Review of Compressed Gas Energy Storage Technology Research

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Abstract: Against the backdrop of the rapid development of global renewable energy, the insufficiency of grid peak shaving capacity and the problem of new energy consumption have become increasingly prominent, large-scale energy storage technologies urgently require advancement. This article introduces the research progress of domestic compressed air energy storage technology, analyzes its technical principles, key challenges, and future development directions, and provides references for technology research and development and engineering applications in related fields. Firstly, the fundamental principles of compressed gas energy storage technology are explained, including typical technical routes of compressed air energy storage (CAES), as well as the system types of compressed carbon dioxide energy storage (CCES). Secondly, the latest research progress is summarized from the dimensions of key technologies, system coupling integration, and application scope expansion. Finally, based on the technical bottlenecks and application requirements, the current challenges and future development directions are analyzed. The results show: the CAES technology has established a complete system ranging from component optimization to multi-energy coupling, and has made significant progress in aspects such as gas storage chamber sealing, equipment dynamic control, and system efficiency improvement. CCES technology achieves performance breakthroughs through innovative working fluids, system configuration optimization, and multi-energy coupling. However, both of them face challenges such as improving the reliability of key equipment, dynamic matching of system integration, and reducing initial investment costs. In the future, through interdisciplinary cross-innovation to break through technical bottlenecks, it is necessary to promote large-scale and commercial applications of pressurized gas energy storage technologies, providing core energy storage support for the new power system.

Keywords: Compressed Air; Compressed Carbon Dioxide; Energy Storage; Renewable Energy; Power System

1. Introduction

In recent years, the global deployment of renewable energy has reached an unprecedented pace. According to the “Renewable Capacity Statistics 2026” released by the International Renewable Energy Agency (IRENA), the global installed renewable energy capacity reached 5,149 GW by the end of 2025, with a record annual increase of 692 GW, representing a year-on-year growth of 15.5%. Among the newly installed capacity, wind and solar power accounted for 96.8%, highlighting their dominant role in the ongoing energy transition. During the same period, China's cumulative installed capacities of wind and photovoltaic power exceeded 640 GW and 1,200 GW, respectively, with a combined installed capacity surpassing 1,800 GW for the first time. This accounts for over 45% of the world’s renewable energy capacity and strengthens China’s leading role in renewable energy deployment.

However, the rapid growth has also brought great challenges to the reliable functioning of modern power systems due to the intrinsic intermittency and stochasticity of wind and solar resources, which highlights the limited flexibility of conventional grid infrastructures to balance supply and demand. Therefore, large-scale energy storage has become a key enabling technology to address the temporal and spatial mismatch between renewable electricity supply and electricity demand. Energy storage is gradually becoming a crucial pillar for allowing renewable energy integration, strengthening grid resilience and expediting the transition toward low-carbon energy systems, besides stabilizing the power system operation. Therefore, it is a crucial part in the construction of next generation power systems with high penetration of renewable energy [1].

Currently, various energy storage systems have been created with different technological qualities and application scenarios. Pumped hydro energy storage has reasonably high round -trip efficiency (usually 70-85%) but is highly confined by geographical constraints. Gravity energy storage has the advantages of extended service life and fast construction, but the energy storage capacity is ultimately limited by the mass of storage blocks and the available elevation difference. Electrochemical batteries provide the advantages of fast response and flexible deployment, but suffer from high costs, limited cycle life and safety problems. Redox flow batteries are known for their good cycling stability, but their wide application is limited by low energy density, relatively expensive capital costs and undesired side reactions. Flywheel energy storage devices have advantages of high power density, compact footprint and mature technology. However, they still suffer from restricted discharge duration, high manufacturing cost, mechanical stress, operational noise and safety hazards. Hydrogen energy storage is attracting more and more interest for its capability of long duration energy storage, but the large-scale application is limited by the fact that the technological maturity and industrial infrastructure are not perfect enough [2].

Among these technologies, compressed gas energy storage, such as compressed air energy storage (CAES) and compressed carbon dioxide energy storage (CCES), has emerged as one of the most promising alternatives for large-scale and long-duration energy storage. These systems use air or carbon dioxide as working fluid and have many advantages such as huge storage capacity, long discharge time, relatively good round-trip efficiency, long service life and flexible site selection. Therefore, compressed gas energy storage has drawn more and more attention as an essential technology to facilitate large-scale renewable energy integration and improve the operational flexibility of future low -carbon power systems. Table 1 presents the advantages and limits of representative energy storage methods.

2. Overview of Compressed Gas Energy Storage Technologies

Compressed Gas Energy Storage Technologies (CGES) is a process to store electrical energy by compressing gaseous working fluids into high-pressure energy reservoirs and then letting the stored energy expand via gas expansion to create electricity in times of high demand. Due to its high energy storage capacity, extended discharge time and operational flexibility, CGES has emerged as a viable technology for grid flexibility enhancement and wide scale renewable energy penetration. Based on the working fluid, the CGES is largely divided into CAES and CCES, which have similar working principles but different thermodynamic properties and system configurations.

Table 1. Advantages, Disadvantages and Status of Representative Energy Storage Technologies

Energy storage technology	Advantages	Disadvantages	Technology status
Lithium-ion batteries	High energy density, fast response	High cost, cycle degradation	Commercialized
Lead-acid batteries	Low cost, mature technology	Low energy density, short cycle life	Mature technology
Nickel-cadmium batteries	Mature, reliable	High cost, toxic materials	Utility applications
Vanadium redox flow batteries	Long cycle life, large capacity	Low energy density, high cost	Long-duration storage
Supercapacitors	High power density, fast charging	Low energy density, high cost	Short-duration storage
CAES	Large capacity, mature technology	Geological constraints, high capital cost	Commercial demonstration
CCES	High energy density, environmentally friendly	High capital cost, low technology readiness	Demonstration stage
Flywheel energy storage	High power density, long cycle life	High cost, self -discharge	UPS, frequency regulation
Pumped hydro energy storage	High efficiency, large capacity	Site-dependent, high capital cost	Commercialized
Hydrogen energy storage	Long-duration storage, high energy density	Low efficiency, high cost	Emerging technology

2.1 CAES

Over the last decades, several CAES configurations have been developed to improve system efficiency and operational flexibility, such as diabatic CAES (D-CAES), advanced adiabatic CAES (AA-CAES), isothermal CAES (I-CAES), liquid air energy storage (LAES), supercritical CAES (SC-CAES), underwater CAES (UW-CAES) and pumped hydro CAES

(PH-CAES).

2.1.1 D-CAES

The operating principle of D-CAES is illustrated in Figure 1. The first commercial D-CAES plant was commissioned at Huntorf in Germany in 1978 [3], where compressed air was reheated by natural gas combustion before expansion, resulting in a round-trip efficiency of approximately 42%. A schematic of the system is presented in Figure 2. The McIntosh plant in the United States, commissioned in 1991, increased the efficiency to approximately 54% through exhaust heat recovery. Although D-CAES can improve grid flexibility and reduce the cycling frequency of conventional thermal power plants, its dependence on natural gas combustion results in additional carbon emissions. Consequently, it is gradually being superseded by advanced concepts, particularly AA-CAES, which eliminates fuel combustion while achieving higher energy efficiency and lower carbon emissions.

