

Physical Energy Storage Technologies: Basic Principles, Parameters and Applications

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Abstract. Physical energy storage is a technology that uses physical methods to achieve energy storage with high research value. This paper focuses on three types of physical energy storage systems: pumped hydro energy storage (PHES), compressed air energy storage (CAES), and flywheel energy storage system (FESS), and summarizes the advantages and disadvantages of each technology by collecting and evaluating the principles, components and technical parameters. In addition, this paper presents the practical applications of the technologies and finally provides an outlook on future developments. The results show that PHES technology is the most mature and has the advantages of high efficiency and long lifetime, but the current application is rather single and can be developed in the direction of variable speed/underground/seawater pumped storage in the future; CAES has larger energy capacity and longer service life, outstanding peak regulation capability, and can manage energy as well as provide power for vehicles, but its efficiency and energy density are low and need further optimization in the future; FESS has the advantages of short response time and power density, and minimal environmental effects, but currently it is mostly used for small-scale occasions and military purposes due to its small capacity, and its self-discharge rate is large, and it is being developed in the direction of increasing capacity and improving safety in the future. This paper aims to provide a systematic summary of the progress of physical energy storage technology, so as to provide information to support further research on physical energy storage.

Keywords: Physical energy storage, Compressed air energy storage, Pumped hydro energy storage, Flywheel energy storage system.

1. Introduction

As a result of the emergence of a new phase of the global energy revolution, the energy structure is gradually transforming, and renewable energy will gradually take the dominant position. According to the Renewables 2020 Global Status Report [1], the total global energy installed in 2019 increased by 2,588 GW compared with the previous year, and renewable energy increased by 200 GW, accounting for 7.7%, of which the main increase is in solar energy (115 GW), wind energy (60 GW) and hydroelectricity (16 GW). However, wind and solar as the representative of renewable energy generation are highly dependent on natural conditions, with strong volatility and intermittency [2], therefore, power storage technology is bound to become essential technical support for the stable, safe and efficient functioning of power grids, how to choose the right energy storage technology (EST) has become a key issue for the smooth improvement of new energy. However, clean energy generation, represented by wind and solar power, is highly dependent on natural conditions and is highly volatile and intermittent. Therefore, the selection of suitable power storage technologies to ensure stable grid operation has become a key issue for the smooth growth of new energy sources.

Nowadays, ESTs worldwide are roughly three types: chemical, electromagnetic and physical energy storage. Chemical energy storage technology has made rapid development in recent years, but its high cost, short cycle life, small capacity and safety issues are still the main bottleneck limiting its development [3]; for electromagnetic energy storage, it has not been applied to a large scale due to the short time of research and the superconductivity technology supporting its stable operation still

has a lot of problems. Physical energy storage, on the other hand, has large-scale, long-life, low-cost, environmental protection, and has a broad application area and huge development potential [4]. Furthermore, China places a high priority on the improvement of physical energy storage, and the Chinese Academy of Sciences and local governments at all levels have made significant investments in this area. Thus, it can be seen that physical energy storage technology is of strategic importance to the transformation and upgrading of energy in China.

This paper provides a comprehensive overview and analysis of three techniques involved in physical energy storage (PHES, CAES and FESS) from principles, technical parameters to application prospects, to provide references for further research and improvement of physical energy storage technology in the world.

2. Pumped hydro energy storage

2.1. System composition and working principle

Pumped energy storage (PHES) is widely regarded as the world's most advanced large-scale physical energy storage technology. It consists of two linked reservoirs positioned at various heights, with the upper and lower pools connected by pipes, and stores energy in the form of the gravitational potential energy of water. An electric motor turns electricity into mechanical during the charging period by moving the water from lower altitude to higher altitude via a pipe. Once the power system is under low load, water stored in the higher can return to the lower pool under the action of a turbine, and the gravitational potential energy is converted into mechanical energy, and electrical energy is generated again with the help of a generator.

Fig. 1 illustrates a typical structure of a PHES power plant. In this case, the upper and lower reservoirs are used to store water at higher and lower terrain, respectively, and there is an inlet at the outlet of the upper reservoir that acts as a closed pipe during maintenance. A pair of penstocks between the two reservoirs is used to serve the purpose of transporting water in overcoming the height difference. The connection between the penstocks and the lower reservoir is equipped with turbines with loads (flat pressure towers, used to reduce pressure and improve control efficiency), generators and motors, which are connected to an external circuit for the output of electrical energy.

