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Review

Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications

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ABSTRACT

Decarbonization of the electric power sector is essential for sustainable development. Low-carbon generation technologies, such as solar and wind energy, can replace the CO_2-emitting energy sources (coal and natural gas plants). As a sustainable engineering practice, long-duration energy storage technologies must be employed to manage imbalances in the variable renewable energy supply and electricity demand. Compressed air energy storage (CAES) is an effective solution for balancing this mismatch and therefore is suitable for use in future electrical systems to achieve a high penetration of renewable energy generation. This study introduces recent progress in CAES, mainly advanced CAES, which is a clean energy technology that eliminates the use of fossil fuels, compared with two commercial CAES plants at Huntorf and McIntosh which are conventional ones utilizing fossil fuels. Advanced CAES include adiabatic CAES, isothermal CAES, liquid air energy storage, supercritical CAES, underwater CAES, and CAES coupled with other technologies. The principles and configurations of these advanced CAES technologies are briefly discussed and a comprehensive review of the state-of-the-art technologies is presented, including theoretical studies, experiments, demonstrations, and applications. The comparison and discussion of these CAES technologies are summarized with a focus on technical maturity, power sizing, storage capacity, operation pressure, round-trip efficiency, efficiency of the components, operation duration, and investment cost. Potential application trends were compiled. This paper presents a comprehensive reference for developing novel CAES systems and makes recommendations for future research and development to facilitate their application in several areas, ranging from fundamentals to applications.

1. Introduction

The Egypt Climate Agreement and the Glasgow Climate Pact, forged by the United Nations (UN) climate conferences, COP27 and COP26, reaffirm their commitment to limit global temperature rise to 1.5 °C above pre-industrial levels. Through these efforts, the UN has called upon parties to accelerate the development, deployment, and dissemination of technologies, and the adoption of policies, to transition towards low-emission energy systems, including by rapidly scaling up the deployment of clean power generation and energy efficiency measures [1–3]. Power generation systems based on wind, solar, and other renewable energy sources do not cause carbon dioxide emissions. As these systems have experienced considerable cost reductions, they are increasingly being deployed globally and are likely to constitute a large share of future power generation [4,5]. As the world transitions to decarbonized energy systems, emerging large-scale and long-duration energy storage technologies are critical for supporting the wide-scale deployment of renewable energy sources [6–8]. Large-scale grid storage is expected to be a major source of power-system reliability. The demand for energy storage in power systems will gradually increase after 2035, with energy storage shifting approximately 10% of the electricity demand in 2035 [9]. The "Energy Storage Grand Challenge" prepared by the United States Department of Energy (DOE) reports that among all energy storage technologies, compressed air energy storage (CAES) offers the lowest total installed cost for large-scale application (over 100 MW and 4 h). It also offers the lowest levelized cost of storage (LCOS) because of its low unit energy capital cost and high cycle/calendar life [10].

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1.1. Compressed air energy storage concept

CAES, a long-duration energy storage technology, is a key technology that can eliminate the intermittence and fluctuation in renewable energy systems used for generating electric power, which is expected to accelerate renewable energy penetration [7,11–14]. The concept of CAES is derived from the gas-turbine cycle, in which the compressor (CMP) and turbine operate separately. During charging, air is compressed and stored with additional electricity, and the compression heat is stored in a thermal energy storage (TES) unit for future use. During discharging, air is released, either heated by burning fuel or stored thermal energy to generate electricity [13,15]. Compressed air is stored in underground caverns or up ground vessels [16,17].

The CAES technology has existed for more than four decades. However, only Germany (Huntorf CAES plant) and the United States (McIntosh CAES plant) operate full-scale CAES systems, which are conventional CAES systems that use fuel in operation [12,15]. The Huntorf CAES plant of 290 MW was commissioned in 1978, and the system roundtrip efficiency was 42%. This was augmented to 320 MW in 2006 [18]. To improve its performance, further modifications were proposed by Jafarizadeh et al. [19], including regeneration with a recuperator and turbo-expander, to cool down compression process using evaporative cooling, and vapor compression refrigeration. The simulation results indicated that the modification could improve the plant round-trip efficiency to as high as 57.33% [19]. Both commercial and advanced CAES systems were discussed in Ref. [20]. It is possible to improve the round-trip efficiency and application feasibility via various modifications, such as increasing the metallurgical resistance of equipment, improving the efficiency of rotating equipment, enhancing the performance of heat exchangers (HXs), introducing different cycles of low-temperature heat recovery, and the possibility of CAES hybridization with industrial facilities and by-products [19,20].

However, these two diabatic CAES (D-CAES) systems do not recover the compression heat during charging and utilize fossil fuels during discharging. Hence, this system is arguably more similar to gas turbine technology than pure energy storage plants. Many recent studies have focused on advanced CAES for thermomechanical energy storage as it has been demonstrated to have the potential to offer low-cost, large-scale, and fossil-fuel-free operation [21]. As discussed in Ref. [22], the energy density and cost of CAES systems should also be considered. For example, liquid air energy storage (LAES) reduces the storage volume by a factor of 20 compared with compressed air storage (CAS).

Advanced CAES systems that eliminate the use of fossil fuels have been developed in recent years, including adiabatic CAES (ACAES), isothermal CAES (ICAES), underwater CAES (UWCAES), LAES, and supercritical CAES (SC-CAES) [18,23]. CAES was evaluated as a competitor to pumped hydro storage and Li-ion battery storage for stationary storage applications. A DOE report predicts that CAES can potentially be installed at approximately 60 GW·h in 2030, as illustrated in Fig. 1 [24].

The main components of CAES include a motor, CMP, HX, storage vessel, an expander, and a generator [25–27]. The research and development (R&D) of CAES is based on the thermodynamic cycle design and analysis, component design and analysis, and system integration and demonstration. This paper presents an overview of recent R&D of advanced CAES systems from three perspectives: system description, theoretical studies, and experiments and demonstrations. The major characteristics and parameters of these advanced CAES technologies (i.e., ACAES, ICAES, LAES, SC-CAES, UWCAES, and CAES coupled with other technologies), are presented in the following sections.

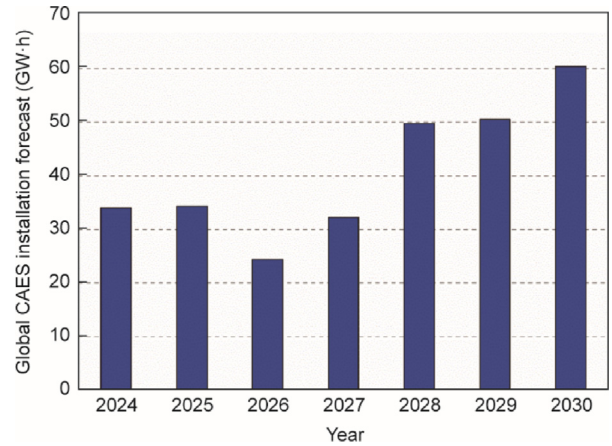

Fig. 1. Projected addressable market for CAES technology [24].

1.2. Previous reviews on CAES

Many researchers have reviewed and summarized the research progress on CAES from various perspectives. These publications were reviewed, and the main conclusions are as follows.

Bazdar et al. [28] summarized the application of CAES in integrated energy systems such as CAES–organic Rankine cycle (ORC), –desalination, –biomass, –solar, and –wind. Detailed parameters, such as the round-trip efficiency, capital cost, and exergy efficiency of the integrated system, are presented in detail. The CAES design criteria and application potential, scale design optimization, and role of CAES in microgrids, distribution grids, and energy market environments are discussed.

Hamiche et al. [29] briefly introduced a classification of CAES technologies, the characteristics of each type of CAES technology, and CAES projects globally. They focus on the trends in the application of CAES technologies, for example, for integration with solar photovoltaic (PV) to improve the resilience of smart grids and the construction of the energy internet.

Borri et al. [30] briefly outlined the development history, classification, working principles, and applications of CAES technology and applied bibliometric techniques to analyze 2542 documents retrieved from the Scopus database in terms of the year of publication, country of publication, and keywords. Thus, they identified the research trends in CAES, which have recently included aspects related to off-design characteristics, ACAES for heat energy storage development, and the integration of CAES with combined heating and cooling systems.

Matos et al. [31] focused on CAES projects globally and outlined insights into the regulatory frameworks and policies reported in different countries, identifying the drivers and impediments faced in the development of energy storage systems.

King et al. [32] briefly described several CAES technologies and current large-scale CAES projects and proposed several methods for storing compressed air utilizing subsurface properties. This review emphasized the evaluation and comparison of the potential of combining renewable power generation systems with underground storage capacity in CAES plants in India and United Kingdom for large-scale applications.

Guo et al. [33] briefly described the characteristics of various CAES technologies and reviewed the optimal design of CAES from three key aspects: system analysis and optimization methods, non-design characteristics of the system, and design methods for non-designed operations. They also presented challenges and development trends in three key areas.

Gouda et al. [34] focused on an overview of the liquid piston (LP) technology for CAES applications, providing comprehensive and integrated knowledge of thermodynamics, fluid flow, and heat transfer mechanisms within LP. Particular attention has been paid to thermal management issues and measures to enhance heat transfer proposed and implemented by different researchers to achieve efficient LPs.

Olabi et al. [35] described various types of CAES systems and presented different components (CMPs and expanders) applicable to various CAES systems. Three categories were discussed: reciprocating expanders, rotary expanders, and turbo machines. Reciprocating and rotary expanders were recommended for micro- and small-scale CAES, whereas turbo machines were reported to be more suitable for large-scale CAES. The recommended operational conditions for reciprocating expanders were a high pressure ratio and low rotational speed. Rotary expanders operate at medium pressure ratios and low rotational speeds. Turbomachines were recommended to operate under a high-rotational speed and low-pressure ratio of a single stage. The design advantages and disadvantages of underground and aboveground CAS systems, such as salt caverns, were discussed. The system's mode of operation was explored, and the health and safety issues associated with energy storage systems were explored.

Zhou et al. [36] reviewed TES suitable for CAES systems. They investigated the roundtrip efficiency versus temperature, which was approximately 50%–70%. Various storage materials and configurations were reviewed, including sensible heat storage, packed-bed heat storage, and latent heat storage. Ali et al. [37] presented insights into the materials and applications. The cost must be affordable for application in CAES. Gil et al. [38] investigated high-temperature thermal storage for power generation, reporting that the development of an efficient and cost-effective thermal storage system is crucial for power generation systems.

Zhang et al. [39] discussed and compared the dynamic operation control strategies of CAES systems, which allowed the CAES to operate over a large range suitable to balance the mismatch of fluctuated renewable generation and customer's demand. The review includes an overview and summary of throttling valve control technology, ejector technology, guided vane adjustment technology, and switching valve decompression and expansion technology, which helped integrate and plan the dynamic control strategies of different CAES systems for various energy system applications.

This review provides a comprehensive summary and description of advanced CAES systems, demonstrates the development of the technology both theoretically and experimentally, and compares these advanced CAES systems with respect to technical maturity, power ratings, roundtrip efficiency, and capital costs. The detailed parameters are summarized and presented in a Table.

A comparison of the present review with previous reviews is presented in Table 1 [28–39].

1.3. Novelty of this review

A summary of the literature reviews in Section 1.2 suggests the following gaps in advanced CAES R&D.

The novelty of this review is outlined as follows.

(1) Systematic review of conventional and advanced CAES systems. Advanced CAES systems, as a clean technology, have developed rapidly and have shown potential in large-scale applications in recent years.
(2) Comprehensively summarizes and describes the working principles and characteristics of these advanced CAES systems, which promote R&D and demonstration with theoretical and experimental studies.
(3) The advanced CAES technologies are compared and discussed from different perspectives, considering the technical and economic indicators furnished as a reference in this field.
(4) The detailed parameters of all the advanced CAES technologies are reviewed, summarized thoroughly, and compared in a table for the first time.

This study attempts to review the recent R&D of advanced CAES technologies, thereby presenting an effective summary to serve as a guide for researchers from academia and industry. The remainder of this paper is organized as follows. Section 2 briefly introduces the general principles and development of the CAES. In Section 3, state-of-the-art advanced CAES technologies are reviewed and presented, along with details of their fundamentals and applications. In Section 4, comparisons and discussions are presented and summarized. Finally, Section 5 presents the conclusions of this study.

2. General principle and development of CAES system

2.1. Conventional CAES description

The first CAES plant was built in 1978 by BBC Brown Boveri with the term "Gas Turbine Air Storage Peaking Plant" at Huntorf, Germany. A schematic of the system is presented in Fig. 2. This system represents the first-generation CAES. The air was first compressed during charging, cooled through a HX, and then compressed again. It was then cooled to approximately the ambient temperature and stored in an underground cavern. During discharge, the air is released to a proper pressure and burned in the combustor (CMB) with fossil fuel. Air at high pressure and temperature drives the turbine to generate electricity. The Huntorf plant still exists and was augmented from 290 to 321 MW in 2006. The second was built in 1991 at the McIntosh site, USA by the Power South Electric Cooperative with a power rating of 110 MW [18]. Subsequently, other projects have been announced. However, only a few large-scale CAES plants have been developed to date. Many new attempts with non-fuel-consuming CAES have been made, categorized as advanced CAES systems.

2.2. History of CAES development

A brief history of the CAES development is presented in Fig. 3. The upside presents the development trends in different regions of the world, and the downside summarizes and displays these main projects, for example, large-scale CAES projects, which are categorized into two groups: realized projects and planned projects. The first CAES facility of 220 MW in the United States was planned in 1982 for Soyland Power Cooperative, Inc., an Illinois utility supported by Environmental Science and Engineering, Inc., St. Louis, Missouri, and the US DOE via the Pacific Northwest Laboratory [40]. This planned CAES plant was canceled after a detailed design and evaluation owing to a more moderate growth in electricity demand than expected [18]. A 2700-MW CAES project (300 MW $\times$ 9) was planned in 2000 as a merchant facility to manage the timing value of electricity within diurnal and weekly cycles utilizing an abandoned limestone mine. The Ohio project was contracted by Norton Energy Storage LLC, which was also responsible for the design, construction, and operation [41]. However, the project was terminated by the Ohio Power Siting Board in 2013 owing to a lack of forward movement by the developer [42]. In 2002, the Iowa Association of Municipal Utilities developed a CAES to secure an intermediate electricity supply. Multiple project studies were performed, and the Dallas Center site near Des Moines, on the edge of a favorable wind energy regime, was chosen. Economic studies, site geology, and project marketing have been intensively con-

Table 1
Comparison of reviewed publications on CAES.

