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Research on New Energy Storage Technology: Compressed Air Energy Storage, Forging a New Engine for Economic Growth of Manufacturing Enterprises

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Abstract: Currently, the global energy transition is accelerating, and the large-scale integration of renewable energy has brought many thorny problems to the energy and power systems. In particular, the issues of renewable energy consumption and the difficulty of regulating peak-to-valley differences in the power grid are prominent. Compressed air energy storage, as a new large-scale and long-duration physical energy storage technology, has many advantages such as large scale, long lifespan, low cost, and environmental friendliness. It can solve the problem of difficult grid connection for unstable renewable energy generation such as photovoltaic and wind power, and improve energy utilization. In recent years, the industrialization process has been accelerating, demonstrating huge potential and advantages. This article conducts research and analysis on the industrial logic, technological development, industrialization process, industry competition landscape, and market competitiveness of compressed air energy storage, aiming to provide support for optimizing business layout and structural adjustment of enterprises.

Keywords: Compressed air energy storage; Industrialization; Industry market competition

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1. Overview of new energy storage

1.1. Definition and classification of energy storage

Energy storage refers to the process of storing energy through media or equipment and releasing it when needed. Broadly speaking, energy storage can be classified into three categories: electrical energy storage, thermal energy storage, and hydrogen energy storage. Among them, electrical energy storage is currently the most dominant form of energy storage.

In electrical energy storage, it can be further classified into three categories based on different storage principles and energy conversion mechanisms: physical energy storage, electromagnetic energy storage, and electrochemical energy storage. Among them, physical energy storage is currently the most mature, lowest-cost, and largest-scale energy storage method, mainly including pumped hydro storage, compressed air energy storage, and flywheel energy storage.

1.2. Application scenarios of energy storage

Energy storage can be divided into three major application scenarios: generation side, grid side, and user side. Among them, there are many power demand scenarios on the generation side, including peak shaving and valley filling, ancillary services for the electricity market, and grid connection of renewable energy. The grid side is mainly used to alleviate grid congestion, delay the expansion and upgrading of transmission and distribution equipment, etc. The purpose is to improve grid stability, smooth network demand, reduce grid investment, and provide electricity trading and comprehensive services. User-side energy storage is mainly used for self-generation and self-consumption of electricity, peak-valley price arbitrage, capacity electricity bill management, and improvement of power supply reliability.

1.3. Current status of China’s energy and electricity

In September 2020, China made a solemn commitment to the world at the 75th United Nations General Assembly: China strives to reach peak carbon dioxide emissions by 2030 and aims to achieve carbon neutrality by 2060. In 2021, the State Council issued an action plan for peaking carbon emissions by 2030, proposing that the proportion of non-fossil energy consumption should reach about 20% by 2025 and about 25% by 2030. However, the integration of renewable energy into the power grid poses significant challenges to the stability and reliability of the existing grid operation, specifically in two aspects:

(1) Time mismatch: The peak generation times of wind and solar power do not align with peak electricity demand. Wind power output is lower during the day and higher at night, while photovoltaic power output drops sharply during cloudy or nighttime conditions.

(2) Space mismatch: The nine major clean energy bases are concentrated in the “Three Norths” regions, while areas with high electricity demand are mostly located in central and eastern China. This spatial mismatch increases the pressure on cross-regional grid regulation and significantly raises the risk to grid stability.

1.4. Comparison of various energy storage technologies

The table below outlines the mainstream technical routes for mechanical, electrochemical, chemical, and thermal energy storage. Each energy storage technology exhibits optimal performance in different application scenarios based on its output power, energy density, storage capacity, and charge-discharge time (**Table 1**).

Upon comprehensive comparison, compressed air energy storage stands out due to its long-term power and energy transfer capability, excellent stable output, environmental adaptability, and system integration ability. It offers advantages such as large scale, low cost, high reliability, strong safety, and environmental friendliness.

