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# Compressed Air Energy Storage (CAES) for Hongsha Hydropower: Evaluating Technologies for a Sustainable Transition

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**Abstract:**
Compressed Air Energy Storage (CAES) has attracted considerable interest in recent years due to its crucial function in integrating renewable energy and regulating power systems. Its advantages include large storage capacity, relatively low cost, and adaptability to diverse application scenarios, making it a promising solution for addressing the intermittency and volatility of renewable energy sources such as solar and wind power. As a mature and reliable energy storage technology, CAES can effectively smooth power fluctuations, support grid balancing, and provide emergency backup power. In the global context of transitioning toward a low-carbon economy and sustainable development, CAES is increasingly recognized as a critical technology to optimize power system operations, improve energy resilience, and ensure grid stability, thereby facilitating the broader adoption of clean energy. The compressed air energy storage system can significantly enhance the capacity of renewable energy consumption and alleviate the pressure of peak-to-valley difference in the power grid. In the future, its potential for large-scale application in large-scale power systems deserves continued attention and in-depth research.

**Keywords:** Compressed Air Energy Storage; Energy Efficiency; Energy Density; Energy Duration; Energy Generation Speed.

## 1. Introduction

Compressed air energy storage (CAES) is considered a critical technology in the field of energy storage. With its large capacity, low cost, and wide-ranging applications, it has attracted much attention in renewable energy and power dispatching. As a mature storage solution, CAES is vital for reducing renewable energy power fluctuations, optimizing power systems, enhancing energy resilience, and maintaining grid stability during the global drive for low-carbon and sustainable development.

As China moves towards the twin goals of ecological conservation and expansion of renewable energy, the limitations exposed by the reduction of hydropower highlight the urgent need for scalable and long-term energy storage technologies, and China's hydropower sector is facing challenges posed by multiple factors such as water scarcity, ecological conservation policies, and aging dam facilities. This paper presents a systematic assessment of the energy efficiency characteristics of isothermal, insulated, liquid piston, and gas turbine-assisted CAES systems using secondary data based on peer-reviewed literature and authoritative reports published in 2020 and beyond, comparing them in four main areas: energy efficiency, energy density, energy duration, and power generation rate. CAES, with its ability to be operated at a lower operating cost and with higher energy efficiency, has become theA solution for power conditioning and renewable energy stabilisation.According to the latest research results, the energy efficiency performance and energy density of CAES have been significantly improved, especially in isothermal CAES systems, which are theoretically able to achieve 80% energy efficiency with a response time of less than 2 minutes [1], and energy density of liquid CAES (Fig2) is as high as 720 MJ/m [2]. However, their practical deployment is still limited by the high initial investment, geographic constraints, and traditional energy infrastructure limitations. The global energy transition needs to strike a balance between decarbonisation and ecosystem protection. China's hydropower sector is a clear case in point, where the River Ecology Protection Law (2021) forces more than 40,000 small dams - including the Hongsha station in Hunan province - to operate at 60 per cent of their capacity, sacrificing 200 MWh per week (Hunan Provincial Government, 2022 )in order to protect aquatic biodiversity.The reduction in the growth of hydropower clearly demonstrates the vulnerability of relying only on variable renewable energy sources such as solar wind, a "lesson" that Europe will learn during the energy crisis of 2022.

In conclusion, while CAES is not a panacea, it is uniquely valuable as a strategic transition technology in balancing ecological costs and grid stability.In summary, although CAES cannot solve all energy storage and grid scheduling problems alone, as a strategic transition technology, it has unique value in balancing ecological costs and grid stability.With the continuous maturity of the technology and enhanced policy support, the role of CAES is anticipated to become increasingly significant in the future,energy mix and provide effective support for the green transition on a global scale.As China moves towards the twin goals of ecological conservation and expansion of renewable energy.

## 2. Methods

A literature review approach is employed in this study to systematically investigate the characteristics of various types of compressed air energy storage systems (CAES), such as the commonly used D-CAES, A-CAES, I-CAES, L-CAES, and L-P CAES,by analysing quantitative data from high-quality, peer-reviewed academic papers as well as official research reports published since 2020.and other types.The study focuses on in-depth analyses of the differences between the various types of CAES systems in terms of thermal management strategies, energy storage mechanisms, and overall operational performance.In order to ensure the accuracy and comparability of the analysis results, each performance indicator is carefully classified and compared, and the differences are clearly shown in the form of graphs and charts, which makes the information more intuitive and clear.