Authors	Year	Technology development	Characteristics	TES	Economy	Commercialization status	Technical comparison	Challenges	Future trends	Article features
Present Study	2023	√	√	√	√	√	√	√	√	A comprehensive review of advanced CAES system R&D from both theoretical and experimental perspectives, and a comparison of CAES in terms of techno–economic indicators
Bazdar et al. [28]	2022	√	√	√	√	√	√	√	√	A review of the research progress in CAES and the challenges it faces from the perspective of CAES integration, optimal design and scheduling, and the role of CAES in microgrids, distribution grids, and energy markets
Hamiche et al. [29]	2023	√	√	√	×	√	×	×	√	CAES plays a significant role in the development of the energy internet and smart grids
Borri et al. [30]	2022	√	√	√	×	√	×	√	√	A brief overview of CAES advances through bibliometric analysis methods and assess research trends and future prospects for CAES systems
Matos et al. [31]	2022	×	×	×	√	√	√	×	√	Review of CAES facilities and programs and overview of energy storage regulatory frameworks and policies
King et al. [32]	2021	√	×	×	×	√	×	×	×	Overview of current CAES projects and analysis of potential underground storage capacity of India and United Kingdom
Guo et al. [33]	2023	√	√	×	×	×	×	√	√	An overview of the current status and challenges of CAES thermodynamic design
Gouda et al. [34]	2021	√	√	×	×	√	×	√	×	A Review of techniques for enhanced heat transfer in LP
Olabi et al. [35]	2020	√	√	√	×	√	√	√	×	The operating modes of the system are discussed, as well as the health and safety issues related to energy storage systems, and a comparison is made between different expansion machines
Zhou et al. [36], Ali et al. [37], Gil et al. [38]	2019 20242010	√	√	√	×	×	√	√	√	All types of TES were reviewed for integrating into CAES and improve whole performance
Zhang et al. [39]	2023	√	×	×	×	√	√	√	×	Dynamic operational control strategies for CAES systems

The"√" in the table indicates that there is relevant content in the article, while the "×" indicates that there is no relevant content.

ducted. In 2011, the project was terminated owing to the geological limitations [43]. In 2006, the Huntorf CAES plant was retrofitted by adjusting its inlet temperature and pressure 28 years after its operation. The output power was increased from 290 to 321 MW [18]. Japan planned to develop CAES in 2000. A relative investigation was conducted to drill a borehole 600 m in depth to evaluate the sedimentary rock surrounding the CAES cavern, consisting mainly of conglomerates in northeastern Kyushu, Japan [44].

The Pacific Gas and Electric Company (PG&E) was awarded funding from the DOE and other sources to demonstrate a 300 MW–10 h CAES utilizing a porous rock reservoir in San Joaquin County, California, in 2011 [45]. PG&E's CAES project was planned to proceed in three phases: ① project definition and compliance; ② plant construction, commissioning, and operation; and ③ plant monitoring and technology transfer. It is expected to be commissioned by 2021 but no recent announcements have been made regarding this project.

An advanced ACAES concept was developed in the ADELE project in Germany in 2010 by the RWE Power Company [18]. The generation was designated to exceed 200 MW with a total storage capacity of 1 GW·h [46,47]. The project entered the next phase of ADELE-ING in 2013 [18]. The concept involved high pressure and temperature, and the main components of the CMP, expander, and high-temperature thermal storage unit were analyzed. However, progress stalled in 2017 owing to "uncertain business conditions" [48].

New York State Electric & Gas worked with the federal DOE on an energy-efficient energy storage system and launched a 150-MW

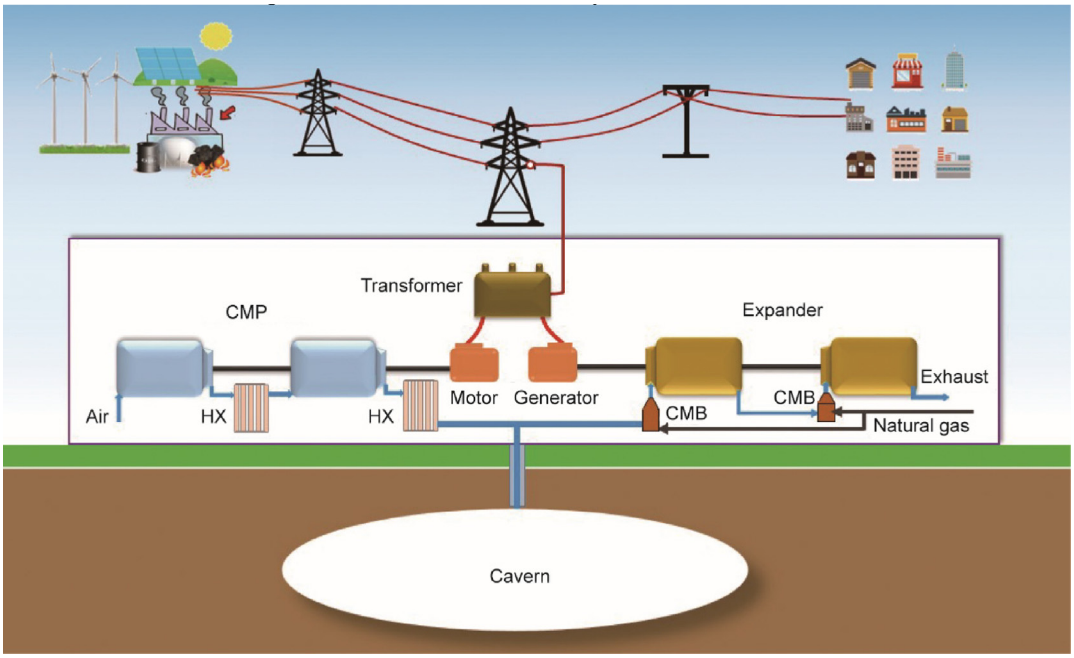

Fig. 2. Schematic of conventional CAES system. CMB: combustor.

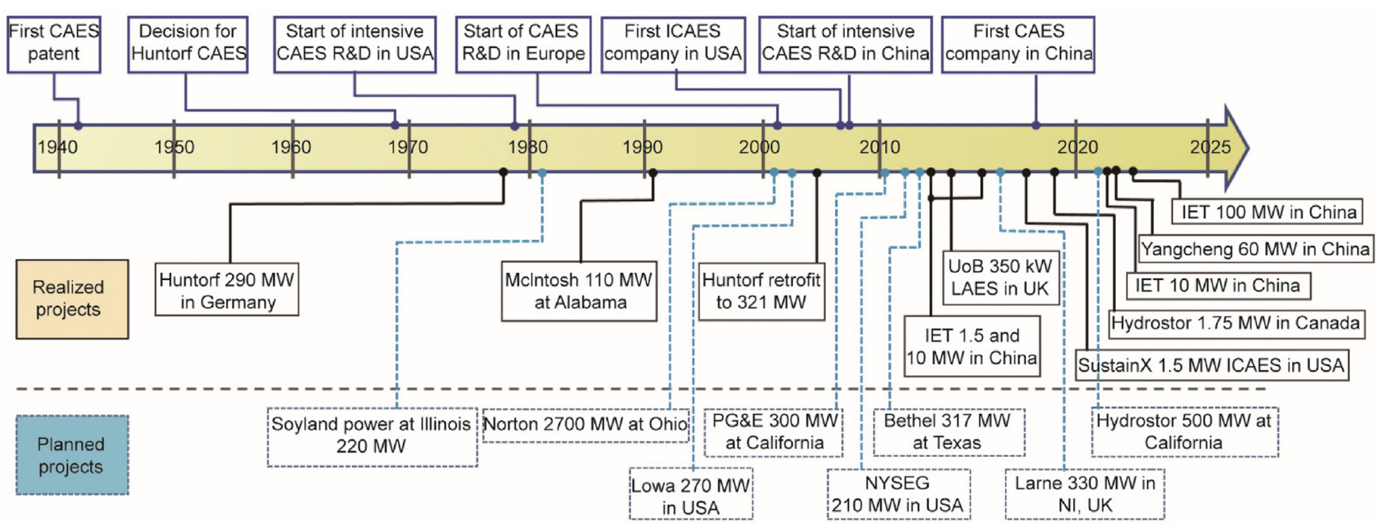

Fig. 3. Brief development history of CAES with main projects. IET: Institute of Engineering Thermophysics, Chinese Academy of Sciences; PG&E: Pacific Gas and Electric Company; UoB: University of Birmingham; NYSEG: New York State Electric & Gas; NI: Northern Ireland.

CAES demonstration program on the side of Seneca Lake in New York in 2010; a salt cavern was utilized for air storage [49]. The proposed project comprised three phases: Phase 1 to develop a front-end engineering design, including project capital costs; Phase 2 to complete plant construction with a target in-service in mid-2016, and Phase 3 to realize commercial demonstration, testing, and two years of performance reporting. While phase 1 was completed accordingly, the remaining two phases were cancelled [49,50]. The Apex Bethel Energy Center (BEC), LLC (Apex), proposed the construction of the BEC, a 317-MW CAES facility in Anderson County, Texas, in 2013, and planned to be commissioned in 2020. The key applications of this project include black start, frequency regulation, ramping, and renewable energy time shifts [18,32]. There was no official news on the state of the plant.

SustainX developed a 1.5-MW ICAES demonstration in 2013 [51]. The Highview Power Company cooperated with Professor Ding at the University of Leeds (then University of Birmingham) to develop a 350-kW LAES demonstration in London in 2012 [52]. Researchers from the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, developed a 500-kW CAES system in Wuhu, China, in 2014 [53]. In Japan, a 1-MW CAES plant adjacent to the Higashiizu wind farm of Tokyo Electric Power Company Holdings, Inc. was installed in Shizuoka Prefecture in 2017 [54]. The plant had two 500-kW basic units, enabling the charging/discharging of a maximum of 1 MW. The Ministry of Economy, Trade, and Industry inspected the pre-utilization of this CAES plant in March 2017. It operated for one and a half years and closed in October 2018 [54]. The Hydrostor company led the construction of a 1.75-MW CAES demonstration in Goderich, Ontario, Canada, in 2019 [55]. A 500-MW CAES facility was announced by Hydrostor to be constructed in Kern, California, USA. A 330-MW CAES plant with two 165-MW trains was planned to be built in

Larne, Northern Ireland, utilizing an underground salt formation for storage [18]. Fundamental research on large-scale CAES was conducted, and the geological conditions of the salt cavern were inspected. Gaelectric Energy Storage company, which administrated this project, withdrew its planning application [56]. The Israeli technology company—Augwind, founded in 2012, announced that a small-scale air-battery energy storage pilot was almost completed in the Arava Desert, Israel.

Since 2010, a team at the Institute of Engineering Thermophysics (IET), Chinese Academy of Sciences, has developed novel types of CAES. The SC-CAES was first proposed by Chen et al. [57]. The team developed advanced small to large scale, including 1.5, 10.0, and 100.0 MW demonstrations. The details of this projects are discussed in the following content.

The abovementioned projects are listed and compared in Table 2 [18,32,40,41,43,45,48–50].

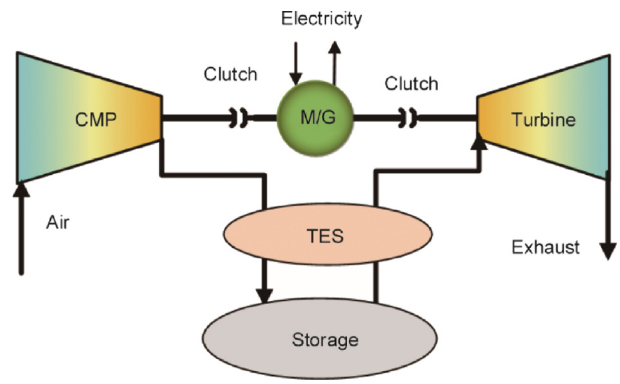

Fig. 4. Schematic of ACAES system. M/G: motor/generator.

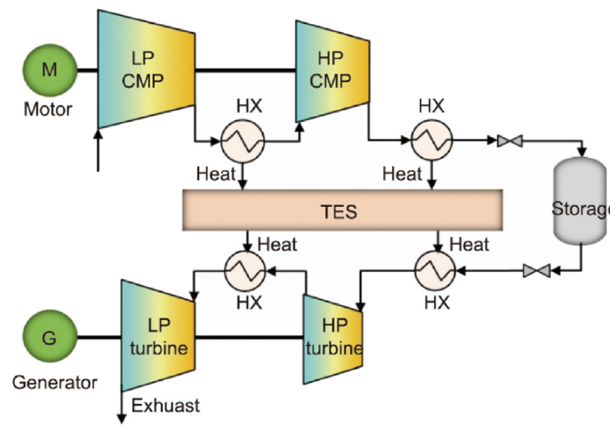

Fig. 5. Schematic of CAES–TES.

3. State-of-the-art advanced CAES systems

3.1. CAES with TES

3.1.1. System description

No fuel was added to the CAES with TES. The compression heat produced when compressing the air was stored and reutilized during discharging (Fig. 4). As illustrated in Fig. 4, which demonstrates an ACAES, the system has a one-stage CMP and an expander. The air temperature exceeded 800 K when the pressure is above 10 MPa. This results in a compact configuration and high-temperature TES. The other type is illustrated in Fig. 5, which has two or more CMP and expander stages. The pressure ratio of each stage is lower than that of the ACAES, as is the temperature of the TES [18]. TES can also store thermal energy from other sources, such as solar energy and waste heat, to improve system efficiency. Thus, the temperature of the TES is related to the stages of the CMP; the lower the stages of the CMP, the higher the temperature of the TES. The temperature range was generally 370–800 K. TES materials can be solid, fluid, or solid–fluid mixtures, and the configuration is of two types: two-storage tanks with fluid TES materials and packed beds with solid TES materials [36]. Recent studies have established that the roundtrip efficiency of ACAES system is roughly in the range of 60%–80%, and the energy density is roughly in the range of 1.8–72.0 $MJ{\cdot}m^{-3}$ [18,58].