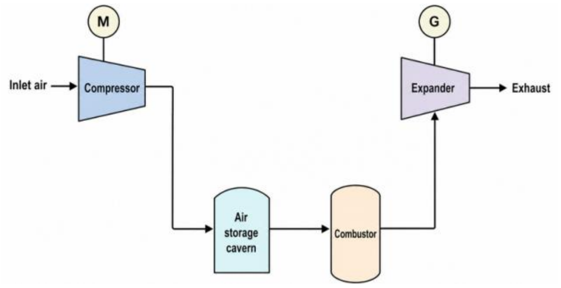

Figure 1. Afterburning Compressed Air Energy Storage System

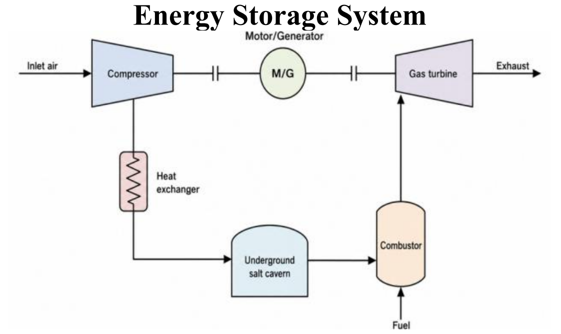

Figure 2. The Working Principle of Huntorf Power Station in Germany

2.1.2 AA-CAES

With the advancement of research, the concept of AA-CAES was proposed [4], as illustrated in Figure 3. By eliminating the combustion chamber used in conventional diabatic systems, AA-CAES introduces thermal energy storage to achieve full recovery of compression heat. During the charging process, the heat generated from air compression is stored in thermal energy storage units, while during discharging, the stored heat is reused to reheat high-pressure air before expansion.

The configuration greatly enhances the system performance, with the round-trip efficiency reaching 60-70%, an increase of about 15-25 percentage points over the standard diabatic systems. Moreover, the absence of fossil fuel combustion allows zero-carbon operation, hence AA-CAES is one of the most promising technological routes in the CAES sector. However, large-scale deployment is still limited by factors such as low energy storage density and volumetric limits of the system.

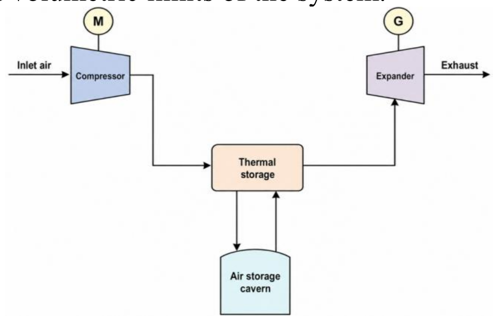

Figure 3. Adiabatic Compressed Air Energy Storage Advanced

2.1.3 I-CAES

The I-CAES concept is based on near isothermal compression and expansion by means of a liquid piston system as shown in Figure 4. The liquid piston is pumped (often water or oil with a high specific heat capacity) in order to compress the air under near isothermal conditions during the charging process. The compressed air is subsequently cooled via a heat exchanger and stored in a pressurized reservoir. When it is released, the high-pressure air moves the liquid piston. This piston drives a hydraulic turbine, which generates energy. Gas-liquid heat exchange keeps the temperature almost constant during expansion.

I-CAES achieve compression and expansion processes close to the optimum isothermal condition thanks to an effective heat transfer between the liquid piston and air. This greatly decreases thermodynamic irreversibility and increases the safety of the system by eliminating thermal stress on system components due to high temperatures, while reducing the overall energy consumption. This therefore makes I-CAES a high potential candidate for diverse application scenarios.

In practice, however, it is still difficult to achieve entirely isothermal operation due to restrictions of heat transport, albeit theoretically advantageous. In particular excellent heat dissipation during compression is important.

Conventional spray cooling methods suffer from insufficient heat transfer area and limited control accuracy of liquid injection. Therefore, enhancing heat transfer performance during the compression process remains a key technical challenge for I-CAES development. Promising solutions include the use of hybrid cooling media and the integration of advanced high-efficiency heat exchangers such as microchannel heat exchangers [5].

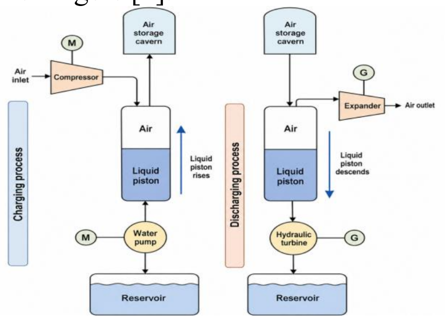

Figure 4. Isothermal Compressed Air Energy Storage System

2.1.4 LAES

Unlike conventional energy storage technologies that convert electricity into high-pressure gas potential energy, LAES stores energy in the form of cryogenic thermal energy, as illustrated in Figure 5. During the charging process, compressed air is precooled via a regenerator and subsequently liquefied through throttling, then stored in an insulated cryogenic tank under atmospheric pressure. Meanwhile, the compression heat is recovered and stored in a thermal energy storage system. During discharge, the liquid air is pressurized by a cryogenic pump, vaporized through heat exchange in the regenerator, and further heated using stored thermal energy to produce high-temperature, high-pressure gas that drives a turbine generator for electricity production.

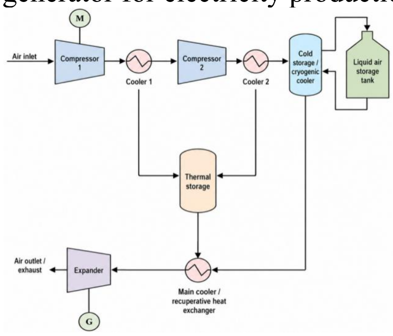

Figure 5. Liquid Compressed Air Energy Storage System

Owing to the significantly higher density of liquid air—approximately 750 times that of gaseous air—LAES exhibits substantial advantages in energy storage density and site flexibility, making it particularly suitable for locations with limited geographical constraints. However, the overall system requires additional liquefaction and cryogenic processing units, resulting in increased system complexity and relatively low round-trip efficiency compared with other CAES-based technologies.

2.1.5 SC-CAES

Supercritical fluids exhibit combined characteristics of high liquid-like density and gas-like compressibility. In SC-CAES systems [6], air is compressed into a supercritical state (T > 132 K, P > 3.79 MPa), followed by heat recovery through heat exchangers. The working fluid is then stored in the cryogenic tank in liquid form at ambient pressure.

