SOLID ENERGY STORAGE TECHNOLOGIES BASED ON GRAVITY POTENTIAL ENERGY

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Abstract. *In contemporary energy systems, energy storage plays a pivotal role, offering benefits such as grid stability improvement, increased integration of renewable energy sources, enhanced energy system efficiency, preservation of fossil fuel resources, and reduced environmental impact during energy generation. Globally meeting these requirements without adverse environmental effects is attainable through the utilization of gravity energy. Gravity energy presents an attractive option for energy storage due to its inexhaustible nature, lack of reliance on harmful resources, and global accessibility. Employing a gravity-based power generation mechanism involves storing off-peak electricity as potential energy, subsequently releasing it when power demand arises during discharge mode.*

Keywords: *technical pathway, motor-generator unit, grid stability, primary components, power system, application*

Introduction

Energy is the most common consumer good and continues to be a key element in global progress. However, the outcomes of pollution and climate change have spurred an urgent need to transition to renewable energy sources for electricity generation. Traditional energy resources are projected to be depleted in a few years, leaving insufficient fuel for electricity generation. While alternative renewable sources such as solar, wind, and biomass energy are valuable, they are also volatile and intermittent. To ensure the secure and consistent functioning of power systems amidst fluctuating power sources, energy storage technology has emerged as the most efficient solution. Consequently, energy storage technology has become one of the hottest topics in energy research [1], attracting significant attention.

The odds of solid gravity energy storage technology (SGES)

Based on existing research, SGES offers several advantages compared to other technologies:

(1) This method relies solely on physical processes, ensuring high safety and environmental friendliness. Additionally, it is clean and low-carbon, causing minimal impact on the natural environment, in line with the principles of sustainable and green development [1].

(2) Gravity energy storage exhibits significant environmental adaptability, allowing flexible arrangement according to requirements and suitability for "distributed" energy storage. There are no specific conditions or prerequisites for weight storage, transport, and power generation [2].

(3) This method of power generation boasts a lengthy cycle life and is cost-effective. The weights primarily consist of concrete, local materials, or other recycled materials, which can be reused for decades. Minimal weight loss occurs during operation, ensuring sustainability and efficiency [3]. However, existing literature has not systematically summarized the recent advancements in gravity energy storage technologies and their practical applications, mainly due to the technical intricacies involved in gravity energy storage. As a result, this paper aims to analyze the various types, applications, and future prospects of such energy storage systems.

Tower Solid Gravity Energy Storage Technology (T-SGES)

The primary components of the T-SGES system consist of weights, motor-generator units, ropes, transmission equipment, and a weight-bearing tower. The process of converting electrical and mechanical energy involves lifting and stacking weights through the tower, as illustrated in Figure1.

During periods of surplus electricity in the grid, the control center oversees the movement of a trolley on the cantilever to precisely lift bricks from lower positions and stack them onto higher bricks. This action increases the height and gravitational potential energy of the lifted bricks. Simultaneously, the motor consumes the excess electricity from the grid, effectively converting it into gravitational potential energy. Conversely, when the grid experiences electricity shortages, the high bricks are lowered to lower positions, driving the motor to generate electricity. This process converts the gravitational potential energy stored in the high bricks back into electricity, which is then fed back into the grid.

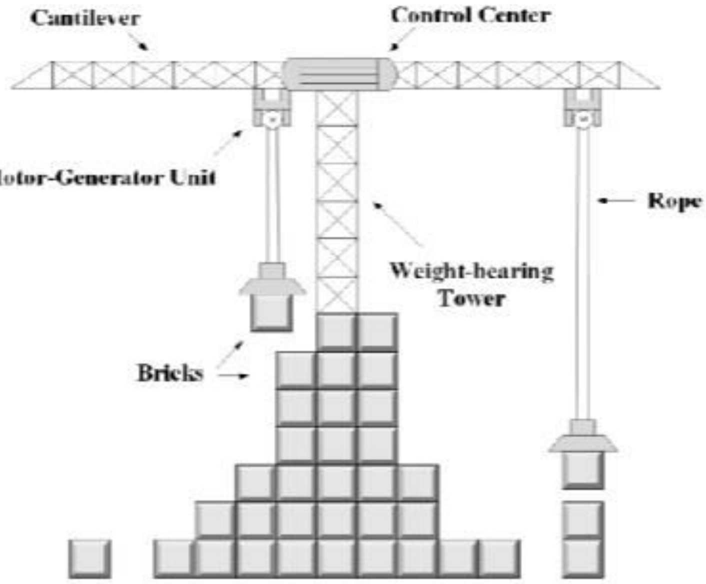

Figure 1. Schematic diagram of T-SGES

The tower incorporates six cantilevers (although only two are depicted in Fig. 1) that can operate simultaneously to enhance the efficiency of weight stacking. Enabled by software, the tower can coordinate the movement of multiple blocks through the drive mechanism, enabling each block to independently adjust to various heights.

Throughout the duration of the project, the bottom weight remains stationary, serving as a foundational platform for the placement of the remaining weights at specified heights [4, 5].

The energy storage capacity of T-SGES is determined by equation (1):

$$E_{\mathrm{T}} = \eta_{\mathrm{T}} \cdot \sum_{i=1}^{n} m_i \cdot g \cdot h_i \tag{1}$$

where: η_T the output efficiency of the T-SGES;
m_i the mass of its block;
h_i is the effective height of its block (here is the height of the block's bottom to the ground);
n is the total number of blocks.

