH FOR THE JIU VALLEY

**ALEXANDRU BOGYE[1], DAN CODRUȚ PETRILEAN[2]**

**Abstract**: This research addresses the urgent challenge of industrial reconversion in the Jiu Valley (Valea Jiului, Romania) through the lens of sustainable industrial design. The study presents the design and theoretical validation of a small-scale, modular gravity-energy storage "tower." Unlike earlier concepts focusing on the reuse of deep mine shafts—which face significant structural and dewatering constraints—this research proposes a decentralized, surface-level solution. The prototype integrates a high-torque Brushless DC (BLDC) motor with a planetary gearbox to achieve efficient energy conversion (targeting >70% round-trip efficiency). By utilizing local mining waste (sterile) as the functional mass, the system serves a dual purpose: providing decentralized energy storage and functioning as a symbolic artifact of the region's transition from extraction to sustainability.

**Keywords**: Gravity Energy Storage (GES), Just Transition, Post-Mining Regeneration, Sustainable Design, Modular Systems.

## 1. INTRODUCTION

The Jiu Valley, a historically significant mono-industrial mining region in Romania, faces profound socio-economic challenges in its transition away from coal. Mandated by EU decarbonization policies and supported by the Just Transition Fund, this shift necessitates not only economic diversification but also the creation of new technological emblems to replace the singular identity of mining [6].

Initial investigations explored the repurposing of decommissioned mine shafts for large-scale gravity energy storage. However, analysis revealed critical obstacles: structural degradation of shaft linings, high energy costs for continuous dewatering, and prohibitive capital risks.

[1] *PhD Student Eng., University of Petrosani, alexbogye@upet.ro*
[2] *Prof. Habil. PhD. Eng., University of Petrosani, danpetrilean@upet.ro*

Consequently, this paper proposes a strategic alternative: the development of a modular, scalable gravity-energy storage *vertical tower*.

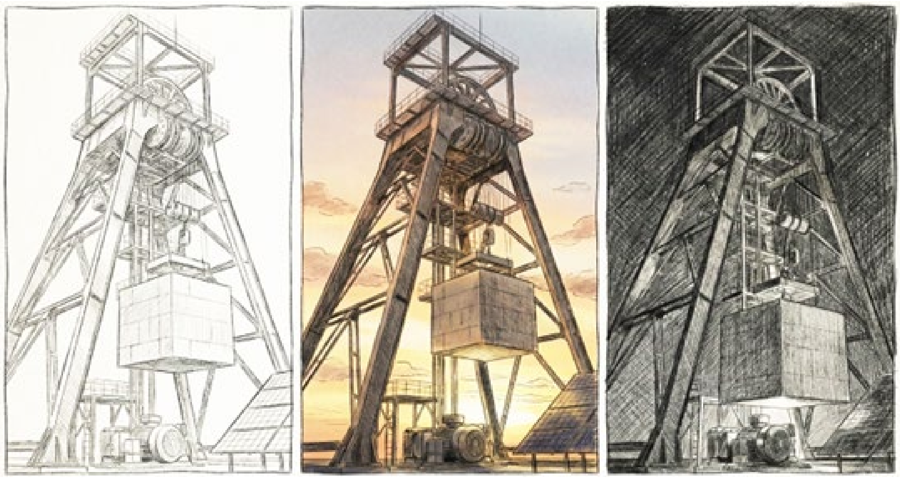

**Fig. 1.** Simulation of an Operational Energy Cycle and PV Coupling (Day, Sunset, Night)

The objective of this work is twofold:

- **Engineering Feasibility:** To validate a mechanism for efficient gravity-based energy storage suitable for decentralized applications.
- **Symbolic Integration:** To design the system using local materials (mining waste), ensuring it acts as a tangible emblem of the circular economy in the Jiu Valley.

## 2. THEORETICAL BACKGROUND AND STATE OF THE ART

Gravity Energy Storage (GES) is gaining traction as a long-duration storage solution. While Pumped Hydro Energy Storage (PHES) dominates the market, it is geographically constrained. Solid Gravity Energy Storage (SGES) offers a versatile alternative. Current state-of-the-art systems, such as those by Energy Vault or Gravitricity, focus on grid-scale applications (MWh capacities) using massive infrastructure [1, 3]. However, there is a distinct gap in the literature regarding micro-scale systems designed for community or localized industrial use. This research addresses that gap, focusing on "dry" gravity storage where the potential energy is stored in a composite mass lifted by an electromechanical winch [4].