This arrangement combines the thermal recovery benefits of AA-CAES with the cryogenic storage features of LAES. Under operating conditions with charging and discharging pressures of 12 MPa and 9.501 MPa, respectively, a round-trip efficiency of up to 67.41% has been reported. The operating principle is illustrated in Figure 6. During charging, air is compressed into the supercritical region, cooled to near-ambient conditions via thermal storage heat exchangers, liquefied using recovered cold energy, and stored in a cryogenic tank while compression heat is simultaneously recovered. During discharge, the liquid air is pressurized back to the supercritical state, exchanging heat with cold storage units before being reheated by recovered compression heat and expanded to generate electricity.

SC-CAES offers relatively high energy conversion efficiency and improved energy storage density, making it suitable for long-duration and large-scale energy storage applications. However, its practical deployment is constrained by high capital cost, mainly due to the requirement for high-strength pressure vessels and cryogenic infrastructure.

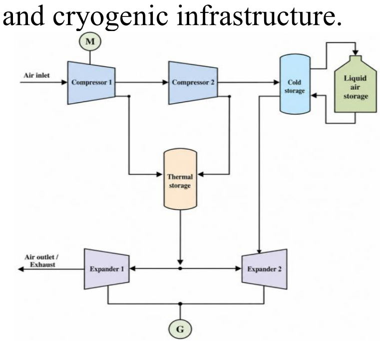

Figure 6. Supercritical Compressed Air Energy Storage

2.1.6 UW-CAES

The UW-CAES system innovatively deploys the air storage unit in an underwater environment, utilizing hydrostatic pressure to achieve near-constant-pressure operation. During both charging and discharging processes, the stable water pressure enables compressors and turbines to operate close to their design conditions, effectively mitigating efficiency losses caused by pressure fluctuations in conventional CAES systems. In addition, the absence of a minimum pressure requirement eliminates the need for auxiliary energy consumption to maintain storage pressure, thereby improving the utilization efficiency of compressed energy. Meanwhile, the underwater pressure environment reduces mechanical pressure requirements for storage vessels, significantly enhancing system safety. The system configuration is illustrated in Figure 7.

Depending on whether the compressed air is in direct contact with water, UW-CAES can be classified into two configurations: a closed isobaric system using flexible storage vessels and an open isobaric system based on rigid containers. The system can be effectively integrated with offshore wind power to form a “offshore generation-subsea storage-onshore supply” energy chain, thereby improving renewable energy utilization efficiency. However, UW-CAES is still at the laboratory and small-scale demonstration stage, and large-scale commercialization has not yet been realized. Moreover, the requirement for maintaining constant pressure conditions and the use of long underwater pipelines lead to high system complexity and increased capital costs.

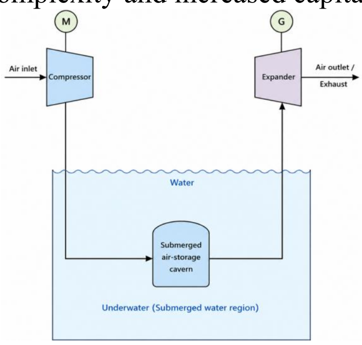

Figure 7. Underwater Compressed Air Energy Storage System

2.1.7 PH-CAES

PH-CAES technology, developed by the research team led by Wang Huanran at Xi’an Jiaotong University [7], integrates the advantages of pumped hydro energy storage and compressed air energy storage into a hybrid energy storage system, offering high operational efficiency, reduced land occupation, and broad application potential. Compared with conventional CAES systems, the key distinction lies in replacing compressors and expanders with high-pressure water pumps and hydraulic turbines, respectively, thereby effectively addressing the challenges of thermal management during compression and heating requirements during expansion.

The operating principle is illustrated in Figure 8. During the charging process, surplus electricity or renewable energy drives pumps to transfer water into a pressure vessel, converting electrical energy into compressed air potential energy. During discharge, high-pressure air in the vessel forces water through a hydraulic turbine, releasing stored energy to generate electricity.

With further development, the research team has proposed several advanced configurations, including constant-pressure PH-CAES systems, hybrid systems coupling adiabatic and near-isothermal compression, and advanced pumped-hydro compressed air hybrid systems, continuously promoting technological evolution. In addition, Zheng et al. [8] evaluated a conceptual 40 MW/200 MWh PH-CAES plant integrated with pumped hydro storage and reported a round-trip efficiency of 70.81% under optimized operating conditions.

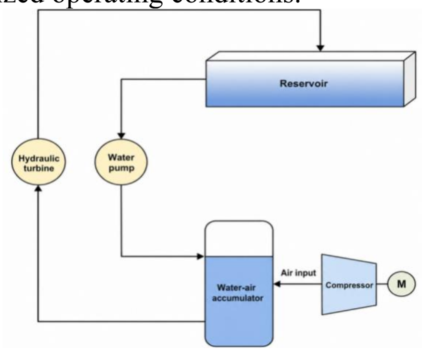

Figure 8. Pumped Compressed Air Energy Storage System

2.2 CCES

CCES technology has evolved from advanced adiabatic compressed air energy storage (AA-CAES) and the Brayton cycle. By utilizing CO_2 as the working fluid, CCES operates in a closed-loop thermodynamic cycle and takes advantage of the unique thermophysical properties of CO_2, including its high density and favorable compressibility near the critical point.

Depending on the phase state of CO_2 during the charging and discharging processes, CCES technologies can generally be classified into three categories: transcritical compressed carbon dioxide energy storage (TC-CCES), supercritical compressed carbon dioxide energy storage (SC-CCES), and liquid carbon dioxide energy storage (LCES).

2.2.1 TC-CCES

TC-CCES refers to a CCES system in which the thermodynamic state of CO_2 crosses its critical point (31.1°C and 7.38 MPa) during the charging and discharging processes. Specifically, CO_2 is compressed from a subcritical state to a supercritical state during energy storage and subsequently expanded back to a subcritical state during power generation. Energy is therefore stored and released through thermodynamic processes involving phase transitions across the critical region.

As illustrated in Figure 9, TC-CCES systems typically operate with a relatively low pressure on the low-pressure side. Multistage compression with intercooling is typically used to remove the heat created during compression between stages to lessen the compression work. In the discharge process, multi-stage expansion and inter-stage reheating are employed to compensate the temperature loss in the expansion phase and improve the output of the turbine. This arrangement makes use of the advantageous thermodynamic properties of CO_2 in the transcritical region, to improve the energy conversion efficiency and to minimize the irreversible losses due to the large pressure ratio compression and expansion operations. Thus, TC-CCES exhibits great benefits in thermodynamic performance and scalability, which makes it a suitable candidate for large-scale energy storage applications.