## 3. Results

### 3.1 Energy Efficiency

CAES (Compressed Air Energy Storage) uses compressed air as the energy storage medium and stores and releases energy through compression and expansion processes. The energy efficiency of CAES generally refers to the ratio of the effective electrical energy output to the electrical energy input during its energy storage and release processes. It reflects the degree of energy utilization in the process of converting electrical energy into the potential energy of compressed air and then converting it back into electrical energy by the CAES system. The energy efficiency of CAES is significantly influenced by the choice of thermal energy management method during the air compression process. An analysis of the thermal energy management methods in Diabatic CAES (D-CAES), Liquid CAES (L-CAES), Adiabatic CAES (A-CAES), and Isothermal CAES (I-CAES) is presented below.

Fig1 ranges from 46% to 54% [3] mainly relying on the temperature difference of the external environment to regulate the temperature of the compressed air. Through effective management of the temperature difference and heat recovery, DCAES can reduce the energy losses during the compression and expansion processes, thus improving the overall efficiency of the system. For example, the heat generated during air compression is stored in a thermal energy storage device and later used to heat the air during expansion when the energy is released.

Fig1 typically ranges from 45% to 70% [4]. This system compresses and stores air when there is a surplus of electricity, liquefying the air. Liquid air can be stored in

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specialized tanks at lower temperatures and in a smaller volume. Moreover, liquid air can be stably stored for a long time, making it suitable for applications that require long - term and continuous energy storage and regulation. It is relatively high, ranging from 72% to 80%. [5]. The I - CAES system comprehensively utilizes other power - generation technologies (such as gas turbines or heat pumps) to achieve more efficient energy management and conversion. During the compression and expansion processes, this technology achieves isothermal conditions through thermal management techniques and special equipment (such as hea exchangers, cooling systems, and thermal storage systems). Compared with traditional CAES, I - CAES reduce energy losses caused by temperature fluctuations.

The energy efficiency of the currently popular Adiabatic Compressed Air Energy Storage (A - CAES) (Fig1) ranges from 70% to 75% [5] The A - CAES system is characterized by effective thermal management, especially the heat recovery and reuse during adiabatic compression and expansion processes. It overcomes the heat loss problem during the air compression process in traditional CAES, thus improving the system's efficiency. The core innovation of A - CAES lies in the adoption of thermal energy storage technology to recover the core innovation of A - CAES lies in the adoption of thermal energy storage technology to recover the heat generated during the compression process, instead of simply dissipating it. A - CAES typically employs sensible heat storage technology, using sensible heat storage media such as water or rock salt and other materials to absorb and store heat. Thermal energy storage.Technology plays an important auxiliary role.