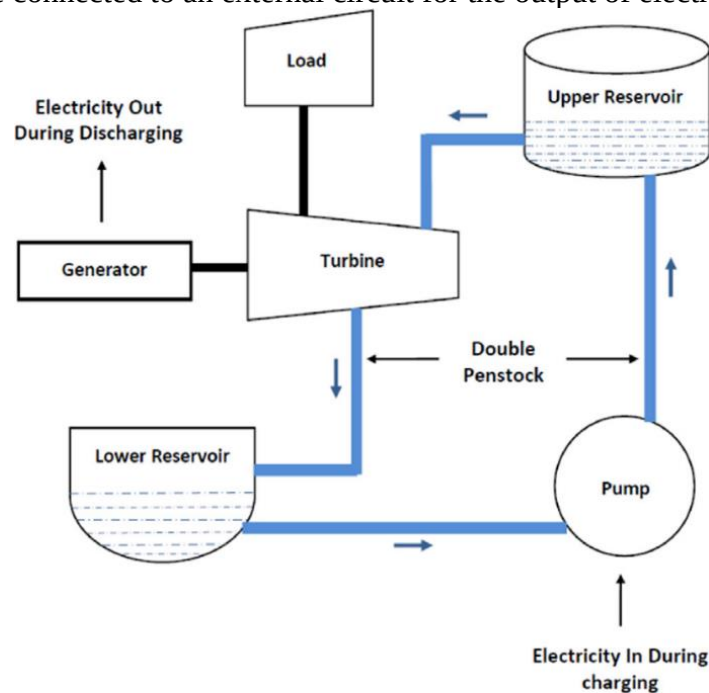


Figure 1. Structure of a typical PHES power plant [5].

2.2. Technical characteristics and performance parameters

Table 1 lists some technical and performance parameters of pumped hydroelectric energy storage systems, including energy and power density, universal installed capacity, response time, lifetime and efficiency. The self-discharge rate is not listed in the table and has a value of 0.005%-0.02%/day according to Benato & Stoppato's study [6].

Table 1. Technical characteristics of PHES [7-9].

Power density (W/L)	Energy density (Wh/L)	Energy capacity (MWh)	Response time (s)	Calendar life (year)	Efficiency (%)	Lifetime (cycles)
0.45 – 1.5	0.5 – 2	500 - 8000	~ 180	40 - 60	65 – 85	$> 0.5 \times 10^4$
					70 – 80	$10^4 - 3 \times 10^4$
					70 – 85	$10^4 - 6 \times 10^4$
					50 – 85	
					75 – 78	
					65 – 90	

Observing the data in the table, it is clear that in addition to the mature technology development, PHES has many advantages that are incomparable to other energy storage technologies, such as long lifetime, high cycle times, and very low self-discharge rates, high efficiency, and very low storage costs. PHES can also track load fluctuations and respond to extreme load variations, according to Rehman et al., while being used to adjust the frequency and ensure voltage stability [5]. PHES also has several drawbacks, including limited energy and power density, strong geographical constraints, and high investment costs with long payback periods. In addition, it can alter the ecological environment and thus may affect sustainability.

2.3. Applications and development prospects

In addition to conventional PHES, many new forms of PHES have emerged, such as variable-speed systems, underground systems and seawater systems. Due to the limitation of space, the paper only introduces variable speed pump turbines and seawater pumped storage. As for underground pumped storage, it is generally transformed by the waste coal mine, and the basic structure and working principle are the same as conventional pumped storage, so it will not be repeated here.

2.3.1 Variable-speed pumped storage (VPS).

Variable speed pumped storage (VPS) is one of the new research concepts of PHES and represents the future direction. Fig. 2 shows a simple schematic of VPS. It is indeed a *brand-new* technology for the world, but Japan has already made a breakthrough in this area since the 1990s [10]. It is easy to conclude that VPS has excellent regulation performance, which is reflected in the fact that the response time and regulation speed of VPS are significantly better than those of fixed-speed units. This advantage means that VPS can better track the working process and frequency changes of wind power and other less stable power sources, and make timely rate and power adjustments, as a result, the grid will be less affected by new renewable resources [11]. Furthermore, the speed control device enables the turbine to operate in the high-efficiency region for as long as possible, which improves the efficiency of the turbine; due to the increased operating head range, the height of the upper reservoir dam can be reduced, thus saving construction costs.

