

Types, applications and future developments of gravity energy storage

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Abstract. In recent years, the clean and environmentally-friendly renewable energy technologies have developed rapidly. How to ensure balance and flexible output of power system has become a new challenge after all kinds of volatile power sources are connected to the power system. Among different forms of stored energy, gravity energy storage, as a kind of physical energy storage with competitive environmental protection and economy, has received wide attention for its advantages such as high safety, high cost-performance, great environmental-friendliness and strong environmentally adaptation. This paper firstly introduces the basic principles of gravity energy storage, classifies and summarizes dry-gravity and wet-gravity energy storage while analyzing the technical routes of different types of gravity energy storage. Separated into groups of dry and wet gravity energy storage, these storage shows similar features and promising advantages in both environmental and economical way. Among them, LEM-GES shows a new concept of storage and will be the target for future study. Then follows an analysis of the practical applications of gravity energy storage in real scenarios such as mountains, wind farms, oceans, energy depots and abandoned mines, and finally an outlook on the future development trends of gravity energy storage technology.

Keywords: gravity energy storage, types, applications, wet gravity energy storage, dry gravity energy storage.

1. Introduction

To tackle the scarcity and environmental pollution of traditional fossil energy, the renewable energy industry has been developing rapidly in recent years. Represented by wind and solar energy, such energy is characteristic of randomness, volatility and intermittency. New challenges of power balance and flexible output will be faced in case of its large-scale access to the power grid [1]. In an effort to guarantee the safe and stable operation of power system after various types of variable power sources, energy storage is the most effective solution. Therefore, the energy storage technology has currently become one of the hottest topics of energy research [2].

At present the energy storage technology can be divided into such five main forms as mechanical energy storage, electrochemical energy storage, chemical energy storage, electrical energy storage and thermal energy storage. Gravity energy storage is a kind of mechanical energy storage and its energy storage medium is mainly divided into water and solid matter. The energy storage medium is lifted on the basis of the different height to achieve the charging and discharging of the energy storage system [3]. As shown by the existing studies, compared with other energy storage technologies, the technology of gravity energy storage for power generation has the following advantages: (1) It is purely physical, highly safe and environmentally friendly. In the workflow of weight transport, potential energy storage, and mechanical-energy power generation, this power generation does not involve any chemical reaction and runs safely and reliably. Besides, it, clean and low-carbon, has little impact on the natural environment, according with the concept of sustainable and green development [4]. (2) Strong in environmental adaptability, flexible in arrangement as needed and suitable for "distributed" energy storage. There are no special conditions and requirements for the weight storage, transport and power generation. Hence the power plants of gravity energy storage are basically free of limitations from external conditions such as site selection and weather, and can be applied flexibly [5]. (3) Such power generation is long in cycle life and low in cost. Weights are

mainly made of concrete or local materials, or other recycled materials, and can be recycled for decades. There is little loss of weights during operation [6]. According to the related studies, as an environmentally-friendly and economically-competitive physical energy storage, gravity energy storage is gradually developing from theoretical conception to practical application [7]. However, the available literature has not systematically summarized the latest progress of the related technologies to gravity energy storage and their application in practical situations due to more technical routes of gravity energy storage. Therefore, this paper analyzes the types, applications and future development of such energy storage.

This paper firstly presents the types of gravity energy storage and analyzes various technical routes. Secondly, analysis is given to the practical applications of gravity energy storage in real scenarios such as mountains, wind farms, oceans, energy depots and abandoned mines. In the end, the future development of gravity energy storage technology is prospected.