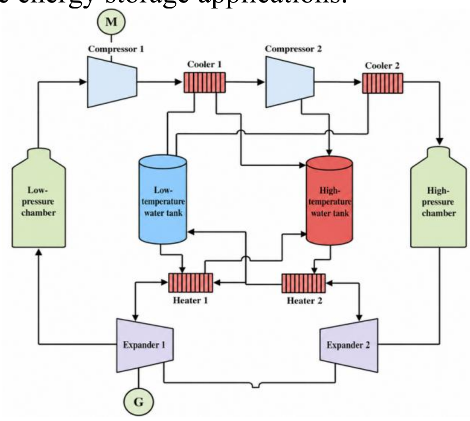

Figure 9. Transcritical Energy Storage System with Compressed Carbon Dioxide

2.2.2 SC-CCES

SC-CCES means a CCES technology where the CO_2 working fluid is always in a supercritical state during the whole charging and discharging cycle. It exploits the unique thermophysical properties of supercritical CO_2 which possesses the high density of liquids and excellent flow characteristics of gases. Energy is stored and released by a closed cycle of compression, thermal energy storage and power generation by expansion. In contrast to transcritical systems, SC-CCES does not involve phase transitions over the critical point, and so does not require gas-liquid conversion, thereby allowing for a more stable energy conversion process based on a single-phase working fluid.

As shown in Figure 10, the operating principle of SC-CCES is generally similar to that of TC-CCES. However, because the working fluid remains in the supercritical region throughout the cycle, relatively small pressure ratios are required during compression and expansion. Consequently, single-stage compression and expansion processes are typically sufficient to satisfy operational requirements, resulting in a simpler system configuration and reduced equipment complexity.

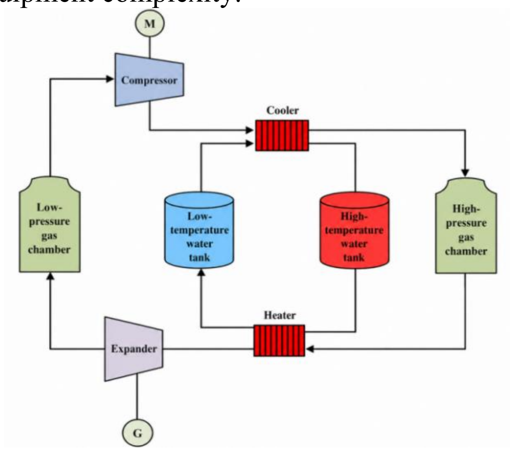

Figure 10. Supercritical Compressed Carbon Dioxide Energy Storage System

Despite these advantages, SC-CCES faces several technical challenges. Since both the high -pressure and low-pressure storage reservoirs operate at elevated pressures, further increasing the storage pressure on the high-pressure side is constrained by system safety considerations and pressure-vessel design limitations. Moreover, the relatively low compression and expansion ratios restrict the power output of compressors and turbines, limiting the amount of energy that can be stored and recovered during each cycle. As a result, improvements in energy storage density and round-trip efficiency remain challenging for conventional SC-CCES systems. Therefore, the advancement of thermodynamic cycle design, heat management and system integration approaches are anticipated to be the focus of future investigations to better capitalize the benefits of supercritical CO_2 and to boost overall system performance.

2.2.3 LCES

LCES employs liquid CO_2 as the energy storage medium in both the high-pressure and low-pressure reservoirs. As shown in Figure 11, the LCES system is developed from the transcritical CCES configuration with the addition of a cold storage unit and dedicated liquefaction and vaporization processes. By introducing phase-change storage, the system significantly increases energy storage density while maintaining relatively high cycle efficiency.

During the charging process, liquid CO_2 from the low-pressure reservoir first passes through the cold storage unit, where it absorbs the cooling capacity released during the liquefaction process. The working fluid is subsequently compressed through multistage compressors with intercooling and converted into a supercritical state. It is then liquefied and stored in a high-pressure liquid CO_2 tank. During discharge, the high-pressure liquid CO_2 is vaporized into a supercritical state and expanded through multistage turbines with interstage heating to generate electricity. After expansion, the low-pressure gaseous CO_2 is cooled and liquefied in the cold storage unit before returning to the storage tank, thereby completing the closed-loop cycle.

Compared to TC-CCES and SC-CCES systems, the LCES has more liquefaction and vaporization processes, which need more cooling capacity and more efficient thermal management procedures. Consequently, system design places greater emphasis on heat integration and cold energy recovery. Nevertheless, the incorporation of liquid-phase storage enables a substantial increase in energy storage density with only a limited impact on round-trip efficiency. Owing to this unique advantage, LCES is widely regarded as one of the most promising CO_2-based energy storage technologies for large-scale and space-constrained applications. A comparison of the energy storage density and round-trip efficiency of LCES and representative compressed-gas energy storage systems is presented in Table 2.

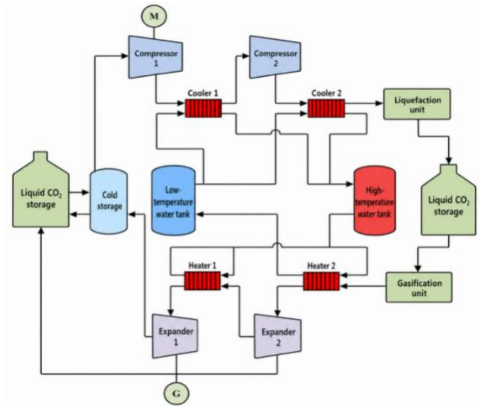

Figure 11. Liquid Compressed Carbon Dioxide Energy Storage System

Table 2. Energy Storage System Comparison Table

Energy storage system	energy storage efficiency /%	energy density /(kWh/m^3)
Adiabatic compressed air energy storage	67.22	2.91
Liquid carbon dioxide energy storage	56.64	36.12
High pressure side liquefied carbon dioxide energy storage	60.69	8.07

2.3 Summary of CGES Technologies

CGES technologies are widely recognized as one of the most promising solutions for large-scale and long-duration energy storage due to their advantages in storage capacity, operational flexibility, reliability, economic viability, and environmental sustainability. Among the different technological paths, CAES and CCES are the two main branches with CAES being the most mature and commercially produced technology at now.

The adoption of CAES systems has evolved substantially, especially in China, where the technology has moved past the demonstration phase of hundred-megawatt projects and is progressing towards gigawatt-scale applications. However, the relatively low energy density of compressed air is an intrinsic restriction. Methods like air liquefaction and supercritical operation can boost storage density, but tend to add system complexity and capital cost.

Carbon dioxide has more favorable thermophysical characteristics than air for energy storage applications. The comparatively low critical temperature and pressure of CO_2 allow phase transitions between gaseous, liquid and supercritical phases, leading to more flexible designs of thermodynamic cycles.

Furthermore, under the same working condition the density of CO_2 is much higher than the air, the storage volume can be reduced significantly and the overall energy storage density can be possibly increased. Therefore, CO_2 based thermodynamic energy storage systems have been increasingly attracting attention as a possible alternative to provide high-density and high-efficiency energy storage solutions in future low-carbon energy systems with high penetrations of renewable energy.