3.1.2. Theoretical studies

The ACAES was introduced in 1976. The theoretical round-trip efficiency was as high as 73% [59]. Theoretical studies were conducted with respect to the CMP/expander stages, air temperature, HX effectiveness, dynamic operation, and modeling. An ACAES system with a five-stage CMP and five-stage expander was simulated. The storage temperature is approximately 400 K, under which HXs, CMPs, and TES materials are accessible in current industries [18]. The entire system operates with startup, stop, dynamic operation, partial load, thermal inertia of the components, and volumetric effects of the pipes and HXs. Via a comprehensive analysis considering these factors, it is concluded that the startup time is approximately 4.50 min; the system roundtrip efficiency is 71.79%, and the exergy destruction distribution is as follows: CMP 9.24%, expander 6.84%, HXs of CMP 4.17%, HXs of CMP 2.50%, throttle 3.64%, and other devices of the ACAES system approximately 1.00% [60].

The finite-time thermodynamics methodology involves time and size factors in a cycle, which is suitable for properly analyzing and optimizing CAES systems, considering the characteristics of charging and discharging processes, heat transfer and storage, and air storage [61]. The analysis illustrated the effect of the compression pressure ratio versus expansion pressure ratio, CMP efficiency versus expander efficiency, and stored temperature versus

Table 2
Comparison of demonstrated projects of CAES.

Project Title	Location	Year	Status	Type	Generation power
Huntorf CAES plant [18]	Germany	1978	Retrofitted in 2006	D-CAES	321 MW
McIntosh CAES plant [18]	USA	1991	Operation	D-CAES	110 MW
Illinois CAES [40]	USA	1982	Canceled	D-CAES	220 MW
Ohio Project [41]	Texas, USA	2000	Terminated in 2013	D-CAES	2700 MW
Dallas Center Project [43]	Iowa, USA	2002	Terminated in 2011	D-CAES	–
PG&E Project [45]	California, USA	2011	No recent announcement	D-CAES	300 MW/3000 MW·h
ADELE Project [18,48]	Germany	2010	Terminated in 2017	ACAES	200 MW
Seneca Lake Project [49,50]	New York, USA	2010	Canceled	D-CAES	150 MW
BEC Project [18,32]	Texas, USA	2013	No official news about the plant	D-CAES	317 MW

thermal release temperature on the roundtrip efficiency. This methodology and its results present the design details for better performance of the ACAES system [61].

The selection of the TES is crucial for the overall performance of the ACAES (or CAES–TES). For these materials, the three major TES types are sensible, latent, and thermochemical [62]. They can be categorized into three types according to the operating temperature. The first one is the high-temperature system with storage temperatures above 400 °C. Rocks are recommended materials for such high temperatures. The research project ADELE utilized such high-temperature TES system, and the roundtrip efficiency was estimated to be 70% [46]. Molten salt is one of the best commercially available sensible TES materials at temperatures higher than 400 °C [63], and phase change TES material such as solar salt ($NaNO_3$–KNO_3 60–40 wt%) with an operating temperature of 290–565 °C utilized in concentrating solar power (CSP) plants. Molten chloride salts are considered the most promising materials of TES for the next-generation molten salt technology, which can be operated at up to 750 °C because of their excellent thermal properties and low costs [63]. The second one is the medium-temperature process with storage temperature between 200 and 400 °C. The slightly lower cycle efficiency is compensated by the applicability of off-the-shelf CMP technology and TES media, such as molten salt or thermal oil, which are already utilized in similar applications. Thermal oil and rock beds are suitable for middle and high-temperature TES (below 400 °C) [38,63]. The third on is the low-temperature process with storage temperature below 200 °C. The major advantages of low-temperature ACAES are the applicability of liquid TES media, which can be pumped, enabling the utilization of common HXs, and the applicability of off-the-shelf compression and expansion devices. Water is the most available and affordable sensible TES selection with relatively high heat capacity, and it is suitable for low-temperature TES (below 200 °C) [36].

The HX required for ACAES are also highly nonstandard and, like CMPs/expanders, must operate with variable mass flow, a design and control challenge [64]. Moreover, ACAES require considerably larger contact areas than conventional after coolers, and it is important to ensure that this does not lead to exceedingly large pressure losses in all HX stages. Controlling the balance of the HX is also challenging [65].

3.1.3. Experiments and demonstrations

The CAES requires high efficiency and a wide operating range for the CMP and expander. The internal flow features and aerodynamic performance were studied, which indicated that the efficiency was greater than 90% [66]. Various strategies have been studied to increase the operation range; for example, the flow rate range of the CMP can be increased by 31.5%, and the pressure ratio range can be increased by 427.4% by adjusting the guided vanes appropriately [67]. A high-pressure CMP test rig was built by Meng et al. [68,69] (Fig. 6), and the results were experimentally verified.

A pilot-scale demonstration of the ACAES was constructed. However, this study mainly focused on a packed-bed combined sensible/latent TES device installed in an air storage cavern [70,71]. The results demonstrated that the storage capacity was 12 MW·h at a temperature as high as 820 K, and the TES efficiency was between 76% and 90%. The round-trip efficiency of this ACAES is 63%–74% [70,71].

A large-scale ACAES was planned in ADELE, Germany a decade ago. The storage pressure was approximately 10–20 MPa, and the storage temperature was approximately 920 K utilizing a packed-bed TES system [72]. The project was partially canceled because of the technical challenges of the high-temperature requirements for TES materials and CMPs [18]. The EDF Company plans to develop CAES technology by storing air in EDF's existing gas storage facilities. The EDF's initial plan is to assess a 5-MW plant in 2023 and then work on how to scale up to a larger (100+)-MW scheme [73]. The IET demonstrated ACAES. One was a 1.5-MW system in Langfang City, China, in 2013, and another was a 10-MW system with a round-trip efficiency of 60.2% in Bijie City (Fig. 7), China, in 2016 [36]. The 1.5-MW system in Langfang City has dual cycles and therefore can also operate as a SC-CAES, as introduced in Section 3.4. Furthermore, a commercial demonstration of a 10-MW ACAES system was completed and connected to the grid by IET in Feicheng City, China, in 2021 (Fig. 8), and a 100-MW ACAES system was constructed and is currently in commissioning at Zhangjiakou City, China, as illustrated in Fig. 9; the round-trip efficiency was approximately 70%.

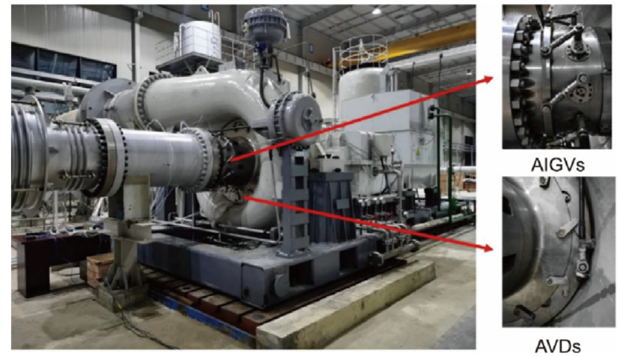

Fig. 6. Centrifugal CMP test rig. AIGVs: adjustable inlet guide vanes; AVDs: adjustable vaned diffusers.

3.2. Isothermal CAES

3.2.1. System description

The ICAES is illustrated in Fig. 10. During the charging process, the ambient air is compressed, and the compression heat is directly or indirectly transferred to a liquid with a high heat capacity. During discharging, the compressed air drives the expander, and the extra heat is directly or indirectly transferred to the air from the liquid with a high heat capacity, similar to an isothermal CMP. Separators were placed after the isothermal CMP and expander to drain the liquid from the air. The ideal ICAES system efficiency can be as high as 90%, and the energy density can be as high as 47 $kW·h^{-1}·m^{-3}$ [18,74,75]. Generally, the round-trip efficiency and energy density of ICAES range from 66.0% to 96.0% and 3.6 to 90.0 $MJ·m^{-3}$, respectively [18,77].

Fig. 7. 10-MW CAES system at Bijie City.

Fig. 8. 10-MW CAES system at Feicheng City.

Fig. 9. 100-MW CAES system at Zhangbei City.

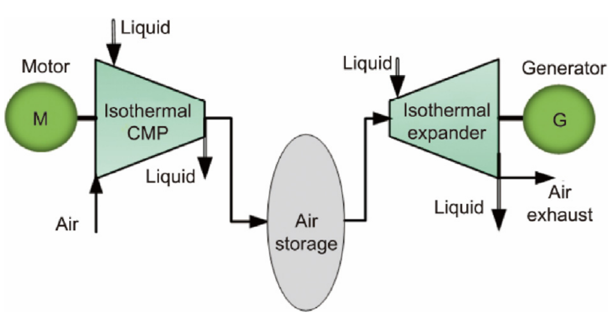

Fig. 10. Schematic of ICAES system.

3.2.2. Theoretical studies

With respect to heat transfer, two methods exist for realizing isothermal compression and expansion: CMP/expander surface heating (indirect heat transfer) and secondary fluid heating (direct heat transfer) [78]. For direct heat transfer, the liquid was injected into the airflow. The two fluids were separated after compression and expansion. For indirect heat transfer, the fluid flows around the components to absorb the compression heat or heat the expansion air through the component's wall and certain devices (e.g., inside porous media). Alternatively, the compression/expansion process is divided into many stages; thus, the air is cooled down by intercoolers after each CMP stage and heated by the interheaters before each CMP stage.

An offshore ICAES (OICAES) system that utilizes direct heat transfer to realize isothermal processes was proposed [79]. A 200-MW ICAES case was studied. The results demonstrated that the energy storage capacity and power delivery rate affected the OICAES efficiency, which was between 61% and 82%, respectively. The capital investment cost is 1457 USD$\cdot$kW^{-1} for a 10-h 200-MW system, which is 145.7 USD$\cdot$kW$^{-1}\cdot$h^{-1} [79].

Instead of the conventional solid (metal) piston of volumetric machinery, a LP utilizes a column of liquid (usually water) to compress air or expand it for charging or discharging [34]. The main advantages of a LP are that gas leakage can be avoided, and dissipation due to friction is largely reduced, leading to a higher efficiency than solid piston machinery [34]. Fig. 11 [80] illustrates an ICAES with a LP and spray cooling for enhanced heat transfer—mainly comprising a CAS tank, two working cylinders for air compression/expansion, a reversible hydraulic pump/turbine for water flow, a motor/generator to store/generate electricity, and two pumps to spray water. Air was utilized as the energy storage medium, and water as the power generation medium. Both cylinders generated compressed air during the charging period, which was delivered to the CAS tank. When Cylinder A was in the air compression process, the water in Cylinder B was pumped by the hydraulic pump to Cylinder A, and Cylinder B was pumped by the ambient air intake process. Subsequently, the two cylinders change their operation modes in the next cycle. Thus, continuous energy storage was achieved. Compressed air enters Cylinder B during the discharge period, driving the water level to generate electricity through the hydraulic turbine. Water flowed into Cylinder A from Cylinder B to push the expanded air out. Subsequently, the two cylinders change their operation modes in the next cycle. These two cylinders operate individually with all the valves on or off to generate compressed air and electricity. The air pressure was 10 MPa, and the round-trip efficiency reached 76% [80].

3.2.3. Experiments and demonstrations

A ground-level integrated diverse energy storage (GLIDES) system recently proposed at the Oak Ridge National Laboratory (USA) stores energy via gas compression. A prototype was constructed and tested [77,81–83]. A LP and hydraulic machines operate to realize isothermal compression and expansion inside high-pressure vessels that seal the leakage between the piston and cylinder [77]. The storage pressure was in the range of 20–30 MPa. The system is predicted to achieve round-trip efficiency ranging from 66% to 82%, with an energy density in the 2.46–3.59 MJ$\cdot$m^{-3} range. A prototype developed at Oak Ridge National Laboratory can generate power of 2 kW. The experimental electrical round-trip efficiency indicated efficiencies of 24% and 97% with a peak pressure limited to 13 MPa (Fig. 12 [82]) [77,81–83].

This study investigated an isothermal CMP by ejecting water droplets through different nozzles. The temperature of the exhaust from the cylinder was more than 50 K lower than that of near-adiabatic compression. The polytrophic component was reduced to 1.161 [84]. An isothermal expander was developed and tested, as illustrated in Fig. 13 [85]. Direct heat transfer was realized by spraying tiny water droplets into the cylinder. They concluded that specific work increased by 15.7% [85].

A liquid-piston CMP experimental setup was constructed to study convective heat transfer and correlate the equations for isothermal compression modeling [86]. The volumetric pump is 4 kW, and it can drive the LP to move at nearly constant speeds for a large range of velocities $U_{pist} \in [0.08–1.20]$ m$\cdot$s^{-1}. The length of the compression chamber was between 2.00 and 6.00 m, and the mean diameter was 0.03–0.10 m. The results demonstrated that the air temperature and pressure increased gently at the beginning

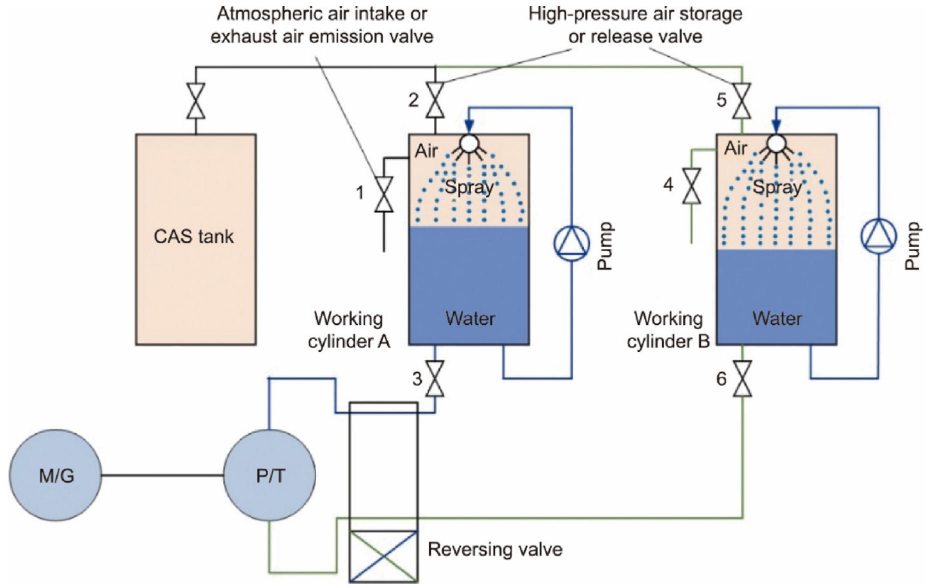

Fig. 11. Schematic of ICAES with LP and spray cooling. P/T: pump/turbine. Reproduced from Ref. [80] with permission.

