Analysis on the Status of Compressed Air Energy Storage (CAES) in China and Future Development Trends

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Abstract: To achieve the ambitious goals of carbon peaking and carbon neutrality, China is vigorously developing renewable energy sources to replace the combustion of fossil fuels. Concurrently, in recent years, China has also been intensively developing new energy storage technologies to mitigate the fluctuations caused by the integration of renewable energy into the grid. Among these new energy storage technologies, the development of Compressed Air Energy Storage (CAES) technology stands out. Although relatively mature, CAES has not yet been widely applied, presenting significant research potential. This article will start by comparing CAES technology with traditional Pumped Hydro Energy Storage (PHES) to analyze the advantages of CAES. It will then systematically examine various types of CAES technologies, predicting the future development trends of this technology in China based on the status. The analysis concludes that CAES is the most promising new energy storage technology in China. In the future, it is expected to achieve performance comparable to pumped hydro storage, enabling large-scale applications across diverse scenarios.

1 INTRODUCTION

With the development of society, people's standard of living is continuously improving, leading to an increase in energy demand. Currently, the combustion of fossil fuels remains the primary means of energy acquisition in China, leading to a continuous increase in atmospheric greenhouse gas concentrations and carbon emissions. In 2020, China officially proposed the "dual carbon" goals of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. This objective has significantly accelerated the development of renewable energy. In recent years, China has vigorously developed renewable energy sources such as wind and photovoltaic power. However, these energy sources are characterized by volatility and randomness, necessitating the integration of energy storage technologies to mitigate issues arising from the mismatch between power supply and demand (Wu et al, 2001). Energy storage technologies enable the large-scale and efficient utilization of renewable energy, thereby promoting the transition to low-carbon energy and sustainable development. In recent years, China has been seeking low-cost, high-efficiency, and sustainable energy storage technologies to support the future new power system.

Energy storage systems can generally be divided into two primary categories, traditional and novel. Pumped Hydro Energy Storage (PHES), as an efficient and widely used traditional energy storage technology, holds the largest share of installed capacity among energy storage technologies in China. However, its construction and operation are significantly influenced by terrain and water conditions, and it has reached a bottleneck phase with increasing development costs, indicating limited future growth. In the realm of emerging energy storage technologies, Electrochemical Energy Storage (EES) currently holds the largest share. Nonetheless, it remains immature and is constrained by numerous factors such as the challenges of end-of-life disposal and very high development costs, making it far from ready for large-scale application. CAES, the second most installed emerging technology after electrochemical storage, has seen rapid development in China in recent years and has reached a relatively mature stage, as shown in figure 1. CAES boasts inherent advantages such as large storage capacity, environmental friendliness, short

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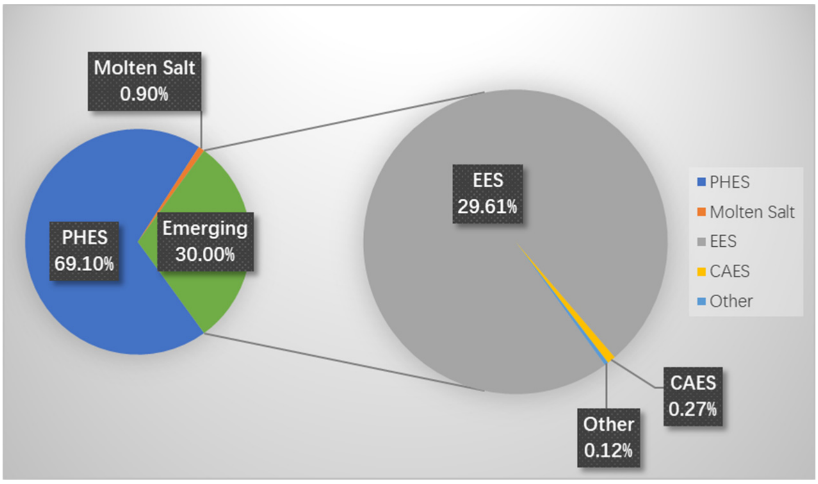

Figure 1: The cumulative installed capacity of operational energy storage projects in China (as of the end of June 2023)

construction periods, and long operational lifespan. These attributes give it significant development potential and the prospect of large-scale commercial deployment in the future.

