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REVIEW ARTICLE

Compressed CO_2 energy storage technology and its integration with CO_2 capture, utilization and storage: A review and perspective

Qian Wu[1], Yang Li[2], Liang Yin[3], Qianguo Lin (✉)[3]

1 College of Environmental Science and Engineering, North China Electric Power University, Beijing 102206, China
2 China Petrochemical Corporation, Beijing 100728, China
3 Research Institute of Carbon Neutrality, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200030, China

HIGHLIGHTS

- Advancements and prospects of CCES and its integration with CCUS are proposed.
- A comprehensive performance comparison of various CCES system is presented.
- Synergistic potential of CCES-CCUS integration is highlighted.
- Applications, challenges and future trends for CCES-CCUS integration are discussed.

Keywords:
Compressed CO_2 energy storage (CCES)
Carbon capture utilization and storage (CCUS)
Performance evaluation
CCES integration
CO_2 utilization
Geological storage

ABSTRACT

Compressed carbon dioxide (CO_2) energy storage (CCES) has emerged as a promising large-scale energy storage technology, characterized by high energy density, moderate critical temperature, and operational flexibility. Concurrently, carbon capture, utilization and storage (CCUS) technology represents a critical pathway toward carbon neutrality for energy systems. The integration of CCES with CCUS is attracting growing research interests due to its unique potential to synergize energy and carbon flows within a closed-loop framework. This paper provides a comprehensive literature review of technological advancements in CCES and offers a perspective on its integration with CCUS. First, the fundamental working principle, system configurations, key performance indicators, and emerging demonstration projects of CCES are introduced. Subsequently, cutting-edge research and key challenges of CCES system are reviewed, focusing on optimization of CO_2-based mixed working media, efficient liquefaction of low-pressure CO_2, development of low-cost and safe CO_2 storage facilities, enhancement of system performance through integration, and evaluation of dynamic behaviors. A central focus is placed on the integration of CCES with CCUS, highlighting how this synergy transforms CCES from a pure storage technology into a multi-functional tool for carbon management. This integration enables infrastructure sharing, dual-function storage (for energy and CO_2), and improved economics. Finally, this review identifies key directions for future research, including advancing efficient system integration, developing high-precision transient simulation models and dynamic control algorithms, ensuring long-term safety of geological reservoirs under cyclic injection-extraction operations, and establishing multi-objective optimization and multi-criteria assessment frameworks to support the commercial deployment of integrated CCES-CCUS systems.

1 Introduction

Renewable energy power generation has emerged as an imperative solution, driven by the growing global demand for clean and low-carbon electricity. However, the inherent intermittent generation patterns and stochastic power fluctuations of renewable energy sources, particularly wind and photovoltaic (PV) power, have intensified operational stability challenges for power grids [1–4]. To address these challenges, innovations in

✉ Corresponding authors. E-mail: qianguo.lin@sjtu.edu.cn (Q. Lin)

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flexibility enhancement and dynamic grid control have been introduced to maintain an adequate and stable electricity supply. By storing electricity and releasing it when needed, energy storage systems can effectively mitigate the impact of renewable energy variability and enhance the stability and flexibility of power grids.

Compressed gas energy storage (CGES) is a technology that uses air or other gases as a working medium to enable large-scale energy storage [5]. Recently, compressed CO_2 energy storage (CCES), which employs carbon dioxide (CO_2) as the working medium, has attracted increasing attention. The emergence of CCES is driven by the favorable properties of CO_2, such as chemical inertness, good thermal stability, non-combustibility, and non-toxicity. Its near-ambient critical temperature (31.4 °C) allows CO_2 to be liquified more efficiently and easily than air (−141 °C) [6]. In addition, supercritical CO_2 (SC-CO_2) combines offers excellent thermophysical properties, including low viscosity, high density, good thermal conductivity, and a high diffusion coefficient [7–10]. Therefore, CCES represents an advanced frontier in CGES technology and shows a greater potential for energy storage compared to compressed air energy storage (CAES).

Given these advantages, numerous studies in recent years have focused on various aspects toward CCES technology development and improvement. More recently, the integration of CCES with carbon capture, utilization, and storage (CCUS) has emerged as a prominent research area, due to its dual benefit of energy storage and emission reduction. This review aims to summarize the current state of research and development in CCES, identify the key technical challenges, and explore future trends. In particular, it provides insights into the integration of CCES with CCUS, offering guidance for future research and development in this evolving field.

2 Working principle and performance evaluation of CCES

2.1 Working principle of CCES

CCES technology is an extension and innovation of CAES, enabling the spatial and temporal transfer of electricity by converting electricity into mechanical and thermal energy for storage. In contrast to CAES, CCES must operate as a closed-loop to prevent CO_2 emission into the atmosphere. Consequently, an additional tank is required to store low-pressure CO_2. Similar to CAES, the fundamental working principle of CCES revolves around two coupled thermodynamic cycles: charging and discharging.