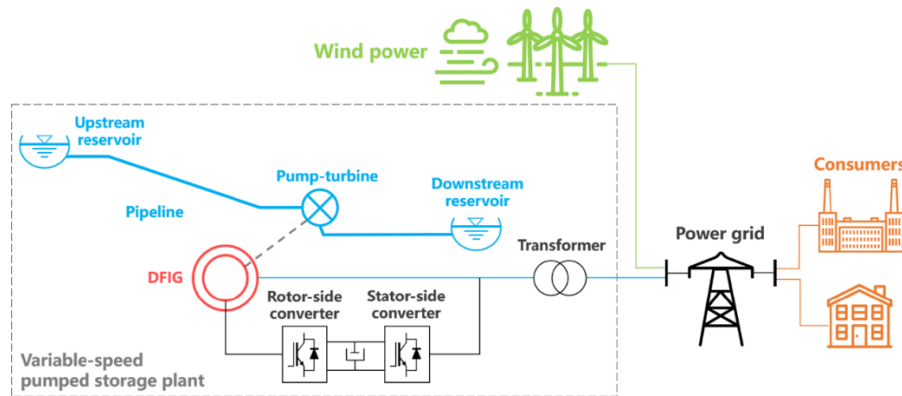


Figure 2. Schematic diagram of VPS [12].

2.3.2 Seawater pumped storage (SPS).

As mentioned above, PHES has two key drawbacks: geographical limits and poor energy density, both of which severely limit the technology's development. Therefore, a seawater energy storage technology called "Storing Energy at Sea (StEnSea)" was developed. The main body of the system is several hollow concrete spheres, each sphere contains a hydro generator and a pump.

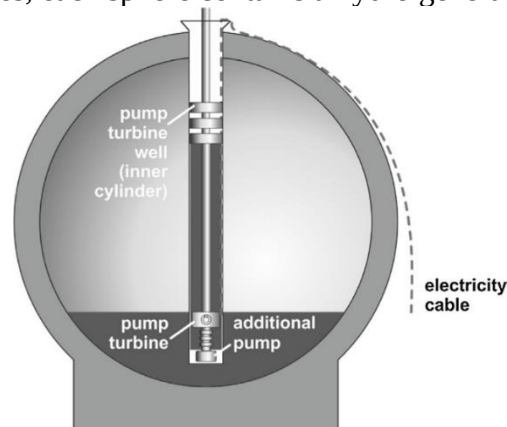


Figure 3. A cross-sectional view of StEnSea [13].

An image of StEnSea is shown in Fig. 3. When the grid power is low and there is additional capacity, the pumps use it to pump seawater outside for energy storage, however, when the load is large and the greatest amount of power is required, the doors in spheres allow enabling salt water to flow in and spin the turbines for power generation. The researchers expect each sphere to continuously generate electricity for up to four hours if a 5 MW hydroelectric generator is used [14]. This means that a single power generation could store 20 MWh of electricity and effectively impact the European grid. In any case, there is no doubt that all the evidence points to the importance of PHES as a technology in the energy revolution and its development prospects are very promising.

3. Compressed air energy storage

3.1 System composition and working principle

CAES technology uses air compressors to compress and store gas in confined spaces, such as mines and salt caverns and is a relatively mature and well-known physical energy storage technology. The gas turbine heats the compressed gas when energy is needed, which expands to release energy, so CAES essentially converts elastic potential energy into electrical energy.

3.1.1 Components.

Overall, the main CAES components include the air compressor, the gas storage system, and the heating system. Different from common industrial compressors, the compressors in CAES have high efficiency, large air mass per unit time, and a high compression ratio. There are various compression

schemes based on the practical situation in the system [15]. For gas storage systems, generally, underground salt caverns, artificial caves or mines can be used as gas storage. Due to the high requirements of the gas storage chamber in the geological environment, the widespread use of CAES is limited. The heating system is one of the key factors in determining the efficiency of the system. While traditional D-CAES requires an additional heat source to heat the air, in NSF-CAES systems thermal energy from the compressed gas is stored to heat the air entering the turbine. This method is called thermal regeneration technology, in which multi-stage thermal regeneration technology has higher efficiency than a single-stage [15].

