Research on Current Solid Mass Energy Storage (SGES)

Yichen Su*

Beanstalk International Bilingual School, 101300 Beijing, China

Abstract. With the increasing environmental challenge posed by fossil fuel combustion, there has been a significant effort to develop alternative energy sources. In addition, hydropower, once considered as a perfect solution, has recently faced the criticism of deteriorating downstream aquatic habitat. As a result, energy sources that are susceptible to the environment, such as wind or solar, have become some of the few available options. This is accompanied by a raised demand on reliable and efficient energy storage technology. This paper examines solid mass energy storage (SGES), a newly developed energy storage technology by converting excess electricity into gravitational potential energy. The paper also lists out some of its most popular variation and relevant quantitative analysis. With a simple and straightforward mechanism, SGES has the potential to be furtherly improved and popularized for a wider range of application. However, as a newly developed concept, there are very few applicated cases of SGES. This causes a shortage in operational data and analysis on aspects such as facility lifespan, giving out a future research direction in this field.

1 Introduction

Fossil fuels have been regarded as one of the most efficient energy sources since the industrial ages in the 18th century. Pushing the turbine by using steam derived from combustion, therefore, generating electricity, fossil fuels are known and praised for their straightforward mechanism, high economic benefits, energy efficiency, and reliability. This, however, comes with serious environmental issues, namely global warming which is caused by an increase in CO_2 emission. Despite known consequences, large quantities of fossil fuels are still being used in response to the exhausting demand for energy brought by the peaked population [1]. In 2022, the global population exceeded 8 billion, resulting in a global energy consumption of 607 EJ. Among them, over 80% of the energy was contributed by fossil fuels, contributing 23.54 Gt carbon emission in the powering and industrial sectors or about 60% of the year's total CO_2 emission [2].

Driven by these issues, more and more efforts were put into the development of alternative, renewable energy sources and to replace fossil fuels with them. Hydropower, among them, must be the most mature technology. Generating over 4,200 TWh in 2023, hydropower ranked third in energy yields-just behind coal and natural gases-and outnumbered every other

* Corresponding author: Ethansu26sy@bibs.com.cn

renewable source use [3]. China, for instance, emerged as the leading force in the hydropower field. With many of its developing regions located in mountainous terrain, small-sized hydropower stations have become the most dominant energy sources for villages in southern China. However, a policy released by the Ministry of Water Resource in 2018 stated the potential disturbances of hydropower stations on the downstream aquatic habitat of the Yangtze River. The later investigations led to the dismantling of over 3,000 hydropower stations in China, with further limitations and restrictions on the usage of the plant to other 20,000 stations [4]. Such an increased awareness of protecting aquatic habitats brought a heavy blow to electricity consumption in places where hydropower stations were affected. Therefore, it is necessary to supply electricity with other energy sources, namely, solar and wind power.

Wind and solar power have boosted exponentially since the millennium, with their annual yield increasing from 31 and 1 TWh in 2000 to 2,300 and 1,600 TWh in 2023, respectively [3]. However, both technologies face the challenge of generating electricity continuously. As a natural resource, the strength and frequency of wind are completely uncontrollable. This makes wind power insufficient and extremely susceptible in places with a milder climate. Solar energy, on the other hand, is indeed abundant on a daily basis, but its peak hours (morning to noon) do not usually align with the peak of electricity demand (late afternoon to evening). If a place's power supply solely depends on such sources, it is likely for the area to undergo power shortages during peak demand hours.

The application of energy storage systems is needed to address this challenge. When supply exceeds demand, the storage system may consume the electricity generated by wind or solar plants and store it as potential energy-often gravitational potential energy. Conversely, when demand peaks but supply runs short or when under emergencies, this stored potential energy can rapidly be given out or converted back to usable electricity. This paper will provide a comprehensive analysis of solid-mass gravitational energy storage (SGES), focusing on its mechanism, quantitative analysis, state of development, and cases of implementation.

2 Qualitative and Quantitative Analysis on SGES

2.1 Mechanism and Variations of SGES

SGES systems operate in a very simple and straightforward mechanism. In short, it is to store excess energy in the form of gravitational potential energy and gives it out through a generator. This process shares similarities with hydropower plants, but in addition to it, SGES requires the system to consume energy first (therefore, storing the energy in the form of potential energy) before giving it out as usable energy. During stage 1, energy sources such as coal or solar generate excess electricity. The SGES system utilizes this excessed electricity to pull solid masses (typically composed of concrete) into the air using a crane. These masses remain above the ground until an electricity demand occurs, marking the transition to the next phase. During stage 2, the mass will be released and dropped back to the ground. While falling, the wire, with one end connected to a generator and the other to the mass, generates electricity by converting the gravitational force of the falling mass to electricity. This generated electricity is then sent back into the power grid to meet the sudden demand [5]. This means SGES is not limited by geographical or topographical factors such as the difference in elevation as required by pumped-hydro storage systems. Fig. 1 visualizes this process by showing stage 1 and 2.