During the charging process (energy storage), off-peak power or renewable electricity is used to power compressors that pressurize CO_2 from a low-pressure storage tank. Intercooling and heat recovery are employed during this stage, and the pressurized CO_2 is then stored in a high-pressure storage tank. In the discharging process (energy release), the high-pressure CO_2 is preheated via a heat exchanger and expanded through turbines to generate electricity. After expansion, the now low-pressure CO_2 is stored in the low-pressure storage tank for the next cycle.

A typical CCES system primarily consists of four subsystems: a compression unit, an expansion unit, a working medium storage unit, and a cold/heat storage unit. The compression unit includes single-stage or multi-stage compressors with corresponding intercoolers. The expansion unit consists of single-stage or multi-stage expanders equipped with heaters. The CO_2 storage unit employs separate storage tanks at different pressures to store high-pressure compressed CO_2 and low-pressure expanded CO_2. The cold/heat storage unit captures and stores the compression heat during the charging phase, which is later reused to heat CO_2 during the discharging phase.

2.2 Performance evaluation of CCES

The performance evaluation of a CCES system is typically conducted using rigorous thermodynamic and economic models. The thermodynamic analysis, based on the first law (energy conservation) and second law (exergy analysis) of thermodynamics, is used to determine key thermodynamic performance indicators such as round-trip efficiency (RTE), energy storage density (ESD), and exergy efficiency. Meanwhile, the economic analysis, employing the discounted cash flow method, estimates the levelized cost of energy (LCOE) to assess economic feasibility of the system. Figure 1 illustrates the overall modeling framework and the interaction among its components.

2.2.1 Thermodynamic analysis model

This section presents a component-by-component model for a typical multi-stage compression, multi-stage expansion CCES system integrated with thermal energy storage (TES). To ensure the model remain tractable while maintaining reasonable accuracy, the following assumptions are commonly adopted [11,12]: The CCES system operates under steady-state conditions. CO_2 is treated as a pure substance throughout the entire process. Irreversibility in compressors and expanders is represented by constant isentropic efficiency. Pressure

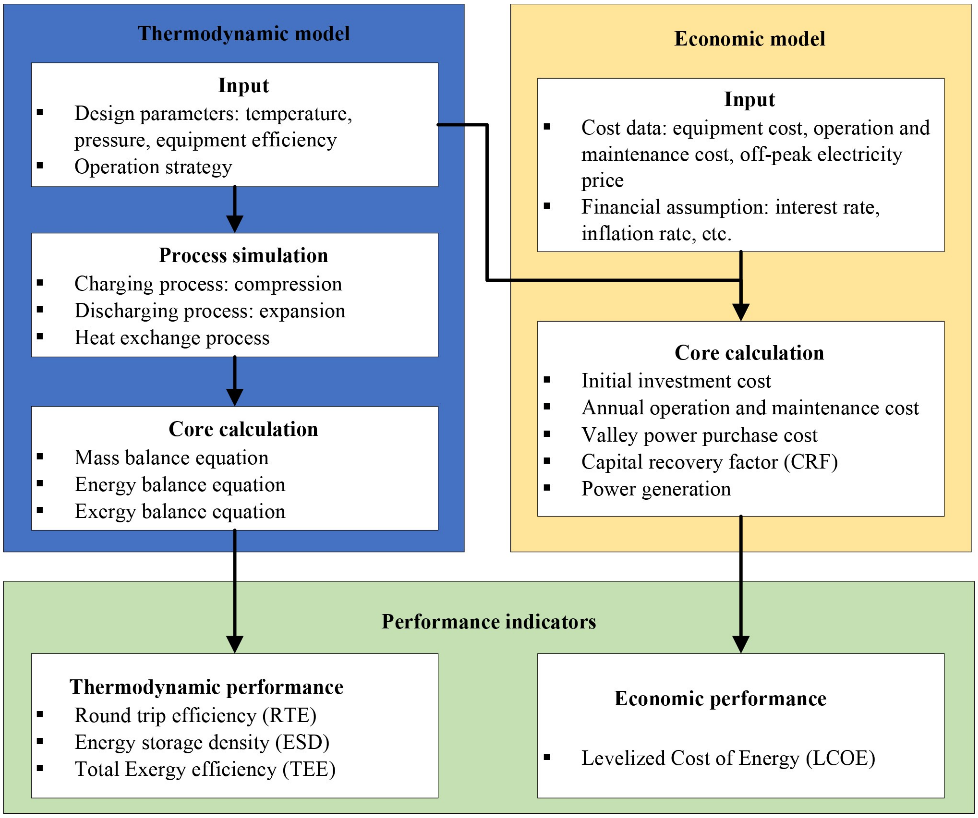

Fig. 1 Modeling framework for the thermodynamic and economic performance evaluation of a CCES system.

drops in heat exchangers and piping are considered negligible. Changes in kinetic energy and potential energy are considered negligible.

