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Gravity Energy Storage Technologies: A Review of the Solid Gravity Energy Storage Applications

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ABSTRACT. The usage of renewable energy sources is increasing to reduce the carbon footprint. Renewable energy sources provide limited electricity generation and cannot meet the variable energy demand. Large-scale energy storage systems are needed for sustainability. The applicability of energy storage technology depends on many factors such as energy source, site availability, energy density, storage time, storage capacity, system cost, environmental impact, reliability, durability, and system integration capacity. Solid gravity storage technology is a promising new alternative in large-scale energy storage. There are various types of SGES systems classified according to the application method. In this paper, studies on various SGES methods are reviewed. Studies on the applicability factors of SGES systems and their integration into the electricity grid are evaluated. SGES technology has advantages in terms of geographical compatibility, storage volume, security, and energy conversion efficiency. It has been observed that successful results have been obtained in the theoretical studies. However, there is a need for the development of physical simulations and more comprehensive techno-economic analyses.

Keywords: Sustainability, Renewable Energy, Energy Storage Technologies, Solid Gravity Energy Storage

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1. INTRODUCTION

Meeting the energy demand is an important situation to solve in today's world. The depletion of fossil fuels and the harm they bring about the outdoors are facts that cannot be ignored. The usage of renewable energy resources is increasing in line with the goals of sustainability and carbon footprint reduction for the Green World [1]. The fact that renewable energy production methods cannot provide continuous production and the amount of energy demanded is unpredictable has made it necessary to develop energy storage systems to be used when required [2]. The difference between the amount of energy production and consumption is consistently changing. In this context, energy storage systems are of great importance as they can be used when needed and have critical importance in sustainability [3]. The applicability of energy storage systems depends on their certain characteristics. These characteristics are indicative of the overall quality, long-term sustainability, and successful applicability of the systems. Applicability of an energy storage system; It depends on many factors such as energy source, site availability, energy density, storage duration, storage capacity, system cost, environmental impact, reliability, durability, and system integration capacity [4]. Today, the biggest type of energy needed is electrical energy, and the focus of many studies is on the storage of electrical energy [5]. Wind and solar energy sources require an energy storage system due to intermittent energy production. These systems increase the power stability of the generated energy and ensure its integration into the grid and frequency and voltage management. These systems increase the power stability of the energy produced and provide network integration, frequency, and voltage management [6]. Various energy storage methods are utilized to store energy in different types and convert it into electricity when necessary. None of the developed energy storage technologies can fully meet the required characteristics [7]. For this reason, it is important to compare energy storage systems according to the purpose of the planned application of the system to be selected and analyze the applicability factors in detail [8]. A very important prerequisite for sustainable and clean energy solutions is the further development of large-scale energy storage technologies.

2. GRAVITY ENERGY STORAGE TECHNOLOGIES

Energy storage technologies; it is classified under 5 main headings according to the energy storage form: electrochemical, electrical, chemical, mechanical, and thermal. Among those forms, mechanical energy storage methods are classified under three subheadings: kinetic

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energy storage, elastic potential energy storage, and gravitational potential energy storage technologies.

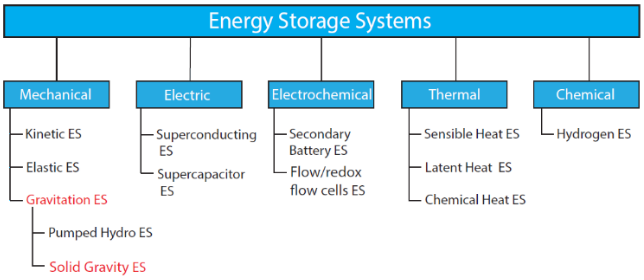

Fig. 1. Energy storage classification

Gravitational energy storage (GES) technology uses the power of gravity to store electrical energy. Although GES technology is considered a new method, it has been used in dams and hydroelectric power plants long since with the pumped hydro energy storage technology (PHES) method. It has been observed that in many of the studies examined, Solid gravity energy storage technology (SGES) is referred to as GES. But GES technology includes not only the use of solid weights but also PHES technology.[9] SGES technology is seen as an innovative and promising new solution method for storing large-scale renewable energies. PHES technology has difficulties arising from geographical limitations and the use of water as a heavy material. In contrast, a Solid Energy Storage System (SGES) is more advantageous compared to PHES in terms of geographical compatibility, energy density, and efficiency. SGES provides a more economical solution by using high-density solids as a heavy material. Compared to the commonly used Battery Energy Storage System (BES) and Hydroelectric Energy Storage (HES) technologies, SGES is safer and superior in terms of grid synchronization and inertia. This superiority helps the stable operation of power systems containing high amounts of renewable energy. Compared to Liquid Air Energy Storage (LAES), although SGES has less energy density, it has higher cycle efficiency. Thus, SGES has wide application potential in regions that are not suitable for PHES but have rich access to renewable energy sources and is considered an alternative solution to PHES. [10] In this article, studies on GES technology methods and the applicability factors of SGES technology, which is a new energy storage method, are evaluated.