However, despite these advantages, CCES technology is less mature than CAES. Most current systems are still at the pilot or demonstration stage and have yet to be deployed on a big commercial basis. This is a remarkable milestone, since the world's first 10 MW/80 MWh CO_2 energy storage demonstration project was successfully connected to the grid in Wuhu, Anhui Province, China in December 2023 [9]. The project is a major step toward commercialization of CCES and demonstrates the potential role of CCES in assisting large-scale integration of renewable energy resources.

In summary, CAES now has superior technological maturity and substantial engineering experience, but CCES provides significant advantages in energy storage density and thermodynamic efficiency. Future work should seek to improve system efficiency and reduce capital costs, optimize thermal management tactics, and accelerate large scale demonstration and commercialization activities to fully realize the potential of compressed gas energy storage technology.

3. Key Research Progresses

3.1 CAES

CAES research has shifted from component-based optimization to system-level integration and multi-energy coupling. Existing researches are mainly focused on the design of thermodynamic cycle, performance of compressor and expander, thermal energy storage technologies and underground air storage system, forming a complete technology framework to improve the system efficiency, operational flexibility and large scale deployment.

Much effort has been spent to enhancing thermodynamic performance and optimizing system parameters. Cao et al. [10] created a four -stage CAES simulation model and a system efficiency of 63% was reached. Hu et al. [11] also presented a dual-evaluation framework with round-trip efficiency and energy storage density, and the overall performance of the system was affected by the mass flow ratios of charging and discharging. In this work, Zhang et al. [12] constructed a full-process model of a 300 MW CAES plant and investigated the startup features of compressor and turbine, which delivers vital dynamic data for the design of large-scale control system. In a related study, Jin et al. [13] developed an off-design thermodynamic model with decoupled temperature and pressure processes, which extended classical steady state assumptions and explained the effect of operating conditions on system performance. Furthermore, Ma et al. [14] used a modular optimization framework to optimize the thermal cycle design and expansion procedures with electrical efficiency and thermal usage as assessment criteria. In addition, a multi-stage optimization technique was presented by Wang et al. [15] to extend component level optimization to life-cycle system design.

Recent research has put greater emphasis on the importance of dynamic operation and transient performance. Full-cycle dynamic models considering impacts of thermal inertia have shown that mass and energy transfer processes inside CAES systems can be strongly influenced by startup, shutdown and variable-load conditions. Such techniques provide more realistic representations of transient thermodynamic behavior than conventional steady-state models, and open new avenues for operational optimization under changing renewable energy inputs.

Another major study subject is the aerodynamic properties and off-design regulation of compressors. Qin et al. [16] used aerodynamic parameter matching and stage-reduction redesign to increase compressor stability. Shi et al. [17] proposed three-dimensional blade stacking technology, which reduced the maximum equivalent stress of compressor blades by 32.1% and greatly improved the structural reliability. Zhang et al. established a wide-operating-range simulation model and systematically evaluated constant-pressure, sliding-pressure and pressure-regulation modes. The results indicated that the adjustment of inlet guide vane is the most important measure to improve the adaptability of compressors under variable operating conditions.

At the same time, there have been significant advances in the design of turbines and the development of dynamic control strategies. Ma et al. [18] used three-dimensional computational fluid dynamics coupled with finite element analysis to study the low-cycle fatigue behavior of high-pressure turbine casings and developed a reliable method to predict the lifetime. Gu et al. [19] introduced the aerodynamic design, structural configuration and fast-start capability of a 300 MW expansion turbine, which provides an engineering basis for the large-scale application of CAES. Zhang et al. [20] pointed out that intercooling conditions have a great influence on the operating characteristics of final-stage compressors in a 300 MW system. Zhu et al. [21] proposed a variable-universe fuzzy adaptive PI control strategy, which reduces the maximum frequency deviation by 10.1% compared with traditional PI control methods. Wang et al. [22] optimized the operation of deep sliding-pressure turbine and gave advice on supplementary air injection schemes and selection of optimal operating pressure.

In addition to thermodynamic cycle optimization, increasing attention has been directed toward underground air storage technologies, which are essential for large-scale CAES deployment. Wang et al. developed a triaxial permeability testing system that provides key parameters for storage cavern site selection. Excellent sealing performance of polyurethane mortar (PPM) was shown by Jiang et al., with tensile strength 2.45 MPa, elastic modulus 39.16 MPa, and permeability 10-21-10 -22 m2, which meet fully the sealing requirements of compressed air energy storage (CAES) systems. The spatiotemporal distribution of the temperature field has a direct impact on the integrity and reliability of the sealing structure. Cai et al. [23] studied the tunnel-type storage cavern by using computational fluid dynamics (CFD) simulations and found a local hot spot with a temperature of 670.56 K. Their results demonstrated that the optimized cavern layout and airflow organization could effectively alleviate the excessive temperature concentrations. Li et al. [24] further improved the thermodynamic modelling frame and clarified the dominant factors to limit the overall system efficiency.

But the present cavern thermodynamic models often fail in heat-transfer prediction, particularly in overestimating heat loss at the high-pressure storage stage and overestimating supplementary heating at the low-pressure stage. To solve this problem, Jiang et al. [25] proposed a mixed convection heat-transfer mechanism, which greatly improved the accuracy of temperature prediction and provided a more reliable theoretical basis for cavern volume optimization.

The importance of coupled thermo-hydro-mechanical processes in underground storage caverns has been pointed out in more recent studies. Advanced numerical simulations have shown that operational modes, pressure fluctuations and thermal interactions can considerably affect cavern efficiency and structural safety. Moreover, lined rock caverns and artificial underground chambers have been increasingly regarded as promising alternatives to salt caverns due to their broader geographic applicability and improved deployment flexibility.

In the field of multi-energy integration, Zheng et al. developed a green hydrogen production system incorporating CAES, as illustrated in Figure 12, achieving a curtailed electricity rate of only 2% and a green hydrogen production cost of 19.3 CNY/kg, thereby demonstrating superior economic performance compared with lithium-ion battery storage. Ma et al. proposed a combined-cycle gas turbine (CCGT)-CAES hybrid power plant, which expanded the operational range of the plant despite a modest efficiency reduction of approximately 2%. Liu et al. recovered waste heat from the final-stage CAES turbine using a heat pump, resulting in a 3.75% improvement in overall energy utilization efficiency.

Xu et al. and Qian et al. independently proposed coupling schemes between CAES and coal-fired power units, significantly enhancing peak-shaving capability and operational flexibility. Liang et al. developed a combined cooling, heating, and power (CCHP) system integrated with CAES, achieving an overall energy utilization efficiency of 70.31%. Li et al., Jiang et al., and Zhao et al. studied coupling paths of CAES with ultra-supercritical power units, wind turbines, and molten-salt thermal storage, respectively, which advanced the transformation of CAES into coordinated multi-energy operation.

