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CURRENT STATUS AND PROSPECTS OF ADVANCED COMPRESSED AIR ENERGY STORAGE IN CHINA

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Abstract: Under the "dual carbon" target, the intermittency and fluctuation of renewable energy generation pose challenges to grid stability, making energy storage technologies crucial for enhancing energy utilization efficiency and ensuring power system security. Among these, compressed air energy storage (CAES) has emerged as a key large-scale storage solution due to its advantages in scalability, longevity, and cost-effectiveness. This paper analyzes the fundamental principles, technological classifications, and application status of CAES in China. Studies indicate that China has successfully developed multiple hundred-megawatt-scale non-combustion CAES demonstration projects, with system efficiency reaching 65%–70%, and has achieved breakthroughs in salt cavern storage, supercritical compression, and phase-change thermal storage technologies. However, CAES in China still faces challenges such as geographical limitations, high investment costs, and an underdeveloped market mechanism. Future advancements can be driven by technological optimization, large-scale deployment, and policy incentives, ultimately establishing CAES as a core technology for renewable energy integration and grid peak shaving, thus contributing significantly to the realization of the "dual carbon" target.
Keywords: Compressed air energy storage; Energy storage technology; Current status and prospects

1 INTRODUCTION

Guided by the "dual carbon" strategic objective, renewable energy sources such as solar and wind power have been rapidly expanding, accelerating the transition toward a low-carbon energy structure in China. However, their inherent intermittency and instability pose significant challenges to the stable operation of power grids. Large-scale energy storage technologies provide an effective and economical means to mitigate curtailment of wind and solar power and facilitate peak shaving and valley filling for power grids.[1]Energy storage solutions include CAES, electrochemical storage, pumped hydro storage, and flywheel storage [2]. Among them, pumped hydro storage currently dominates due to its low cost and high efficiency. However, its application is constrained by geographical and hydrological conditions.
As a large-scale physical energy storage technology with significant development potential, CAES offers advantages such as scalability, long lifespan, and cost efficiency, making it widely applicable in smart grid peak shaving and large-scale renewable energy integration. It serves as a critical solution for addressing the mismatch between energy supply and demand. Additionally, CAES enables the storage and conversion of multiple energy forms, including cold, heat, and electricity, facilitating integration with various thermal systems, thereby enhancing operational flexibility and overall efficiency [3]. This paper introduces the fundamental principles and classifications of CAES, discusses its application in China, and examines future challenges and prospects for CAES technology development in the country.

2 WORKING PRINCIPLE OF COMPRESSED AIR ENERGY STORAGE SYSTEMS

CAES is a technology that converts electrical energy into compressed air and releases it for power generation when needed. As illustrated in Figure 1, during periods of low electricity demand or excess renewable energy generation, the system uses electrical energy to drive a compressor, compressing air to high-pressure conditions for storage in underground caverns, gas tanks, or high-pressure containers. The compression process generates substantial heat, which traditional systems typically dissipate. Advanced systems, however, incorporate thermal storage technologies to recover this heat, thereby improving overall efficiency.