3.1.2 Classifications of CAES.

There are many classification standards for compressed air energy storage, the most common way is to classify according to whether the auxiliary heat source is needed, and the source of its heat energy. According to the above standards, CAES technology is mainly divided into three types: diabatic (D-CAES), adiabatic (A-CAES) and isothermal (I-CAES).

D-CAES is a conventional air compression technology that requires heating from an external heat source to release energy, as shown in Fig. 4. However, since the choice of external heat source for this system is usually fossil fuel, D-CAES can cause a certain degree of environmental pollution. Furthermore, the heat produced by D-CAES is wasted as it escapes into the air when the gas is compressed, thus becoming one of the main reasons why the efficiency of this system cannot be further improved.

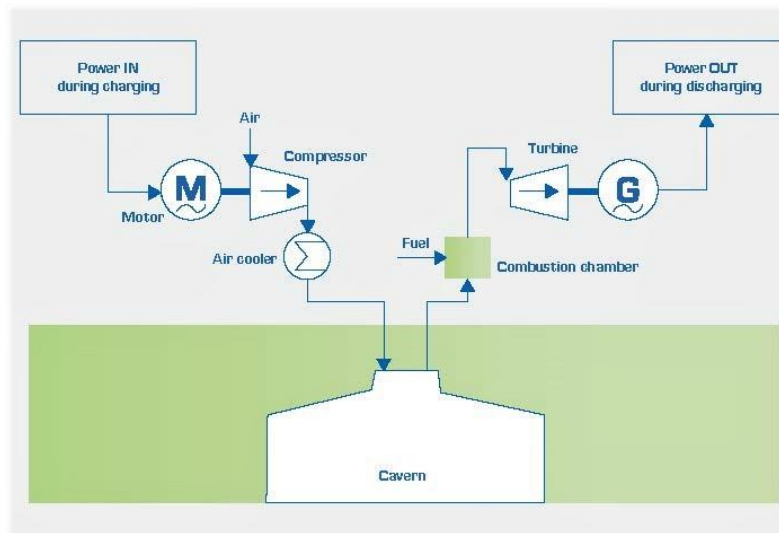


Figure 4. Schematic of a D-CAES system [16].

A-CAES can be divided into two types: A-CAES with a TES and A-CAES without a TES. As shown in Fig. 5, the heat generated during the compression of A-CAES with TES is extracted from the airflow and captured by the thermal management system in the TES facility for later reuse. Therefore, A-CAES with TES does not rely on external heat sources and shows a bigger energy density. A-CAES without TES stores the thermal from compressed air in a confined space. The energy storage pressure of this process is lower, so the energy density is lower than the former.

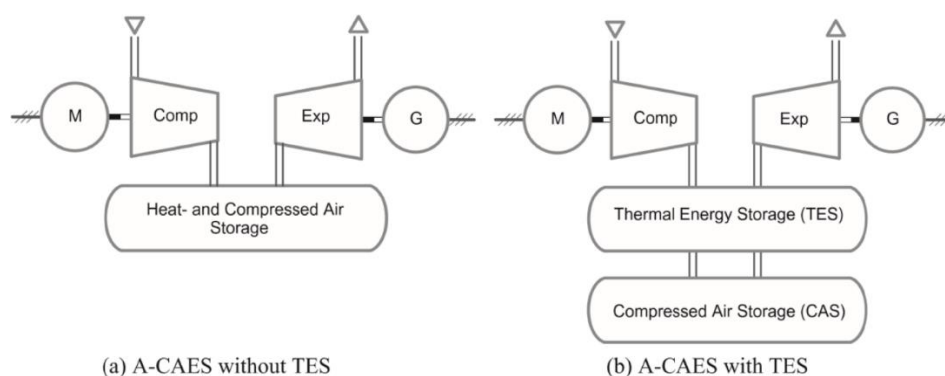


Figure 5. Schematic of an A-CAES system [17].

I-CAES believes that constant low temperature is the best way to increase compressed air efficiency, so achieving isothermal expansion is the ideal goal for I-CAES [18]. In practical applications, to avoid the complicated operation of controlling the temperature, the air is stored in the space close to the ambient temperature, which makes the round-trip efficiency of this process higher than other CAES, and it is also cleaner.