Recent research has expanded the further role of

CAES in integrated energy systems. Dynamic scheduling models that include CAES, renewable generation, carbon management mechanisms, and power-to-gas technologies have been shown to significantly improve renewable energy accommodation and system flexibility. Moreover, the advanced energy management strategies based on multi-energy flow coordination have demonstrated that CAES can effectively support the low-carbon operation of integrated electricity-heat-gas systems in high renewable penetration scenarios. These trends suggest that future CAES applications will probably transition from stand-alone storage facilities to extensively integrated multi-energy infrastructures that can concurrently offer energy storage, peak regulation, and carbon reduction services.

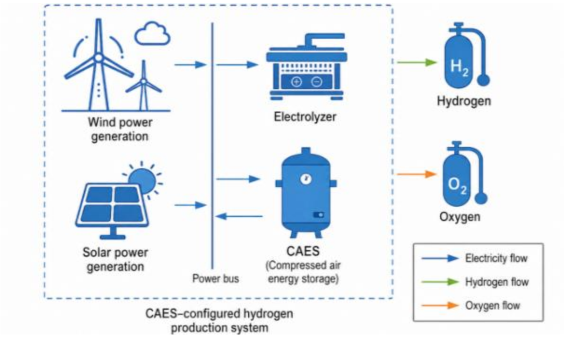

Figure 12. Configure the Hydrogen Production System of CAES

3.2 CCES

CCES has been a promising large-scale energy storage technology in recent years due to its high energy density, flexible operating properties and compatibility with low-carbon energy systems. The research scope has gradually expanded from the optimization of thermodynamic cycles to the integration of systems and practical engineering applications, which has formed a complete research framework including working fluid enhancement, improvement of system configuration, adaptation of scenarios and multi-energy coupling.

The first studies were mainly focused on the optimization of working fluid to improve the thermodynamic performance of CO_2 based energy storage systems. Dong et al. [26] developed a supercritical CO_2 energy storage system, the round-trip efficiency and energy storage density were 37.21% and 8.31 kWh/m^3, respectively. However, the energy loss near the critical pressure region limited its performance. In order to overcome the condensation limitations of pure CO_2, Wang et al. proposed the CO_2/R41 mixed working fluid system, and the energy storage density of 9.36 kWh/m^3 was achieved by liquid-phase storage. Then Gao et al. proposed a new transcritical CCES system with temperature-swing adsorption of 13X zeolite, which can realize real-time internal heat recycling and store CO_2 at high density under low pressure. Liu et al. further developed an adsorption-based storage system with a guanidine sulfate solution, which has an energy storage density of 14.45 kWh/m^3 and a cycle efficiency of 69.43% at a low pressure of 0.1 MPa. Hao et al. coupled concentrated solar thermal energy with a supercritical CO_2 storage cycle, achieving a storage efficiency of 75.51%. They demonstrated that the performance could be significantly improved by coordinating the utilization of working fluids and external heat sources.

Along with the development of the working fluid, large efforts have been made to optimize system configurations and reduce thermodynamic irreversibilities. Chen et al. reported Aspen Plus simulations showing that the main contributors to exergy destruction in supercritical CO_2 storage systems are heaters and compressors, while in liquid CO_2 systems, compression and expansion units are the dominant factors for exergy losses. Li et al. show that off-design operating conditions can significantly degrade system performance, leading to a 7.2% reduction in round trip efficiency and significant degradation of energy storage density, beyond the traditional steady state analyses. Comparative studies by Zhang et al. [27] showed that the performance of the compressor and discharge pressure have a major effect on the efficiency of liquid CO_2 storage systems, and the turbine efficiency is more critical for electrothermal CO_2 storage technologies. Qiao et al. optimized the heat exchanger temperature-difference allocation strategies for the utilization of low-grade thermal energy and achieved a round-trip efficiency of 79.62% without external heat input. Economic evaluations have also been receiving growing attention. Zhao et al. found that a 100MW/1000MWh CCES plant would need a peak-to-valley electricity price difference of 1.46 CNY/kWh to be economically viable. Furthermore, the comparative studies by Shi et al. and Hao et al. demonstrated that two-stage compression arrangements are generally better than three-stage configurations in terms of cycle efficiency, exergy efficiency, and energy storage density. Wang et al. also proposed a gas-liquid phase change storage system with an energy storage efficiency of 65.35% and an estimated payback period of approximately 5.5 years.

With the technology maturing, researchers have looked more and more at how CCES can be applied in a range of deployment scenarios. To solve the large space demand of conventional gas storage facilities, Zheng et al. proposed a dual working fluid energy storage system suitable for integrated energy supply in industrial parks, and obtained an energy storage density of 3.85 kWh/m^3 and an efficiency of 70.20%. Considerable attention has also been paid to geological storage applications. Liu et al. developed a coupled well-reservoir model and reported the daily cycle efficiency of aquifer-based CO_2 energy storage systems to be 93%. Further studies by Chen et al. have shown that the increase in aquifer depths can lead to higher storage efficiencies, emphasizing the importance of geological conditions in the design and operation of the system.

More recently, coupling CCES with other energy technologies has been an important research direction for improving system flexibility and overall energy utilization. Xu et al. proposed a CCES system assisted by heat pump that improved the charging and discharging efficiency by 9.35% compared with the conventional compressed-gas combined heat and power systems. Wang et al. [28] proposed a tri-generation coupled system with a steam ejector to realize the thermal-electric decoupling, which can greatly alleviate the electrical load demand under rated thermal conditions. Yan et al. combined liquid CO_2 energy storage with coal-fired power plants and achieved a 37.4% enhancement in peak-shaving capability by means of dual-loop design. At a larger system level, Zhang et al. proposed a virtual power plant optimization framework that incorporates carbon capture and storage (CCS), power-to-gas (P2G), and liquid CO_2 energy storage (LCES), thus, improving the accommodation of renewable energy and economic performance. Wang et al. also studied a solar thermal-transcritical CO_2 system coupled to the system and found that the system load behavior and thermal management are greatly affected by the heat source temperature variations. Li and Wang et al. also studied the coupling of supercritical CO_2 energy storage with coal-fired power units, and identified the main operating parameters affecting the exergy efficiency and dynamic response characteristics of the charging and discharging processes.

Besides system integration, the dynamic operation and off-design performance of CCES systems have been increasingly focused in recent years. In contrast to traditional steady state studies, dynamic studies have shown the crucial role of operating strategies, storage properties and pressure management on system efficiency and operational flexibility. Recent studies have shown that optimizing the operating conditions of supercritical CO_2 can increase the discharge duration and improve round-trip efficiency under variable load conditions. Furthermore, comparative studies of two-stage gaseous CCES systems demonstrated that the energy and exergy performances can differ significantly under different charging and discharging modes, which highlights the importance of dynamic modeling for real-world grid-scale applications. These results indicate that the dynamic operation should be a key research focus for closing the gap between the theoretical system design and real-world applications.