The fundamental principles governing system operation are based on the conservation of mass and energy, along with the entropy production, which are mathematically expressed in Eqs. (1)–(3) [13].

$$\sum m^{\text{in}} = \sum m^{\text{out}}, \tag{1}$$

$$Q^{\text{in}} + \sum (mh)^{\text{in}} + P^{\text{in}} = Q^{\text{out}} + \sum (mh)^{\text{out}} + P^{\text{out}}, \tag{2}$$

$$\sum \frac{Q}{Te} + e^{\text{gen}} = \sum m^{\text{out}} s^{\text{out}} - \sum m^{\text{in}} s^{\text{in}}, \tag{3}$$

where m denotes the mass flow rate of CO_2; Q is the heat transfer rate; h and s represent the specific enthalpy and specific entropy, respectively; P is the power; and e^{gen} is the entropy generation. The superscript in and out indicate the inflow and outflow conditions of the system, respectively.

2.2.1.1 Charging process

The isentropic efficiency of the compressor (η_c) is defined as the ratio of the work input required for an isentropic (ideal, reversible, and adiabatic) compression process to the actual work input for achieving the same outlet pressure. This definition yields the following expression, as shown in Eq. (4).

$$\eta_c(i) = \frac{h_c^{\text{is,out}}(i) - h_c^{\text{in}}(i)}{h_c^{\text{out}}(i) - h_c^{\text{in}}(i)}, \tag{4}$$

where η_c is the isentropic efficiency of the compressor; $h_c^{\text{is,out}}$ is the isentropic outlet enthalpy of the compressor; h_c^{in} and h_c^{out} are the actual enthalpies at the inlet and outlet of the compressor, respectively; and i denotes the stage number within the compressor train.

During the charging process, the total power input to the compressor train can be calculated using Eqs. (5) and (6).

$$P_{\text{ch}}(i) = m_{\text{ch}}\left(h_c^{\text{out}}(i) - h_c^{\text{in}}(i)\right), \tag{5}$$

$$P_{\text{ch}} = \sum_{i=1} P_{\text{ch}}(i), \tag{6}$$

where the subscript ch indicates the charging process.

2.2.1.2 Discharging process

The isentropic efficiency of the expander (η_e) is expressed as Eq. (7).

$$\eta_e(j)=\frac{h_e^{in}(j)-h_e^{is,out}(j)}{h_e^{in}(j)-h_e^{out}(j)}, \tag{7}$$

where η_e is the expander isentropic efficiency; $h_e^{is,out}$ is the isentropic outlet enthalpy of the expander; h_e^{in} and h_e^{out} are the actual enthalpies at the inlet and outlet of the expander, respectively; and j represents the stage number of the expander train.

During discharging process, the power output of the expanders can be calculated using Eqs. (8) and (9).

$$P_{di}(j)=m_{di}\left(h_e^{in}(j)-h_e^{out}(j)\right), \tag{8}$$

$$P_{di}=\sum_{j=1}P_{di}(j), \tag{9}$$

where the subscript di indicates the charging process.

2.2.1.3 Heat exchange process

During the charging process, intercoolers are used to recover compression heat. In discharging process, the compression heat stored is transferred to CO_2 via reheaters. The heat exchange between the hot and cold fluids in both intercoolers and reheaters is assumed to be ideal, without heat loss. The enhanced logarithmic mean temperature difference method is used to address the heat exchange process [14]. The heat flux in the intercoolers or reheaters is expressed by Eq. (10), while the heat exchanger effectiveness is defined by Eq. (11).

$$Q_{he}=m_{cold}\left(h_{cold}^{out}-h_{cold}^{in}\right)=m_{hot}\left(h_{hot}^{in}-h_{hot}^{out}\right), \tag{10}$$

$$\varepsilon_{he}=\frac{Q_{he}}{Q_{max}}, \tag{11}$$

$$Q_{max}=\min\left(m_{cold}\left(h_{cold}^{ideal,out}-h_{cold}^{in}\right),m_{hot}\left(h_{hot}^{in}-h_{hot}^{ideal,out}\right)\right), \tag{12}$$

where Q_{he} denotes the heat flux of the heat exchanger; ε_{he} is the effectiveness of the heat exchanger; Q_{max} represents the theoretical maximum heat transfer; $h_{cold}^{ideal,out}$ is the specific enthalpy of the cold fluid when its outlet temperature equals the inlet temperature of hot fluid, while $h_{cold}^{ideal,out}$ is the specific enthalpy of the hot fluid when its outlet temperature equals the inlet temperature of the cold fluid;

2.2.1.4 Thermodynamic performance indicators

According to the first law of thermodynamics, energy efficiency is defined as the ratio of useful energy output to energy input. In the context of CCES, this energy efficiency is generally referred to as the RTE [15]. RTE is defined as the ratio of total output power to total power consumed over a complete energy storage and release cycle [16,17], expressed by Eq. (13).

$$\text{RTE}=\frac{P_{di}t_{di}}{P_{ch}t_{ch}}, \tag{13}$$

where t_{di} and t_{ch} represent the discharging time and charging time in an energy storage cycle, respectively.

Volumetric energy storage capacity (ESD) is another key performance indicator for CCES systems. Operationally, ESD is defined as the ratio of total power output to the total volume of working fluid stored across charge-discharge cycles [18], given by Eq. (14).

$$\text{ESD}=\frac{P_{di}t_{di}}{V_{HST}+V_{LST}}, \tag{14}$$

where V_{HST} and V_{LST} denote volumes of the high-pressure storage and low-pressure storage tanks, respectively.