3.2 Technical characteristics and performance parameters

Table 2 evaluates the technical parameters of some energy storage systems. CAES has a larger energy capacity and longer lifetime but a very lower energy density. Because CAES is composed of multiple subsystems, the choice of different schemes will lead to deviations in actual efficiency, and the efficiency of different types of CAES is quite different. In general, the efficiency of CAES is low compared to other technologies which are 40% to 70%. By improving the efficiency of subsystems, the system efficiency will be greatly improved. Additionally, CAES is considered one of the cleanest ways to store energy. CAES can also be coordinated with energy sources, such as wind power to drive air compressors. Since the storage space is often set underground, saving above-ground space is also a major advantage of CAES [18].

Table 2. Energy storage characteristics of different processes [19-24].

Energy storage system	Power density (W/L)	Energy density (Wh/L)	Power rating (MW)	Energy capacity (MWh)	Lifetime (year)	Efficiency (%)
LS CAES	0.5 – 2	1 - 6	100 - 1000	Less than 1000	20 - 40	40 - 70
SS CAES	More than 2	Greater than 6	0.003 – 10	Less than 0.1	More than 23	65
Lithium-ion battery	1000 – 10,000	100 – 500	1 – 100	0 - 10	4- 20	75 - 97
Lead-acid battery	1 - 500	40 - 90	0 - 40	1- 40	5- 15	63 - 90
Supercapacitor	More than 100,000	10 - 30	0 – 0.3	0 – 0.0005	10 – 30	84 - 95
Fuel cell	More than 500	500 – 3000	Less than 50	0.312	5 – 20	20 - 66

3.3 Applications and development prospects

Huntorf is the world's first commercial energy storage power station based on D-CAES technology, but during operation, the workload fluctuates greatly. After 1985, the usage became less due to the connection to a larger grid containing PSH. This means that CAES is uncompetitive as the primary means of power supply. More commonly, Huntorf is used as an alternative when other energy storage methods fail. In addition, due to the longer start-up times of other types of power plants,

CAES tends to provide short-term power during the vacuum period before the start-up of other power generation methods. Another method is to supplement the power supply during evening peak hours and periods of heavy electrical load. Overall, Huntorf exceeded expectations and was an engineering success. McIntosh is the second commercial D-CAES storage facility. Since McIntosh has an additional heat recovery system to recycle the heat lost by the gas turbine, the efficiency is somewhat improved over the Huntorf. In recent years, the ALELE project in Germany, which was expected to use AA-CAES technology to build a large-scale energy storage facility with a cycle efficiency of 70%, was later halted for commercial reasons. The Bethel Energy Center is planned to be built in Texas and is expected to provide 324 MW of electricity in ten minutes of a cold start when it becomes operational in 2025.

With regards to future development, CAES as a whole is still in the early stage of development, and the system efficiency is low. Due to its outstanding peak shaving capability, CAES is expected to be an excellent tool for energy management. Additionally, CAES can convert compressed energy into mechanical energy that powers vehicles [18].

4. Flywheel energy storage systems

4.1 System composition and working principle

As a storage technology that has existed for thousands of years, flywheel energy storage systems (FESS) have become increasingly popular with modern technological advances, becoming a reliable form of physical energy storage. The principle of FESS can be described as the rotating mass principle. This means that the flywheel stores energy by converting the external electrical input into its kinetic energy of rotation, accelerating when storing energy and decelerating when releasing it. Rotor, motor/generator (M/G), bearings, power electronics and housing are the primary components of the FESS [25]. Fig. 6 shows a typical FESS system. Next, this paper will describe several parts of FESS in detail.

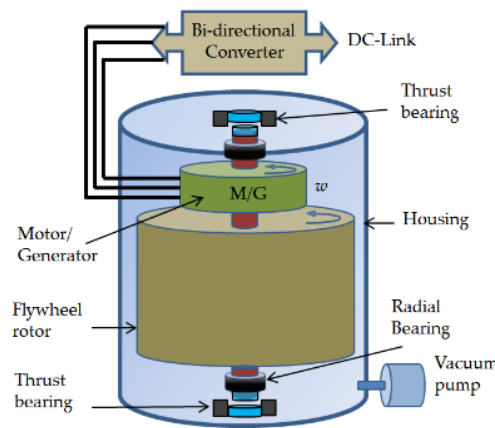


Figure 6. Structure and components of a flywheel [26].