Table 1. The mainstream technical routes for mechanical, electrochemical, chemical, and thermal energy storage

Classification	Energy storage type	Power / capacity (MW)	Efficiency	Lifespan	Storage duration	Response time	Energy density (Wh/L)	Construction Period	Investment Cost (RMB/kW)	Advantages	Disadvantages
Mechanical energy storage	Pumped hydro	100–5,000	65–75%	Dam: 100 years, Motor equipment: 40–60 years	4–10 hours	Minute-level	0.2–2	6–8 years	4,500–7,000	Mature technology, lowest cost	Special site requirements
	Compressed air	10 - 350	40–70%	30–50 years	>4 hours	Minute-level	2–6	12-18 months	4,000–6,000	High capacity, low cost	Site restrictions (e.g., salt caverns)
	Flywheel	Up to 5	>90%	20 years	1 sec–30 min	Millisecond-level	20–80	6 months–1 year	10,000–15,000	High efficiency, rapid response	Low energy density, high cost
Electrochemical energy storage	Lithium-ion battery	Typically 10–100	85–98%	5,000+ cycles	Min–hour level	Millisec–sec	200–400	6 months	1,200–1,700	Relatively mature, highest efficiency	High cost, resource constraints, safety concerns
	Sodium-ion battery		>80%	50,000+ cycles	Hour level	Millisec–sec	150–300	6 months	900–1,200	Lower cost, abundant resources, safer	Lower cycle life and efficiency
	All-vanadium flow battery		75–85%	10,000 cycles	4 hours	Millisecond-level	15–30	3–6 months	11,000–13,000	High efficiency, long lifespan	High cost, vanadium resource constraints
	Iron-chromium flow battery		70–75%	10,000 cycles	4–12 hours	Millisecond-level	10–20	3–6 months	≈ Pumped hydro at 1GW scale*	Safe, cold-resistant, long lifespan	Low energy density
	Lead-acid battery		70–90%	2,000–4,000 cycles	Min–hour level	Millisec–sec	40–60	4–5 months	800–1,000	Relatively low price	Short deep-cycle lifespan
Chemical energy storage	Hydrogen storage	Gigawatt-scale	30–50%	10–20 years	Days–months	Minute-level	600	2 years	~13,000	High capacity, scalable, versatile applications	High cost, safety issues, low efficiency
Thermal energy storage	Molten salt storage	Hundred MW-scale	<60%	25 years	Hour level	Hour level	70–210	2 years	~5,000	Long lifespan, high safety, low material cost	Large footprint, demanding design/process controls

2. Overview of compressed air energy storage

2.1. Compressed air energy storage

Compressed air energy storage is a physical energy storage method that uses air as the storage medium. Based on completed and ongoing projects, the system efficiency (electric energy conversion efficiency) of the 10-megawatt level can reach over 60%; the design efficiency of systems above the 100-megawatt level can achieve 70%; and the efficiency of advanced compressed air energy storage systems can approach 75% [1]. With the continuous advancement of industrialization, compressed air energy storage is expected to form a complement and alternative to pumped hydro storage.

2.2. Policy driving the implementation of compressed air energy storage technology and industry

Between 2021 and 2025, the Chinese government issued a series of policies to promote the industrial development of compressed air energy storage. Policies from the National Development and Reform Commission, the National Energy Administration, the Ministry of Science and Technology, and the Ministry of Industry and Information Technology all identify air energy storage as a key development direction, promoting its standardization, scale, and commercial application [1].

In March 2022, the National Development and Reform Commission and the National Energy Administration's "14th Five-Year Plan" for New Energy Storage Development Implementation stated that "by 2025, new energy storage will transition from the early stages of commercialization to a stage of scale development, with conditions for large-scale commercial application. It aims to promote the engineering application of 100-megawatt-level compressed air energy storage technology. The key technology of 100-megawatt-level compressed air energy storage is identified as a critical research direction for new energy storage core technology equipment during the 14th Five-Year Plan."

3. Compressed air energy storage industry chain and market prospects

3.1. Industry chain overview

The upstream of the compressed air energy storage industry chain consists of equipment and resources, mainly comprised of six main components of the compressed air energy storage system: air compressors, turboexpanders, thermal storage and heat exchange systems, air storage tanks, electric motors/generators, control systems, and auxiliary equipment [2]. Among them, air compressors, turboexpanders, and heat exchangers are the core equipment of the compressed air energy storage industry, accounting for 20%, 20%, and 12% of the cost, respectively. The midstream primarily includes technology providers and project builders, while the downstream directly connects with power generation, grid, and user sectors. The industrialization development mainly relies on upstream equipment updates and midstream technology iterations.

3.2. Upstream: Equipment manufacturing

3.2.1. Centrifugal compressors

Compressed air is generated through compression, converting electrical energy into the internal energy of high-temperature and high-pressure air, enabling electrical energy input. Centrifugal compressors determine the efficiency of compressed air energy storage systems and have high technical barriers.