2.2.1.5 Exergy analysis

From the viewpoint of the second law of thermodynamics, irreversibility in thermodynamic processes leads to exergy losses in real systems. Exergy analysis provides a systematic methodology to quantify and identify these exergy destructions.

The exergy balance equation for each equipment can be expressed as Eq. (15) [19]:

$$\dot{E}_F(k)=\dot{E}_P(k)+\dot{E}_D(k), \tag{15}$$

where $\dot{E}_F(k)$ is the fuel exergy (or input exergy); $\dot{E}_P(k)$ is the product (output) exergy; and $\dot{E}_D(k)$ is the exergy destruction due to irreversibility or technical limitations. k denotes the system component.

For the entire CCES system, the overall exergy balance is given by Eq. (16) [20,21]:

$$\dot{E}_{F,tot}=\dot{E}_{P,tot}+\sum_{k=1}^{K}\dot{E}_D(k)+\dot{E}_{L,tot}, \tag{16}$$

where $\dot{E}_{F,tot}$ is the total fuel exergy input of the entire system; $\dot{E}_{P,tot}$ is the product exergy output; and $\dot{E}_{L,tot}$ represents the exergy loss to the environment.

Exergy efficiency quantifies how closely a system operates relative to its theoretical reversible limit by accounting for irreversibility, entropy generation, and environmental interactions [19]. To better evaluate component performance, the exergy efficiency and relative exergy destruction for each component are defined by Eqs. (17) and (18) [22]:

$$\eta_{ex}(k)=\frac{\dot{E}_P(k)}{\dot{E}_F(k)}, \tag{17}$$

$$y_{\mathrm{D}}(k)=\frac{\dot{E}_{\mathrm{D}}(k)}{\sum_{k=1}^{K}\dot{E}_{\mathrm{D}}(k)}, \tag{18}$$

where $\eta_{\mathrm{ex}}(k)$ denotes the exergy efficiency and $y_{\mathrm{D}}(k)$ is the relative exergy destruction of component.

For the entire CCES system, the total exergy efficiency (TEE) is calculated as the ratio of total exergy output to total exergy input [23], as shown in Eq. (19):

$$\mathrm{TEE}=\frac{\dot{E}_{\mathrm{P,tot}}}{\dot{E}_{\mathrm{F,tot}}}. \tag{19}$$

By sequentially solving Eqs. (1)–(19) for the charging and discharging processes under the stated assumptions, the overall energy efficiency, ESD, and exergy efficiency of the system can be determined.

2.2.2 Economic analysis model

Economics is a critical criterion for evaluating the feasibility of a newly proposed system. In terms of economic performance, the most commonly used quantitative indicator for energy storage systems is the LCOE which represents the levelized cost per unit of electricity output over the lifetime of the system, typically expressed in \$/kWh or \$/MWh [15]. Using discounted cash flow analysis, the LCOE of a CCES system can be mathematically expressed as Eq. (20) [24–26]:

$$\mathrm{LCOE}=\frac{\sum_{t=1}^{T}\frac{C_{\mathrm{A,t}}+C_{\mathrm{M}}\cdot(1+\mathrm{IFR})^{t-1}+C_{\mathrm{VE}}}{(1+\mathrm{DR})^{t}}}{\sum_{t=1}^{T}\frac{P_{\mathrm{di}}\cdot t_{\mathrm{di}}\cdot N_{\mathrm{cyc}}}{(1+\mathrm{DR})^{t}}}, \tag{20}$$

where C_{A} is the annual capital investment cost; C_{M} is the annual maintenance cost; C_{VE} is the purchase cost of valley electricity; N_{cyc} is the annual cycle number of the CCES system; IFR is the inflation rate; DR is the discount rate, and T is the lifetime of the CCES power station.

The annual capital investment cost of the CCES system can be obtained by converting the total capital investment cost of system components, as shown in Eq. (21):

$$C_{\mathrm{A,t}}=\mathrm{CRF}\cdot C_{\mathrm{tot}}, \tag{21}$$

where CRF is the capital recovery factor and C_{tot} is the total capital investment cost, including the purchase and installation costs of each component in the CCES system.

The CRF, which calculates the annual payment required to repay a loan over its lifetime, is expressed as Eq. (22):

$$\mathrm{CRF}=\frac{\mathrm{IR}\cdot(1+\mathrm{IR})^{T}}{(1+\mathrm{IR})^{T}-1}, \tag{22}$$

where IR represents the interest rate.

The annual maintenance cost C_{M} and the purchase cost of valley electricity C_{VE} can be calculated using Eqs. (23) and (24), respectively [27].

$$C_{\mathrm{M}}=\mathrm{OM_p}\cdot P_{\mathrm{di}}+\mathrm{OM_{di}}\cdot P_{\mathrm{di}}\cdot t_{\mathrm{di}}\cdot N_{\mathrm{cyc}}, \tag{23}$$

$$C_{\mathrm{VE}}=c_{\mathrm{VE}}\cdot P_{\mathrm{ch}}\cdot t_{\mathrm{ch}}\cdot N_{\mathrm{cyc}}, \tag{24}$$

where $\mathrm{OM_p}$ and $\mathrm{OM_{di}}$ are the specific operation and maintenance costs related to the nominal power capacity and annual discharged electricity, respectively; and c_{VE} is the price of valley electricity.