Another emerging research trend is the deep integration of CCES in low-carbon integrated energy systems, as shown in Figure 13. Recently, the gas-liquid phase-change CO_2 energy storage has been integrated in energy systems with CCS, P2G, renewable energy resources and carbon management mechanisms. These integrated frameworks have shown great potential in enhancing the utilization of renewable energy, operational flexibility, and economic performance through coordination of multiple energy carriers and carbon flows. Furthermore, the integration of carbon trading and green certificate mechanisms has demonstrated significant potential in enhancing the commercial competitiveness of CCES-based energy systems, underscoring the increasing importance of CCES in facilitating carbon-neutral energy transitions.

The existing studies have significantly improved the thermodynamic performance, economic feasibility and application flexibility of CCES technologies. However, there still remain challenges in dynamic operation, large-scale engineering deployment, and coordinated optimization under integrated energy system environments. Hence, future research should address pathways to enhance system adaptability to varying operating conditions, economic competitiveness, large-scale demonstration projects and deeper integration with renewables, carbon management technologies and multi-energy systems.

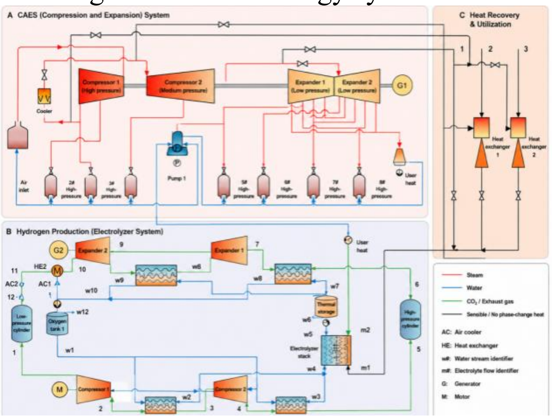

Figure 13. Ternary Coupling System Structure

3.3 Gas Storage Facilities

One of the most relevant elements affecting the development and large scale deployment of both compressed air energy storage (CAES) and compressed carbon dioxide energy storage (CCES) technologies are gas storage facilities. Existing storage technologies can be categorized into underground geological reservoirs, artificial caverns, metal storage facilities and composite-material based storage systems.

Underground geological formations like salt caverns, aquifers and hard-rock caverns are regarded as the most appropriate options for large-scale energy storage, owing to their high storage capacity and relatively low construction costs. Among these, salt caverns have achieved the highest technological maturity and have already been used in commercial CAES plants, such as the Huntorf and McIntosh plants. Salt caverns have very low permeability, good sealing performance and good mechanical stability, so they can bear the frequent pressure changes during the process of charge and discharge. However, the availability of salt formations limits their use geographically and the high salinity environment may increase the rate of equipment corrosion. He et al. [29] applied this concept to CCES applications and developed a system using two salt caverns located at different depths as high and low pressure storage chambers respectively, thereby combining CO_2 storage with geological sequestration.

Another promising geological option is aquifer storage, where compressed gas is injected into porous formations, after displacing groundwater. Such systems have high storage capacity, rather stable operating pressures and low construction cost. However, their practical applications are still limited due to the rigorous site selection requirements, high exploration uncertainties and lack of engineering experience. Aquifer energy storage has not been deployed commercially so far, and it is still at the research and demonstration stage to date. Hard-rock caverns have better geographical availability, higher space utilization and good structural stability compared with salt caverns and aquifers. But they are more expensive to build because of the need for extensive excavation and also the need for additional sealing measures to prevent gas leakage.

Another storage method is the use of artificial caverns, where underground chambers are intentionally constructed to store gas in a compressed state. Typical examples are lined rock caverns and reinforced concrete storage chambers. These facilities can achieve relatively large storage capacities and high operating pressures, and allow greater flexibility in site selection. However, there are still great challenges in high capital investment and long-term sealing reliability. In particular, the underwater concrete storage chambers can keep the storage pressure almost constant and enable quasi-isothermal charge and discharge processes. However, corrosion and operational safety issues have hindered their practical realization.

The most common surface storage systems are metallic storage facilities like above-ground pressure vessels and pipeline storage systems. The pressure vessels have excellent sealing performance, high operating pressure and flexible installation without considering geological conditions. However, their applications in large-scale energy storage systems are limited by their relatively low storage capacity, high production costs, and fatigue failure under cyclic loading. Pipeline storage has similar advantages but lower construction costs and more flexibility in placement; however, fatigue-related problems remain during long-term operation.

To overcome the limitations of the conventional metallic storage facilities, there has been an increasing attention on composite-material-based storage technologies, such as composite pipelines, membrane storage chambers and flexible gas bags. Composite materials are lighter, more resistant to corrosion and better at withstanding fatigue than their metal counterparts. For example, reinforced thermoplastic composite pipes have the potential to reduce material and fabrication costs by more than 25% while providing high pressure resistance and sufficient flexibility for coil-based transportation and installation. However, the complexity and cost of advanced composite materials have so far restricted their use in commercial energy storage applications.

In conclusion, the selection of gas storage facilities is a compromise between storage capacity, economic cost, geographical adaptability, operational safety and long-term reliability. Underground geological storage remains the preferred solution for large scale commercial projects while above ground metallic and emerging composite material storage systems provide greater deployment flexibility. Future research should be directed towards improving the safety of storage, reducing the construction cost and developing flexible storage solutions to support distributed and integrated energy systems.

4. Challenges and Future Perspectives

4.1 Technical Challenges

Although the recent progress in the field of compressed gas energy storage technologies such as CAES and CCES is promising, several technical and economic challenges are still to be overcome, which hinder the large-scale commercialization and widespread deployment of these systems. The main challenges are related to the development of key equipment, system integration, operational intelligence and economic competitiveness.

The development of high performance compressors and expanders is one of the most difficult problems. However, CAES and CCES have different thermophysical properties of their working fluids, leading to the need for different design of turbomachinery. In CAES systems, the air is in the gaseous phase during the entire cycle and use is made of centrifugal compressors and axial turbines. While these devices use relatively mature technologies and require only moderate sealing, their large physical size can increase the cost of installation and maintenance. On the other hand, CCES systems are operated with CO_2 in the supercritical, transcritical or liquid state. The very large changes in fluid density and thermodynamic properties during compression and expansion impose stringent demands on equipment efficiency, structural strength, sealing performance and corrosion resistance. Thus, keeping a high efficiency and reliability under variable operating conditions remains still a big challenge for future CCES development.

Energy storage facilities are another big bottleneck. Both CAES and CCES systems rely heavily on geological conditions for the construction and operation of large-scale storage reservoirs. Salt caverns show excellent performance in commercial applications but are restricted in geographical availability. Alternative solutions such as hard rock caverns, aquifer storage, lined rock caverns and artificial underground chambers are also in active development, but need further verification of long-term sealing performance and economic feasibility. Additional challenges for the underwater compressed air energy storage technologies such as UW-CAES and PH-CAES will be the pressure resistance, corrosion resistance, and long-term durability of storage materials.