In the domestic compressor market, downstream owners choose to purchase from Shaanxi Blower Power, Shenyang Blower Group, or import for small and medium-sized projects. Medium to large projects are sourced from Shaanxi Blower Power or imported, while very large projects are dominated by Siemens. Shaanxi Blower Power holds an 82% market share in localized air separation compressors.

3.2.2. Turbine expanders

Turbine expanders are critical components for power generation, converting the internal energy of high-temperature and high-pressure air into electrical energy through air expansion, enabling electrical energy regeneration.

Currently, international leaders such as Atlas and Mitsubishi Heavy Industries dominate, especially in very large turbine expansion equipment. Domestic manufacturers, including Jintongling, Kaishan, Hangyang, and Sichuan Air Separation Group, compete with foreign players for market share in large and smaller equipment.

3.3. Midstream: Technology provision and project construction

This segment includes technical support, design and development, system integration, and construction operations. Key technology providers are the Institute of Engineering Thermophysics of the Chinese Academy of Sciences (CAS) through its subsidiary, and universities like Tsinghua. Project construction involves companies like China Energy Engineering Group and Power Construction Corporation of China. Currently, China leads globally in compressed air energy storage technology and project development.

3.4. Downstream: Investment operators and end users

This segment connects with power generation, grid, and user sides, playing a pivotal role in peak shaving, valley filling, frequency regulation, phase modulation, energy storage, and emergency backup.

4. Compressed air energy storage technology analysis

4.1. Technological development timeline

Compressed air energy storage technology originated in the 1950s [3], primarily in Europe and the US. Chinese universities and research institutes began exploring this technology after 2000, evolving from initial stages to a global leading position within 10–20 years. Based on traditional methods, various new air energy storage techniques have been developed, including Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), Supercritical Compressed Air Energy Storage (SC-CAES), Liquid Air Energy Storage (LAES), Wind and Solar-Driven Liquid Air Energy Storage (WS-LAES), and Thermal Storage Compressed Air Energy Storage (TS-CAES).

4.2. Factors influencing technological development

The progress of compressed air energy storage technology is influenced by multiple factors:

Technological innovation and maturity: Improving system efficiency, reducing or eliminating combustion equipment to prevent energy consumption and fuel waste, and technical maturity of liquid air storage, which affects the industry chain and investment costs.

Policies and market promotion: Large-scale energy enterprises and research institutions are in the technical iteration and trial operation phases. The transition to commercialization relies on government policies supporting renewable energy and energy storage technologies, such as subsidies, tax incentives, and market access. The proportion of renewable energy in the power grid also affects market demand for compressed air energy storage.

Environmental and resource considerations: Traditional compressed air energy storage relies on fossil fuel combustion, unsuitable for China's resource constraints. The need for special geographical conditions for large-scale air storage facilities, like high-airtightness caves, salt caves, and abandoned mines, influences the site selection of energy storage power stations. However, this can also facilitate resource utilization and generate revenue from salt caves and abandoned mines.

4.3. Future technology development trends

With the increasing global demand for energy transformation and low-carbon development, as well as continuous technological advancements and gradual cost reductions, compressed air energy storage (CAES) technology is poised to embrace a broader development prospect. Firstly, the efficiency and stability of CAES technology will be significantly improved through continuous technological advancements. Secondly, the enhancement of technological maturity will directly drive down production costs, and large-scale production will further reduce unit costs, making CAES technology more economically competitive. Thirdly, there will be coordinated development across the upstream and downstream industries of the CAES industry chain.

5. Industrialization process of compressed air energy storage

5.1. Equipment manufacturing

Upstream equipment for compressed air energy storage, such as air compressors, turbine expanders, electric motors, and generators, has relatively mature product supply lines and enterprises. As key equipment in new energy storage systems, the performance of compressors and expanders restricts the energy conversion efficiency of the entire system.

Currently, there is still a certain gap between the technological level of turbine expanders used in high-end fields in China compared to the international advanced level, especially in terms of research and development (R&D) and production capacity. Therefore, domestic enterprises are gradually increasing R&D investments in manufacturing processes and material performance for key turbine components, aiming to narrow the quality and performance gap in equipment usage.