3 Recent research on CCES

3.1 CCES systems

Based on thermodynamic phase transitions of CO_2 between high-pressure and low-pressure sides in CCES, four distinct configurations emerge, each exhibiting characteristic trade-offs between efficiency and storage density: liquid CO_2 energy storage (LCES) system [28], transcritical compressed CO_2 energy storage (TC-CCES) system [29], supercritical compressed CO_2 energy storage (SC-CCES) system [29], and vapor-liquid compressed CO_2 energy storage (VL-CCES) system [30].

3.1.1 LCES system

CO_2 as a working fluid exhibit phase transition advantages over liquid air energy storage systems, demonstrating superior thermodynamic adaptability due to its near-ambient critical temperature (31.1 °C). Based on this, Wang et al. [18] designed an energy storage system using liquid CO_2, referred to as the LCES system. In this system, CO_2 is maintained in the liquid state on both the high- and low-pressure sides. As illustrated in Fig. 2 [31], during charging, low-pressure liquid CO_2 absorbs heat in a cold regenerator and undergoes a phase change. It is then compressed through multiple stages with intermediate cooling, after which the pressurized CO_2 gas is condensed back into liquid form via dedicated liquefaction processes, enabling high-pressure cryogenic storage. During discharging, the high-pressure liquid CO_2 vaporizes, then expands through multi-stage expanders with intermediate reheating, driving turbine-generator sets to produce electricity. The expanded low-pressure CO_2 is reliquefied using stored cryogenic capacity, and the liquid CO_2 returns to the low-pressure tank, completing the thermodynamic cycle of the LCES system. This design leverages the easy liquefaction properties of CO_2 and increased volumetric energy density in the liquid phase, significantly reducing storage infrastructure requirements.

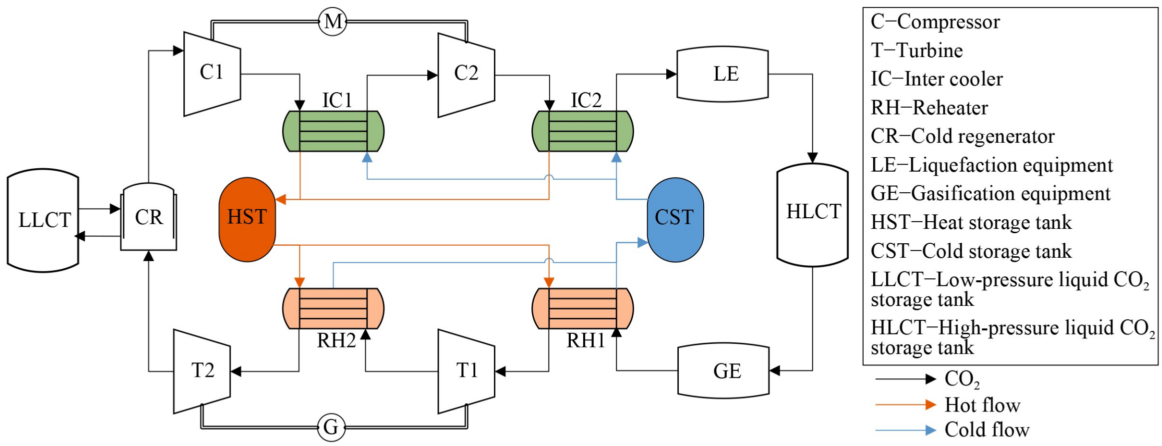

Fig. 2 Flowchart of LCES system.

3.1.2 TC-CCES system

In pursuit of enhanced performance in CO_2-based energy storage system, Zhang et al. [32] developed a transcritical CCES system utilizing CO_2 Brayton cycle, also known as TC-CCES system. This innovative configuration maintains supercritical CO_2 on the high-pressure side while preserving liquid-phase CO_2 on the low-pressure side, achieving notable improvements on energy density through a phase-differentiated storage strategy. As shown in Fig. 3 [29], during charge process, low-pressure liquid CO_2 absorbs heat in an accumulator and vaporizes into a gaseous state. The gaseous CO_2 then undergoes multi-stage compression with intercooling, elevating it to the supercritical state while minimizing compressor power consumption. The resulting SC-CO_2 is then stored in high-pressure containment vessels. The discharge process employs a complementary approach, utilizing multi-stage expansion with interstage reheating to enhance turbine output work. Following expansion, vapor CO_2 is condensed back to the liquid phase through heat exchange with the cold energy stored during charging, completing the energy cycle. The liquid CO_2 is ultimately stored in low-pressure tank, maintaining system pressure differentials for continuous operation.