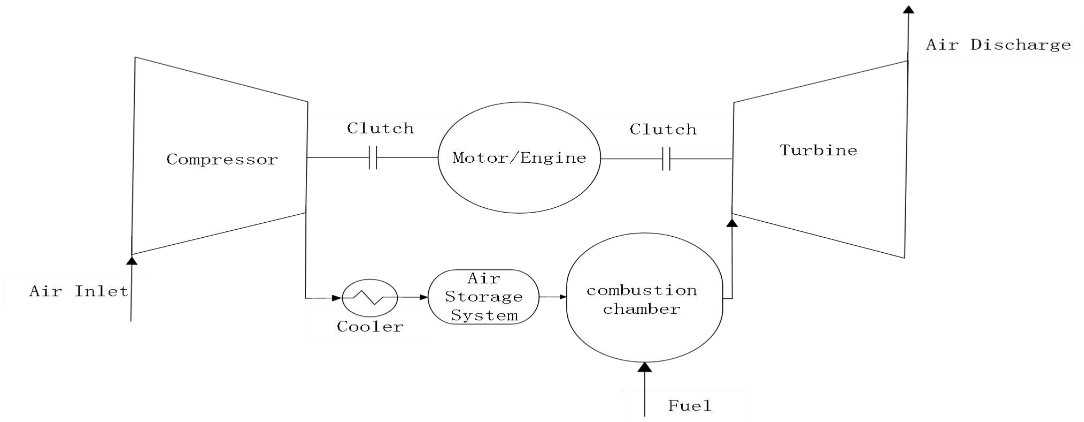

Figure 1 Schematic Diagram of Compressed Air Energy Storage

When electricity demand rises or grid peak shaving is required, the stored high-pressure air is released and expanded through turbines to drive a generator for electricity production. Traditional CAES requires preheating of the air before expansion, often achieved through natural gas combustion to enhance expansion efficiency. In contrast, advanced CAES recovers the previously stored thermal energy to provide sufficient heat for expansion, eliminating the need for additional fuel, making the system more efficient and environmentally friendly.

This process involves energy conversion and management across multiple stages, including air compression, storage, thermal management, and expansion for power generation. CAES is well-suited for large-scale, long-duration energy storage, effectively balancing grid loads, improving renewable energy utilization, and serving as an emergency backup power source. While traditional CAES systems suffer from efficiency losses due to heat dissipation, advancements in thermal energy recovery and isothermal compression have significantly improved modern CAES efficiency, positioning it as a pivotal technology in the large-scale energy storage market. The typical lifespan of CAES systems ranges from 30 to 40 years, depending on the engineering quality of the facility [4].

3 TECHNOLOGICAL CLASSIFICATION OF COMPRESSED AIR ENERGY STORAGE SYSTEMS

Since the 1940s, extensive research has been conducted on CAES technology, leading to multiple classifications based on working medium, thermodynamic processes, and system structures. The existing CAES technologies can be broadly categorized into two main branches [5]:

3.1 Classification Based on Thermal Management

3.1.1 Advanced adiabatic compressed air energy storage

AA-CAES is a closed-loop energy storage technology that achieves high-efficiency thermal energy recovery, encompassing three primary stages: compression, storage, and energy release (Figure 2). The system utilizes heat exchangers to capture the thermal energy generated during compression and later reuse it to preheat the air entering the turbine, enabling heat exchange throughout the storage and release processes. The key feature of AA-CAES lies in its adiabatic process and thermal energy reutilization.

Compared to traditional CAES, where compression heat is typically dissipated and air must be reheated via natural gas combustion during expansion, resulting in energy loss and carbon emissions, AA-CAES optimizes this process to enhance efficiency and sustainability.