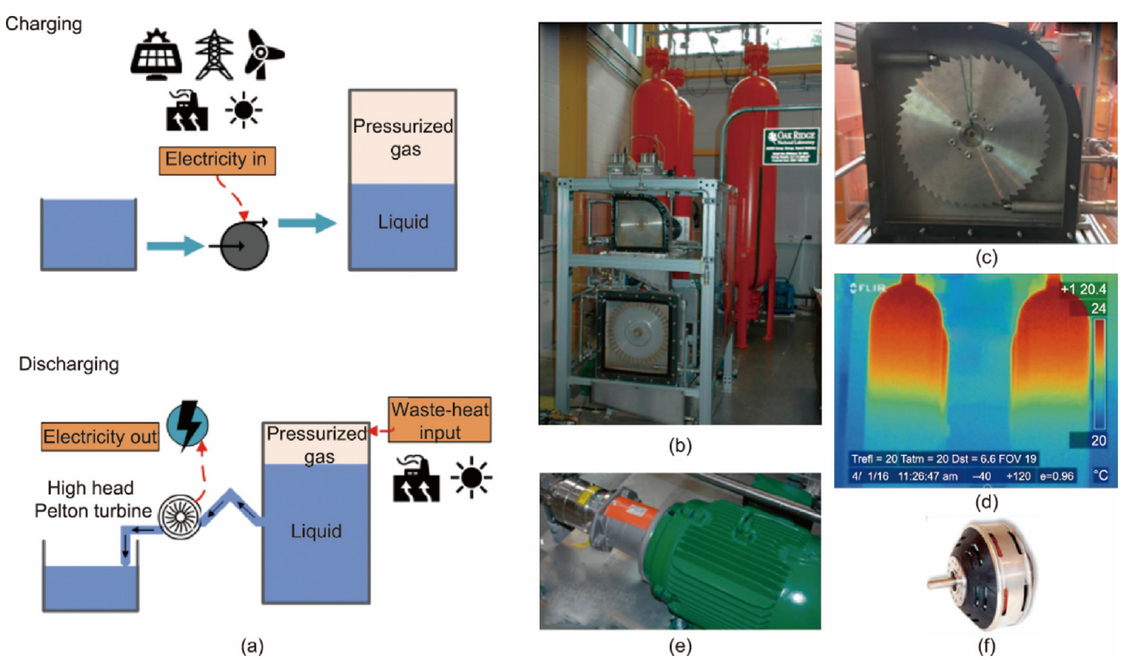

Fig. 12. GLIDES prototype. (a) GLIDES system, (b) overall system and pressure vessels, (c) Pelton turbine, (d) infrared image of pressure vessels during charging, (e) charging pump/motor, (f) electric generator. Reproduced from Ref. [82] with permission.

and quickly from the bottom to the top when compressed with a piston velocity of approximately 0.125 m·s^{-1}. The energy flux between air and water increased from 100 to 600 W, and the Nusselt number increased from approximately 20 to 160 [86]. The marine environment has significant advantages for CAES, whether for cooling compression systems or for maintaining air pressure. REMORA [86–87] is a novel ICAES patented by Segula Technologies (France). The working principle of REMORA utilizes LP technology to compress air at a constant temperature, store energy in a reservoir installed on the seabed, and store high-pressure air in underwater gas-storage tanks. This concept is particularly suitable for the large-scale storage of ocean energy. Segula Technologies proposed an ICAES system with a 15-MW floating platform and underwater tanks with a storage capacity of 90 MW·h, which could feed back up to 70% of the electricity stored. The group is currently investigating compressed air chambers in the lab [86,87]. Maisonnave et al. [87] from Segula Technologies briefly introduced the system's working principle and proposed an efficient platform layout scheme for subdividing energy conversion systems into different power ranges to minimize energy losses and optimize the development of this power system. Neu et al. [86], one of the researchers at REMORA Technology Development (SEGULA Technologies Company), conducted extensive research on the heat transfer characteristics of LP. By analyzing the experimental results of large-sized chamber LP air compression, the possibility of approaching isothermal compression can be improved by modifying the experimental parameters, such as the compression chamber's length, diameter, pressure, and LP velocity. A correlation

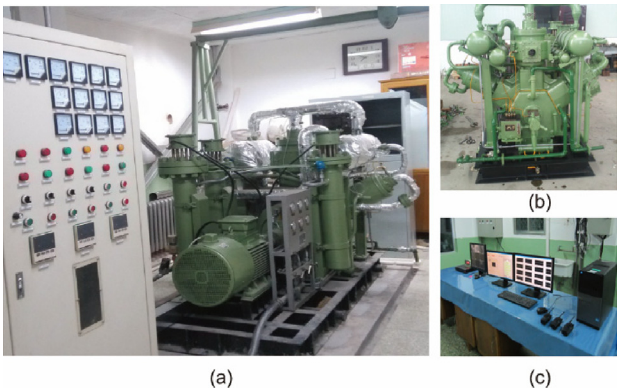

Fig. 13. Piston expander experiment. (a) expander testrig, (b) expander, (c) data acquisition system. Reproduced from Ref. [85] with permission.

between the parameters and the convective heat transfer characteristics was established with the Reynolds number, Prandtl number, and geometric ratio to predict the Nusselt number. Subsequently, the internal flow structure of air in the LP was further investigated with 2D particle image velocimetry (PIV) [88] by measuring the presence of two continuous flow regimes that can be repeatedly generated during compression. The experimental setup comprised a compression chamber that was 0.906-m long and 0.0518-m in diameter, with a piston moving at 0.0333 $m{\cdot}s^{-1}$. The first phase is repeatable and axisymmetric and is composed of a centrally accelerated column and an annular reverse flow. From the 24% displacement point along the piston stroke, the flow became unstable in the high-shear zone, resulting in a typical Kelvin–Helmholtz instability structure and a highly chaotic mix. A 3D computational fluid dynamics (CFD) model of a low-pressure CMP utilizing finite volume method (FVM) and volume of fluid (VOF) methods was investigated by Gouda et al. [89]. The results were verified by comparison with existing experimental data. The results demonstrated different flow patterns during compression. The establishment, evolution, and transition to a fully chaotic flow structure of axisymmetric flow structure are in line with Neu and Subrenat's experimental results in Ref. [88]. Recently, utilizing a combination of CFD simulation and experimental testing, Gouda et al. [90] studied the flow patterns and heat transfer characteristics of a complete thermodynamic cycle composed of low-pressure air compression, isochoric cooling, and expansion (CCE) stages. The temperature fields of different airflow patterns, transitions, and cycle stages were visualized, analyzed, and compared. The results demonstrated that, during the expansion stage, the rapid establishment, evolution, and destruction of the axisymmetric flow structure can be identified as a fully chaotic flow structure. At the tested piston velocity (0.033 $m{\cdot}s^{-1}$) and compression/expansion ratio (CR = ER = 4.8), the LP can realize a near-isothermal cycle and has high compression, expansion, and overall efficiencies (up to η_c = 91.2%, η_e = 94.7%, and η_{cycle} = 86.3%). The numerical parameter study results demonstrate that a lower wall temperature can slightly improve the compression and expansion efficiencies, whereas a slower piston velocity is favorable for improving the overall efficiency.

The porous inserts inside the compression and expansion cylinders enlarge the heat transfer surface and enhance heat transfer. Both compression (pressure ratio of 10) and expansion (pressure ratio of 6) processes were tested [91]. In the compression cylinder, the power density was increased by 39-fold at 95% efficiency, and the efficiency could be enhanced by 18% at power density of 100 $kW{\cdot}m^{-3}$ with these porous inserts. In the expansion cylinder, the porous inserts increased the power density threefold at 89% efficiency. The inserts can also help improve efficiency for a given power density, and the expansion efficiency can be increased from 83% to 90% at 150 $kW{\cdot}m^{-3}$ power density [91–93]. The experimental setup of the LP CMP with an inserted metal wire mesh sheet is illustrated in Fig. 14 [94]. The compression chamber was made of polycarbonate with a diameter of 88 mm and height of 170 mm, which was installed inside a cylinder. The atmospheric air was compressed to approximately 0.28 MPa. The experimental results demonstrate that the peak air temperature can be reduced by 26–33 K with a metal wire mesh. The metal wire mesh was observed to improve the isothermal efficiency of compression to 88%–90% from the base efficiency of 82%–84% [94].

SustainX built a 1.5-MW ICAES demonstration. Here, a water-based foam heat transfer method was developed inside a cylinder to improve the isothermal efficiency of a CMP/expander. The theoretical round-trip efficiency of the ICAES is approximately 100%. The test results of the 1.5-MW prototype demonstrated a round-trip efficiency of 54% [51]. However, no recent progress has been reported for SustainX.

3.3. Liquid air energy storage

3.3.1. System description

A schematic of the LAES is illustrated in Fig. 15 [95–98]. During charging, the purified air is compressed via multistage compression, cooled by the stored cold energy, and recirculating cold air. The air then flows through a cryoturbine or Joule–Thomson throttling valve and becomes liquid air, which is stored in a cryogenic (Cyro) tank (~78 K and near-ambient pressure). The compression heat was stored for future use. Liquefying air reduces the air volume by a factor of 700 [99]. The charging process is closely related to the liquefaction industry and usually involves conventional air liquefaction technology. During charging, a subcritical operating pressure of approximately 0.6–1.0 MPa.

The air is first compressed and cooled until it reaches a liquid state, often utilizing cycles such as the simple Linde–Hampson cycle, precooled Linde cycle, dual-pressure Linde, and simple Claude cycle for air liquefaction, as illustrated in Fig. 16 [52]. This was a self-refrigeration process. One stream of compressed air is first cooled and then throttled through a throttle valve or expanded in an expander, leading to a lower temperature as a coolant, which is utilized to cool the main stream [98,100]. The first LAES pilot-scale demonstration plant of the Highview Power Company (UK) indicated that a separate stream was extracted and expanded as a coolant [100]. This coolant stream is removed, which reduces the amount of liquid air compared with the total air inlet into the system. These conventional air liquefaction techniques result in low round-trip efficiency of LAES [99,101,102]. During discharge, liquid air is pumped to a higher pressure and delivered to a cold storage device. The cold energy of the liquid air is transferred and stored for future use. The liquid air was gasified. Air is heated again by stored heat or other heat sources and enters the expander to generate electricity. Because the density of liquid air is much higher than that of compressed air, the storage volume can be reduced by a factor of 20. The energy density was approximately 120–200 $kW{\cdot}h{\cdot}m^{-3}$, and the round-trip efficiency was estimated at approximately 50%–60% for large-scale systems. If additional heat is added, the efficiency can exceed 70% [52,96,98,103–105].

3.3.2. Theoretical studies

The LAES concept was first proposed by Smith at the University of Newcastle in 1977 for electricity peak shaving [106]. Researchers in academia and industry have studied the fundamentals and applications of LAES. The storage and reutilization of high-grade cold energy storage at approximately 73 K and the investigation of suitable and efficient cold storage materials are fundamental to increasing system performance [103]. The LAES system configu-

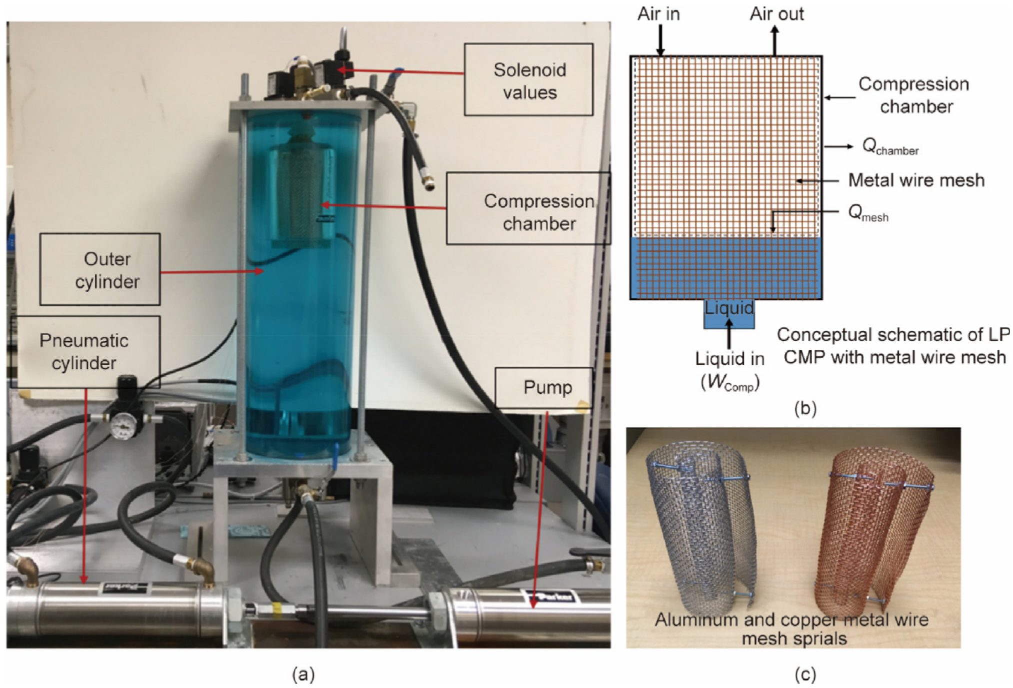

Fig. 14. Experimental setup of LP CMP with metal wire mesh insert. (a)Experimental setup of LP CMP, (b) conceptual schematic of LP CMP with metal wire mesh, (c) aluminum and copper metal wire mesh sprials. W_{comp}: work of compression; $Q_{chamber}$: heat transfer from gas to surrounding through compression chamber; Q_{mesh}: heat transfer from gas to liquid through the metal wire mesh. Reproduced from Ref. [94] with permission.