2. Types of gravity energy storage

GES is a type of mechanical energy storage that uses water or solid substances as a medium to control the difference of the medium's heights to achieve the charge and discharge process. It can be separated into two subcategories: wet gravity energy storage and dry energy storage. Wet gravity energy stores gravitational potential energy based on water. It mainly uses electric generators and pump turbines to achieve the conversion between potential energy and electrical energy. Generally, its charging and discharging process is achieved by controlling the water valve, electric generator current and other factors. The wet energy storage contains specific types of storage technology such as PHES (Pumped Hydroelectricity Energy Storage), GPM (Gravity Power Module), HHS (Hydraulic Hydro Storage) / GBES (Ground-Breaking Energy Storage), and UOSS (Underwater Ocean Storage Systems). Dry energy storage stores gravitational potential energy based on heavy solid masses. It mainly uses cranes, cable cars, rail trains, winches and other structures to achieve the heavy lifting and falling control. It mainly contains electric generators for energy conversion, and controls electric generator currents and other parameters to achieve the charging and discharging process. Types of dry energy storage include ARES (Advanced Rail Energy Storage), Gravitricity, Energy Vault, and LEM-GES (Linear Electric Machine Gravity Energy Storage).

2.1. Wet gravity energy storage

2.1.1 PHES (Pumped Hydroelectricity Energy Storage).

The principle of pumped energy storage technology is to use the different gravitational potential energy of water at different heights to convert electrical energy and water's gravitational potential energy to each other. The pumped Hydroelectricity Energy Storage consists of two reservoirs at different heights. As shown in Fig. 1, when energy storage is needed, electrical energy drives electric motors and pumps to lift water from the lower reservoir to the upper reservoir, and when power generation is needed, water from the upper reservoir drives turbines and generators to generate electricity. PHES has the advantages of mature technology, high efficiency (70 %~85 %), large energy storage capacity (GWh level), and long life cycle (25~60 years). In onshore pumped energy storage system, because it requires two reservoirs upstream and downstream, PHS has harsh geographical requirements, including the need to consider the topography, geology, water and other conditions, and the initial investment is huge, usually requiring a construction cycle of 8-15 years. For the current stage of energy storage technology, Pumped Hydroelectricity Energy Storage is the most mature application, accounting for more than 90 % of the grid-connected energy storage devices worldwide [8].

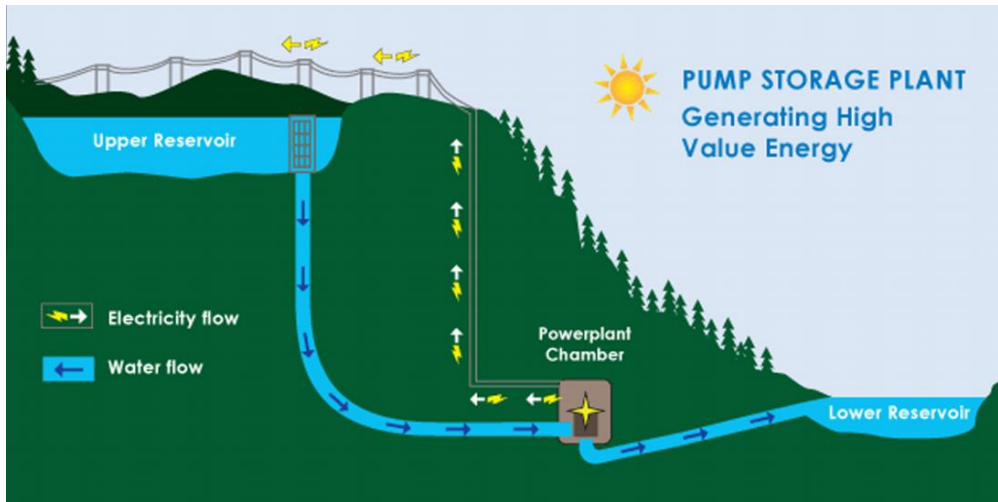


Figure 1. Pumped hydroelectric energy storage [8].

The underground PHES, UPHES, and Piston-based PHES are specific cases of PHES. The underground PHES places the lower reservoir underground in order to ensure a high vertical displacement without consuming a large surface area. It is mainly used to explore the viability of the use of deep mines and open pit mines [8]. Piston-based PHES uses the combination of water and pistons to achieve the storage and conversion of energy. When the water pushes the pistons up, the potential energy is stored, and when the pistons drop and push water into the electric generator, the gravitational potential energy is converted to electricity.

