The Principle, Status and Development of Compressed Air Energy Storage Technology

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Abstract: Compressed Air Energy Storage (CAES) is an emerging energy storage technology with significant potential for addressing the intermittency and volatility of renewable energy sources. CAES systems work by storing electricity when it's not in high demand, and using it to compress air. This compressed air is then kept underground or in containers above ground. When there's a spike in demand for electricity, the stored compressed air is released to power a generator, helping to balance out the supply and demand. CAES has several advantages, including large storage capacity, low operational costs, and long lifespan, making it highly suitable for energy balancing and peak shaving in large-scale power systems. Moreover, a good and efficient way is that CAES systems, when they're hooked up with renewable energy sources, can stash extra energy when there's a lot being made and then let it out when production slows down. This paper aims to provide a comprehensive understanding of CAES by exploring its types, principles, and technologies. It will delve into various CAES configurations, including traditional isothermal CAES and more advanced adiabatic CAES, which improves efficiency by capturing and reusing the heat. The paper will also analyze the environmental impacts of CAES, addressing concerns such as potential impacts on local ecosystems and the carbon footprint associated with different CAES technologies. Furthermore, it will propose feasible solutions to mitigate these impacts and enhance the sustainability of CAES systems. By offering an in-depth analysis and a forward-looking perspective, this paper seeks to inform and engage readers on the future development and applications of CAES, emphasizing its contribution to building a more resilient and sustainable energy infrastructure.

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1 INTRODUCTION

CAES is an emerging energy storage technology with significant potential to address the intermittency and volatility of renewable energy sources. CAES systems work by using electricity during periods of low demand to compress air which is then stored and released to drive a generator and produce electricity during periods of high demand. Compared to traditional battery storage, CAES offers advantages such as large capacity, low cost, and long lifespan, making it particularly suitable for energy balancing and peak shaving in large-scale power systems (Budt et al, 2016). Currently, several CAES projects worldwide have been put into commercial operation or are under construction and planning stages. For instance, China's Jiangsu Jintan and Zhangbei demonstration projects have successfully connected to the grid, showcasing the feasibility and benefits of CAES in practical applications. Additionally, the development of new storage technologies, such as salt cavern storage, artificial cavern storage, and abandoned mine storage, provides more flexible and efficient solutions for CAES. In the future, with continuous technological advancements and growing market demand, CAES is expected to play an increasingly important role in the global energy structure, providing a solid foundation for achieving sustainable energy development goals. The aim of this paper is to help people easily understand the types, principles, and technologies of CAES. It aims to analyze the environmental issues associated with CAES, propose feasible solutions, and provide an outlook on the equipment, technology, and application scenarios of CAES.

2 OVERVIEW OF CAES

2.1 Development Process and Classification

The history of CAES technology can be traced back to the late 19th century, but it was not until the 1970s

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that this technology began to be developed for electrical energy storage applications. The first stage of development occurred at the end of the 19th century. At that time, compressed air was used as the power source with the aim of driving mechanical equipment. In the 1900s, some industrial applications began using compressed air, for example, in mining and railway systems. The second stage marked the beginning of modern CAES systems. In the 1970s, with the emergence of the energy crisis, people began to seek various energy storage solutions. In 1978, the world's first commercial CAES project commenced operations in Huntorf, Germany. This facility utilized surplus electricity during low demand periods to compress air, and the compressed air was then released during peak demand periods to generate electricity through turbines. In the 1980s, the McIntosh power plant in Alabama, USA, became the second facility to implement CAES technology, demonstrating its potential in electricity grid peak shaving. The third stage involves technological progress and changes. From the 1990s to the 2000s, advancements in technology enabled more efficient management of thermal energy and pressure in CAES systems, enhancing system efficiency. Researchers began exploring more efficient compressed air energy storage technologies such as Advanced Adiabatic Compressed Air Energy Storage (AA-CAES). From the late 2000s to the present, with the rapid development of renewable energy, CAES technology has been recognized as an effective solution for storing renewable energy, especially for intermittent sources like wind and solar power (Chen et al, 2016). The underground salt cavern systems in CAES technology have incorporated many innovative elements, abandoned mines, or natural gas fields as storage sites, and developing systems that reduce or eliminate dependence on burning natural gas. CAES technology can be classified based on scale as shown in figure 1.