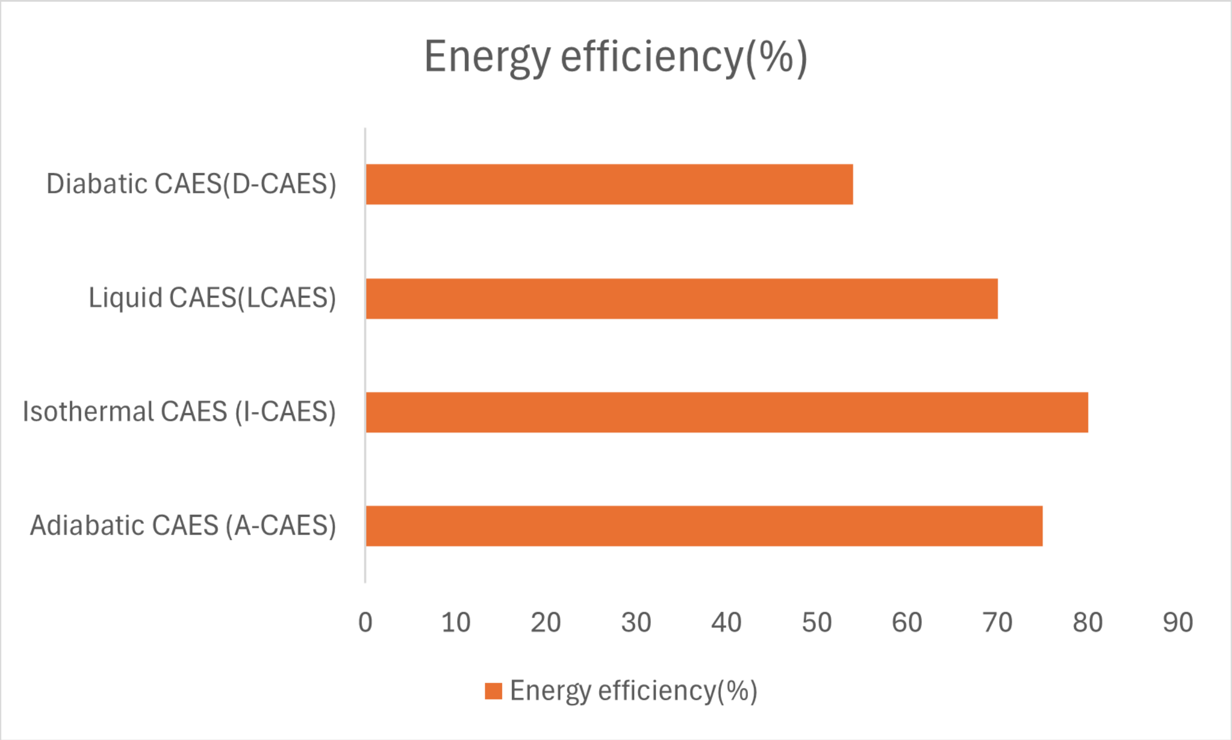


**Fig. 1 Graph of the energy efficiency of different types of CAES.**

Data from: [3,4,5]

### 3.2 Energy Density

The amount of energy stored per unit volume or mass in an energy storage system is referred to as energy density. It is a key indicator for evaluating the performance of various energy storage devices.

This section discusses the energy density of Liquid-Piston Compressed Air Energy Storage (L-CAES), Isothermal Compressed Air Energy Storage (I-CAES), and Adiabatic Compressed Air Energy Storage (A-CAES) based on temperature management, gas density, and equipment airtightness.

According to [2], L-CAESs energy density is 720.00 MJ/m³ (Fig2). This high energy density is primarily due to the characteristics of the liquid- piston mechanism and the properties of the working fluid, which optimizes the airtightness of the equipment. In L-CAES, air is compressed and stored in a liquid Form, and liquid has a significantly higher density compared to the gas. This allows more air to be stored within the same volume, making the energy density of L-CAES nearly ten times that of A-CAES.

According to Fig2, I-CAES demonstrates relatively higher energy density. The average I-CAES's energy density is 90.00 MJ/m³. This is because the isothermal process effectively manages heat transfer, minimizing energy losses during compression and expansion. The heat exchangers and thermal management systems used in I-CAES enable more efficient energy storage and extraction, this results in greater energy density than that found in other CAES systems.

A-CAES, as one of the more widely studied types of CAES, has a unique energy density distribution. According to [6], its energy density is 72 MJ/m³ (Fig2). The adiabatic process means that no heat exchange occurs with the surroundings during compression and expansion. However, compared to I-CAES, the lack of continuous thermal management during operation leads to relatively lower energy density.

In conclusion, among the three types of CAES, Liquid Compressed Air Energy Storage (L-CAES) achieves the highest energy density of 720.00 MJ/m³, followed by I-CAES at 90.00 MJ/m³. These higher values reflect the ability of these two systems to maintain or utilize stable thermal conditions during compression and expansion, thus improving energy storage efficiency. In contrast, Adiabatic Compressed Air Energy Storage (A-CAES) has a significantly lower energy density of only 72 MJ/m³. Despite its lower energy density, A-CAES remains valuable for large-scale energy storage projects due to its simpler basic design and potential cost-effectiveness.