2.1.2 GPM (Gravity Power Module).

The Gravity Power Module is composed of a piston, a water container and a return pipe connected to the turbine pump. The GPM hydraulically lifts a huge piston inside a deep vertical shaft. The piston descends, forcing water back through the turbine to generate electricity (as shown in Fig. 2). The main shaft of a commercial-scale unit is typically between 30 and 100 meters in diameter and 500 to 1,000 meters deep, providing an electrical output of 40 to more than 1,000 MW for 4 hours or more, depending on the requirements and the size.

The energy storage capacity of GPM is conditioned by the mass of the piston and the height that the piston can be lifted. The energy can be stored for a long time (about 6~14 h) at grid level, and the energy conversion efficiency is estimated to reach about 80 % [8]. The stored energy can be recycled. This provides a new way for utilization of off-peak electricity and consumption of renewable energy, with a small land area and a high energy density.

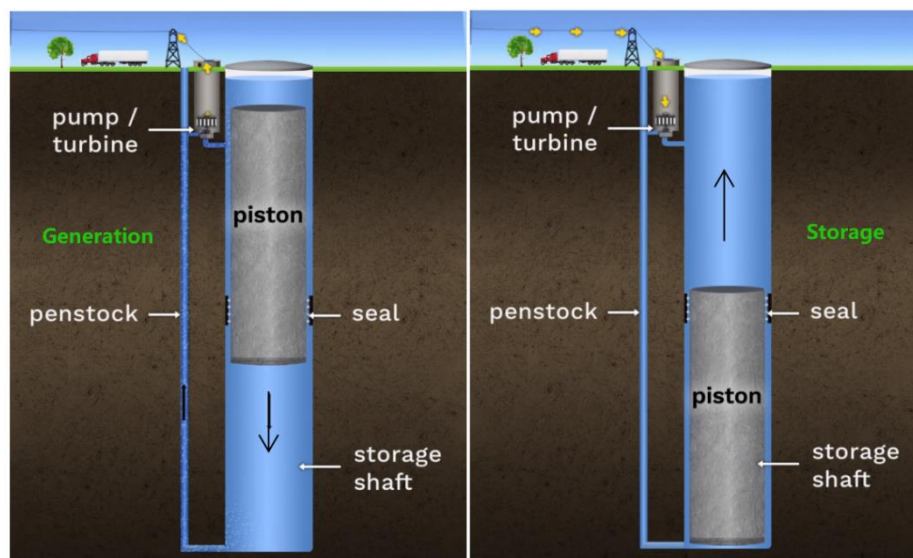


Figure 2. Gravity Power Module [9].

2.1.3 HHS (Hydraulic Hydro Storage) / GBES (Ground-Breaking Energy Storage).

The Hydraulic Hydro Storage stores surplus energy by pumping water to lift a large, cylindrical mass. The cylinder is lowered, and the pressurized water drives a turbine to generate electricity when energy is demanded. The piston is mainly built using earthworks and concrete or mining technologies [10].

2.1.4 UOSS (Underwater Ocean Storage Systems).

In recent years, energy storage technology for marine energy has developed rapidly. UOSS shares a similar mechanism with PHES (Pumped Hydroelectricity Energy Storage) and CAES (Compressed Air Energy Storage) on land.

Traditional PHES requires relatively immaculate geographical conditions, including topography, geology and water sources. Its initial investment is huge and its construction generally takes 8-15 years. Large areas of land and vegetation need to be flooded in the construction of large reservoirs. This even gives rise to ecological and migration problems. According to the design of UOSS, the ocean can be directly used as a lower reservoir, so only an upper reservoir needs to be built. When electricity needs generating and energy storing, the seawater is discharged from the upper reservoir to the ocean through the pump turbine unit first, and then the gravitational potential energy of seawater converted into electric energy. Subsequently, the seawater is pumped to the upper reservoir and stored in the form of gravitational potential energy of seawater (as shown in Fig. 3). This is applicable to coastal areas and islands, and can reduce the damage to the environment and construction cost [11].