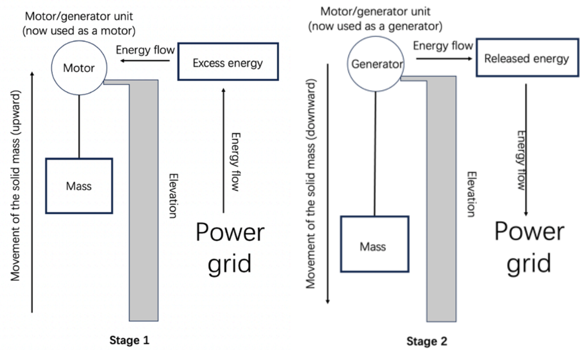

Fig. 1. SGES mechanism

There are three main SGES variations: Tower SGES (T-SGES) and Shaft SGES (S-SGES). Other variations such as Piston SGES (P-SGES) and sub-variations under it are also put to development and are relatively less mature.

T-SGES is one of the most mature systems. First developed by the Swiss-American company Energy Vault in 2017, the system comprises a modular T-shaped tower (weight-bearing tower and the cantilever), cranes on the cantilever, and a motor/generator unit on the crane. As explained in 2.1, the storage of excess energy in T-SGES is achieved by lifting masses up into the air with it. The lifted blocks are usually stacked up on different levels (stair-step configuration) to maximize space usage. The higher a block is above the ground, the more gravitational potential energy it holds, giving out more electricity when dropped. When demand occurs, the crane moves to the level of blocks that store the desired amount of electricity. The gravitational force of the falling block will allow the rope to generate electricity through the generator unit. A prominent advantage of this design is its high scalability, meaning the storage unit can be freely scaled up or down depending on the actual need. According to Energy Vault, the storage capacity of its T-SGES design may vary from 10 MWh to several GWh [5, 6]. Fig. 2 shows a schematic diagram of a T-SGES system.

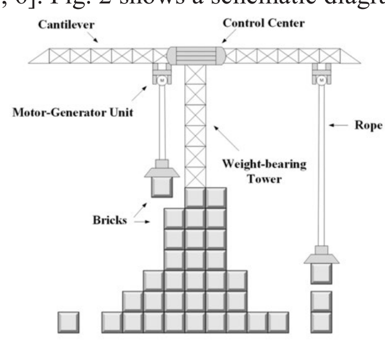

Fig. 2. Schematic diagram of T-SGES [5]

The second variation, S-SGES, has few differences compared to the previous variation. Similar to that of T-SGES, the mechanism of S-SGES also depends on the pull-drop maneuver of solid masses. The main difference between the two is the location of the system. The S-SGES system is buried underground, with a vertical hole of over 300 m dug into the ground and two motor/generator units installed on opposite sides. Two wires connected to the motor/generator units hold a single piece of solid mass in the hole through fixed pulleys and function similarly to the ropes in T-SGES [5, 7]. Fig. 3 shows a schematic diagram of a S-GES system.

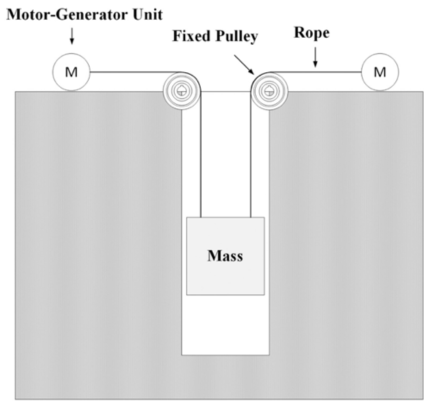

Fig. 3. Schematic diagram of S-SGES [5]

2.2 Facility Lifespan

The empirical lifespan of an SGES system is hard to determine due to lacked samples to refer to. However, theoretical estimation exists and gives an average lifespan of 30-50 years. T-SGES, according to Energy Vault, may perform for over 35 years; S-SGES with a life span of up to 50 years; and P-SGES variations for 40-60 years [5].

Factors that will affect the lifespan and reliability of an SGES system, however, can be speculated or projected. The most prominent must be the material composition of the solid masses. Considering factors such as erosion that may damage the solid blocks, the composition or material used must be taken into consideration to maximize their lifespan. Energy Vault has proposed composing these blocks out of locally sourced waste, but its feasibility and effectiveness are still yet to be tested. This factor will also affect the duration of energy storage. If the solid blocks erode or lose weight due to natural factors when they are in storage mode, they will generate or return less energy back to the grid than how much they have consumed to be lifted.

2.3 Cycle Efficiency

The efficiency cycle of energy storage technology, or the ratio between the consumable output when giving off energy and the input when converting electricity into a storable form, is another crucial factor in its evaluation. Current SGES systems are reported to have a cycle efficiency of 80%-90%, a figure that is considerably higher than the 40%-70% of compressed air energy storage and 70%-85% of hydro-pumped energy storage [5, 8, 9]. Specifically, T-SEGS operates with an efficiency of 90%; S-SGES at about 80%-90%; and P-SGES at a relatively lower 75%-80% [5]. However, most of the figures only exist on a theoretical aspect. The practical figure is still yet to be tested from application cases.