T-SGES necessitates numerous weights because those comprising the foundational platform do not participate in energy storage, resulting in a low utilization rate of the weights. To enhance cost-effectiveness, the utilization of low-cost composite bricks crafted from recycled waste materials can be implemented. The efficiency of the system heavily relies on the permanent magnet synchronous motors that are employed to facilitate frequent starts and stops while delivering ample torque. Ensuring the rope possesses high mechanical strength is crucial, and this can be achieved by either increasing the number of ropes or utilizing pulley sets. The load-bearing tower resembles a tower crane but features more cantilevers, typically six, to fulfill its operational requirements [4, 6].

(a) **(b)**

Figure 2. EV1CDU prototype schematic

Energy Vault, a US-based company, represents T-SGES and has introduced several variations of tower gravity storage products, one of which is the EV1 tower gravity storage device (EV1CDU, Energy Vault 1 Commercial Demonstration Unit) in Castion, Ticino, Switzerland, in July 2020, as depicted in Fig. 8 (a) and (b). An analysis conducted by Fyke [4] revealed that the standard energy storage capacity of EV1CDU is 35 MWh, with the potential to fluctuate between 20 MWh and 80 MWh. The tower arm radius measures 42 meters, while the tower's height reaches 120 meters, covering an area of approximately 5600 square meters. The system comprises 35-ton composite bricks totaling 5000 pieces, capable of reaching a peak power output of 4MW within 2.9 seconds, with discharge times spanning between 8 to 16 hours and achieving up to 90% cycle efficiency. The estimated service life of the system is between 30 to 40 years.

Mountain Mine-Car SGES (MM-SGES)

The primary components of this technical pathway consist of weights, motor-generator units, cables, transmission equipment, rails, and inclined surfaces, as illustrated schematically in the accompanying Fig. 3.

The technical process involves converting electrical energy into gravitational potential energy by transferring weights between high and low stacking platforms. During periods of excess power in the grid, the motor will pull the mine car from the lower stacking platform along the rail to the upper stacking platform. Conversely, when there is insufficient electricity, the mine car on the upper stacking platform will be gradually lowered to the lower stacking platform. Simultaneously, the mine car will rotate the motor through a chain mechanism to generate electricity. This process effectively converts gravitational potential energy back into electricity, which is then fed back into the grid.

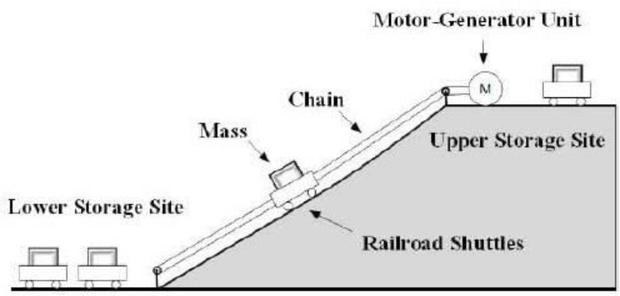

Figure 3. Schematic diagram of MM-SGES

There are stringent requirements for the mechanical strength of the cables, which assist in hauling the mine cars, while rails are employed for guiding the mine cars. Optimal operation of the mine cars necessitates a moderate slope on the ground, typically ranging from approximately 6 to 25 degrees. A slope that is too gentle may negatively impact efficiency, while one that is too steep places greater demands on the equipment.

This particular technical approach, as well as T-SGES, incorporates highly modular weights, resulting in similar energy storage capacity equations between the two systems, such as equation (1). However, MM-SGES exhibits higher frictional resistance compared to T-SGES, a distinction that can be quantified as follows by equation (2):

$$f_{ex} = \mu \cdot m_i \cdot g \cdot cos\theta \tag{2}$$

where: μ is the kinetic friction factor;
m_i is the total mass of single minecars and their loads;
g the acceleration due to gravity on Earth;
θ is the gradient.

In the context of T-SGES, where θ = 90 degrees, the frictional force (fex) is zero. In contrast, for MM-SGES, fex represents the sliding friction occurring between the mine car and the rail. Consequently, assuming the same level of frictional resistance within the transmission equipment, MM-SGES exhibits reduced cycle efficiency compare d to T-SGES due to the added frictional resistance.

The technology offered by Advanced Rail Energy Storage (ARES), a US-based company, is characterized by its energy storage equipment comprising multiple tracks with a capacity of 5MW. Its scalability allows for the adjustment of energy storage capacity ranging from several MWh to dozens of GWh by altering factors such as the number of mine cars, gradient, and length of the slope. Additionally, the rated power can be varied between 5MW and 1GW, provided suitable geographical conditions, as illustrated in Figure 16 (a) and (b) [7].

(a) **(b)**

Figure 2. EV1CDU prototype schematic

Conclusion

Compared to other large-scale energy storage technologies, Solid Gravity Energy Storage (SGES) technology offers several advantages including minimal geographical constraints, high storage capacity, efficient cycling, extended lifespan, low electricity costs, and enhanced safety. This innovative approach holds promise to revolutionize current large-scale energy storage practices. However, challenges persist in SGES research. Uncertainty surrounds the selection methods of various technical routes under specific conditions, necessitating further techno-economic evaluations. Existing research predominantly focuses on established technical routes, lacking innovation in core technologies. Moreover, optimal parameter designs for certain technical routes remain insufficient, and there's a dearth of understanding regarding equipment and grid interaction effects across different technical routes. To address these issues, it is advisable to concentrate on the following areas:

- Conduct comprehensive techno-economic studies on each technology route to assess their viability.
- Investigate major obstacles in existing technical routes, optimizing factors such as materials, sizes, and costs to foster vertical development and explore new avenues for innovation.
- Combine several technical routes and even different types of energy storage technologies.

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