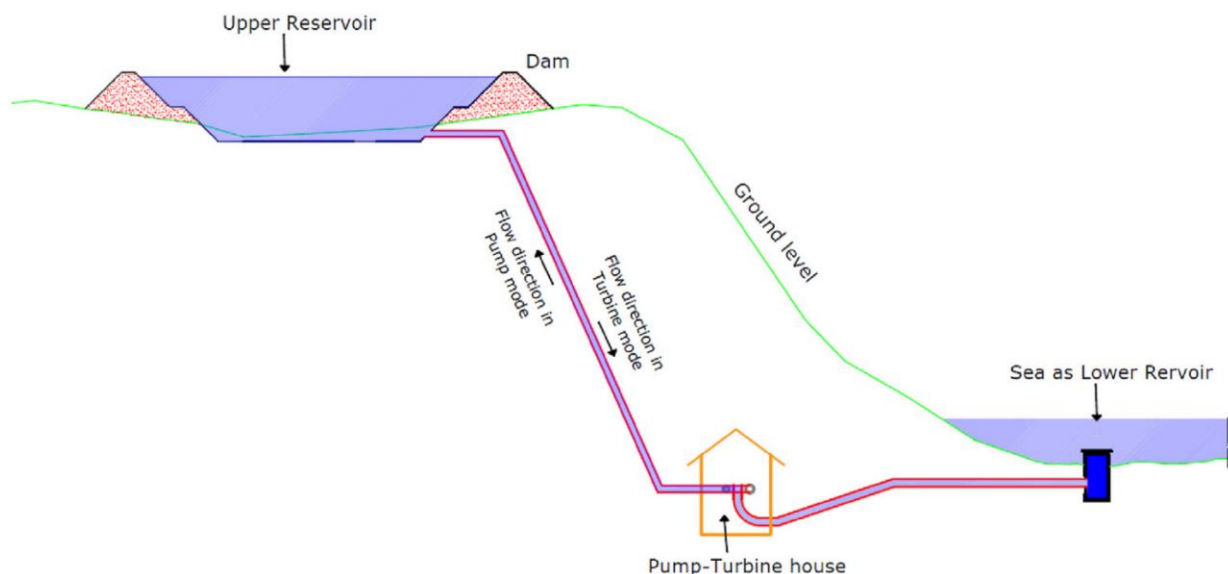


Figure 3. Typical sketch of Ocean energy storage systems [12].

The underwater compressed-air energy storage system can be applied in the areas with appropriately deep waters. As an ideal deep-water source, ocean is a desirable place for application of underwater compressed-air energy storage technology. Such a technology can be widely used to store energy at medium and large scale in the coastal areas, islands, ocean platforms and offshore renewable energy farms. The above system being coupled with offshore wind power, the energy conversion system on the ocean platform can convert the electricity produced by the marine REG device into high-pressure compressed air and store it in the submarine gas storage device. When needed, such compressed air will be released to generate electricity, and the stable electricity transmitted to the onshore grid through the submarine cable. This can increase the utilization rate of renewable energy.

2.2. Dry gravity energy storage

2.2.1 ARES (Advanced Rail Energy Storage).

ARES is a rail-based traction drive system. It uses surplus renewable energy or grid power to transfer masses to higher altitudes via rail. The system is unloading as the blocks descend, each weighing approximately 45-64 tons and performing a 16 km route. This energy storage system takes advantage of the mountainous terrain and rail vehicles to achieve high-capacity energy storage in outdoor environments [13]. However, ARES has topographical constraints, as its installation requires an area with height differences. The civil construction cost of leveling the hillside is high, and further structural optimization is needed.

2.2.2 Gravitricity.

Gravitricity is based on lifting and lowering a heavy block along the vertical axis of the ground. It makes use of heavyweights, which are released into a vertical shaft using winches that double up as dynamos. It aims to use old or abundant mines to reduce the cost of digging deep burrows. So generally, it is used in mines and construction environments.