## 3. METHODOLOGY AND SYSTEM DESIGN

The research employs a mixed-methods approach, combining mechanical design simulation with socio-cultural analysis.

### 3.1. Mechanical Design: The Cube

The proposed device is a modular tower structure. To maximize the gravitational potential energy ($E_p = mgh$) within a compact footprint, the design utilizes a vertical frame of **5 meters** in height with a base footprint of **2m x 2m**.

**Structural Specifications**

To withstand the dynamic loads of the 4.5 t moving mass and potential wind loads (given the outdoor placement), the frame utilizes industrial-grade structural steel.

- **Material:** S355 Structural Steel (European Standard EN 10025), chosen for its superior yield strength compared to standard construction steel.
- **Profile:** Square Hollow Sections (SHS) $150 \times 150 \times 6\,mm$ are selected for the main columns to ensure buckling resistance, reinforced with diagonal bracing using SHS $80 \times 80 \times 4\,mm$.

**The Mass Block Design**

The core component is the "Mass Block," designed to maximize density while utilizing local waste materials. The mass consists of a concrete matrix reinforced with sterile rock from local mining dumps.

- **Target Density** ($\rho$): $3500\ kg/m^3$;
- Target Mass ($m$): $4500\ kg$

To determine the physical dimensions of the mass block required to fit within the tower, we calculated the volume based on the material density:

$$V = \frac{m}{\rho} = \frac{4500}{3500} \approx 1.29\ m^3 \tag{1}$$

The design constraint requires the mass block to match the system's structural footprint of 2m x 2m. Based on this footprint ($A = 4\ m^2$), the height of the block (*H*) is derived as:

$$H = \frac{V}{A} = \frac{1.29}{4} \approx 0.32\ m \tag{2}$$

Thus, the mass block is designed as a slab with approximate dimensions of 2m x 2m x 0.32m. This geometry maximizes the available vertical travel distance within the tower structure compared to a taller cubic block.

### 3.2. Mechanical Design: The Vertical Tower

To ensure efficiency and precise control, the drive train moves away from standard induction motors in favor of permanent magnet technology [7].

- **Motor Specifications:** A **3 kW, 48V High-Torque Brushless DC (BLDC)** motor is selected. While the power requirement for slow lifting is lower, the 3 kW rating provides necessary thermal headroom and peak torque capability during acceleration phases.

- **Transmission:** A multi-stage **planetary gearbox** with a reduction ratio of **150:1** is coupled to the motor. This configuration is essential to convert the high-speed output of the BLDC motor into the massive torque required to lift 4.5 tonnes (approx. 44.1 kN force).
- **Cabling System:** The mass is suspended by a redundant cabling system to ensure safety. The design specifies **Galvanized Steel Wire Rope**, $\emptyset 14\ mm$, **6x36 IWRC** (Independent Wire Rope Core). With a Minimum Breaking Load (MBL) exceeding 10 tonnes per cable, a dual-cable configuration ensures a Safety Factor (SF) > 4.
- **Braking System:** The system incorporates a fail-safe electromechanical brake that engages automatically upon power loss, preventing uncontrolled descent of the mass.