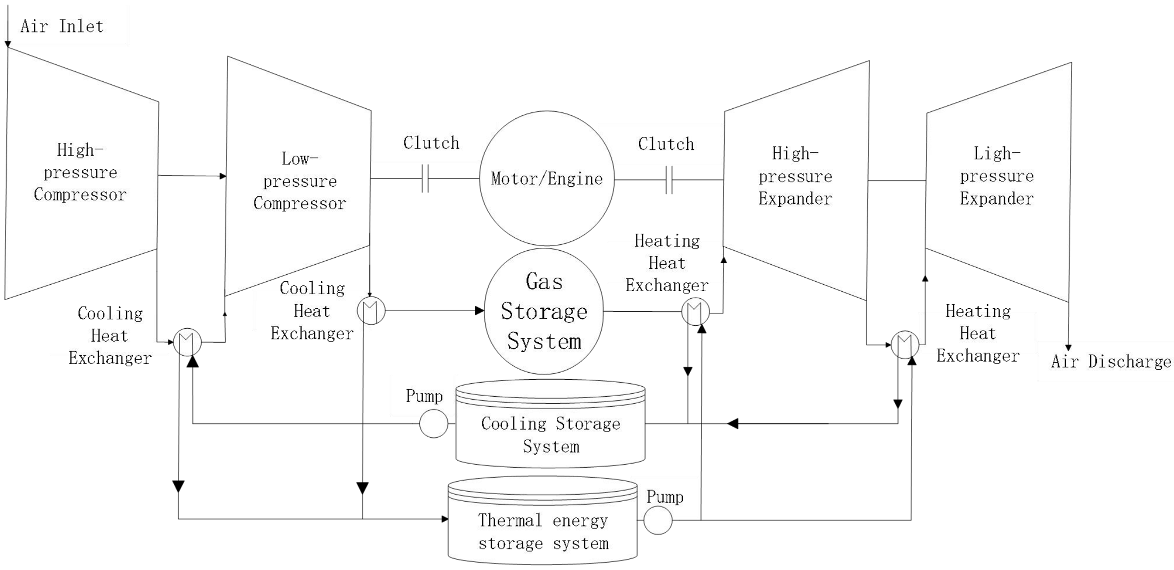

Figure 2 Schematic Diagram of Advanced Adiabatic Compressed Air Energy Storage

3.1.2 Traditional diabatic compressed air energy storage

D-CAES, also known as combustion-based CAES, is a traditional CAES technology that operates through charging and discharging processes. During charging, external electrical energy drives a compressor to compress air, which is then stored in underground caverns or high-pressure containers. The heat generated during compression may be stored or released [6]. During discharge, when power is needed, the compressed air is released, expanded through turbines to generate electricity. If thermal energy was previously stored, it can be used to preheat the air before expansion, improving power generation efficiency.

Compared to conventional gas-fired power plants, D-CAES reduces fuel consumption, making it suitable for large-scale grid peak shaving and renewable energy regulation. However, it faces challenges such as geographical constraints, efficiency limitations, and reliance on natural gas. Early CAES projects, such as Germany's Huntorf power station [7], achieved an average efficiency of only 42% due to heat dissipation losses (Figure 3). The McIntosh power station in the U.S. improved efficiency to approximately 54% by integrating gas and steam turbines in a combined cycle approach (Figure 4).