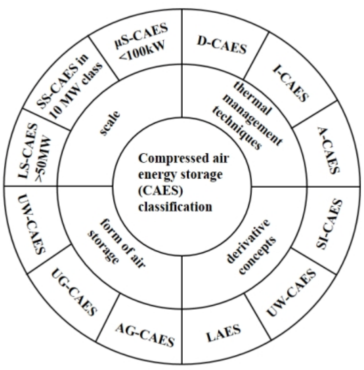

Figure 1. Classification of CAES (Picture credit: Original)

2.2 Working Principles of CAES

The storage and release of energy are the two stages of the working principle of CAES. The energy storage stage is further divided into three steps. First step is air compression when there is excess electricity in the grid, this electrical energy is used to drive compressors, compressing the air into a high-pressure state. Second step is heating management. The generated heat is released into the environment, which is a result of the compression process in traditional CAES systems. While in advanced CAES systems, this heat is captured through efficient heat exchangers and stored in specialized thermal energy storage devices such as high-efficiency insulated thermal storage systems, typically using solid or liquid heat media. The third step is storing the compressed high-pressure air underground, in storage tanks, or other containers. When electricity is needed, the high-pressure air in the storage devices is released. In traditional systems, the compressed air must be preheated by burning natural gas or other fuels to ensure it has enough heat during expansion. However, in advanced systems, the high-pressure air is heated by stored heat through heat exchangers, restoring its expansion energy. Then comes power generation - electricity is produced by a generator driven by an expander or turbine powered by the preheated high-pressure air. Finally, after passing through the turbine, the air's pressure and temperature decrease and it is released into the atmosphere.

2.3 Pros and Cons of CAES

2.3.1 D-CAES

When air is compressed, the temperature rises significantly, but this heat is usually not retained and is directly released into the air. Before releasing the compressed air, it is necessary to reheat it by burning natural gas and other fuels. This makes sure that the air has enough energy when it expands again. The advantages of D-CAES include two points. First, it is easy to install and control. Second, when the air reservoir is empty, it can operate as a gas turbine (Nojavan et al, 2018, Shafiee et al, 2016). The disadvantages of D-CAES include two points. First, during the charging process, energy is lost in the form of heat, resulting in significant energy waste. Second, during the discharging process, it preheats the air before expansion by burning fossil fuels, leading to considerable environmental issues.

2.3.2 I-CAES

In a perfect isentropic compression and expansion process, the heat produced during compression gets stored using a heat exchanger to cut down on energy loss. When it comes to the ideal isentropic expansion process, the previously stored heat is reclaimed and used again for the expansion process, which boosts the system's efficiency. I-CAES has its perks. First off, it really maximizes heat transfer during compression or expansion and keeps heat loss at bay thanks to some nifty heat exchange (Ren et al, 2019). Plus, when it comes to storing compressed air energy, it brings together great economic performance and high efficiency (Olabi et al, 2021, Patil et al, 2020). But there are downsides too. For one thing, in the whole heat exchange dealer, its compression and expansion take their sweet time to make sure everything's just right. And when it comes to getting that near-isothermal compression happening, its compressors stick with tradition and have low heat transfer characteristics (Patil et al, 2020).

2.3.3 A-CAES Without TES

The super squished high-pressure air gets shoved into underground storage tanks or other high-pressure containers. Meanwhile, the heat made during the squishing process gets stored in a thermal energy storage gadget. When it's time to let out some energy, the high-pressure air is set free from its storage spot, warmed up through a heat exchanger, and then used to spin a turbine and make electricity. After passing through the turbine, the air's pressure and temperature are reduced, and the air is then released into the atmosphere. The advantages of A-CAES include two points. First, during its expansion process, the air no longer needs reheating, reducing energy consumption. Second, its overall application significantly reduces thermal energy loss (Dooner & Wang, 2020). The disadvantages of A-CAES include two points. First, because of material challenges in air tanks, more expensive storage vessels are needed to store high-temperature compressed air (Dooner & Wang, 2020). Second, due to compression technology challenges, air cannot be compressed to high pressure without cooling, reducing its energy storage potential (Dooner & Wang, 2020).