2 INTRODUCTION AND COMPARISON OF RELEVANT ENERGY STORAGE TECHNOLOGIES

2.1 PHES

PHES is currently the most widely used and technologically mature large-scale energy storage technology in China. It has been established as a traditional energy storage technology, with significant utilization and development within the country. The energy is converted in the form of gravitational potential energy and electrical energy. A pumped storage system mainly consists of two reservoirs at different altitudes. During periods of low electricity demand, excess electrical energy is used to drive the pump motor units to transfer water from the lower reservoir to the upper one. In this stage, energy in the form of electricity is converted into the potential energy of water. When the demand for electricity rises, the stored water flows from a higher elevation to a lower one, driving the generator to produce electricity and converting potential energy back into electrical energy. The earliest pumped storage power plant in China was built in the 1960s. As of 2021, the total capacity of PHES in China reached 36.39 million kW (Li et al, 2023). According to China's "Pumped Storage Medium and Long-term Development Plan (2021-2035)," the total installed capacity of pumped storage will exceed 62 million kW by 2025 and reach 120 million kW by 2030 (Zhou et al, 2023). The development of China's PHES industry is expected to continue accelerating in the future, with an average annual installed capacity projected to exceed 6 million kW within the next decade, tripling the current scale. In conclusion, PHES is anticipated to remain the primary method of energy storage in China in the future.

2.2 CAES

CAES, similar to pumped storage, falls under the category of mechanical energy storage. However, it represents a relatively mature form of new energy storage technology. In China's array of new energy storage technologies, its installed capacity ranks second only to electrochemical energy storage, and it has experienced rapid development in recent years. The operational principle of CAES involves utilizing surplus electrical energy to power compressors for air compression, thereby converting it into the pressure energy of compressed air. When there is a need for electricity, the stored compressed air in tanks, caverns, or other storage spaces is released to drive turbines, generating electricity and thus transforming the stored energy back into electrical energy. The origin of CAES dates to the 1940s when German engineer Stal Laval patented the concept of storing electricity using air in underground storage chambers, marking the advent of CAES technology. In China, the development of CAES technology began relatively late, only starting in the 21st century. The 10 MW compressed air energy storage power station in Feicheng, Shandong Province, is the country's first grid-connected commercial CAES power station, which successfully delivered power for the first time on August 4, 2021. China possesses abundant natural geological resources, such as salt caverns, which have significant potential for utilization.

2.3 Comparison of PHES and CAES

PHES, as the earliest developed and most mature technology, has numerous advantages including large energy storage capacity, low operating costs, high power output, and high efficiency. However, it also has inherent disadvantages, such as a heavy reliance on geographic conditions like significant elevation differences. As the scale of construction expands, the difficulty of development increases. Additionally, pumped storage projects are expensive to build, have long construction periods, and may cause environmental pollution during construction. CAES, in contrast, not only shares the advantages of large storage capacity, high system efficiency, and long storage duration, but also boasts lower construction costs, shorter construction periods, and zero pollution—advantages that pumped storage does not have. However, both technologies share common drawbacks, including slow start-up speeds and low energy density, which are critical issues that need to be addressed in the future. Table 1 shows the specific data comparison between the two technologies.

Table 1: Comparison of CAES and PHES

Parameter	PHES	CAES
Energy Storage Power (MW)	100-3000	50-500
Operational Lifespan (a)	40-60	20-40
Efficiency (%)	70-85	40-55 (up to 70% with heat recovery)
Cost ($/kWh)	0.05-0.15	0.10-0.20
Construction Period (a)	4-10	2-5
Start-up Speed	Minutes to tens of minutes	Minutes to tens of minutes

Despite the advantages, pumped storage in China has reached a period of bottleneck, making significant breakthroughs difficult. In contrast, CAES is in a rapid development phase, with the potential to achieve cost parity with pumped storage and large-scale commercialization in the future (Li et al, 2023). To meet the “dual carbon” goal, China is expected to implement a series of environmentally friendly energy storage support policies, further promoting the development of zero-pollution energy storage technologies like CAES. CAES has enormous potential for future development and is highly valuable for research and development.

3 THE CLASSIFICATION OF CAES

3.1 Classified by Storage Capacity

CAES can be classified based on storage capacity into large-scale CAES systems, small-scale CAES systems, and micro CAES systems (Zhang et al, 2023). Large-scale CAES systems typically operate at the 100 MW level, offering the greatest peak shaving capabilities and the largest scale. These systems are usually integrated with sustainable energy, for instance, photovoltaic power generation, hydrogen, and wind power. Because of their reliance on natural spaces like caverns and mines for air storage, large-scale CAES systems are often constrained by geographical location. Small-scale and micro CAES systems, on the other hand, utilize artificial high-pressure containers, such as high-pressure storage tanks, for air storage. Small-scale CAES systems, with power capacities around 10 MW, can couple with renewable energy sources like wind energy, offering high flexibility without the need for additional generators (Tan et al, 2019). These systems are suitable for residential areas and small grids. Micro CAES systems have power capacities three orders of magnitude lower than small-scale systems, with weaker power generation capabilities and smaller air storage spaces. However, they offer greater flexibility and ease of installation and removal, making them ideal for home backup energy or vehicle-mounted systems.