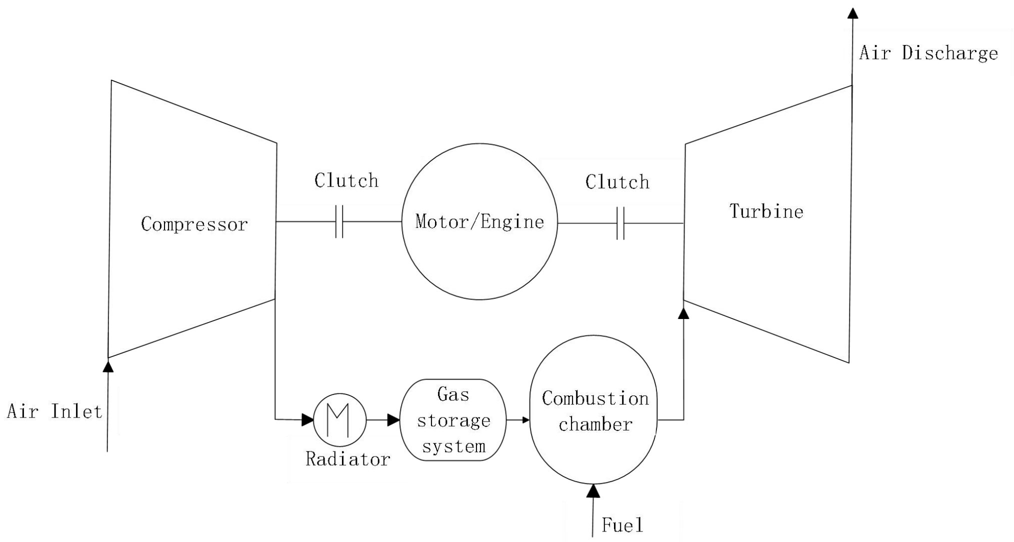

Figure 3 The Huntorf Principle of Germany

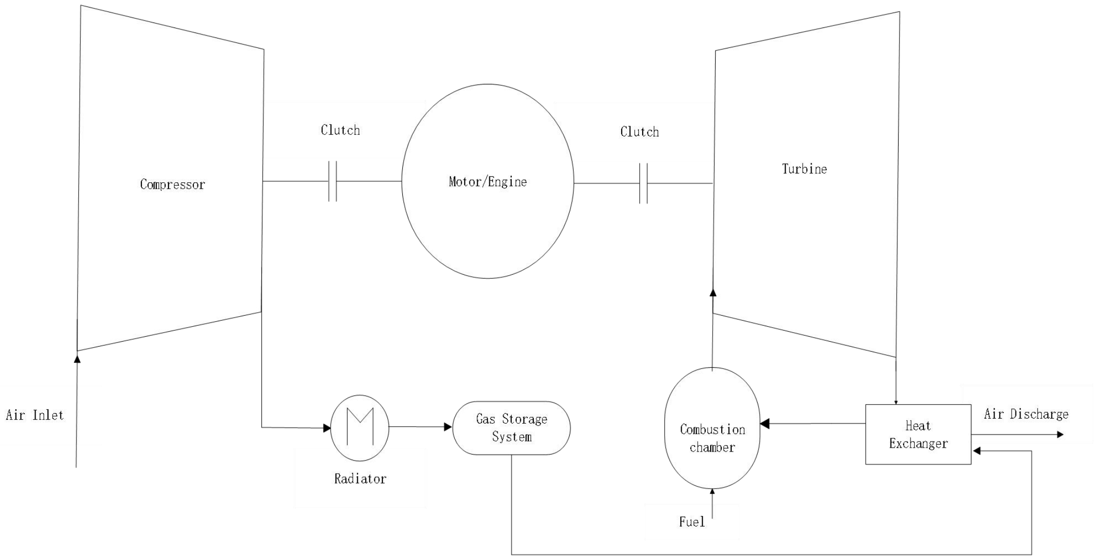

Figure 4 The McIntosh Principle of the United States

3.2 Classification Based on Medium Coupling

3.2.1 Closed-cycle Liquid-Piston Compressed Air Energy Storage

LP-CAES is an innovative CAES technology that incorporates liquid pistons (typically water or oil) in the gas compression and expansion process, enhancing energy storage efficiency while reducing environmental dependencies (Figure 5).

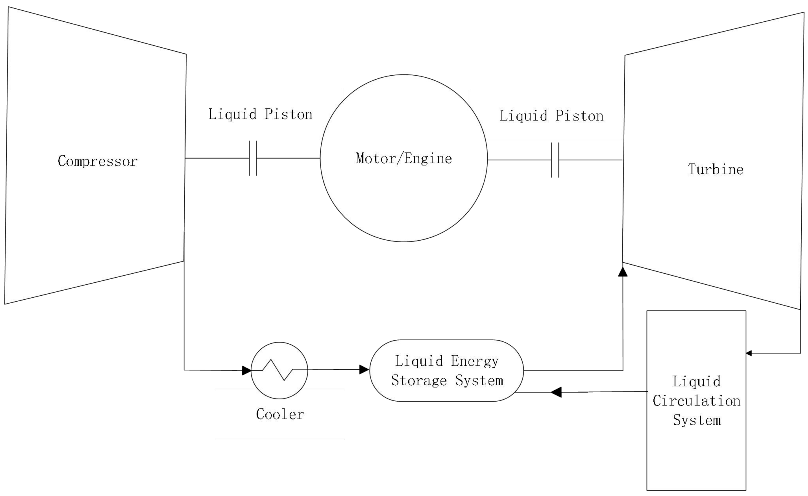

Figure 5 Closed-cycle Liquid-Gas Compressed Air Energy Storage

3.2.2 Open-cycle Liquid-Gas Compressed Air Energy Storage

OC-CAES integrates conventional CAES with liquid piston technology. The process involves air liquefaction, cryogenic storage, and expansion for power generation [8]. During charging, compressed and purified air is cooled to -196°C, transforming into liquid air for storage in insulated tanks to minimize thermal losses. During discharge, the liquid air absorbs ambient or industrial waste heat, rapidly vaporizing into high-pressure air to drive turbines, enhancing overall system efficiency (Figure 6).