3. TYPES OF SGES TECHNOLOGY

Unlike other systems that require a specific landform, SGES has various methods that can be adapted to geographical regions. SGES has emerged as an alternative and complementary method to overcome this problem. Different models of SGES are distinguished based on the solid energy storage media, transport methods, and platforms used.

3.1 Tower solid gravity energy storage (T-SGES)

The T-SGES method was developed by the Energy Vault Company. The system consists of a central tower with six lifting arms. The arms are capable of lifting concrete blocks 120 meters high and weighing 35 tonnes. These blocks, used for energy storage purposes, are stored as potential energy by stacking or dismantling regularly on the tower. The theoretical energy storage capacity of the system is 35 MWh and can quickly provide a maximum power of 4 MW to the electric grid; This can happen in as little as 2.9 seconds. Energy conversion efficiency can reach up to 96% and the concrete blocks used can be obtained from local sources and adapted to different geographies. The electricity production cost was determined as 44.58 dollars/MWh. In 2023, Energy Vault developed a project with 100 MWh storage capacity and 25 MW generation capacity in Zhejiang in cooperation with China Tianying Company [11].

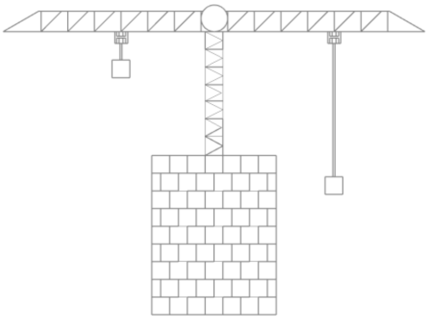

Fig. 2. Tower solid gravity energy storage

The capacity of the T-SGES system is directly proportional to brick mass and tower height. As height increases, storage capacity increases quadratically. However, an increase in height also increases system costs and technical requirements, so the tower height usually does not exceed 120 meters. Brick quality is related to the needs of the robot arm and system performance, and as quality increases, costs generally decrease while technical requirements increase. The output and discharge power of the system depends on the brick mass and the downstream speed; speed adjustments are a cost-effective way to increase the power capacity. The downstream velocity is proportional to the height, which sets the power limit, and meeting power requirements and height standards are essential for system effectiveness [12].

3.2 Shaft solid gravity energy storage (S-SGES)

Gravitricity, a company based in Scotland, has developed an innovative shaft model. This model can produce energy from 1 MW to 20 MW, using huge rocks weighing between 500 and 5000 tons, with a system with a total capacity of 12,000 tons [13]. This system can provide energy for periods ranging from 5 minutes to 8 hours and has an efficiency rate of 80% to 90%. The company has enabled the system to reach maximum power with a mechanism that can lift and lower a 50-ton load in 11 seconds. Gravitricity, which built a 0.25 MW capacity demonstration facility in Edinburgh in 2021, started a 2 MWh capacity energy storage project in Europe in 2022. SGES technology offers advantages such as long life, fast response time, and flexibility in operating modes. It also operates at a much lower cost than lithium batteries. However, the system faces several challenges. These include steel cable unraveling due to insufficient torque, shaking and turning of heavy loads, and insufficient crane capacity. [14] Gravity Power Company developed a solar energy method using abandoned mines in 2011. The main distinguishing point of this method is the usage of stone instead of water as the energy storage medium. [15] In 2020, the China University of Mining and Technology aimed to increase energy storage capacity by using two abandoned mines and building channels at different heights between these mines. This approach optimizes the release of potential energy during operation while facilitating the horizontal transport and storage of heavy objects. [16]

3.3 Piston solid gravity energy storage (P-SGES)

The P-SGES system consists of various components that play critical roles in energy storage and conversion processes. First of all, the gravity piston is positioned in a water-filled chamber, enabling the conversion of electrical energy into potential energy. This process is managed by the engine-generator and pump-turbine units, and in case of excess energy, it is carried out by pumping water and elevating the piston. Energy storage capacity is directly related to the dimensions, efficiency, and friction factors of the piston. The system has the potential to increase energy density and efficiency by using high-density materials. [17]