2.2.3 Energy Vault.

Similar to Gravitricity, Energy Vault achieves the conversion of energy by lifting and dropping pistons. Energy Vault proposes a gravitational energy storage and generation solution based on concrete block storage towers. When electricity is abundant, a crane lifts the concrete blocks from the ground and stacks them high like blocks, converting the energy into potential energy of the concrete block tower, which is the storage phase; when electricity is needed, the concrete blocks are dropped in sequence, releasing the heavy potential energy and converting it into electricity.

2.2.4 LEM-GES (Linear Electric Machine Gravity Energy Storage).

The Linear Electric Machine Gravity Energy Storage is composed of a piston, a shaft and an electric machine. It levels up and lowers down the piston to store gravitational potential energy and convert potential energy into electricity. The mechanism is similar to Gravitricity and other dry gravity energy storage, but since it replaces rope with magnet, the efficiency would be much higher.

3. Application

There are many structures of solutions for gravity energy storage with their own advantages and disadvantages, so different climatic conditions and terrain features should be combined in the design of gravity energy storage systems during the application of practical scenarios. The following summarizes the application of different types of gravity energy storage in practical scenarios

3.1. Mountain Gravity Energy Storage

The concept of Mountain Gravity Energy Storage, or MGES, involves storing excess energy from the grid by raising sand or gravel to a higher elevation. This is achieved using a pair of cranes, which load the material into storage containers, before pulling them up to height on a cable.

The gravity energy storage by using the mountain drop and the lifting of solid weights is more stable in structure and stronger in load-bearing capacity than artificial structures. the Mountain Gravity Energy Storage (MGES) proposed by IIASA Research Institute mainly uses the terrain of steep mountains to store energy through the potential energy of gravel, as shown in Fig. 4. When power is abundant, an electric system similar to a ski lift is applied to lift the gravel-filled container to the top of the mountain for storage; when power consumption is at its peak, gravity is relied on to transport the gravel from the upper top back to the ground and generate electricity by releasing the gravel potential energy. The institute believes that mountain gravity energy storage system is a longer duration and larger scale energy storage than lithium battery energy storage system [14].

ARES (Advanced Rail Energy Storage) proposed in 2014 a locomotive ramp track system where locomotives go up and down the track for energy storage and release, with construction starting in

Nevada in 2020. The technology has been successfully tested in pilot projects, and its first commercial deployment will be connected to the California grid.

3.2.StEnSea energy storage systems

The idea of StEnSea project was proposed by German scholar Horst Schmidt-Böcking in 2011 [15]. The StEnSea energy storage device are hollow spheres (internal diameter is about 30 meters), and each sphere contains 2 sets of devices inside: (i) water pumps; (ii) hydroelectric generators (as shown in Fig. 4). These spheres will be placed on the seabed at a depth of about 700 meters in the coastal area, and when there is surplus power in the power system, the surplus power is used to drive the pumps to discharge the water inside the device into the sea. When the power system needs the device to generate electricity, the device will open a valve to bring in seawater to drive a hydroelectric generator, thus completing the generation of electricity during peak periods of use. The developers of StEnSea project expect that if more than 80 subsea energy storage devices are combined to generate electricity, the scale of energy storage will be sufficient to effectively respond to the need for electricity [16]. This project helps develop and utilize seawater energy storage, but the current difficulties lie in the bulk production of spherical energy storage devices, and the installation of communication facilities to support the subsea system and subsea grid transmission to be optimized.