3.2 Classified by Idealized Change of State

3.2.1 Diabatic Compressed Air Energy Storage (D-CAES)

D-CAES, also known as traditional compressed air energy storage, improves compression efficiency through inter-stage cooling during the gas compression process. In the energy release process, external heat sources or fossil fuel combustion are used to heat the air, driving the expansion turbine. The combustion heat increases the air temperature, enhancing the enthalpy of the compressed air and its work capacity, thereby improving cycle efficiency (Zhang et al, 2023). Due to significant heat dissipation to the environment, the cycle efficiency of D-CAES typically reaches only about 40%.

3.2.2 Adiabatic Compressed Air Energy Storage (A-CAES) & Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)

A-CAES addresses the low efficiency of D-CAES to some extent by storing the heat generated during air compression in thermal storage devices, which is subsequently utilized to raise the heat of the compressed air in the energy discharge phase. This technique does not require burning fossil fuels, making it clean and environmentally friendly. Although the construction costs are higher, the cycle efficiency is significantly improved, reaching 55% to 75% (Wu et al, 2023). AA-CAES is a further advancement of A-CAES, involving more advanced technologies and system designs. As an "upgraded version" of A-CAES, AA-CAES can achieve even higher efficiency.

3.2.3 Isothermal Compressed Air Energy Storage (I-CAES)

I-CAES is a new type of energy storage that maintains the air temperature within a specific range during the compression and expansion processes using specialized temperature control methods (He & Sun, 2022). According to thermodynamic theory, isothermal compression consumes the least compression work, while isothermal expansion produces the most expansion work (Dib et al, 2021). I-CAES systems generally use liquids with high specific heat capacity, such as water or oil, to provide a nearly constant temperature environment. This increases the contact time between the gas and the liquid, ensuring that the gas approaches isothermal conditions during compression, thereby minimizing heat loss and improving the overall cycle efficiency (Wu et al, 2023). Although the theoretical efficiency can reach up to 90%, achieving this in practical designs is challenging. The development costs are high, and the technology is still at a low level of maturity.

3.3 Other Emerging Technologies of CAES

In recent years, to achieve green energy storage and the dual carbon goals, China has innovated and derived several new technologies in the CAES field. The main advancements include Liquid Air Energy Storage (LAES) and Supercritical Compressed Air Energy Storage (SC-CAES).

3.3.1 LAES

LAES is a thermomechanical energy storage technology that uses electrical or renewable energy to compress purified air to high pressure. The compressed air is then cooled and liquefied by passing through a cryogenic storage unit, storing the excess energy in the form of low-temperature liquid air. During the energy release phase, the liquid air is pressurized by a cryogenic pump and then re-gasified by extracting cold from the storage unit. Driven by heated high-pressure gas, the turbine functions and produces electricity. Liquid gas possesses a higher density compared to compressed gas, providing LAES with higher energy storage density and efficiency (Xu, 2023). Additionally, the high density means that a large amount of storage space is saved, indirectly reducing dependence on specific geological conditions such as underground salt caverns and mines.

3.3.2 SC-CAES

SC-CAES is a technology first proposed by Chinese researchers. SC-CAES fully utilizes the properties of supercritical fluids. This type of fluid has excellent heat conversion capabilities and its molecules are packed very tightly. At the same time, it also possesses high solubility, as well as low viscosity, high diffusion coefficient, and good permeability of supercritical gases. The operating principle is as follows: During the energy storage phase, the air, after processing, is at a supercritical condition. (temperature > 132K, pressure > 37.9 bar) (Xu, 2023). The heat of compression is transferred using a thermal storage heat exchanger, cooling the air to ambient temperature and subsequently liquefying it through isobaric cooling, with the compression heat being recovered and stored. The compressed air, now in liquid form, is stored at atmospheric pressure in low-temperature storage tanks. During the energy releasese phase, liquefied air is pressurized to supercritical levels using a low-temperature pump. It then passes through a cold storage heat exchanger, which recovers cold energy as well as releases heat, warming the air to ambient temperature. Finally, the air expands through an expander to perform work, simultaneously absorbing the stored compression heat from the energy storage phase. The SC-CAES system removes the need for burning fossil fuels and extensive corresponding storage facilities. It achieves an energy density of up to 3.4×105 kJ/m^3 and a round-trip efficiency of 67% (Zhang et al, 2023).