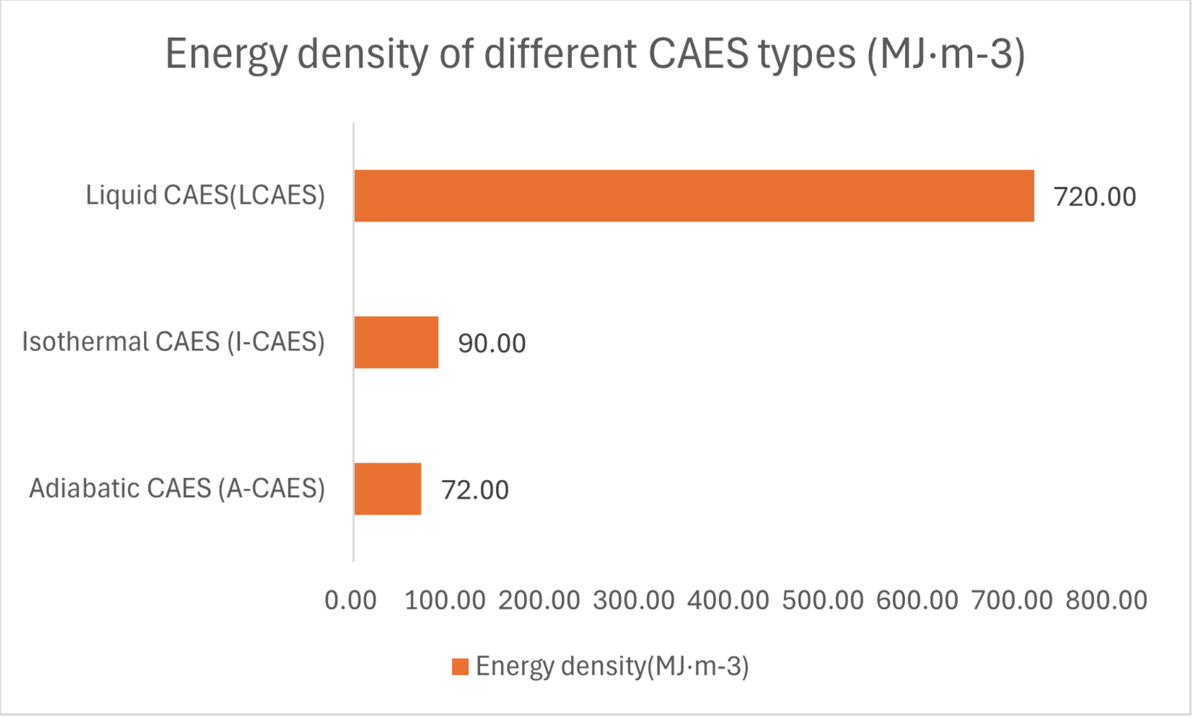


**Fig. 2 Graph of the energy density of different types of CAES.**

Data from: [2,4,6]

### 3.3 Energy Duration

The annual energy loss rate of CAES systems is only 0.5% to 1%, ensuring efficient long-term energy storage with minimal energy loss. This feature makes CAES ideal for applications that demand long-term energy storage, such as seasonal storage.

In terms of lifespan, whether it is large-scale CAES, small-scale CAES, above- ground CAES, or underground CAES systems, the expected lifespan Firanges from 20 to 40 years.[4] The consistency in the expected lifespan across.

These different types of CAES systems indicates their strong durability and reliability, supporting the feasibility of deploying CAES infrastructure for grid-scale use over multiple decades.

### 3.4 Energy Generation Speed

Energy generation speed refers to the time required for an energy storage system to begin delivering usable electricity to the grid after activation. In the context of CAES systems, generation speed is primarily determined by two key parameters: startup time and ramp-up time, Startup time is defined as the interval between receiving a dispatch signal and the initial delivery of electrical output. Ramp-up time refers to the duration required to increase the system's output from the initial level to its full rated capacity.

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As shown in Fig.3, the three CAES types differ significantly in their generation speeds. D-CAES has the longest response time, reflecting the slowest generation speed. A-CAES offers a moderate response time, while I-CAES is the fastest, capable of delivering full power within two minutes. These differences are largely attributable to the mechanical and thermal characteristics of each system.