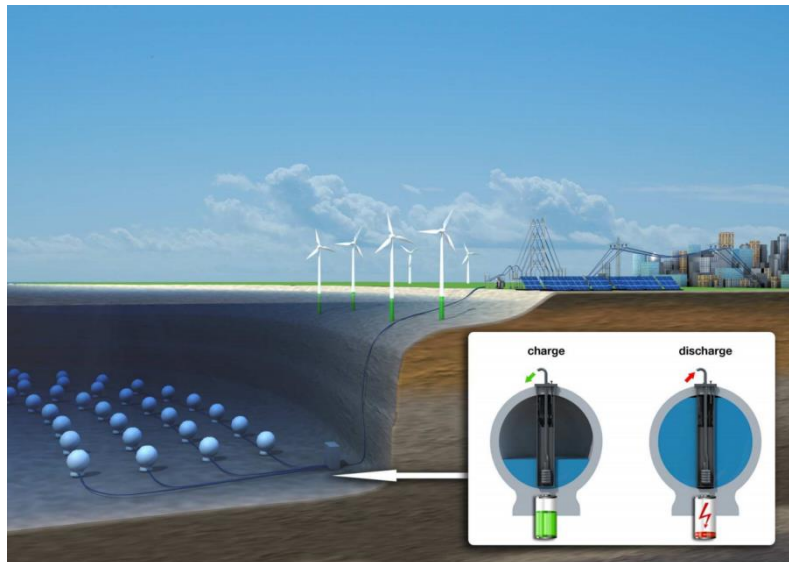


Figure 4. The StEnSea Project [16].

3.3.Energy Vault system

In 2018, Swiss gravity energy storage company Energy Vault unveiled its model of an innovative gravity energy storage device with an energy storage solution conceived to build a giant steel tower for energy storage that relies on gravity and 35 tons of bricks to store and release energy [17]. When electricity demand is low, a crane uses surplus power from the grid to lift the bricks and stack them on top. When the demand for electricity rises, the bricks are lowered to release kinetic energy back into the grid.

3.4.Gravity energy storage with suspended weights for abandoned mine shafts

Gravity energy storage system is placed on the ground or under the sea, usually affected by meteorological conditions or changes in marine ecology, in practical applications, the use of underground space abandoned mines to build gravitricity energy storage system has become a new trend. The British Gravitricity company uses abandoned mines to build energy storage devices, re-engineering 150~1500 meters depth of abandoned drill shafts, after the completion of the transformation of the use of electric motors to repeatedly lift and put down 500~5000 tons of heavy objects [18]. The principle of this energy storage device is to use the motor to lift the weight to a

certain height when the power is abundant, release the weight when it is needed to generate electricity, and release the stored energy to generate electricity during the falling of the weight. The advantages of this energy storage system are the low cost of retrofitting abandoned mines, better safety and less damage to the natural environment. Of the approximately 85,000 abandoned legacy mines in Australia, 3,000 are currently being rehabilitated, repurposing the existing infrastructure of abandoned mines, addressing the risk and waste of abandoned mines not being used for long periods of time, and reducing energy storage costs. In future large-scale applications, the problem to be overcome by this energy storage scheme is that the size limitation of the shaft opening in the abandoned mine will affect the load capacity of the motor and the release of the heavy load, on the other hand, the problem of swaying and deformation of the rope during the release of the heavy load needs to be further solved.

4. Conclusion

As global climate change and energy environment issues become increasingly stressful, gravity energy storage will be used in a wider range of energy storage technologies because of its high environmental friendliness and general durability in the long run. These features can help tackle the problem of pollution and short in energy supply. There are many structures of solutions for gravity energy storage with their own advantages and disadvantages, so different climatic conditions and terrain features should be combined in the design of gravity energy storage systems during the application of practical scenarios. The gravity energy storage based on mountain drop and abandoned mine transformation will become the focus for research in future designs. This relates to the fact that mountains have a stronger and more stable load-bearing capacity. The recycling of abandoned mines helps to lessen the impact on the environment, shorten the construction period of gravity energy storage system and reduce its cost. However, the optimization of the construction site and technical details need to be studied in depth. With the still dominant status of PHES, wet gravity energy storage like StEnSea energy storage system would become popular in the expected years when humans take the utilization of areas in ocean into more sincere consideration. Moreover, the LEM-GES becomes a new target of gravity energy storage and explored a new way to improve the efficiency by reducing the friction work. With the study of electric magnet goes on, the LEM-GES will be more efficient. So, no matter on ground or in the ocean, at present or in the future, the gravity energy storage has promising advantages as a storage technology.

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