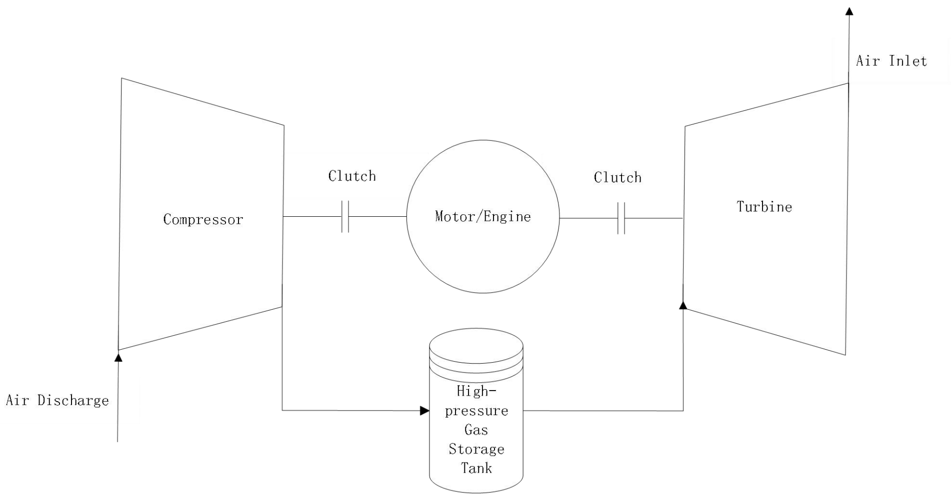

Figure 6 Open-cycle Liquid-Gas Compressed Air Energy Storage

3.3 Comparison of CAES Technologies

Different CAES technologies exhibit variations in efficiency, carbon emissions, application scenarios, and fundamental design philosophies, as shown in Table 1.

From a thermodynamic optimization perspective, AA-CAES achieves energy recycling through thermal storage devices, addressing the second law of thermodynamics by reducing entropy increase, thereby improving system efficiency. In contrast, D-CAES discards compression heat, representing a "thermodynamic compromise" that prioritizes engineering simplicity but results in lower efficiency and higher carbon emissions.

Liquid-air coupled systems introduce innovations in cross-medium energy transfer. The closed-cycle system enforces near-isothermal processes through the incompressibility of liquids, effectively controlling the polytropic exponent (n) in gas compression. The open-cycle system leverages natural geological formations as "natural pressure vessels," integrating CAES with geophysical environments. These design differences lead to distinct advantages: closed-cycle systems rely on advancements in material science and engineering, while open-cycle systems depend on geological exploration technologies.

Table 1 Technical Comparison of Compressed Air Energy Storage Technologies

Technology Type	Efficiency (%)	Carbon Emissions	Application Scenario	Core Challenge
AA-CAES	65-75	Low	Large-scale grid peak shaving	High cost of thermal storage materials
D-CAES	40-52	High	Retrofitting conventional power plants	Dependence on fossil fuels
Closed-cycle LP-CAES	60-70	Low	Distributed energy storage	Sealing and circulation stability
Open-cycle LP-CAES	55-65	Low	Geographically adaptive storage	Dependence on specific geological conditions

4 APPLICATION OF CAES TECHNOLOGY IN CHINA

In recent years, China has increasingly focused on CAES technology, with early explorations centered around demonstration projects,as shown in Table 2. The Institute of Engineering Thermophysics at the Chinese Academy of Sciences proposed a supercritical CAES system combining liquid air storage and traditional CAES in 2009, which led to the construction of a 1.5 MW pilot system in Langfang in 2013. This project validated the feasibility of a non-combustion CAES approach, marking China's transition from laboratory research to engineering verification.

Following this, several large-scale projects emerged. In 2017, the Bijie 10 MW non-combustion CAES demonstration project was commissioned, introducing salt cavern storage and achieving 60% efficiency. In 2021, the 10 MW commercial CAES power plant in Feicheng, Shandong, demonstrated economic feasibility, followed by the commissioning of the 60 MW Jintan salt cavern storage project in Jiangsu, which achieved 60% efficiency and significantly reduced gas storage costs.

By 2024, China entered a phase of large-scale CAES deployment. The Feicheng 300 MW salt cavern storage project was commissioned, boasting a 65% efficiency rate and a 100% domestically produced equipment supply chain. Concurrently, the 300 MW "Energy Storage No. 1" project in Yingcheng, Hubei, pioneered a "salt-electricity joint operation" model, enhancing local renewable energy consumption. By 2025, China's total planned CAES capacity is expected to exceed 7.5 GW, covering key regions such as Northwest and East China, marking a rapid expansion from kilowatt-scale prototypes to hundred-megawatt-scale commercial operations.