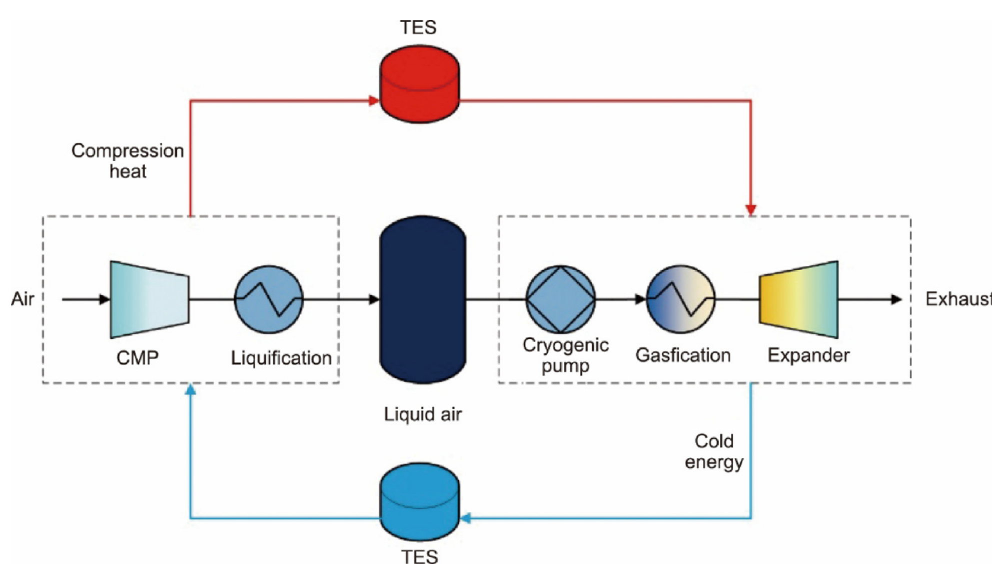

Fig. 15. Schematic of LAES system. Reproduced from Ref. [97] with permission.

ration is presented in Ref. [107]. The working principle, cold energy storage device, and system performance are also discussed. The study concluded that the reutilized cold energy of liquid air for the generation process can double the roundtrip efficiency achieved without reutilized cold energy. The efficiency of the system exceeded 70% [107]. LAES systems typically adopt a packed-bed cold energy storage configuration with a high thermal efficiency of more than 85% [103]. Temperature distribution and variations in a granite pebble-packed bed at pressure of 0.1 MPa and 6.5 MPa and lowest temperature of 78 K were investigated. The thermocline behavior of the transient temperature during charging and discharging has been revealed [108]. Because many HXs were utilized in the system, different pinch points of the HX affected the round-trip efficiency. For a pinch-point temperature difference of 5–15 K, the thermodynamic analysis indicated that a decrease of 5 K led to a drop in the round-trip efficiency of 2.2%. However, a smaller pinch-point temperature difference requires a higher cost HX owing to the larger heat transfer area. There should be a balance between thermodynamic performance and economics [52,104].

The application of LAES has also been widely studied, such as liquid air/nitrogen as an energy carrier to store renewable energy

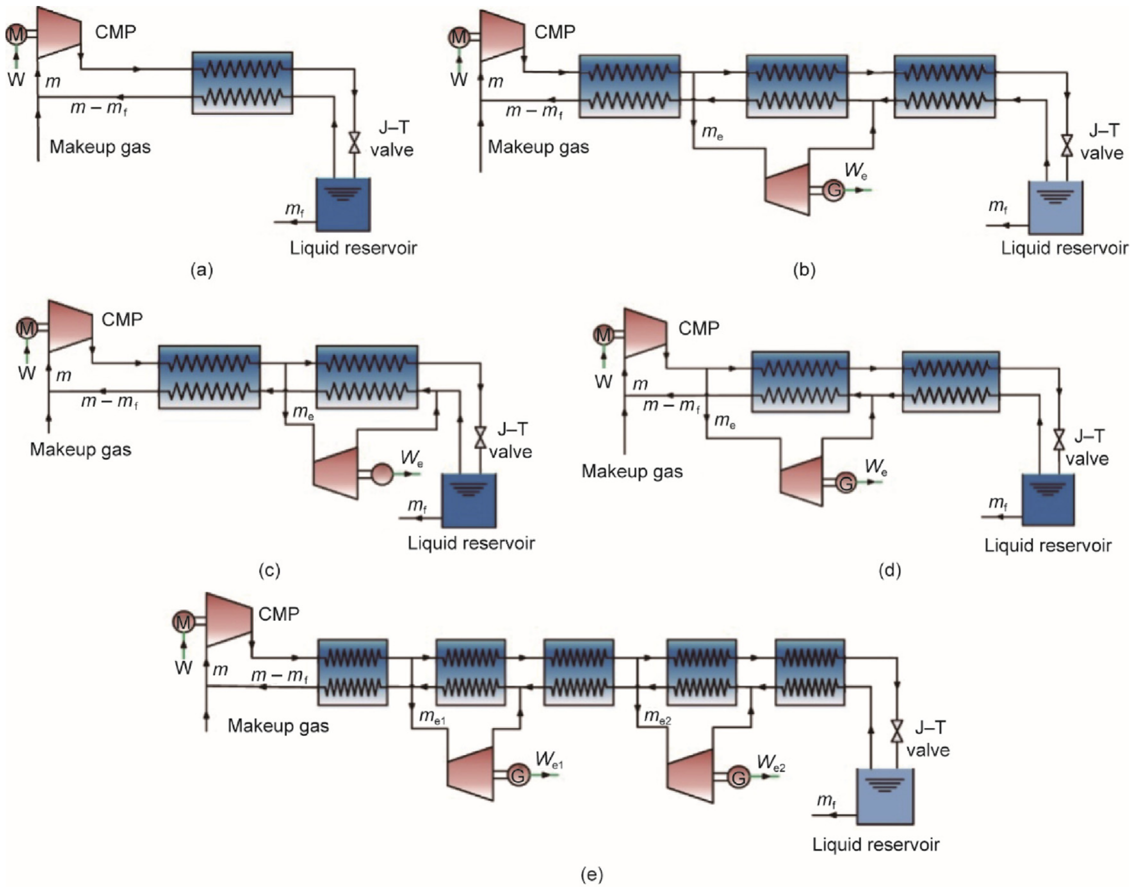

Fig. 16. Common liquefaction cycles [52]. (a) Linde–Hampson cycle; (b) Claude cycle; (c) Kapitza cycle; (d) Heylandt cycle; (e) Collins cycle.

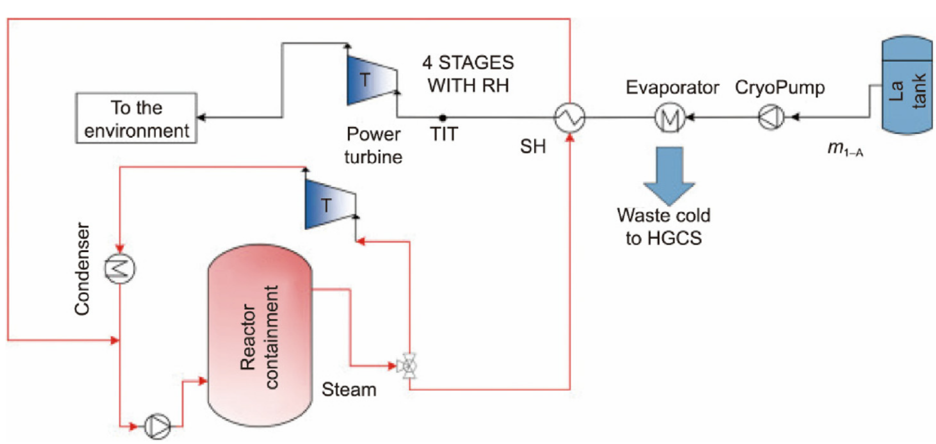

Fig. 17. Schematic of integrated LAES-NPP system [109].

and transmit it to other places, and the provision of multifunctional services such as peak-shifting, cold chain transportation, black start, frequency regulation, and ammonia synthesis [97]. A hybrid system of a LAES with nuclear power plants (LAES-NPP) was proposed, which was utilized to store surplus electricity from nuclear power plants at off-peak times, and the roundtrip efficiency of the LAES was increased by recovering waste heat from the power plant (Fig. 17). The round-trip efficiency is 71% [109]. Because the temperature region of the LAES is large, no single fluid can fully cover it. A combination of two different fluids (propane and methanol) was utilized to store and recover cold energy (high-grade cold storage), which was also utilized as a working fluid for heat transfer, as well as a cold storage medium with a high heat capacity. Air was stored in the liquid state, reducing the storage volume by ten times compared with the utilization of pebbles or concrete as a medium [103,109]. A decoupled LAES in which liquid air is generated by renewable energy-rich areas and transported to end-utilization sites was proposed and analyzed [110]. The Cyro-thermoelectric generation (TEG) method was utilized to recover Cyro energy effectively during discharging. Although the Cryo-TEG has a lower thermal efficiency of 9.0% compared with conventional Cyro-rankine cycles (RC) of 39.5%, it provides a better economic performance. The levelized cost of electricity of the Cryo-TEG could be as low as 0.0218 USD·kW·h^{-1}, which is almost four times less than that of the Cryo-RC. The decoupled LAES system achieved electrical round-trip efficiency of 29% and a combined cooling and power efficiency of 50% [110].

3.3.3. Experiments and demonstrations

Substantial progress in LAES technology development has been made because of collaborative research by the University of Leeds (UK), the University of Birmingham (UK), and the Highview Power Company. A 350.0-kW/2.5-MW·h LAES pilot plant was constructed in London in 2012 [111]. The measured round-trip efficiency was 8% because of the plant's small size, as much cold energy was not recovered. However, the optimized process model predicts a net round-trip efficiency of up to 60% [100]. The LAES plant was constructed in London and relocated to the Birmingham Center for Energy Storage at the University of Birmingham, led by Professor Yulong Ding (Fig. 18) [52]. In 2018, Highview Power continued developing a pre-commercial LAES plant (5 MW/15 MW·h) in Manchester [97]. This commercial demonstration was commissioned in 2020, according to Highview's announcement. The Highview Power Corporation also announced the construction of the first commercial LAES plant (50 MW/250 MW·h) in 2020; later, the scale increased from 250 to 300 MW·h. The plant is projected to become operational by 2024 [98].

Fig. 18. LAES plant at University of Birmingham [52].

3.4. Supercritical CAES

3.4.1. System description

The SC-CAES combines the features of both ACAES and LAES systems, as illustrated in Fig. 19 [112]. The concept of SC-CAES, developed by Chen et al. [57], utilizes the supercritical characteristics of fluids (air, temperatures above 132 K, and pressures above 3.79 MPa) to enhance the overall system performance. During charging, air is pressurized and cooled to a liquid state, and a regulator valve or Cyro turbine is utilized to decrease the pressure and temperature. The generated liquid air and compressed heat are stored separately. Unlike LAES, there is no separate stream as a coolant for producing cooling energy. The Cyro energy of liquid air during discharging is stored and utilized in the charging process. During discharge, liquid air is pumped to a certain pressure above the supercritical state, the stored heat is absorbed, and the cold energy of the liquid air is stored. The pressurized air then enters the turbine to generate electricity. In the supercritical state, the air pressure is generally higher than 3.79 MPa, and the air temperature is generally higher than 132 K. The overall compression/-expansion ratios of the CMP/expander units were 38–340. The pressure ratio during charging is significantly higher than that of LAES [57,112,113]. Under supercritical conditions, the heat transfer coefficient is enhanced compared to liquid air or compressed air, which is an effective factor for improving the overall system performance because of the large capacity for cold and heat storage [108,112,114]. The system energy density is as large as 3.46×10^5 kJ·m^{-3}, approximately 20 times larger than that of conventional CAES. Thus, a large cave is not needed [112]. The range of round-trip efficiency of the SC-CAES system is 52%–71%, and the energy density is similar to that of LAES [112,113].

3.4.2. Theoretical and experimental studies

Thermodynamic analytical solutions and exergy analyses are also conducted. The proposed analytical solution is precise for predicting the SC-CAES system. Moreover, it is suitable for simulating other types of CAES. They concluded that cold storage and liquefaction were the main factors affecting the total exergy destruction of the system [113].

A liquid turbine was investigated as an energy-recovery device by replacing the throttling valve during depressurization in SC-CAES systems [115,116]. Thus, the exergy destruction of the entire

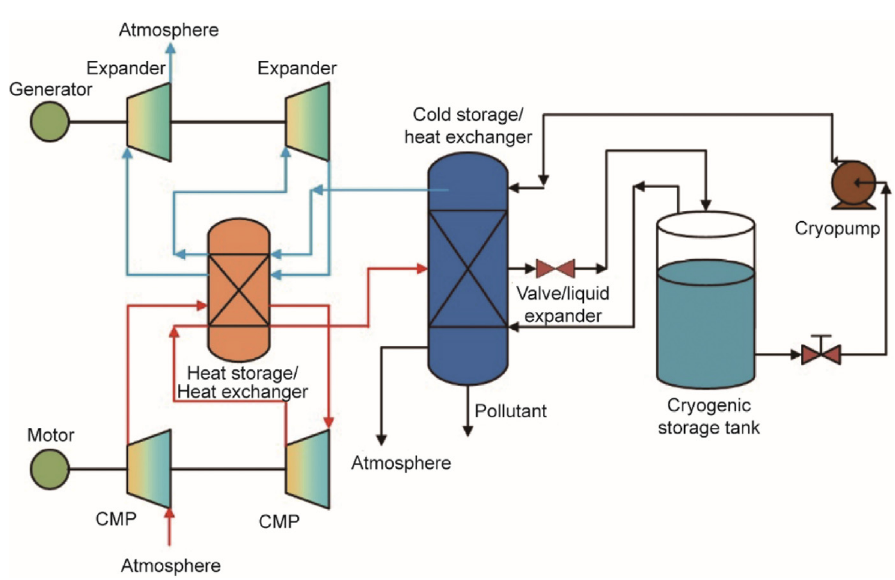

Fig. 19. Schematic of SC-CAES system. Reproduced from Ref. [112] with permission.