4.1.1 Rotor.

Because the rotor is the most important part of the FESS, it will be the subject of the following discussion. As demonstrated in equation (1), the energy of the wheel is proportional to the rotational inertia I and the square of the ω .

$$E = \frac{1}{2} I \omega^2 \quad (1)$$

where E is the total energy. By introducing the flywheel's density ρ , length h and radius r , the stored energy can be expressed in the form of equation (2).

$$E = \frac{1}{4} \pi \rho h \omega^2 r^4 \quad (2)$$

The maximum tensile strength σ of the rotor material dictates the maximum speed limit at which the flywheel can operate, hence it can be represented as the equation (3) [27].

$$\sigma_{max} = \rho \omega^2 r^2 \quad (3)$$

The shape factor K can characterize the maximum speed limit, which determines the flywheel structure [28]. By introducing this coefficient, the specific energy and energy density of the flywheel can be expressed, see equations (4) and (5).

$$\frac{E}{m} = K \frac{\sigma_{max}}{\rho} \quad (4)$$

$$\frac{E}{V} = K \sigma_{max} \quad (5)$$

Equations (4) and (5) show that for a flywheel to achieve a high energy density, it must be as dense as possible and have a higher σ_{max} value. Although metals may have higher tensile strength, they are denser, while composites can satisfy both of these conditions. The performance parameters of flywheels made of several materials are given in Table 3. It is observed that the composite material “Carbon fiber (60%)” has the highest tensile strength and the lowest density, which results in the highest energy density. In contrast, metals and alloys have higher densities and average tensile strengths.

Table 3. Materials for the rotor of FESS [29].

Material	ρ (kg/m ³)	σ_{max} (MPa)	E/m (W/kg)	E/V (kW/m ³)
Steel (AISI 4340)	7800	1800	39	303
Alloy (AlMnMg)	2700	600	38	101
Titanium (TiAl ₆ Zr ₅)	4500	1200	45	202
Fiberglass (60%)	2000	1600	135	269
Carbon fiber (60%)	1500	2400	269	404

4.1.2 Other components.

In addition to the rotor, the other components of the FESS also play a very important role. M/G is the electromechanical interface of the FESS, which acts as a motor when the FESS stores energy and as a generator when it releases energy. Power electronics are used to connect the rotor to the M/G, which is generally a variety of power converters or voltage converters. Bearings also play an important role in FESS. Good bearings can greatly reduce the frictional losses of the rotor and thus increase the efficiency of the device. Common bearings available today include mechanical bearings and magnetic bearings [30]. Housing is the stationary part of the flywheel. The part wrapped by the housing is generally vacuumed to reduce the aerodynamic loss of the flywheel.

4.2 Technical characteristics and performance parameters

FESS has a long cycle life, a quick response time, a high round-trip efficiency (RTE), a good charge/discharge rate, a high power and energy density, and a small environmental effect [8, 31]. Specifically, flywheels have low operational and maintenance requirements, while allowing for quick charging and draining transitions. This means that it can have a service life of over 20 years and hundreds of thousands of charge/discharge cycles. At the same time, it has a very short response time and can transfer significant amounts of electricity in a handful of seconds. Detailed parameters are shown in Table 4. However, the downside is that flywheels self-discharge at a much higher rate than other energy storage media, which means that it could be dangerous if the design is not safe [26].

Table 4. Technical parameters of FESS [8, 32].

Energy storage (MJ)	Cycle life (times)	Calendar life (year)	RTE (%)	Response time (s)	Power density (kW/kg)	Energy density (Wh/kg)
2 - 360	Unlimited	20	70 - 80	A few seconds	~ 5	~ 20
	100,000	20	81			
		20	98			
	< 4 million	20	85 - 90			
		20	86			
		20	85			
	175,000-200,000					

4.3 Applications and development prospects

4.3.1 Uninterruptible power supply (UPS).

UPS uninterruptible power supply is a device that uses utility or battery energy to provide high-quality AC power to loads and is one of the most important application scenarios for FESS. Today, over 80% of power failures last below one second, and 97% last below three seconds [29, 33]. Despite their short duration, they can cause severe voltage and frequency instability. This is where using the FESS as a UPS for electronic equipment can make up the time difference between an external grid outage and the start of the backup power system.