Table 2 Typical Domestic Compressed Air Energy Storage Development in Recent Years

Year	Project Name	Location	Capacity	Project Highlights
2022	Jintan Salt CavernCAES	Jiangsu Changzhou	60MW/300MWh	First non-combustion commercial project, 60% efficiency, annual coal savings of 40,000 tons
2023	Haixi CAES Project	Qinghai Haixi	200MW/800MWh	Largest non-combustion CAES, target efficiency 65–70%, supports Northwest renewable energy base
2024	Feicheng Salt Cavern CAES	Shandong Tai'an	350MW(under construction)	First 300MW-classCAES project, optimized thermal management, expected efficiency 65-70%
2025	Wulanchabu Cold-Climate CAES	Inner Mongolia	50MW/200MWh	First cold-climate CAES, -30°C operational capability, 65% efficiency
2025	Zhangjiakou Supercritical CAES	Hebei Zhangjiakou	100MW	Ground storage alternative to salt caverns,

				supercritical compression for flexible siting
2025	Yunnan Energy Investment CAES	Yunnan	TBD	Integrating with solar resources forhybrid renewable energy utilization

5 CHALLENGES AND FUTURE PROSPECTS OF CAES TECHNOLOGY

5.1 Challenges

Compressed air energy storage (CAES) is currently undergoing large-scale development and has broad application prospects as an energy storage technology. It plays a crucial role in the construction of future intelligent energy systems and in enhancing the regulation capacity of power systems. CAES is expected to provide significant support for future power grids, though there is still room for further development [9].

(1)Geographical Constraints and Gas Storage Bottlenecks

China's salt cavern resources are concentrated in Jiangsu and Shandong, limiting national deployment. Non-salt cavern regions require artificial storage or ground tanks, which are costly and technologically immature.

(2)Economic Viability

While localization has reduced equipment costs by 30%, investment costs must decrease further from ¥5000/kW to ¥2500–3500/kW through scale-up and modular design. Market incentives such as capacity pricing and auxiliary service subsidies remain inconsistent across provinces.

(3)Competition from Other Technologies

Lithium-ion batteries dominate short-duration storage, and hydrogen storage is more suitable for ultra-long-duration applications. CAES must solidify its position as the most cost-effective long-duration storage solution.

(4)Policy and Market Mechanism Gaps

Standardized safety regulations and efficiency benchmarks are lacking. Some provinces mandate energy storage integration but lack clear financial incentives, increasing investment risks.

5.2 Future Prospects

(1)Technological Advancements

Non-combustion CAES efficiency is expected to exceed 70% with advanced heat management and supercritical storage.

(2)Cost Reduction and Localization

Full localization of CAES equipment is expected to further reduce costs to ¥2500–3500/kW by 2025. Expansion in salt cavern storage could lower gas storage costs to ¥0.5/m³.

(3)Diverse Applications

Projects such as Haixi CAES will support large-scale renewable energy bases, while Zhangjiakou integrates CAES with hydrogen production.

(4)Policy and Market Expansion

Subsidies and capacity pricing mechanisms in pilot regions like Shandong and Jiangsu are expected to be nationally implemented, improving project IRR to 8–10%.

6 CONCLUSION

This study analyzes the current status and development prospects of CAES technology in China. Research findings indicate that domestic CAES technology has achieved breakthroughs in hundred-megawatt-scale projects, with system efficiency increasing to 65%–70%, localized equipment costs reduced by 30%, and salt cavern gas storage costs lowered to ¥0.5/m³, demonstrating the scalability and feasibility of non-combustion CAES technology. Compared to pumped hydro storage, CAES offers advantages in geographical adaptability, long lifespan, and multi-energy system integration, making it suitable for grid peak shaving and renewable energy consumption. However, CAES still faces challenges, including uneven distribution of salt cavern resources, high unit investment costs, and competition from lithium-ion and hydrogen storage technologies. Future advancements in supercritical compression and phase-change thermal storage materials are expected to further improve efficiency beyond 70%. Combined with policy support and expanded application scenarios, CAES is poised to become a mainstream long-duration energy storage solution. By

2025, China's total installed CAES capacity is projected to exceed 2 GW, contributing significantly to the achievement of the "dual carbon" target.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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