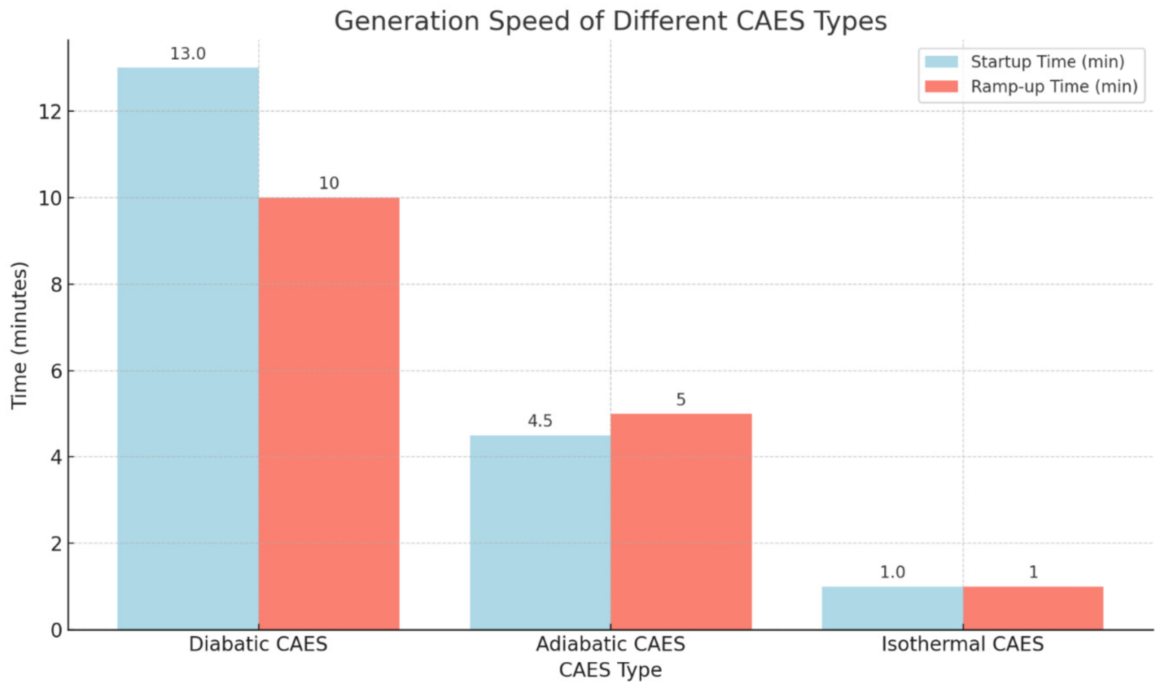


**Fig. 3 Graph of Generation Speed of Different CAES Types**

Data from: [4,5,7,8,9,10,11]

The startup time for D-CAES (Fig 3) ranges from 12 to 14 minutes [5], based on operational data from two of the world's oldest and largest commercial D- CAES plants: Huntorf and McIntosh. A mean value of 13 minutes is used in Chart 3. The ramp-up time for D-CAES systems is estimated at 10 minutes, derived from results in [7] (Fig3). Therefore, the total generation speed for D-CAES systems is approximately 22 to 24 minutes. D-CAES relies on natural gas combustion to reheat compressed air prior to expansion, introducing delays due to ignition lag, thermal stabilization, and controlled ramp-up to avoid thermal shock. These additional steps significantly slow the generation process. Furthermore, facilities like Huntorf (1978) and McIntosh (1991) their legacy control systems are not optimized for rapid ramp-up [8-10].

In comparison, the A-CAES system has a startup time of approximately 4 minutes and 30 seconds [4] and a ramp-up time of 5 minutes [11] (Fig3), resulting in a total generation speed of 9 minutes and 30 seconds. The A-CAES enhances generation speed by capturing and storing heat produced during compression, which is then reutilized during the expansion phase.

However, some time is still required for controlled heat extraction and system coordination, as the process involves separate thermal energy storage (TES) and heat exchanger units, making it slower than I-CAES.

The I-CAES system exhibits the shortest generation time, with both the startup and ramp-up phases taking approximately 1 minute each [8,9] (Fig3), yielding a total generation speed of 2 minutes. I-CAES systems maintain nearly constant temperature throughout the process, allowing compressed air to remain in optimal expansion conditions without requiring additional heating. This eliminates thermal lag and simplifies system architecture. Moreover, many I-CAES units are modular with direct coupling between tanks, compressors, and turbines, minimizing the number of subsystems that need activation. These factors enable I-CAES to achieve the fastest generation speed among the three technologies.