SC-CAES can be reduced. Simulations and experiments are conducted. They concluded that the liquid turbine efficiency was 92% at a design speed of 25017 revolutions per minute (rpm) [116]. Different cold storage materials for the SC-CAES system were comparatively analyzed through simulations and experiments [117]. Sodium chloride was selected as a suitable cold-storage material for the SC-CAES after comparatively analyzing 13 types of cold-storage materials. The experimental results indicated that the density of the NaCl particles was 2.1589 $g \cdot cm^{-3}$. The compressive strength was measured as 6.25 MPa at 77.15 K and 24.45 MPa at 293.15 K, respectively. The average specific heat of sodium chloride particles in the test temperature range is 0.81 $J \cdot g^{-1} \cdot K^{-1}$ (−140–40 °C). Meanwhile, the average value of the thermal conductivity coefficient is 5.8576 $W \cdot m^{-1} \cdot K^{-1}$ in the storage temperature range. It can be concluded that the designed NaCl particles are suitable for long-term and large-scale operations in the SC-CAES system [117]. A 1.5-MW SC-CAES was demonstrated in Langfang City (Fig. 20), which can realize supercritical processes with a system round-trip efficiency of 52.1%.

3.5. Underwater CAES

3.5.1. System description

A UWCAES is illustrated in Fig. 21 [118], which stores compressed air deep in water to create hydrostatic pressure

Fig. 20. 1.5-MW CAES system at Langfang City.

[119,120]. UWCAES includes some facilities above water and storage vessels under the water. These facilities above water are similar to other CAES systems with CMPs, expanders, HXs, TES unit, and so forth. The storage vessel was installed underwater, and the water depth maintained the air at a constant pressure. This system can also be abbreviated as CAES-P. The CMP (charging) and expander (discharging) operate relatively high efficiency at a constant pressure, leading to a high round-trip efficiency. Thermodynamic and economic analyses indicated that the system efficiency was 70.7%, the energy density was 26.07 $MJ \cdot m^{-3}$, and the investment was 3.983 million USD for a 10 MW–4 h system [121]. They concluded that when the discharge pressure and pipeline diameter were increased, the system efficiency increased gradually and then approached a flat trend. If the pipeline diameter is extremely small, it affects the flow features. Thus, the longer the underwater pipe, the lower the system efficiency [120]. According to a literature review, the variation in the round-trip efficiency of UWCAES ranges from 62% to 81%, and the energy density ranges from 26 to 48 $MJ \cdot m^{-3}$ [119,121].

3.5.2. Theoretical and experimental studies

An advanced exergy analysis was conducted on a 2-MW UWCAES system. The system includes a three-stage CMP and a three-stage expander with interstage HXs [122]. The storage pressure for unavoidable and real conditions is 2.08 and 2.61 MPa, respectively. Via advanced exergy analysis, the total exergy efficiency was determined to be 84.3% under unavoidable conditions. However, it was 53.6% under real conditions utilizing the conventional exergy analysis. Major exergy destruction occurred in the final-stage CMP, followed by the first-stage air expander. Moreover, these HXs cause approximately 30% of the total exergy destruction [122].

Storage vessels can be rigid (fabricated concrete caverns) or flexible (fabric airbags). The storage vessel must adapt to the seawater environment with sufficient intensity, sealing, anti-corrosion, and underwater creatures [118,123–125]. Fig. 22 [118] illustrates a UWCAES with isobaric storage reservoirs. Water flows in or out of the underwater reservoir through the ballast during the discharging or charging processes to maintain a constant air pressure. Seymour proposed a concrete tank with dimensions of 30 m × 8 m × 300 m as the storage vessel [123]. Garvey utilized

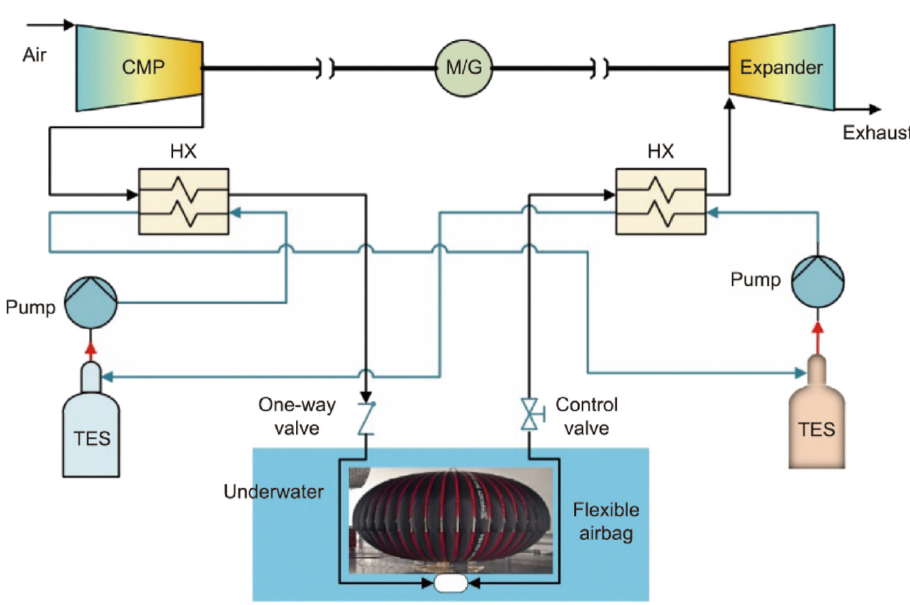

Fig. 21. Schematic of UWCAES system [118].

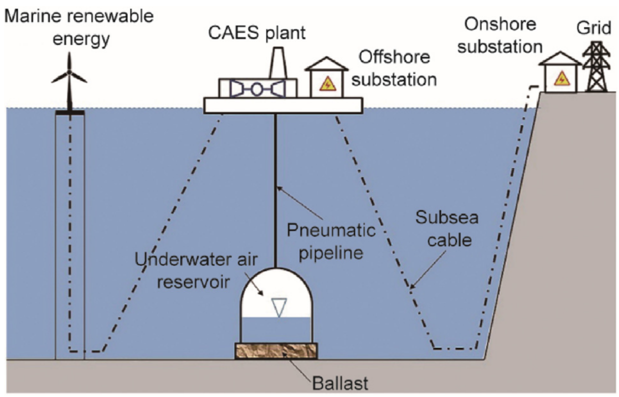

Fig. 22. Schematic of UWCAES. Reproduced from Ref. [118] with permission.

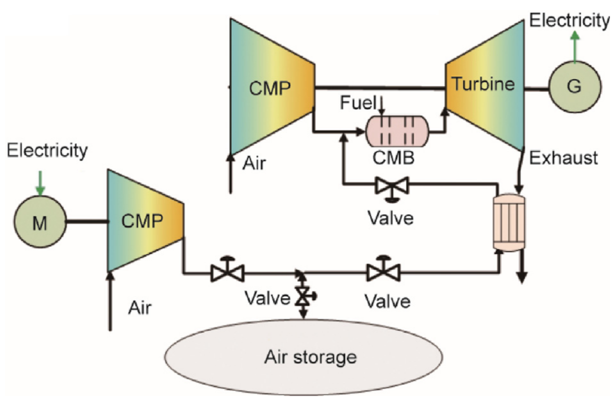

Fig. 23. Gas turbine with CAES system [130].

coated fabric to manufacture a pumpkin-sized flexible airbag to store compressed air [123]. An airbag with a diameter of 1.8 m was first tested in a water tank 2.4 m beneath the water surface. The number of charging–discharging cycles reached 425. Subsequently, a new airbag with a diameter of 5 m was placed in the water at a depth of 25 m. However, leakage problems can occur [126].

The Hydrostor Company installed multiple rigid caissons at a 1.75-MW pilot plant in Lake Ontario in 2015. The air was stored in underwater air storage caissons approximately 60 m below the surface of Lake Ontario.

4. CAES integrated with other systems

Generally, there are two types of CAES coupling systems: One is CAES coupled with other power cycles (e.g., gas turbines, coal power plants, and renewable energy), and the other is with other energy storage technologies [127,128]. When coupled with other power cycles, waste heat can be recovered via the CAES cycle to improve its performance. Moreover, the operating range of the coupled system was significantly enlarged. CAES can also be coupled with renewable energy sources, such as wind, solar, and biomass, to make them more accessible and adjustable.

Hybrid energy-storage systems combine different energy-storage technologies to explore these advantages. For instance, the long-duration types of CAES, pumped hydro storage, are combined with short-duration types of flywheels, super capacitors. Thus, an energy storage system can be installed in many scenarios to realize additional functions [129].

4.1. CAES coupled with other power cycles

A CAES-gas turbine coupled system was investigated based on the GE7FA gas turbine, as illustrated in Fig. 23 [130]. The power output increased by 26.7%, and the heat ratio (kJ/(kW·h)) decreased by 36.5%. A tri-generation system based on a coupling system was analyzed [131]. For a typical daily demand, the power rating of the gas turbine in the coupling system reduced by 30.4%, and the energy-saving ratio was 29.4% compared with the conventional combined cooling, heating, and power (CCHP) [131]. CAES can also be integrated into a distributed generation utilizing a diesel engine as the core generator [27]. Because the load fluctuates over a large range, the energy storage system helps maintain the core engine's stable operation. The system can also reduce the installed engine power size as the peak demand is supplied by the CAES. Based on the experimental results of the Langfang 1.5-MW CAES system, the core engine power of the proposed hybrid system was downgraded by 35.30%, and the fuel-saving ratio was 11.06% [27]. Adding a CAES to a coal power plant can increase its operational range with high efficiency and provide load-following capabilities. It can decouple the heat and power capacity for a combined heat and power plant (CHP) to adopt the future grid system with high effi-

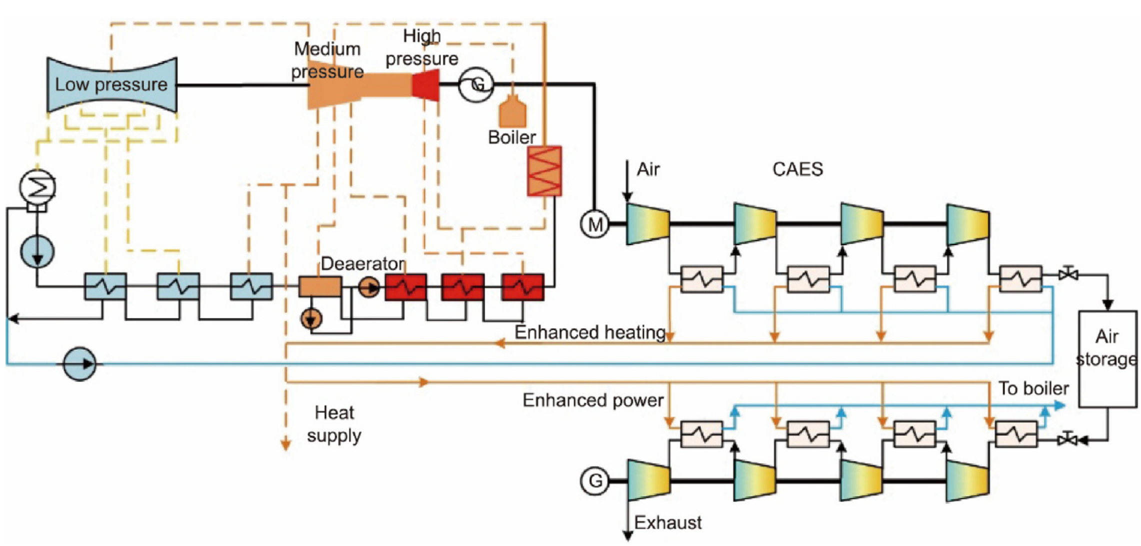

Fig. 24. Coal power plant coupled with CAES [132].

ciency and flexibility [3,132,133]. A coupling system was proposed, as illustrated in Fig. 24 [132]. The exergy efficiency of this coupling system is increased by 4.0%–31.4%, and the heat-power ratio is significantly widened [132,133]. An ACAES combined with a coal-fired power plant (CFPP-CAES) was proposed. This resulted in a tri-generative system. A detailed thermodynamic analysis of an example scenario revealed that 2.85 t of coal could be saved per cycle, and the roundtrip efficiency increased by 2.24% compared with that of the standalone CAES system [134]. To combine the conventional power cycle with renewable energy, a CCHP system combining CAES and solar energy has been proposed, as illustrated in Fig. 25 [135]. Solar energy is introduced to heat the high-pressure air from the air storage cavern to improve the turbine inlet air temperature. An ORC was introduced to recover the heat carried by the air-turbine exhaust. This hybrid system improved the CCHP system performance, and the entire system could operate over a large power range under off-design conditions. For the S-CAES-ORC system, the exergy efficiency reached 68.94%. Take a 180 000 m^2 hotel building as a case study, the results demonstrate that the energy consumption of the S-CCHP-CAES-ORC system can be reduced by 124.78 GJ, and the average energy efficiency increases by 7.72% on a typical day [135].

To address the fluctuation and mismatch between the wind generation and customer load, the CAES can balance the mismatch. When CAES is integrated into wind generation, wind power penetration can be as high as 80%, which is much higher than the 40% without energy storage [136]. CAES can also be coupled with solar and biomass energy. The solar CAES system eliminates the CMB of the conventional CAES and improves the quality of solar power [137]. An ACAES with additional heat from solar energy is more efficient and the round-trip efficiency increases by 9% [138]. A novel CAES system with a variable configuration was proposed for integration with wind generation, as illustrated in Fig. 26. The CMP and expander chains were designed with a low-pressure section and a high-pressure section with a storage vessel between them, which enabled the CMP and expander to operate in parallel or serial modes depending on the pressure value and power rating [139]. Take a 49.5-MW wind farm as an example. The CAES, compression of 40.00 MW, and expansion of 30.00 MW can generate a stable power output of 18.64 MW. The round-trip efficiency is 60.9%. Wind power curtailment was reduced from 83.71% to 28.98% [139]. The coupling systems of CAES with biomass, hydrogen, biogas, and geothermal energy have also been investigated [140–145], which contribute to the high penetration of renewable energy, comprehensive efficiency of energy unitization, and flexibility. A CAHES combines CAES with hydrogen production and utilization (Fig. 27) [144]. Surplus electricity is utilized to compress air and produce hydrogen via electrolysis. At peak time, hydrogen was supplied to the synthesis reactor with the input of CO_2 to generate methane and water as a by-product. Methane is utilized to burn and heat compressed air before expansion, stabilizing the combustion process and guaranteeing an appropriate process temperature. The exhaust heat was also recovered with compressed

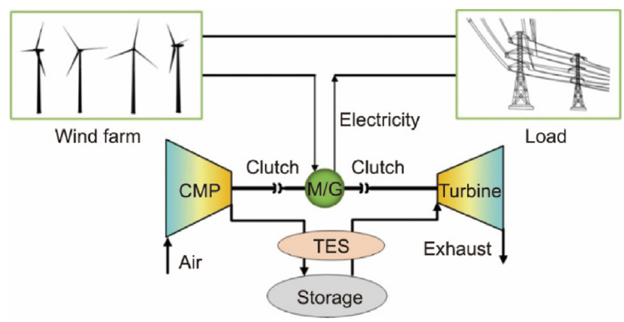

Fig. 26. CAES-wind coupling system.