2.3.4 AA-CAES with TES

During the compression process, the air temperature significantly increases. The heat is stored in thermal energy storage devices (such as high-efficiency insulated thermal storage systems, typically using solid or liquid heat media). The advantages of AA-CAES include two points. First, it has eliminated the need for fuel, making its application environmentally friendly. Second, it achieves the same power generation using a smaller tank, thereby increasing roundtrip efficiency (Dooner & Wang, 2020). The disadvantages of AA-CAES include two points. First, during adiabatic compression, its power consumption increases due to high temperature rise (Chen et al, 2020). Second, in some specific cases, it requires support from high-temperature thermal energy storage technology (Chen et al, 2020).

3 ENVIRONMENTAL ISSUES AND SOLUTIONS OF CAES

3.1 Environmental Issues

CAES technology, while beneficial for regulating power grids and storing energy, also poses several environmental challenges. Firstly, traditional CAES systems usually require the burning of natural gas to heat the air during energy release, which emits carbon dioxide and other greenhouse gases, impacting the environment. Secondly, storing compressed air underground can affect the stability of geological structures, posing potential risks of ground subsidence and potentially impacting the safety and stability of groundwater systems. Additionally, the compressors and turbines in CAES facilities can generate significant noise pollution during operation, disturbing the living environment of nearby residents.

3.2 Solutions

To address the environmental issues associated with CAES technology, several improvements can be implemented. Firstly, advanced energy storage technologies should be adopted. For example, AA-CAES technology stores the heat and reuses it. Thus, it not only reduces dependence on external fuels but also lowers associated greenhouse gas emissions. This system enhances energy conversion efficiency and environmental friendliness through improved thermal management. Secondly, geological assessments and site selection must be improved. During the planning and construction stages of CAES systems, comprehensive geological assessments should be conducted to select sites with stable geological structures and minimal impact on groundwater. Additionally, advanced monitoring technologies can be used to continuously monitor the geodynamics of the underground storage areas, ensuring operational safety and environmental stability. Thirdly, noise control measures should be implemented. Modern soundproofing materials and technologies, such as sound barriers and anti-seismic foundations, should be used in the design and construction of CAES facilities to reduce noise generated during operation. Facilities should also be located as far away as possible from residential and sensitive areas to minimize disturbances to the surrounding environment (Rabi et al, 2023).

Fourthly, environmentally friendly operational strategies should be implemented. Environmental management strategies should be developed and implemented, including demand response, to optimize equipment operating times and loads, reducing energy waste. Furthermore, integrating with renewable energy projects can enhance the sustainability and overall energy efficiency of the system.

Through these measures, not only can the environmental issues faced by CAES technology be resolved, but its application efficiency and sustainability in modern energy systems can also be enhanced, making it a more environmentally friendly and economically viable energy storage solution.

4 DEVELOPMENT STATUS AND APPLICATIONS OF CAES

4.1 Development Status

Currently, the commercially operating CAES projects include the Huntorf plant in Germany, the McIntosh plant in the United States, and the Jiangsu Jintan National Demonstration Project in China, with installed capacities of 290MW×4h, 110MW×26h, and 60MW×5h, respectively. All these three projects utilize salt cavern air storage. The Zhangbei Demonstration Project of the Chinese Academy of Sciences, with an installed capacity of 100MW×4h, uses pipeline steel and artificial cavern air storage and is currently in grid-connected power generation status. The power stations under construction include the Silver City project in Australia, the Bethel project in the United States, and the Carrington project in the United Kingdom, with capacities of 200 MW×8 h, 317 MW, and 50 MW×6 h, respectively. These projects use advanced adiabatic technology with abandoned mine air storage, advanced adiabatic technology with salt cavern air storage, and liquid air technology with liquid tank storage, respectively. Regarding CAES projects in China, there are the following: The Three Gorges Group Ulanqab Demonstration Project with a capacity of 10MW×4h using pipeline steel air storage. The State Power Investment Corporation Hunan Hengyang Project with a capacity of 100MW×4h using salt cavern air storage. The China Green Development Investment Group Golmud Project with a capacity of 60MW×10h using liquid tank air storage.The China Energy Engineering Group Gansu Jiuquan Project with a capacity of 300MW×6h using artificial cavern air storage. Projects in the feasibility study stage include: The Three Gorges Group Hubei Macheng Project with a capacity of 100MW×4h using artificial cavern air storage.The China Energy Engineering Group Shandong Tai'an Project with a capacity of 350MW×4h using salt cavern air storage.The Three Gorges Group Qinghai Xitieshan Project with a capacity of 50MW×4h using abandoned mine air storage. The Sinopec Shengli Oilfield Project with a capacity of 100MW×4h using oil and gas reservoir air storage. The CAES Projects in China can be seen in table 1 and figure 2.