5.2. Representative enterprises for important equipment

With the rapid expansion of compressed air energy storage projects, many domestic manufacturers of air separation equipment have begun to plan their layouts. Among them, Shaanxi Blower Power has signed a strategic cooperation agreement with China Energy Construction Digital Technology Group to jointly develop compressed air energy storage projects; Dongfang Electric, Shanghai Electric, Harbin Electric, and Shenyang Blower Works Group have provided equipment support as suppliers for the 60MW project in Jintan, Jiangsu Province; Jintongling has cooperated with China National Energy Storage to provide equipment for projects in Bijie, Guizhou, and Feicheng, Shandong; and Hangyang Co., Ltd. has provided core equipment for the 500kW liquid air energy storage demonstration project at Tongli Integrated Energy Service Center.

6. Market prospects and investment opportunities

6.1. Market prospects

The rapidly expanding scale of compressed air energy storage (CAES) power stations is expected to drive growth in the upstream segments of the industry chain. Core equipment such as air compressors and turbine expanders may become key factors in this growth.

Based on the predicted cumulative installed capacity of new energy storage technologies in 2028 and 2030 from the "White Paper on Energy Storage Industry Research 2024" released by the China Energy Storage Alliance (CNESA), we assume that the penetration rate of cumulative installed capacity for CAES will increase to 10% and 12% in 2028 and 2030, respectively. Under these assumptions, our calculations show conservative and optimistic estimates for cumulative CAES installed capacity of 16.9GW and 22.1GW in 2028, and 26.5GW and 37.7GW in 2030, representing a tens-of-fold increase compared to 2024 [4,5].

6.2. Investment opportunities

Currently, most leading domestic upstream equipment manufacturers and system integrators are listed on the A-share or Hong Kong stock markets. Leveraging their existing foundations in air separation unit production, these companies are actively positioning themselves in the air energy storage field and expanding their footprints from equipment manufacturing to integrated midstream and downstream operations.

As commercialization gradually takes off, we believe that investors should focus on tracking new processes and materials related to upstream equipment, as well as developments and breakthroughs in domestic substitution and large-scale application of core equipment. Additionally, close attention should be paid to the impact of relevant supportive policies on downstream power station investment and operation.

6.2.1. Key equipment components and technologies

At the current stage, CAES power stations face scenarios such as frequent start-stops and varying operating conditions. This requires further optimization of compressors to enable high-load operation across a wide range of operating conditions and adjust pressure and exhaust parameters under varying conditions. Turbine expanders need to operate efficiently and safely under a wide range of loads and adapt to large fluctuations in pressure and flow rate. Heat exchangers require further optimization in terms of materials, flow channel structures, and process parameters to enhance their heat transfer efficiency.

Therefore, we can focus on the key directions for technological iteration and efficiency improvement of the three major equipment (compressors, expanders, and heat exchangers): investment opportunities in high-temperature compressors, wide-load expanders, and high-efficiency heat exchangers. At the same time, considering that equipment suppliers are basically in a situation of monopoly by listed leading companies, and there are high capital and technical barriers, it is difficult for new entrants to enter. We can also explore upstream core components and technological layout opportunities.

6.2.2. Power station investment and operation

The construction period of compressed air energy storage power stations is relatively short, with a service life of 30–50 years and a payback period of about 10 years. After scaling up, long-term returns can be sought; however, it should be noted that the country has not yet issued clear policies and implementation details for the two-part tariff for other long-duration energy storage technologies. Referring to pumped hydro storage, policy implementation may require a considerable amount of time.

6.2.3. System integration

The main focus of midstream technology provision and implementation includes overall system design, heat exchange systems, control systems, and engineering implementation. Currently, major system integration teams include Professor Mei Shengwei from Tsinghua University and Professor Chen Haisheng from the Institute of Engineering Thermophysics, Chinese Academy of Sciences (IEST, CAS) (China Storage Energy). Team background, technology and research and development strength, and industrialization experience are key considerations.

7. Conclusion and outlook

Although compressed air energy storage technology still faces many challenges in practical application and commercialization, with continuous technological progress and policy support, it is expected to be more widely used globally. Future development trends include improved technical efficiency, cost reduction, and increased market acceptance. Simultaneously, compressed air energy storage technology will complement other energy storage technologies, jointly promoting the development of the energy storage field. Compressed air energy storage technology provides new development opportunities for manufacturing enterprises to optimize their business layouts and structural adjustments, taking into full consideration factors such as technology, cost, environment, market, and policy, in order to create a new engine for economic growth.

Disclosure statement

The author declares no conflict of interest.

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