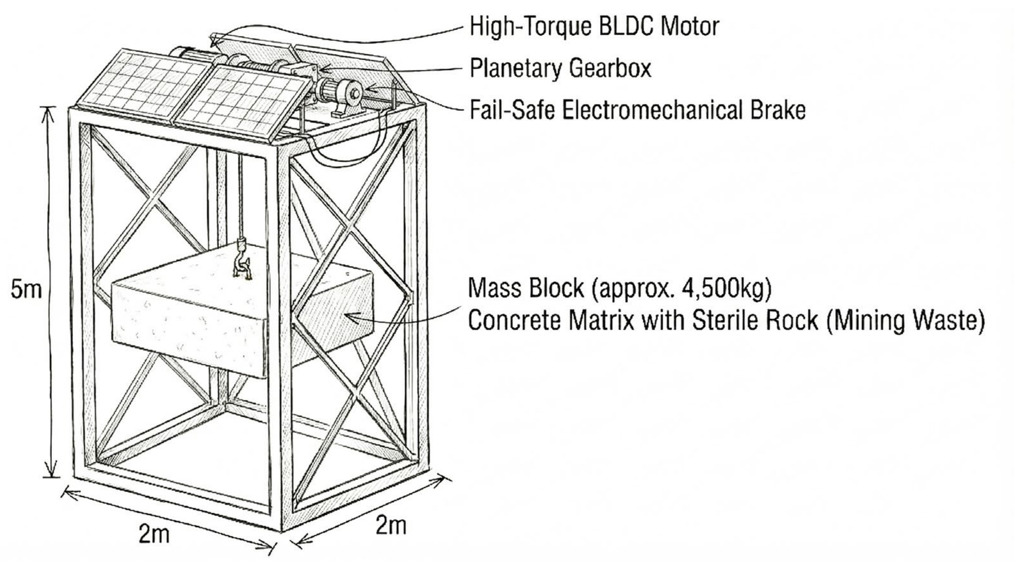


**Fig. 2.** Schematic of the Modular Gravity-Energy Storage Tower with Integrated Photovoltaics.

### 3.3. Mathematical Model

The fundamental principle relies on the conversion of electrical energy into gravitational potential energy ($E_p$) and back. The energy capacity ($E_{el}$) is defined by the next equation:

$$E_{el} = \frac{m \cdot g \cdot h \cdot \eta_{rt}}{3600}\ (Wh) \quad (3)$$

Where:

- $m$ = Mass (kg)

- $g$ = Gravitational acceleration (9,81 m/s$^2$)
- $h$ = Height/Displacement (m)
- $\eta_{rt}$ = Round-trip efficiency (combined efficiency of motor, gearbox, and inverter)

### 3.4. Operational Energy Cycle and PV Coupling

The primary function of the gravity-energy storage tower is to provide mechanical energy shifting, decoupling energy generation from consumption. The system follows a three-phase cycle: Charge, Store, and Discharge.

- **Charging Phase (PV Integration):** Utilizes surplus renewable electricity. The system is powered by **2x 450 Wp Monocrystalline Solar Panels**, providing sufficient power to lift the mass over a 4-6 hours solar window. The motor-generator hoists the Mass Block (4,500 kg) to the maximum possible height. Given the **5m frame** and accounting for the reduced block height (**0.32m**) and mechanical overhead (pulleys, winch), the active lifting height is approximately **4.3 m**.
- **Discharging Phase:** Occurs when energy is needed. The heavy mass block is lowered under controlled conditions, causing the BLDC motor to act as a regenerative generator.

The target round-trip efficiency ($\eta_{rt}$) for this conversion cycle is estimated to be above 70%.

## 4. RESULTS AND DISCUSSION

### 4.1. Prototype Performance Analysis

Applying the mathematical model to the 5-meter vertical prototype yields the following theoretical performance:

- **Mass** ($m$): 4500 kg
- **Height** ($h$): **4.3 m** (Calculated as 5 m total height minus 0.32 m mass block and ~0.4m mechanical clearances)
- **Efficiency** ($\eta_{rt}$): 0.75 (estimated)

$$E_{el} = \frac{4500 \cdot 9.81 \cdot 4.3 \cdot 0.75}{3600} \approx 39.5\ Wh \qquad (4)$$

The revised mass block geometry (2m x 2m footprint) significantly optimizes the vertical travel, resulting in a capacity of **39.5 Wh**. This represents a notable efficiency improvement over cubic geometries, validating the structural stability of the vertical frame.

### 4.2. Scalability Analysis

To achieve commercially viable storage capacities, the system relies on vertical scaling and the utilization of larger functional masses. The 5-meter prototype serves as the validation step for a more ambitious "Mine Skip" industrial implementation. **Table 1** illustrates the scaling potential, contrasting the prototype with a realistic retrofit of existing mining headframe aesthetics.