Table 1. Capacity, Storage Type, and Stage of CAES Projects in China

No.	Project	Capacity (MW×h)	Storage Type	Stage
1	Three Gorges Group Ulanqab Demonstration Project	10MWx4h	Pipeline steel air storage	Demonstration
2	State Power Investment Corporation Hunan Hengyang Project	100MWx4h	Salt cavern air storage	Operational
3	China Green Development Investment Group Golmud Project	60MWx10h	Liquid tank air storage	Operational
4	China Energy Engineering Group Gansu Jiuquan Project	300MWx6h	Artificial cavern air storage	Operational
5	Three Gorges Group Hubei Macheng Project	100MWx4h	Artificial cavern air storage	Planning
6	China Energy Engineering Group Shandong Tai'an Project	350MWx4h	Salt cavern air storage	Planning
7	Three Gorges Group Qinghai Xitieshan Project	50MWx4h	Abandoned mine air storage	Planning
8	Sinopec Shengli Oilfield Project	100MWx4h	Oil and gas reservoir air storage	Planning

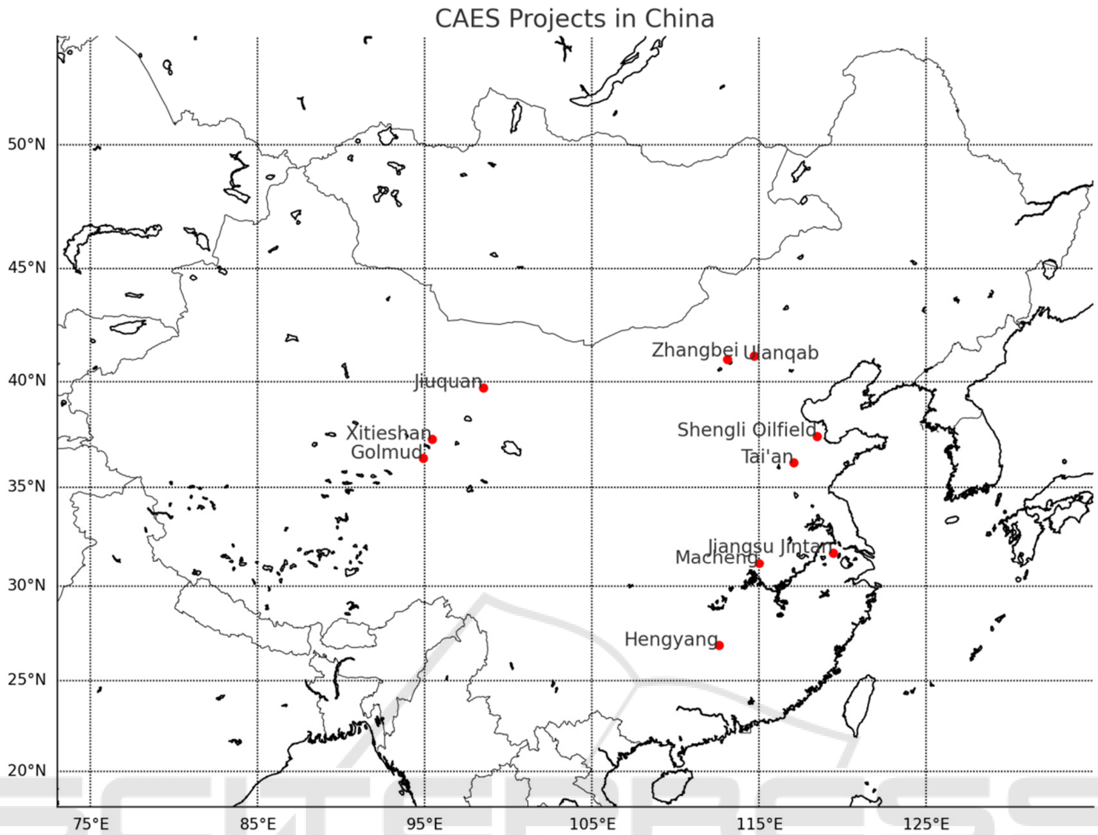

Figure 2. CAES Projects in China (Picture credit: Original)

4.2 Application Scenarios

The CAES system has broad application prospects in the future. First of all, CAES can really help balance out the power supply and demand, do some peak shaving and valley filling, and make the grid more stable. Secondly, it can quickly respond to changes in power demand, serving as a load balancing device with a much faster start-up time compared to traditional power plants. Additionally, in regions with time-of-use pricing, CAES can help users reduce electricity costs. It can also integrate with renewable energy sources such as wind and solar power, enhancing the utilization and reliability of renewable energy (Wang et al, 2017). Finally, CAES systems can serve as backup power sources, ensuring continuous and stable power supply during emergencies or equipment maintenance.

5 OUTLOOK FOR CAES

The installed capacity of CAES has shown a trend of scaling up from kW to MW and even to hundreds of MW, indicating its broad application prospects as an energy storage technology. It is bound to provide certain support to future power grids (Zuogang et al, 2020). Nevertheless, there is still potential for further development, particularly evident in the following areas.

Firstly, CAES plants experience frequent start-ups and shutdowns and variable operating conditions, requiring further optimization of compressors to achieve high-load operation across a wide range of conditions and to adjust pressure and exhaust parameters under variable conditions. Turbine expanders need to operate efficiently under wide-load conditions to adapt to large pressure and flow fluctuations, ensuring safe and efficient operation. Heat exchangers need further optimization in terms of materials, flow channel structure, and process parameters to improve heat transfer efficiency.