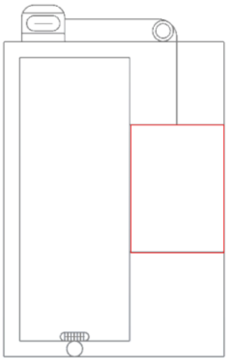

Fig. 3. Piston solid gravity energy storage

Research by Berrada and others. indicates that using steel or concrete to seal energy storage containers is more effective. American companies such as Gravity Power, which have adopted this technology, have shown the fact that the energy storage capacity of P-SGES systems can reach decades of megawatt hours, can be activated in milliseconds and react in seconds at full power, and can also provide uninterrupted energy for four hours and can reach 5 MW with an efficiency of 75-80%. It shows that it can produce nominal power. A project proposed by Heindl Energy aims to hydraulically lift a large rock mass and store potential energy. By discharging pressurized water through turbines, energy storage capacity is increased. The project states that energy storage capacity may vary between 1 MWh and 10 MWh and investment costs may range between \$120,000/MWh and \$380,000/MWh. The solar power system proposed by Zhang in 2018 increases efficiency by integrating shaft energy storage with pumped storage. [18]

3.4 Mountain Cable-Car solid gravity energy storage (MC-SGES)

In the MC-SPP system, the height of the mountain is used for the conversion and storage of gravitational potential energy and electrical energy, which enables more efficient use of mountain resources. To store energy, heavy objects are transported from the foot of the mountain to its summit with the help of a cable car; there is an electric motor and generator here. The descent of heavy objects with the help of gravity makes it possible to produce electricity through a generator. MC-SGES offers a safer alternative with more regular charging and discharging processes compared to tower-type energy storage systems. [19]

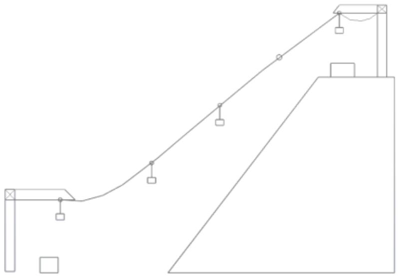

Fig. 4. Mountain Cable-Car solid gravity energy storage

Energy storage capacity and efficiency vary depending on factors such as altitude difference and engine efficiency. The height difference in projects is generally between 200 and 2000 meters, which affects load losses between 90% and 97%. While engine efficiency varies between 75% and 95%, storage efficiency has a value between 68% and 92%. Round-trip efficiency varies between 46% and 85%, and an efficiency above 75% is essential to achieve economic advantage. The output power for MGES is directly related to the time spent. Considering the relationship between time and speed, the efficiency of the system decreases to a minimum when the free fall velocity of about 33 m/s is reached. For this reason, to reach the desired efficiency level in MC-GES, it is recommended that the speed be below 10 m/s. Due to the relationship between speed and slope, it is necessary to avoid areas with steep slopes to prevent the cable car speed from increasing excessively owing to the effect of gravity. In inclined areas, electric motors can be used to control the speed of the cable car. [19,20].

3.5 Mountain Mine-Car solid gravity energy storage (MM-SGES)

AFEZMM-SGES consists of key components. These include weights, motor-generator units, cables, transmission fittings, rails and tilted surfaces. The system transforms electrical energy into gravitational potential energy. It works by moving weights between a high platform and a low platform. When there is a surplus of electricity, the engine pulls the minecart on the rails from the lower platform to the upper platform, while the weight rises and the potential energy increases. As the demand for electricity increases, the wagon on the upper platform is slowly lowered down and this movement produces electricity by causing the engine to rotate [21].

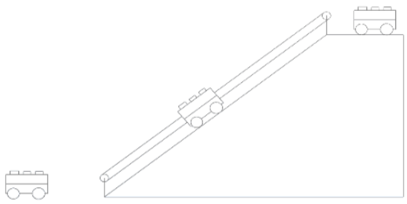

Fig. 3. Mountain Mine-Car solid gravity energy storage

This design was inspired by the use of PHES in places such as mountain slopes or old mines. The regenerative braking motor, which enhances the control and safety of the energy storage system, is located on the upper platform and is connected to the mining wagon by a cable. This technical route involves using gravel or concrete blocks to reduce high costs, and cables and rails that require high mechanical strength for transporting mine wagons [22]. The sloping ground must have a slope of approximately 6° to 25° for the mine wagon to operate efficiently; Too low a slope reduces efficiency, while too high a slope creates difficulties for the equipment [22]. MM-SGES and T-SGES systems have a similar modular structure and their energy storage capacities are comparable. However, the friction resistance of MM-SGES is higher compared to T-SGES.

4. APPLICABILITY ASSESSMENT OF SGES TECHNOLOGIES

In this section, the advantages and disadvantages of the application methods of SGES technology according to applicability factors are examined.