3.1.3 SC-CCES system

The SC-CCES system is developed as an advanced energy storage solution, sharing similar operational process with TC-CCES architectures. This system maintains CO_2 in its supercritical state across all operational phases. As shown in Fig. 4 [29], the energy storage phase involves pressurization and thermal conditioning of low-pressure SC-CO_2 through compression and subsequent cooling, with the processed CO_2 stored in high-pressure tanks. During the energy release phase, the stored high-pressure SC-CO_2 undergoes thermal augmentation prior to expansion-driven power generation and ultimately returns to the low-pressure tanks post-

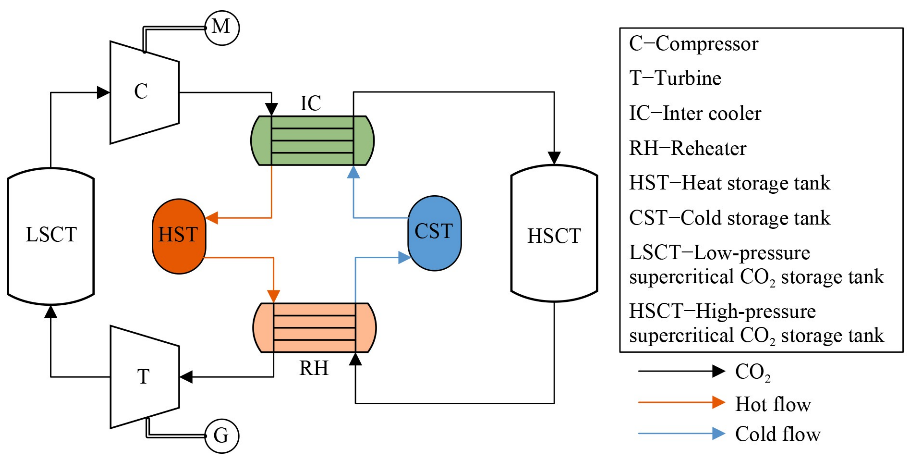

Fig. 3 Flowchart of TC-CCES system.

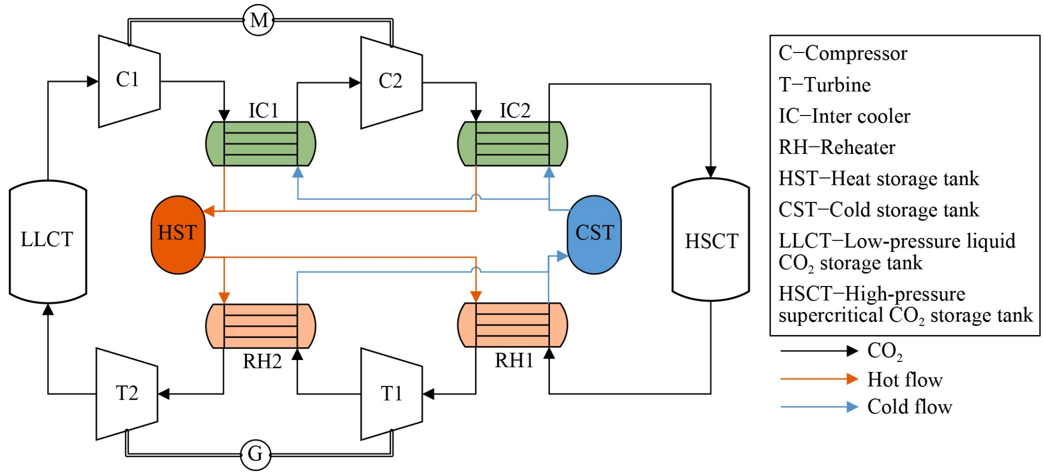

Fig. 4 Flowchart of SC-CCES system.

expansion. Continuous supercritical operation in a SC-CCES system enables simplified single-stage compression and expansion configurations due to reduced pressure and expansion ratios inherent to supercritical fluid behavior. However, the SC-CCES system faces inherent limitations. Both storage tanks operate under high pressure, and safety constraints on the high-pressure side limit further pressure increases, ultimately limiting the potential improvement of RTE.

3.1.4 VL-CCES system

The VL-CCES system, depicted in Fig. 5 [30], represents a modified configuration where gaseous CO_2 is maintained on the low-pressure side, while liquid CO_2 occupies the high-pressure side. This architecture shares operational similarities with LCES systems but eliminates the need for liquefaction of low-pressure CO_2, replacing conventional cryogenic storage with simpler gaseous containment solutions. The increased pressure gradient enables greater energy extraction during expansion phases. However, the low density of gaseous CO_2 necessitates oversized low-pressure containment systems. In practical applications, variable-volume flexible airbags operating at ambient-pressure are used for gaseous CO_2 storage. These expandable airbags dynamically adjust their capacity to maintain near-isobaric conditions throughout the charge–discharge cycles.