Secondly, experts should seek more environmentally friendly external heat sources to replace the fossil fuels traditionally used in supplementary combustion CAES. Technicians need to develop high-performance, low-cost heat transfer media, such as low-melting-point mixed molten salts, to raise the storage temperature of compressor heat and enhance system heat transfer efficiency. As CAES moves toward larger scales, increasing the size of single units can effectively reduce investment costs and improve system efficiency. Gas storage facilities need to make full use of existing salt cavern resources and strengthen research on artificial cavern gas storage facilities to adapt to areas with scarce salt cavern resources.

Finally, as a long-duration energy storage technology, CAES has characteristics such as rapid start-up and shutdown, long cycle life, and strong load adaptability. It has broad applications in peak shaving and valley filling, renewable energy integration, frequency regulation, peak regulation, reactive power regulation, spinning reserve, emergency power supply, and black start. Additionally, as a system capable of storing heat, electricity, and gas, CAES features combined cooling, heating, and power supply, making it well-suited for integration with comprehensive energy systems to leverage its advantages and achieve tri-generation of cooling, heating, and power within comprehensive energy systems.

6 CONCLUSION

The development of CAES technology has progressed significantly, from its initial stages in the late 19th century to its current applications in large-scale energy storage projects. Various CAES projects around the world and in China have demonstrated its feasibility and benefits. Despite the environmental challenges associated with traditional CAES systems, such as greenhouse gas emissions and geological impacts, advanced technologies and improved site selection can mitigate these issues. CAES technology is gonna be a big deal in the global energy game, especially when it comes to bringing together renewable energy sources and making sure we've got a steady power supply. Future advancements in CAES will focus on optimizing system components, developing environmentally friendly heat sources, and enhancing system efficiency, positioning CAES as a key technology for sustainable energy development.

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