4.1 Tower solid gravity energy storage (T-SGES)

The T-SGES system has important advantages such as being able to be installed regardless of geographical limitations, shortening the construction process thanks to the rapid production of weight-bearing towers and blocks in a modular structure, and providing flexibility for different energy storage needs with its modular equipment structure. T-SGES has three shortcomings. Firstly, the mechanical strength of the material limits the load-bearing tower and the height of the tower is limited to 120 m, which affects the energy intensity. Secondly, the need to operate in a high-density environment leads to problems with equipment control and aging, resulting in reduced system safety. This situation is addressed to some extent by the EVRC design [12]. Lastly, Material use efficiency is reduced by some load-bearing blocks that are not used in the energy storage process.

4.2 Shaft solid gravity energy storage (S-SGES)

The main benefit of this technology is that it can achieve a significant height difference using existing mine shafts, offering a superior capacity compared to T-SGES systems, thanks to the full use of heavy loads. For S-SGES systems to respond quickly, weights must be kept in the mine shaft at all times. However, the disadvantages of this technology include excessive pressure and safety risks created by the support structure at the mine entrance. Additionally, the forced use of existing mine shafts increases the geographical limitations of S-SGES systems, and the cost of excavating new vertical shafts makes this technology not economically feasible [23]. Future improvements are hindered by the limited volumes of abandoned mines. This shows that SGES is ideal for small-scale energy storage and that hanging heavy loads for a long time increases energy consumption and reduces efficiency [16].

4.3 Piston solid gravity energy storage (P-SGES)

The main benefits of this technology include modularity and geographical adaptability; In this way, it does not require specific geographical conditions such as flat lands. However, favorable geographical conditions can significantly decrease structure costs. According to analyses conducted by Heindl Energy in 117 locations globally, 43% of these areas are buildable and 3% are quite suitable. Design and construction processes can be standardized, thus expanding the capacity of the storage facility. Thanks to the hydraulic systems' ability to react within seconds, P-SGES systems can regulate voltage and frequency and activate emergency services. However, the disadvantages of this technology include the high costs required to create artificial caves and the need for water resources. Compared to S-SGES, the energy density of P-SGES decreases by approximately 40% due to the buoyancy of water (the density of concrete is approximately 2.5 times that of water). Friction losses are unavoidable due to the piston structure. The whole system requires a high degree of sealing. That's why Heindl Energy uses geomembranes and concrete to seal natural rock fractures and recommends using a "rolling membrane" to keep water under high pressure under the piston; this method aims to reduce frictional losses between the piston and the wall. [24]

4.4 Mountain Cable-Car solid gravity energy storage (MC-SGES)

One of the prominent advantages of MC-SGES technology is that the energy storage system has excellent scalability and low heavy load cost, thanks to its modular structure. Additionally, thanks to the loading and unloading processes, heavy loads are not constantly loaded onto the carriers, allowing the carriers to be used more efficiently. However, this technology also has some disadvantages; for example, the presence of filling stations may reduce the effective height and overall efficiency of the system. Loading and unloading operations can cause equipment wear. In terms of geographical restrictions, it is more limited than MM-SGES and is especially suitable for geographical structures such as mountains and islands. [20]

4.5 Mountain Mine-Car solid gravity energy storage (MM-SGES)

The main advantages of MM-SGES technology are the expandability of the energy storage system thanks to its modular structure, low cost through the use of heavy materials such as gravel, and increased safety by eliminating the need for vertical hanging. According to the ARES report, the initial investment cost of this system is approximately 60% less per storage capacity compared to the PHES system. However, due to the large number of mechanical connections in the system, friction losses are high, which reduces efficiency. Outdoor working conditions can shorten the life of equipment and increase safety risks. It also requires sufficient height difference and large areas for land use, which requires high initial capital, especially in the absence of existing rails [25].

5. CONCLUSION AND DISCUSSION

Improving the efficiency of energy storage technologies plays a critical role in integrating theoretical knowledge with practical applications. Potential energy conversion is maximized, including the use of elastic potential energy to reduce the energy consumption of heavy loads, by optimizing engine power and transport routes. Integration of GES with electric grids requires the development of physical simulation models to analyze dynamic performance, allowing a better understanding of energy conversion processes and increasing efficiency. The successful implementation of GES projects is important for the integration of renewable energy sources and sustainable development. The development of energy storage methods compatible with renewable energy sources is of central importance in achieving future sustainable development purposes. Compared to other large-scale energy storage systems, SGES technology has significant advantages such as low geographical limitations, large storage volume, high energy conversion efficiency, long lifetime, low electricity generation cost, and high security. SGES is a novel and promising technology that has the potential to transform the current architecture of large-scale energy storage systems. However, there are some problems in existing research on SGES. The methods under certain conditions for the selection of different technical paths are unclear and more comprehensive techno-economic analyses are needed. Existing studies focus on existing technical pathways and show a lack of innovation in basic technologies. Optimal parameter design is still missing for some technical routes. Issues such as equipment inadequacy and the interactions of different technical means on the network require research.

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