As shown in Chart 3, the three CAES types differ significantly in their generation speeds. D-CAES has the longest response time, reflecting the slowest generation speed. A-CAES offers a moderate response time, while I-CAES is the fastest, capable of delivering full power within two minutes. These differences are largely attributable to the mechanical and thermal characteristics of each system.

## 4. Conclusion

Each type of CAES system has its own benefits and drawbacks are evaluated based on their impact on energy efficiency, cost, scale and deployability, and the selection of the right system depends on the specific application scenario and regional resource conditions.

Compressed air energy storage (CAES), as a mechanical long-term energy storage technology, demonstrates many unique advantages in the low-carbon transition and flexible dispatch of modern power systems. Compared with electrochemical energy storage systems, it possesses significant advantages in terms of operating life, system safety, environmental impact and scalability, and is particularly suitable for large-scale and long-term energy storage applications.

Firstly, CAES is very safe.Because it operates solely on the compression and expansion of air and does not involve flammable or reactive materials, risks such as thermal runaway and chemical leakage are avoided.This makes CAES a reliable energy storage technology, especially in applications requiring high safety and low risk.Secondly, CAES has a long lifetime, with low mechanical wear and tear on its core components compared to the charge/discharge cycling limitations of electrochemical energy storage systems, with a theoretical lifetime of 30 to 50 years, which makes CAES economically and sustainably more competitive in long-term operations.In addition, CAES has good scalability and site flexibility.Natural gas storage space can be reused in places such as underground salt caverns and abandoned mines, and CAES deployment can be achieved by building artificial gas storage facilities in areas where natural storage conditions are not available.The cost of storage for CAES is about $119 per kWh, which makes it cost-effective in large-scale applications compared to other technologies.Most importantly, CAES operates with virtually no direct carbon emissions and no release of hazardous substances, making it a green and sustainable energy storage technology from an environmental perspective, especially when combined with renewable energy sources such as wind and PV to provide a completely clean energy storage pathway.

Despite its many inherent advantages, CAES faces several technical and practical challenges during large-scale deployment. First, lower energy conversion efficiency is one of its main limitations.Most conventional CAES systems have round-trip efficiencies of only 40 to 50 per cent. which is significantly lower than mainstream electrochemical energy storage technologies, limiting their potential application in energy-efficient demand environments. Secondly, the initial construction phase of CAES usually requires significant capital investment.In order to build a CAES system, high-power compression and expansion equipment, underground natural gas storage facilities, and complex thermal energy management subsystems need to be deployed, which leads to its high overall construction cost.At the same time, conventional CAES systems generate a lot of heat when compressing air, and the air cools dramatically during expansion, a temperature difference that can affect the efficiency of the system.Some advanced CAES systems use thermal management technologies (e.g., heat recovery), but these technologies are still under development and add to the complexity of the system.In addition, CAES projects have long construction cycles, typically four to six years.This delays the realisation of their economic benefits and increases the risks associated with policy and market changes. Most importantly, CAES are not suitable for small, fast-responding energy storage scenarios because of their long start-up and response times.Finally, the operational process of CAES systems involves multiple stages including compression, storage, heat recovery and expansion, which requires highly complex coordination and integration, placing higher demands on the stability and long-term operation of the system.

In conclusion, despite the high safety, long life, good scalability and environmental advantages of CAES, its lower energy conversion efficiency, higher initial investment and construction cycle remain barriers to its large-scale diffusion.With continuous technological advances, especially innovations in heat recovery and efficiency improvement, CAES still has a broad application prospect in the future, especially in supporting flexible dispatch of renewable energy and achieving low-carbon goals and in large-scale energy storage especially applicable to the storage of Renewable resources, including wind and solar energy, which has great potential. As the proportion of renewable energy sources continues to increase, Compressed air energy storage systems play a significant role in the development of new power systems is becoming increasingly important. However, there is still a need to continue to promote breakthroughs in key technologies, cost control and the expansion of application scale.

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