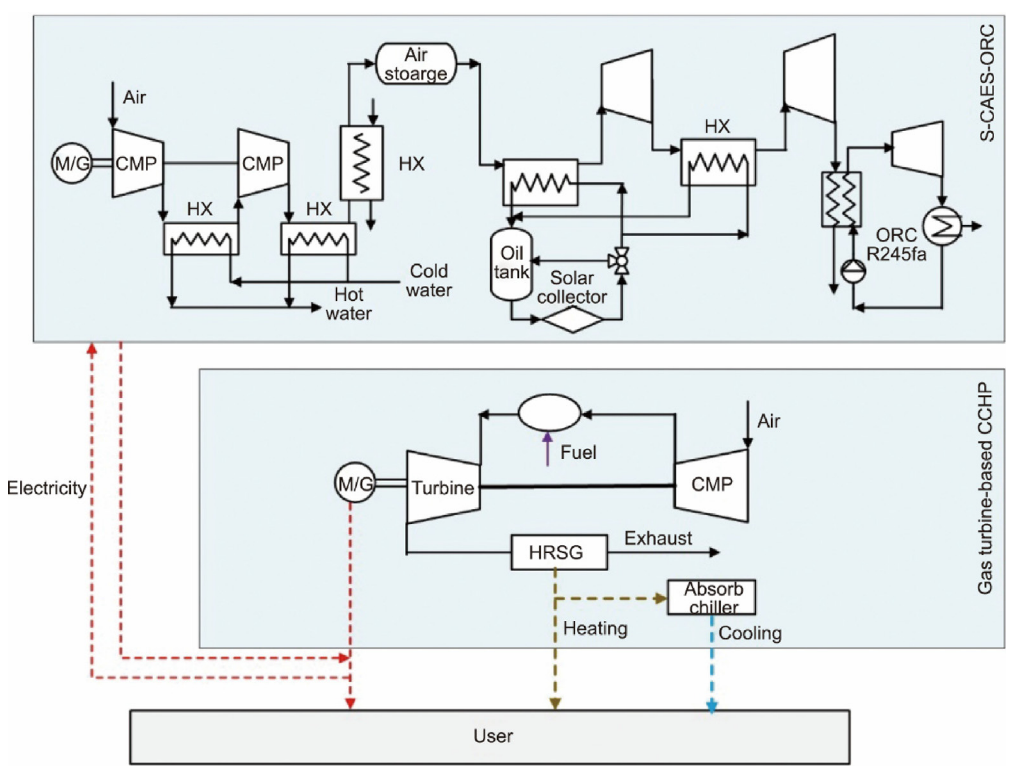

Fig. 25. CCHP-S-CAES-ORC hybrid system [135].

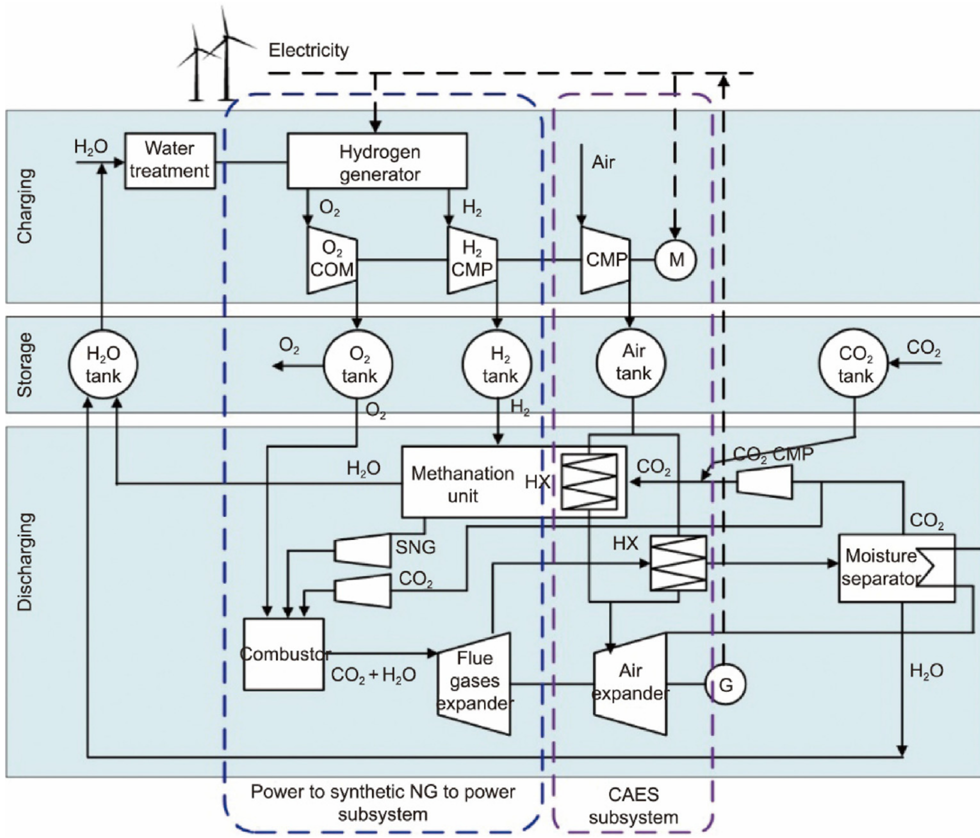

Fig. 27. Schematic of CAES with hydrogen (CAHES) [144].

air. The efficiency of the CAHES is 38.15%, which is much higher than the efficiency of power-to-hydrogen-to-power systems [144].

4.2. CAES coupled with other energy storage technologies

Energy storage systems can perform various functions by combining two or more energy storage technologies. A CAES coupled with a flywheel energy storage system was proposed to mitigate fluctuations in wind power as illustrated in Fig. 28 [146,147]. The fluctuations were categorized into low-frequency and high-frequency groups and filtered for dispatch to the CAES and flywheel systems, respectively. The coupled system is designed to connect to a 49.5-MW wind farm in China to stabilize the wind power generation to 24.18 MW. The utilization coefficient of wind power increased to 93.4% [146].

A novel concept combining compressed air and pumped hydro energy storage systems was proposed in Ref. [148], as illustrated in Fig. 29. The simulation results demonstrated that the energy storage capacity could be as much as 32.50 MW when the vessel height was 500.00 m, the piston diameter was 5.21 m, and the air storage

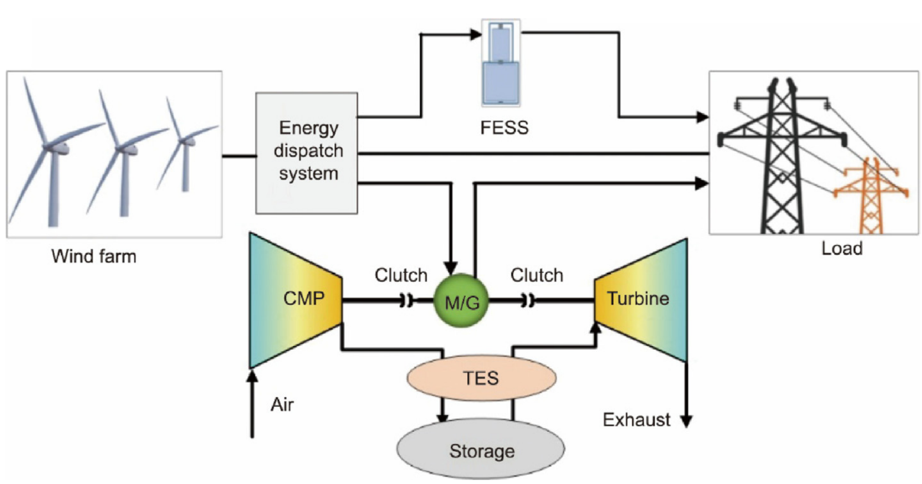

Fig. 28. Schematic of wind-HESS [146]. FESS: flywheel energy storage system.

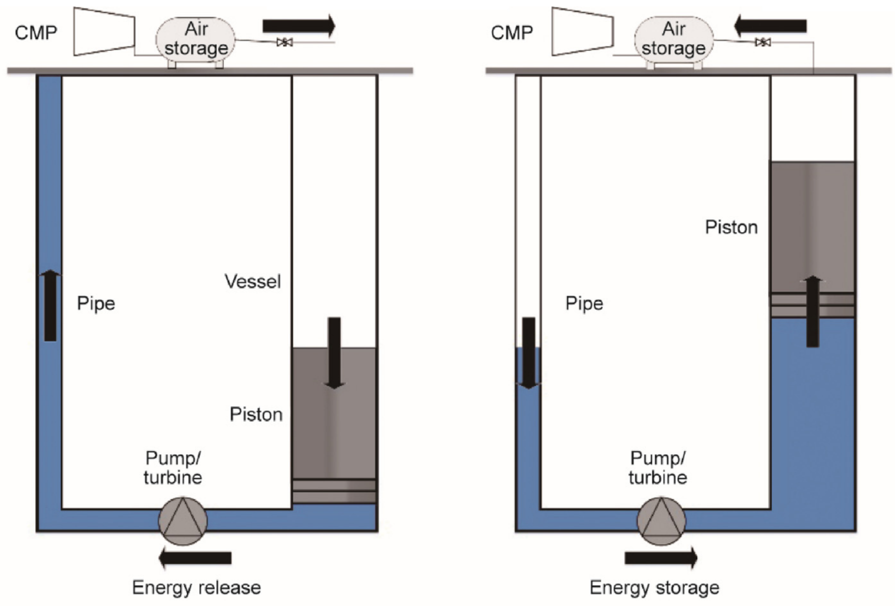

Fig. 29. Schematic of compressed air-gravity energy storage [148].

pressure was 10.00 MPa [148]. Both theoretical and experimental analyses of a pumped hydro-CAES system were performed by Chen et al. [149]. The round-trip efficiency was 51%, and the energy density was 0.33 kW·h·m^{-3}. Once the pump efficiency reached 90%, the round-trip efficiency reached 63% [149].

The parameters of the CAES and other systems are presented in Table 3 [18,79,100,109,135,139,141–144,150–152]. The power capacity of the CAES was in a wide range of 0.1–680.0 MW. The efficiency can exceed 70%. Only the CAES-biomass system produced emissions. These coupling systems are primarily utilized for renewable energy and peak shaving. All these coupling system studies are theoretical.

5. Comparison and discussion

In this section, the characteristics of different CAES technologies are compared and discussed from different perspectives, including the technical maturity level, power/energy capacity, round-trip efficiency, economy, power/energy density, and charge/discharge duration. The potential applications of various CAES technologies are summarized and discussed. Different studies on these CAES technologies demonstrate considerably different performances because of their different applications, researchers, and operating conditions. It is almost impossible to consider all studies and situations; thus, a relatively objective result is presented according to state-of-the-art methods in both academic research and industrial applications. The near future is discussed to support the research, development, and applications of CAES systems.

(1) **Technical maturity.** Technical maturity is roughly classified into three levels, as illustrated in Fig. 30: R&D, demonstration and deployment, and commercialization. A large value represents a greater maturity of the corresponding CAES

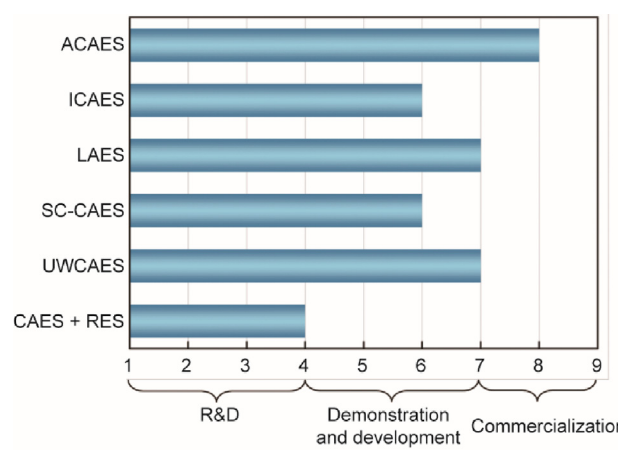

Fig. 30. Technical maturity level of various CAES systems.

Table 3
Parameters of CAES integrated with different renewable sources.

CAES+ renewable sources	Power	Efficiency	Emission	Energy dnsity	Application	Maturity
CAES + wind	0.4–200.0 MW [79,139,150]	45%–77% [79,139,150]	None	1.8–72.0 MJ·m^{-3} [18]	Renewable energy, peak shaving	Theoretical study
CAES + solar	0.1–118.0 MW [135,151,138]	69.6%–76.5% [135,151,138]	None	14.863–17.466 MJ·m^{-3} [135,151,138]	Renewable energy, peak shaving	Theoretical study
CAES + biomass	1.0–4.1 MW [142,152]	37%–70% [141,152]	Biomass emission	1.8–72.0 MJ·m^{-3} [18]	Renewable energy, peak shaving	Theoretical study
CAES + hydrogen	105 MW [144]	38.1%–60.4% [143]	None	1.8–72.0 MJ·m^{-3} [18]	Renewable energy, peak shaving	Theoretical study
LAES + nuclear	0.35–687.00 MW [100,109]	8%–71% [100,109]	None	720 MJ·m^{-3} [100]	Renewable energy, peak shaving	Theoretical study

technology. This indicated that the ACAES technology is the most mature among all these advanced CAES systems, as some commercial demonstrations have been constructed and connected to the grid. LAES and UWCAES technologies are less mature, as only megawatt-level demonstrations have been developed, and related companies have announced the development of large-scale systems. ICAES, SC-CAES, and CAES-RES systems are mainly under theoretical study, and experiments have been conducted. All these theoretical and experimental studies have proven their feasibility and application potential. When conducting fundamental and experimental research to facilitate large-scale CAES applications, more attention should be paid to efficiency, economy, safety, and other aspects.