Thermal management is still a critical issue to system performance. Their performance is directly related to the round-trip efficiency and economics of thermal and cold energy storage systems. Major research priorities are still the reduction of thermal losses, the increase of heat transfer effectiveness, the maintenance of thermocline stability and the development of low-cost high-performance thermal storage materials. CCES systems also need advanced heat exchanger technologies, such as printed circuit heat exchangers, to achieve high heat transfer efficiency at elevated pressures and temperatures due to the distinctive thermodynamic properties of supercritical CO_2.

In addition to the component-level challenges, system integration and intelligent operation are gaining more and more importance as compressed gas energy storage systems are increasingly coupled with renewable energy sources, hydrogen production systems, and integrated energy networks . The interaction of several subsystems is dynamic and brings a complexity in the operational control and energy management. The current simulation tools still show limited accuracy in predicting highly transient and off-design operating conditions. More sophisticated modeling approaches are subsequently required for an accurate representation of coupled thermal, mechanical and electrical processes.

Economic competitiveness is still a big issue. However, compressed gas energy storage technologies require significantly higher upfront capital investment than most competing energy storage technologies, even though these technologies can offer long service lifetimes and large storage capacities. Future projects will become economically viable not only by improvements in energy efficiency and technological maturity, but also by the development of low-cost storage solutions, optimized system configurations and large-scale manufacturing capabilities.

4.2 Future Research Directions

As illustrated in Figure 14, the future of compressed gas energy storage will be more and more influenced by interdisciplinary innovation and the integration of emerging technologies. The profound coupling of energy storage systems with renewable energy sources, hydrogen production technologies, fuel cells and integrated energy systems will be a major research trend. Compressed gas energy storage could play a more important role in supporting carbon neutral energy transitions and increasing utilization of renewable energy through coordinated optimization of electricity, heat, gas and carbon flows.

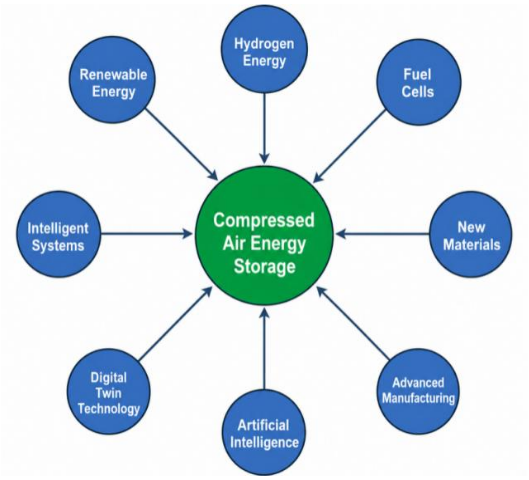

Figure 14. Multidisciplinary Integration Development of Compressed Air Energy Storage

Technological advances in materials science, advanced manufacturing and thermal engineering are expected to further enhance the performance and reliability of key components. Particularly important for improving system efficiency and reducing operational risks will be the development of high efficiency compressors and turbines, corrosion resistant materials, advanced sealing technologies and compact high performance heat exchangers. In parallel, modular and standardised system designs may help to reduce construction periods and investment costs and to accelerate commercial deployment.

It is probable that digitalization and intelligent operation will be the main research directions. The integration of digital twin technologies, artificial intelligence and machine-learning-based optimization methods will allow real-time monitoring, predictive maintenance and adaptive control of energy storage systems. These technologies can significantly enhance operational flexibility, improve fault diagnosis capabilities and support optimal decision-making under variable renewable energy conditions.

From the market perspective, the energy storage industry is moving into a new phase of commercial operation and market-driven development. As policy frameworks move more and more away from mandatory deployment requirements and toward market-oriented mechanisms, the long-term competitiveness of compressed gas energy storage will depend on the establishment of sustainable business models. Expected future projects will generate revenues from a variety of market services including energy arbitrage, frequency regulation, capacity markets, reserve services and ancillary grid support. At the same time, efforts should be made to reduce the life-cycle costs through technological innovation, improving the round-trip efficiency and increasing the system’s service life.

Finally, safety and long-term reliability will be the basic requirements for large-scale commercialization. Therefore, future research should focus on the development of comprehensive monitoring systems, intelligent operation and maintenance platforms, and standardized safety evaluation frameworks to guarantee the stable and secure operation of long service periods. With the advances in technology and increasing renewable energy penetration, compressed gas energy storage is expected to be one of the most important long-duration energy storage solutions in future low-carbon energy systems.

5. Conclusion

Accelerated by the rapid development of renewable energy worldwide, compressed gas energy storage has emerged as one of the most promising long-duration energy storage technologies owing to its large storage capacity, long lifetime, environmental friendliness and potential for grid-scale deployment. This review systematically surveyed the recent development of CAES and CCES, focusing on their operating principles, technological pathways, key enabling technologies, storage facilities, system integration strategies and application scenarios in particular. Both technologies were analyzed in detail, with respect to their state of the art and their current challenges.

Among the various technologies for compressed gas energy storage, CAES technology has reached a relatively high level of technological maturity, and has gradually developed from component-level optimization to system-wide integration and multi-energy coupling. Important progress was achieved in the development of compressors and turbines, thermal energy storage systems, underground energy storage caverns and integrated energy applications. Large scale demonstration projects have accelerated the transition of CAES to gigawatt scale deployment. But the inherent limitation of relatively low energy density of compressed air still stays. Although liquefaction and supercritical conversion technologies can increase storage density, their increased technical complexity and economic costs are barriers to widespread adoption.

To overcome these limitations, CCES utilizes carbon dioxide as the working fluid, which has a higher density and favorable phase-transition characteristics under similar operating conditions. CCES can be used to enable gas, liquid and supercritical phase transformations to achieve significantly higher energy storage density, with reduced storage volume requirement. Therefore, CCES has attracted increasing attention as a promising alternative for supporting large-scale renewable energy integration. However, CCES is still in an earlier stage of technological development than CAES, and many key technologies have not yet reached the maturity required for large-scale commercial deployment. Most existing projects are still at the demonstration and validation stage, and further research is needed to improve system efficiency, reliability and economic viability.

Despite the major advances made in the recent years, the technologies of compressed gas energy storage still face several critical challenges. These include high performance compressors and expanders, advanced storage facilities, efficient thermal management systems and compact heat exchangers for operating under high pressure conditions. Moreover, the increasing complexity of integrated energy systems calls for more advanced methods for dynamic operation, intelligent control and coordinated energy management. The use of digital twin technologies, artificial intelligence and data-driven optimisation methods is projected to assume a growing importance in improving system performance, operational flexibility and reliability.

Looking forward, future research should aim to improve energy storage density, round-trip efficiency, life-cycle costs, and overcome key technological bottlenecks. There is also a need for more work to promote standardization, modular design and large-scale manufacturing to speed up commercial deployment. At the same time, the construction of sustainable business models and diversified revenue mechanisms will be an important means to improve market competitiveness. With the further development of equipment design, materials science, intelligent operation and integrated energy system technology, compressed gas energy storage is expected to become a pillar of the future low-carbon power systems and provide reliable, safe and economically feasible long duration energy storage service for large-scale renewable energy penetration.

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