4 THE STATUS AND CHALLENGES OF THE DEVELOPMENT OF CAES

4.1 Current Development Status in China

CAES has seen very rapid growth domestically over the past decade, gradually moving towards large-scale, mature, and systematic implementation. In China, the performance of CAES equipment has significantly improved, progressing from the 10MW class to the current 300MW class. In 2022, the biggest 350MW salt cavern CAES demonstration project in the world commenced in Tai'an, Shandong Province. This project employs an innovative low-melting-point molten salt high-temperature adiabatic compression technology. Once completed, it will achieve several "world firsts" in the field of CAES. On April 9, 2024, the world's first 300MW CAES power station successfully connected to the grid and began generating electricity in Hubei Province, China, setting three world records in single-unit power, energy storage capacity, and conversion efficiency. These achievements signify that China has elevated CAES technology to a new milestone

4.2 Challenges Faced and Related Development Directions

4.2.1 System Efficiency

With current technology, the theoretical system efficiency of CAES can reach approximately 75%. Although China has become a world leader in this technology, there remains a gap between the actual system efficiency and the theoretical value. In China, the system efficiencies for 1MW, 10MW, and 100MW systems are approximately 52%, 60%, and 70%, respectively, which are still lower than the efficiency of PHES, indicating room for improvement (Xu, 2023). To enhance equipment performance, the country should continue to increase research and development efforts, undertake technological breakthroughs, and address core technical challenges. Additionally, the promotion and application of this novel technology should be strengthened, accelerating the industrialization, commercialization, and large-scale deployment of CAES technology. This will foster a virtuous economic cycle, promoting the perfection and development of the technology.

4.2.2 Construction Costs

Compared to traditional energy storage technologies, the development cost of CAES technology is relatively high, resulting in a higher cost per kilowatt-hour. The primary reason for the high costs is the substantial investment required for constructing artificial air storage facilities, compressors, and expanders. These three key components correspond to three crucial systems. For projects utilizing salt caverns for air storage, the total investment in these three stages accounts for nearly 45% (Zheng et al, 2023). For projects using artificial caverns for air storage, the cost of the storage system alone exceeds 30% (Zheng et al, 2023). In terms of building the compression and expansion systems, China should strive to develop more advanced technologies to control costs. Additionally, related entities should seek ways to achieve large-scale production to reduce costs. For the air storage system, the government should encourage the development of natural storage facilities such as underground salt caverns, which not only have lower construction costs compared to artificial storage facilities but also offer larger storage capacities. Furthermore, for the research and development of all related technologies, government departments should provide financial subsidies and policy incentives.

4.2.3 Air Storage Devices

At the current stage, for CAES, air storage devices in China are commonly located underground, utilizing natural formations or artificially excavated caverns. The selection of storage sites introduces a challenge, for instance, the uncontrollable variations in geological conditions can lead to underground gas leaks, affecting construction and increasing difficulty and costs (Zheng et al, 2023). Additionally, ensuring the airtightness of the storage device itself is a core challenge. Poor airtightness can result in energy loss, increased operational costs, and reduced energy conversion efficiency. If impurity gases leak, it could also pose an explosion risk. To address these issues, relevant safety departments should first implement rigorous monitoring, inspection, and maintenance to prevent accidents. Factors affecting airtightness mainly include the cap rock, lining, and materials of the storage containers (Zhang et al, 2023). Future improvement measures should focus on these three aspects, seeking more suitable materials to enhance the airtightness of the devices and fundamentally resolve the problem.

4.3 Prospects Forecasts

CAES, with its advantages of site flexibility, environmental friendliness, short construction period, and low unit cost, is one of the most promising energy storage technologies in China, offering significant promotion value. Currently, China is in its 14th Five-Year Plan period, which explicitly aims for the transition of new energy storage technologies from commercialization to large-scale development by 2025 (Liu, 2022). Moreover, under the backdrop of the "dual carbon goals," new energy storage technologies, exemplified by CAES, are undoubtedly experiencing a golden development period. It can be predicted that in the coming years, with continuous technological advancements, improvements in system efficiency, reduction in construction costs, and national support, CAES technology is expected to become one of the mainstream large-scale energy storage technologies alongside PHES, helping to alleviate the energy storage burden.

5 CONCLUSION

In comparison to PHES, CAES has the advantages of shorter construction periods, better environmental compatibility, and more flexible site selection. It is currently the only large-scale, long-duration new energy storage technology comparable to PHES, with broad application prospects. At present, under the vigorous promotion of new energy storage technologies in China, CAES is at a critical stage of large-scale commercial development, showing a positive development trend. Although the energy storage efficiency of CAES in China has not yet reached the level of pumped hydro storage, with the continuous maturation of technology and system optimization, and the emergence of new technologies such as LAES and SC-CAES, it can be predicted that in the coming years, CAES will achieve large-scale commercialization. It will be able to compete with pumped hydro storage, becoming one of the key technologies supporting China's achievement of its "dual carbon" goals and promoting the quality of energy storage infrastructure. This article provides a comprehensive introduction to CAES technology and its development status in China, offering a valuable reference for researchers interested in further studying this technology. It is hoped that future analyses will take an international perspective to evaluate the development of this technology, offering recommendations and predictions.

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