(2) **Power capacity and round-trip efficiency.** Fig. 31 illustrates the power capacities of the CAES. Each bar represents a certain type of CAES system stretching over a large range, covering the power capacity of theoretical studies and experimental setups and demonstrations. All CAES systems, except the SC-CAES, were investigated on a large scale to approximately 300 MW. However, only ACAES realized a 100 MW demonstration, and the others were generally approximately 1 MW.

The round-trip efficiencies are illustrated in Fig. 32. This implies that all these CAES systems are of relatively high efficiency of approximately 50%–80%. The results from the experiments and demonstrations are also presented in the figure and are generally lower than the theoretical results, as some are still in the fundamental research stage. Thus, there remains great potential for improving the performance of various CAES technologies. Large-scale demonstrations are required to realize better overall performance and facilitate applications.

(3) **Economy.** The economy of the CAES system is estimated by the energy capital cost, as the CAES technology is regarded as a large-energy capacity technology. This value varies significantly, as illustrated in Fig. 33, owing to the different researchers, methodologies, and CAES configurations. Considering both the theoretical and experimental demonstration plants, the energy capital cost can be lower than 200 USD·kW^{-1}·h^{-1}. Most data are theoretical results because these CAES technologies have not been deployed commercially. Only a few plants have been constructed as prototypes or are in the early stages of commercial demonstration.

Summarizing all the data from previous research, a performance comparison of the above-mentioned CAES systems is presented in Table 4 [10,18,23,25,40,41,47,58,60,61,70,72,74–77,79,81,83,96,100,103,104,108,109,112,113,116,118–121,126,135,139,141,143,144,146,147,150–167]. Details of these data and references are presented.

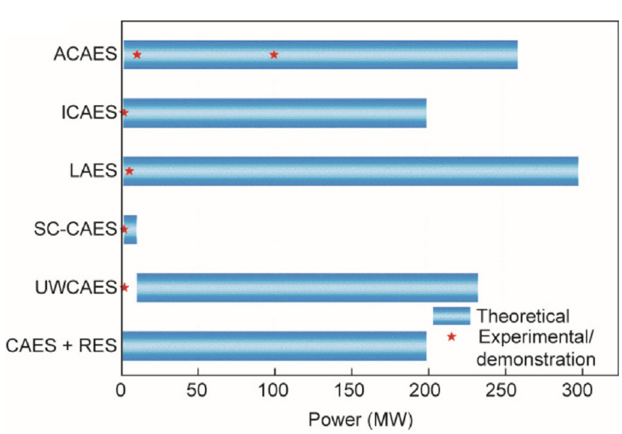

Fig. 31. Power capacities of various CAES systems.

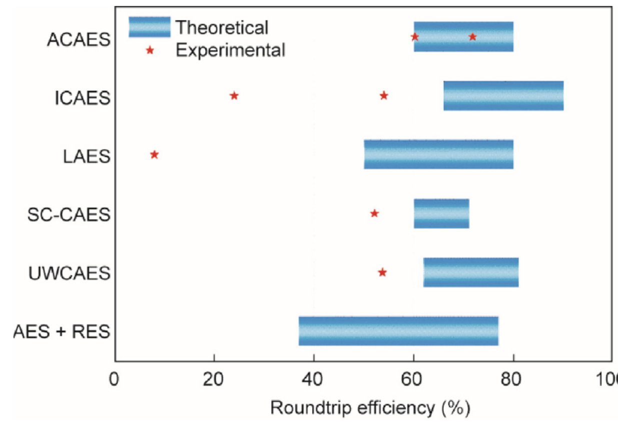

Fig. 32. Roundtrip efficiency of various CAES systems.

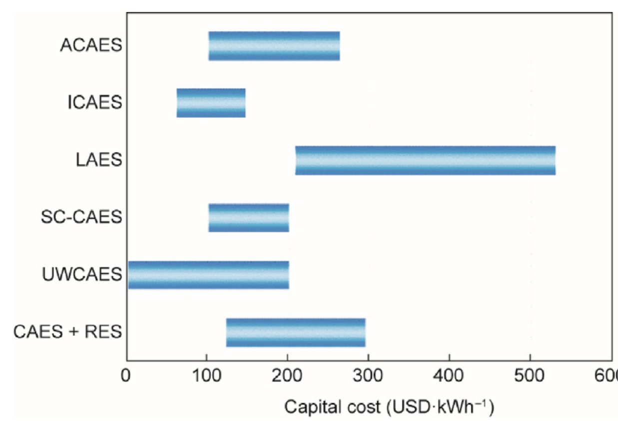

Fig. 33. Capital cost of various CAES systems.

(4) **Near future.** As more than 120 countries, including China, announced a roadmap to reduce CO_2 emissions, leading to carbon neutrality [168], the high penetration of renewable energy must be combined with energy storage to ensure a reliable and flexible electricity supply. The total installed energy storage reached 209.4 GW worldwide in 2022, an increase of 9.0% over the previous year [169]. CAES, another large-scale energy storage technology with pumped-hydro storage, demonstrates promise for research, development, and application. However, there are concerns about technical maturity, economy, policy, and so forth. To realize the commercial application and deployment of CAES and support the high penetration of renewable energy, the following suggestions need to be considered. First, technology demonstrations, ranging from fundamentals to applications, are required. More demonstrations of these mature CAES technologies, for example, ACAES, are needed to improve their maturity and make them commercial in the short run. Some key technologies, operation, and control strategies of LAES and UWCAES must be implemented to realize a larger-scale pilot. Fundamental research on CAES with less maturity, such as ICAES and SC-CAES, needs to be conducted because they have large potentials of high efficiency, compact configuration, and so forth. We also need to optimize the design of the entire system and its key components to bring the system performance closer to a high theoretical

Table 4
Performance comparison of all CAES systems.

CAES types	ACAES	ICAES	LAES	SC-CAES	UWCAES	CAES+RES
Power capacity (MW)	1.5 [25], 10 [153], 20 [60], 100 [76], 260 [47,72]	3 [75], 1–10 [83], 100 [154], 200 [79]	1–300 [103], 0.35 [104], 100–300 [96,100], 250 [109], 270 [155], 5 [104], 100 [100], 60 [156]	1.5–10 [112]	16.35–233.6 [119], 10 [121]	20–40 [147], 15 [146], 0.4–200 [79,139,150], 0.1–118 [135,151], 105 [144], 0.35–68.7 [100,109]
Storage capacity (MW·h)	10 [58], 80 [153], 80 [60], 100 [76], 500 [58]	24 [75], 4-60 [83], 500 [154], 2000 [79]	2.5 [104], 15 [104], 1080 [155], 200–3000 [96], 600 [100]	10 [112]	1000–1072 [119], 40 [121], 42.26 [120]	135 [146], 3930.6 [157]
Efficiency	71.79% [60], 60%–80% [58,61], 63%–74% [70]	77% [79], 66%–82% [81], 90.0%–95.8% [77], 84% [83]	50%-60% [96,103,104], 71.26% [109], 60% [100], 80.62% [158], 52.8% [156]	52.10%-67.41% [112], 60%–71% [113]	77%–78% [119], 70.74% [121], 62%–81% [159]	93.4% [146], 60% [160], 45%–77% [79,139,150], 69.6%–76.5% [135,151], 37%–70% [141,152], 38.1%–60.4% [143], 8%–71% [100,109]
Energy density ($kJ·m^{-3}$)	7742 [60], 10800–11340 [58], 1800–72000 [18]	3600–90000 [18]	432000–720000 [103], 365760 [161]	346000 [112]	27180–47880 [119], 26070 [121]	2430 [160], 1800-72000 [18], 14863–17466 [40,41], 720000 [100]
Compression power (MW)	26 [60], 15.38 [153], 300 [47,72]	275 [79]	100 [96], 39–40 [109], 113.7 [156]	20 [112]	21–265 [119].	12 [146], 260 [47,72]
CMP efficiency	88% [60], 85% [58,61], 75%–98% [58]	75%–98% [74]	90% [109], 85% [158], 89% [100,156]	85% [112]	84% [121], 75% [120]	80%–84% [146]
Expander efficiency	92% [60], 85% [58,61].	92% [75]	92% [109], 85% [158], 80%–90% [100,156]	88% [112], 92% [116]	88% [121], 85% [120,159]	88% [146], 80% [160]
Storage type	Isochoric storage [25,60,70], steel tanks [25], underground caverns [70]	Isochoric storage, steel/carbon fiber pressure vessels [83], underground reservoirs/abandoned pipelines/vessels [83]	Isochoric storage [100,104], LA tanks [103,109], tanks with packed bed [108]	Isochoric storage [113]	Isobaric storage [119,126]	Isochoric storage [146], caverns [146]
Storage pressure, MPa	6–10 [25], 10 [60,61], 0.8–3.3 [70], 2.5–15.0 [162–164]	13–30 [77]	0.1 [104]	0.1 [112]	3.83–5.70 [119]	7-10 [147], 4.0-12.5 [146], 7 [160]
Hours of compression	4 [60], 1 [61,76], 8 [153]	10 [79], 1–4 [77], 4-6 [83]	3 [104], 2–10 [96], 4 [100,155].	5 [165]	5 [119], 4 [121]	15 [146], 4 [160
Hours of generation	3.72 [60], 1 [61,76], 8 [153]	1–4 [77], 4–6 [75,83], 5 [154], 10 [79]	3 [104], 13 [96], 4–24 [100,103,155]	4 [112]	6 [119], 4 [121], 2–3 [126]	9 [146], 4 [160]
Storage volume (m^3)	760 [25], 2110 [58], 3169.6 [58], 6253.841 [153], 37200 [60], 10500 [58], 158481.3 [58]	500 [75], 472.7 [154]	5800 [100]	4 [112]	6000–18000 [159], 900 [119]	64850 [147], 24074 [146], 43170 [157]
Invested cost ($USD·kW^{-1}·h^{-1}$)	100 [153], 121 [153], 260 [166]	145.7 [79], 61 [167]	208 [156], 260–530 [118]	100–200 [23]	100 [121], 1–200 [118]	145.7 [79],122–295 [10]
TES temperature and materials	Pressurized water [60], The packed bed of rocks (550 °C) [70], molten salt, thermal oil (<400 °C) [18], liquid TES media (<200 °C) [18]	–	Low-pressure water [103]	A packed bed cold thermal storage (300 K) [165]	Oil/water [121]	–

limit. Second, the CAES can operate for peak-shaving, balancing load and demand, and ancillary services. However, no mature market model exists for such applications. Relevant policies are suggested to support the utilization of CAES, such as the reimbursement mechanism which is currently attributed to the pumped-hydro storage system, and shared energy storage mode. Third, the diverse applications of CAES, particularly at the system level, should be further expanded to include renewable energy, distributed generation, frequency regulation, and black start.

6. Conclusions

CAES is a long-duration and large-scale energy-storage technology that can facilitate renewable energy development by balancing the mismatch between generation and load. In addition, it can provide ancillary services to the grid. In addition to the two conventional CAES plants (Huntorf CAES plant and McIntosh CAES plant), various other advanced CAES technologies that eliminate fossil fuel consumption have been proposed and developed. This study presented a brief history of CAES systems and recent progress in advanced CAES systems, including system descriptions, theoretical studies, experiments, and demonstrations. The following conclusions were drawn.

Here, we present a brief developmental history of CAES. Two commercial plants in Huntorf and McIntosh are conventional CAES systems. Other studies have also been conducted and planned. These demonstrated or planned projects are summarized and presented. However, conventional systems burn fossil fuels, which are not clean.

The advanced CAES, which eliminates combustion, is considered a clean technology that has attracted widespread attention and intense R&D investment. Various types of advanced CAES systems have been studied and developed, including ACAES, ICAES, LAES, SC-CAES, UWCAES, and CAES coupled with other technologies (CAES-RES). These advanced CAES systems demonstrate great promise for large-scale renewable-energy applications and contribute to carbon neutrality. All these technologies were investigated from the perspective of their fundamentals and applications.

The main parameters and performance of these advanced CAES technologies and CAES integrated with renewable energy sources were reviewed, summarized, and compared. The state-of-the-art advanced CAES technologies, considering technological maturity, power capacity, roundtrip efficiency, and economic performance, are compared and presented. The detailed parameters of the charging power, discharging power, storage capacity, CMP efficiency, expander efficiency, round-trip efficiency, energy density, charging/storage/discharging pressures, storage volume, and investment cost are summarized and presented in a table.

The ACAES reached the stage of large-scale demonstrations (10 MW, 100 MW), which were also connected to the grid. This indicates its potential for commercial deployment. LAES has the largest energy density. The megawatt-level demonstration of the LAES was constructed. However, the principles and configurations are more complex than those of the ACAES. Optimized design and large-scale pilot construction are required to make the technology more mature. The ICAES, UWCAES, and SC-CAES are at the stage of fundamental studies and prototype experiments. Researchers worldwide have been working on these technologies to improve their performance and maturity. The main application of CAES is the integration of renewable energy. Although there has been no such demonstration, the integration can be performed as soon as advanced CAES technologies are sufficiently mature to be commercially deployed.

There is a gap between the experimental and theoretical results in terms of round-trip efficiency. Hence, considerable effort is needed to improve the round-trip efficiency to make it closer to the theoretical upper limit. Market modes and relative policies are suggested for investigation and implementation of CAES applications to advance the deployment of advanced CAES.

CRediT Author Contribution Statement

Xinjing Zhang: Conceptualization, Funding acquisition, Data curation, Writing – original draft, Writing – review & editing, Visualization, Formal analysis, Methodology, Investigation, Project administration. **Ziyu Gao:** Data curation, Writing – original draft, Writing – review & editing, Investigation. **Bingqian Zhou:** Data curation, Writing – review & editing, Investigation. **Huan Guo:** Data curation, Writing – review & editing, Investigation. **Yujie Xu:** Writing – review & editing, Investigation, Investigation, Resources. **Yulong Ding:** Conceptualization, Writing – review & editing, Investigation, Supervision, Resources. **Haisheng Chen:** Conceptualization, Funding acquisition, Writing – review & editing, Investigation, Supervision, Resources, Project administration.

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