3.2 Comparative analysis of CCES systems

CCES technology is increasingly recognized as a promising solution for large-scale energy storage. Extensive research has been conducted to evaluate its thermodynamic performance through energy and exergy analyses. Various CCES configurations exhibit differing

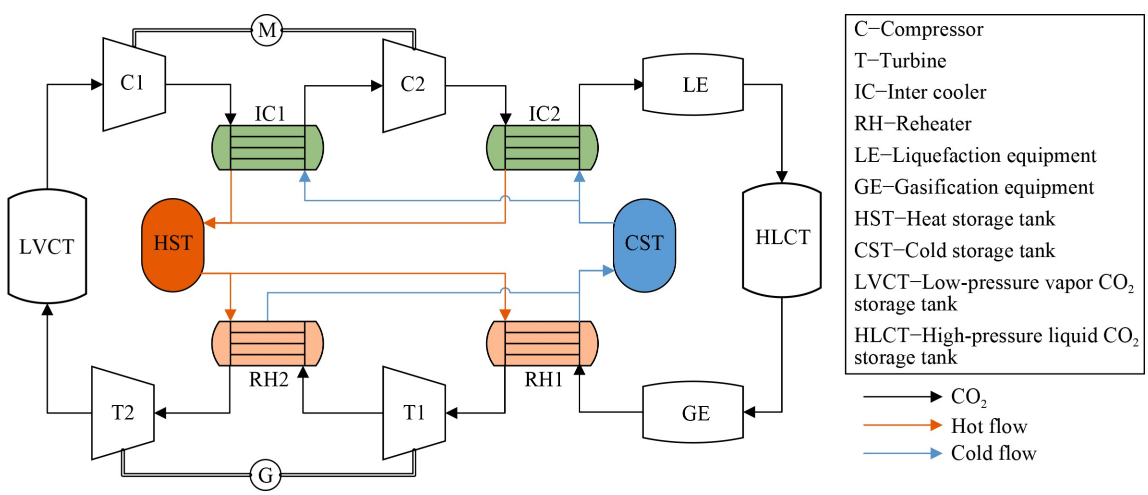

Fig. 5 Flowchart of VL-CCES system.

performances due to structural and operational differences. Ma and Liu [32] conducted a thermo-economic evaluation of an LCES system, reporting a maximum RTE of 56.23%, a peak ESD of 19.90 kWh/m^3, and a lowest LCOE of 0.0907 $/kWh. Zheng et al. [33] compared four CCES systems and found that LCES system exhibited superior overall performance with a 56.20% RTE, 16.23 kWh/m^3 ESD, and 0.131 $/kWh LCOE. Zhang et al. [34] proposed a TC-CCES system achieving 60.69% RTE and 8.07 kWh/m^3 ESD, while Hao et al. [35] optimized TC-CCES by adjusting compression and expansion stages, ratios, and temperatures, achieving an RTE of up to 74.07%. Furthermore, Zhang et al. [36] proposed an adsorption-enhanced TC-CCES system delivering 66.68% RTE, 67.79% TEE, and 12.11 kWh/m^3 ESD. Comparisons between TC-CCES and SC-CCES systems by Zhang and Wang [37] revealed significant differences: TC-CCES achieved 2.6 kWh/m^3 ESD and 60% RTE, whereas SC-CCES delivered 23 kWh/m^3 ESD and 71% RTE. Xu et al. [38] studied isobaric SC-CCES using underwater flexible bags, reporting a split-cycle system with 43.94% RTE and 62.81% exergy efficiency.

Given the variation in modeling assumptions and input parameters across different studies, this paper provides only a general performance trend of different CCES configurations rather than a strict ranking, as summarized in Table 1. Overall, the LCES system requires minimal storage space, enabling the highest ESD. This translates into lower geographical constraints and greater ease of deployment. However, the LCES system involves complex liquefaction and vaporization components, introducing integration challenges and increased capital expenditure (CAPEX). The TC-CCES system, with liquid-phase CO_2 stored at the low-pressure side, avoids special geographical requirements but yields a lower ESD compared to the LCES system. In contrast, systems that store CO_2 in gaseous state at the low-pressure side faces stringent geographical constraints, limiting their widespread deployment. Additionally, TC-CCES systems encounter challenges from abrupt thermophysical transitions of CO_2 near the critical point, resulting in discontinuities in the compression process and requiring specialized compressors [18,38]. The SC-CCES system features the simplest structure, maintaining CO_2 in a supercritical state throughout operation, and achieves relatively high RTE and ESD. Nonetheless, it is limited by high-pressure safety constraints, particularly restrictions on maximum circulation pressure. The VL-CCES system, owing to its high compression and expansion ratios, can reach high RTE. Although the low-pressure side stores CO_2 in a near-atmospheric gaseous state requiring large-volume containment, this significantly reduces ESD and challenges system compactness [29]. Despite this, VL-CCES offers strong technical feasibility and has been demonstrated in operational power plants. Finally, systems employing adsorbent-based storage of low-pressure gaseous CO_2 show promise with considerable RTE and ESD [36], but, adsorbent utilization remains immature and requires further development.