For the **Industrial Mine Skip** scenario, we propose a structure with a **30-meter height**. The design specifies a mass block with a footprint of **5m x 5m**. Assuming a **5m x 5m x 2.3m block**, the mass reaches approximately 200 tonnes, creating a viable energy storage unit for localized grids.

*Table 1.* **Scaling Scenarios**

| Scenario | Height (hstructure) | Mass (m) | Active Drop (h) | Energy Capacity (E) | Application |
|---|---|---|---|---|---|
| **Current Prototype** | 5 m | 4.5 t | **4.3 m** | **~39.5 Wh** | Advanced Demo / Educational |
| **Industrial Mine Skip** | 30 m | ~200 t | ~25 m | ~10.2 kWh | Community / Small Industrial |

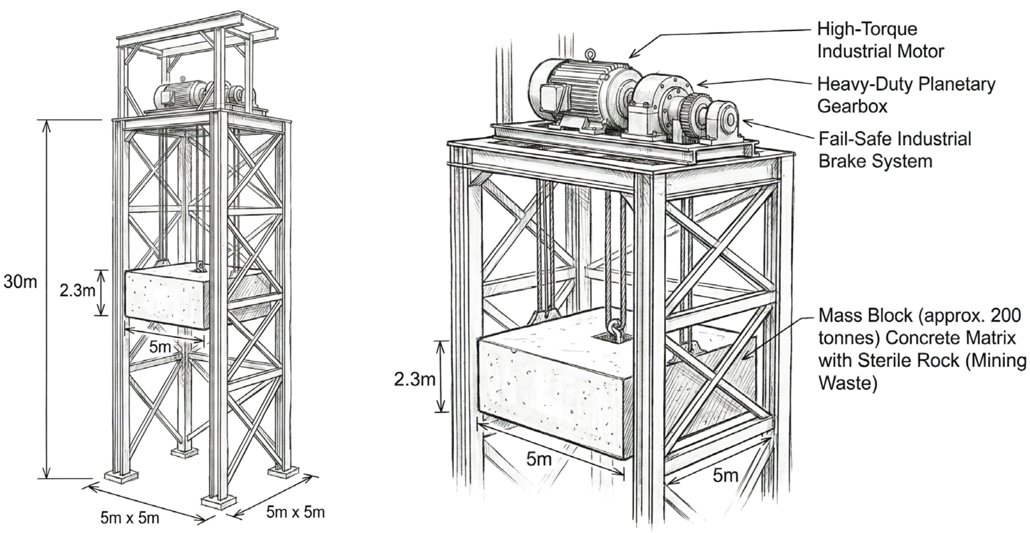


**Fig. 3.** Industrial Mine Skip Scaling Scenario (30 m Height, 200 t Mass)

The analysis indicates that while the prototype confirms the electromechanical principles, real-world application requires the "Mine Skip" scale (30m height, 200t mass) to generate ~10 kWh, which is sufficient to power critical community infrastructure or small industrial loads during peak demand.

## 5. THE SOCIO-CULTURAL DIMENSION

Beyond engineering, the Tower serves as a vehicle for the **Circular Economy**. By integrating mining waste (sterile) into the functional mass blocks, the design transforms a liability into an asset [10]. This aligns with the "Just Transition" framework, preserving the industrial heritage of the Jiu Valley while recontextualizing it for a green future [5]. The tower is designed not just as a machine, but as a vertical industrial artifact, a visible reminder of the community's adaptability.

## 6. CONCLUSIONS

This paper presents the design and theoretical validation of a modular gravity-energy storage system tailored for the Jiu Valley. By using the frame to a **5 m height**, the prototype offers an improved capacity of **39.5 Wh**, validating the electromechanical architecture required for larger systems. The detailed sizing analysis confirms that a **2m x 2m mass block** (4.5 tonnes) fits optimally within the structure, maximizing vertical travel. Furthermore, scaling analysis demonstrates that a **30m "Mine Skip" variant** utilizing a mass block with a **5m x 5m footprint** (200 tonnes) can achieve **~10.2 kWh**, offering a realistic pathway for decentralized energy storage. Crucially, the integration of local mining waste addresses the symbolic requirements of the Just Transition, offering a replicable model for post-mining regeneration that balances technical function with regional identity.

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