4.3.2 Renewable energy sources integration.

Renewable energy sources such as solar and wind are by nature fluctuating and intermittent, so systems composed of them tend to be somewhat unstable. Therefore, the quality and stability of the power supply of current solar and wind energy systems can be improved by developing suitable FESS. Specifically, in wind power systems, when there is no wind, flywheels store excess energy during capacity utilization periods and subsequently release its power to the system; in solar power systems, battery life is improved by first using the energy stored in the FESS [34]. Fig. 7 shows the application of FESS in both systems.

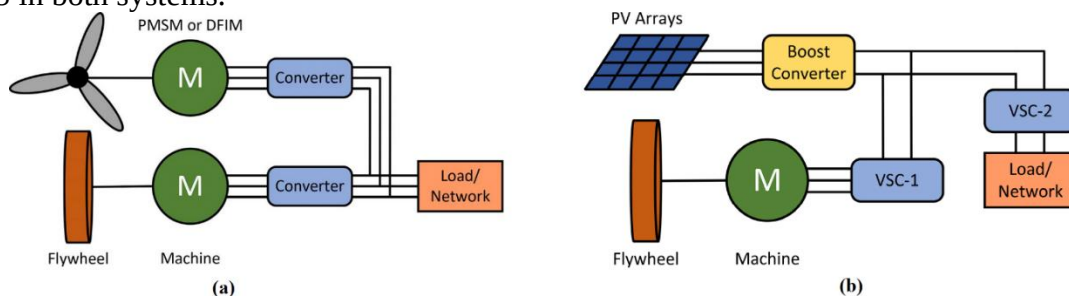


Figure 7. (a) Application of FESS for wind system, (b) application of FESS for solar system [35].

4.3.3 Transportation.

The introduction of FESS in rail transport can result in significant energy and economic savings. For light rail trains (see Fig. 8 for a schematic), the study by Rupp et al. shows that by using FESS with a certain energy and power capacity, energy consumption savings of up to 31% and cost savings of 11% can be achieved [36]. At the same time, FESS can solve the problem of voltage transients in railroad distribution and transmission without increasing the line capacity [35]. FESS is also widely used in hybrid vehicles. When the car needs to achieve uphill and acceleration, the flywheel can provide additional driving force, which helps to save fuel and extend the engine life, while reducing noise and air pollution [30].

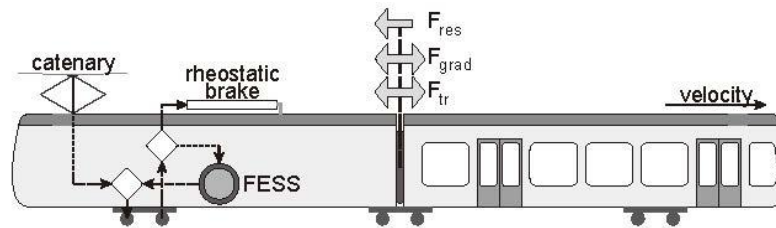


Figure 8. Application of FESS in rail transportation [36].

Besides, FESS can also be applied in other areas such as the military, ocean, space, FACTS devices, etc. [37]. In summary, FESS technology provides a new way to store electric power, and due to its excellent performance parameters and almost no environmental pollution, it is gaining more and more attention and is beginning to be more and more widely used in many industries at home and abroad.

5. Conclusions

As renewable energy sources become more widespread, the study and selection of power storage solutions are becoming increasingly important. Physical energy storage is more mature than chemical and electromagnetic energy storage, and it offers several distinct advantages. A more comprehensive review of the three main forms of physical energy storage, from principles to applications, is presented throughout the paper. Specifically, pumped storage is the earliest and most widely used of the three technologies, with the advantages of mature technology, high efficiency and long life, but the current application is relatively single, and mostly high head, high capacity, the future can be developed in the direction of variable-speed/underground/seawater pumped storage and equipment miniaturization. Compressed air energy storage has a large energy capacity and long service life, and outstanding peaking ability to convert compressed energy into mechanical energy, which is expected to be an excellent tool for managing energy and providing power to vehicles, but the disadvantage is that its system efficiency is low, and the future can be achieved by improving the efficiency of subsystems to achieve a leap in its overall performance. FESS has the advantages of short response time, great round-trip efficiency and power density, and low effects on the environment, but currently it is mostly used for small-scale occasions and military purposes due to its small capacity and high self-discharge rate and low efficiency, which is being developed in the future towards increasing the flywheel unit energy storage capacity, increasing power and improving efficiency. This paper can serve as a resource and source of information for researchers and developers of physical energy storage technology around the world.

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