2.4 Energy Density

No available sources have directly stated the energy density of SGES in J/kg. Therefore, this report will use the T-SGES design from Energy Vault, the most typical SGES variation and the one with the most correlated data presented, as an example for calculations.

As the only design that has been put to commercial use, the company's T-SGES implemented in Rudong, China is reported to have a capacity of 100MWh. Even though no existing sources have directly stated the number of 35,000kg-concrete blocks (a standard size used by the company) used for this project, it can be speculated from an earlier prototype, which has a capacity of 35MWh and is composed of 5,000 blocks, that this project will need to include 14,000 blocks to reach its designated capacity [5]. The following calculation shows the energy density in J/kg:

$$\frac{100MWh}{14,000} \approx 7142.86Wh\ per\ block$$

$$\frac{7142.86Wh}{35,000kg} \approx 0.20Wh/kg = 720J/kg$$

Compared to other grid energy storage technologies, the energy density of T-SGES is relatively smaller. This limitation means that SGES systems depend significantly on the availability of land to reach high storage capacity. As a result, the spatial demand may become a financial challenger in areas where lands are scarce.

3 State of Development

3.1 Mechanism and Variations of SGES

Both tower SGES and shaft SGES are now in development. As pioneers of the field, Swiss-American company Energy Vault developed a modular tower SGES design in 2020. This means the storage system can be scaled either up or down depending on the actual demand of the region. Energy Vault also highlights the design's positive relationship with recycling waste. According to the company, these solid blocks can be composed of locally sourced waste materials, for instance, those from coal combustion, construction, and mining. The system is also compatible with various energy sources, namely solar and wind power, for both industrial use and community maintenance [5, 6].

However, since a tower SGES system is often over 50m high, Energy Vault stresses its possible instability under strong wind conditions. This leads to the follow-up shaft SGES design by Gravitricity from the U.K. Instead of planting the system above sea level, Gravitricity chooses to bury it underground. The company believes that apart from solving SGES instability in harsh climates, this design would also put abandoned mines in the U.K. back to use. According to the company's research, over 3,000 mines now in the U.K. are compatible with their SGES design, of which all of them could fit a storage capacity of 1.07 GWh and 350 of 6.7 GWh [10]. The company also states there are nearly 14,000 potential suitable sites worldwide [5, 7].

3.2 Cases of Application

The only commercial application was initiated in 2022 by Energy Vault in Rudong, China. With a capacity of 100 MWh and an output of 25 MW, the project was planned to be completed by the end of 2023 and the latest update in June 2024 shows that the construction is fully completed and has finished charge-discharge tests earlier in May. The facility is now waiting for the final approvals from the local authority to start operating [11].

Gravitricity, on the other hand, has completed its S-SGES prototype with a £640,000 sponsorship from the UK government. The prototype is in Leith Habour, Edinburgh, and is projected to cost £ 1 million [12]. The system, however, is much smaller in scale compared to what Gravitricity projected. It can only lift 25-50 tons, a figure hundredth of the 12,000 tons on the anticipated model. Further experimentations on a larger scale are still needed for S-SGES.

In addition to the prototype, Gravidity reached an agreement with the American Association of Bioanalysts (ABB) in December of 2023. Specialized in mine hoist for over

130 years, ABB would collaborate with gravidity by adapting their innovation on hoisting technologies into the S-SGES system. gravidity was also planning to engage with mine operators from Europe, India, and Australia, aiming to accelerate the commercialization of S-SGES in these regions [13]. A similar contract was also signed with a local company that promotes the regeneration of abandoned mines in Finland in early 2024. gravidity has received full access to the 1,400-meter-deep zinc and copper Pyhäjärvi mine, one the deepest mines in Europe, and is anticipating the project to be the first commercialized S-SGES in Europe, as shown in fig.4 [14].

Fig. 4. Pyhäjärvi mine in Finnland [14]

4 Conclusion

Solid mass energy storage (SGES) provides a promising yet challenging solution to grid energy storage under the context of global warming and increased awareness on aquatic habitat protection. With a straightforward mechanism of storing excessed electricity in the form of gravitational potential energy, SGES offers a scalable and efficient approach in grid energy storage. However, potential challenges lie in its low energy density and high land usage. Despite its high geographical and topographical adaptability, the reliance on land makes it financially costly to be implemented in expensive regions. In addition, as a newly emerged technology, SGES lacks samples of implementation. Even though now-existing prototypes or projects have proved its feasibility in storage capacity, empirical data such as lifespan and storage duration are still yet to be determined in the long run. As these technologies continue to mature and gain traction within the energy sector, they hold the potential to significantly contribute to a more resilient and sustainable energy infrastructure. By addressing current limitations and capitalizing on their strengths, SGES can play an important role in the transition towards a cleaner and more reliable energy future.

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