Conventional exergy analysis primarily quantifies exergy dissipation within a CCES system but fails to reveal the thermodynamic interactions between different system components [40]. In contrast, advanced exergy analysis identifies avoidable losses and optimization potentials by considering component interdependencies and technical constraints [41–45]. Empirical studies applying advanced exergy analysis across diverse CCES configurations have yielded valuable insights. For instance, He et al. [46] found that the recuperator is

Table 1 Performance comparison of different CCES systems

System type	CO_2 phase		RTE/%	ESD/(kWh·m^{-3})	TEE/%	LCOE/($·kWh^{-1})
	High-pressure	Low-pressure				
LCES	Liquid	Liquid	56.64 [18]	36.12 [18]	51.14 [18]	0.0907 [32]
			65.41 [28]	23.35 [28]	66.80 [28]	0.131 [33]
			56.23 [32]	19.90 [32]		
			56.20 [33]	16.23 [33]		
TC-CCES	Supercritical	Liquid	60.69 [34]	8.07 [34]	52.64 [37]	–
			59.98 [37]	2.6 [37]		
		Vapor	63.35 [29]	497.68 [29]	53.02 [29]	0.087~0.092 [39]
			74.07 [35]			
SC-CCES	Supercritical	Supercritical	62.28 [29]	255.20[29]	51.56 [29]	0.0715/0.0726 [38]
			71.41 [37]	23 [37]	71.38 [37]	
			38.74/43.94 [38]	7.89 [38]	55.85/62.81 [38]	
VL-CCES	Liquid	Vapor	72.66 [30]	0.12 [30]		0.1252[30]

responsible for the highest avoidable exergy destruction in SC-CCES systems. Liu et al. [47] identified the primary compressor as having the greatest optimization potential in TC-CCES systems. In LCES system, the expander emerges as a critical optimization target with the highest techno-economic priority for efficiency enhancement [48]. Zhang et al. [49] reported that the recuperator accounts for 39.17% of exergy destruction in a CCES system. Sun et al. [50] compared two LCES systems without external heat or cold sources and found that compressors and turbines have the highest exergy destruction and associated costs. In addition, CCES systems with multi-stage compression and expansion tend to suffer efficiency losses and increased exergy destruction as the number of stages increases.

3.3 CCES demonstrations

CCES technology is gradually advancing from small-scale demonstrations to commercial applications. Several CCES demonstration projects worldwide are at various stages of development, as summarized in Table 2.

In June 2022, Italian company Energy Dome launched the world's first CO_2 energy storage demonstration project in Sardinia, Italy, with a capacity of 2.5 MW/4 MWh [51]. This system employs large airbags to store CO_2 gas near ambient temperature and pressure. When renewable energy supply exceeds demand, surplus electricity to compresses CO_2 gas into liquid. During grid demand peaks, the liquid CO_2 expands back into gas, driving turbines to generate carbon-free electricity that can be fed directly into the grid. Energy Dome aimed for a LCOE between 50−60 $/MWh within the coming years, and the system efficiency of 75%−80%. By the end of 2023, Energy Dome announced plans to build a corresponding commercial VL-CCES power plant with a capacity of 20 MW/200 MWh and a 10-h duration, targeting completion by early 2025. The company estimates the CAPEX for this project to be less than 50% of that for a comparable 4-hour lithium-ion storage project. Energy Dome also signed an agreement with Alliant Energy to develop an identical project in Columbia County, Wisconsin, USA, utilizing its 20 MW/200 MWh CO_2 energy storage technology [52], with construction planned for 2025 and completion in 2026.

In China, CCES development is progressing rapidly with multiple demonstration projects either operational or under construction. A 10 MW × 2 h VL-CCES demonstration system integrates CCES with flywheel energy storage, utilizing 250000 m^3 of CO_2 as working fluid. This hybrid system achieves RTE exceeding 55%, with capacity costs around 1140 $/kWh, which is higher than that CAES [53].

The Wuhu Conch 10 MW/80 MWh CO_2 energy storage project is China's first large-scale CO_2 energy storage power plant, grid-connected as of July 3, 2025. It employs gas–liquid CO_2 phase change storage. CO_2 emitted from cement production is captured, compressed, liquefied, and stored in a high-pressure tank. During discharge, the compressed CO_2 drives a turbine to generate electricity. Furthermore, waste flue gas below 90 °C from cement kilns serves as a heat source to enhance CO_2 evaporation efficiency via heat storage exchangers. This project integrates CO_2 capture with energy storage, forming a distinctive closed-loop industrial chain model that promotes CO_2 temporary sequestration and circular utilization. The LCOE is estimated at 0.028 $/kWh over a 30-year lifespan, equivalent to thermal power costs. Its innovative "waste heat utilization + carbon recycling + energy storage" approach provides a replicable solution for green transformation in energy-intensive industries.

The Shandong Feicheng 100 MW/400 MWh novel compressed CO_2 molten salt energy storage project employs a hybrid "compressed CO_2 + molten salt thermal storage" technology. Off-peak electricity compresses CO_2 while turbine exhaust steam waste heat is captured stored as molten salt thermal energy at high temperature.

Table 2 CCES applications and engineering demonstrations

Project	Location	State	Capacity	Technical characteristics
CCES and flywheel energy storage [50]	Deyang, Sichuan, China	Operation	10 MW/20 MWh	VL-CCES, RTE 55%
Wuhu Conch 10 MW/80 MWh CO_2 Energy Storage Demonstration Project	Wuhu, Anhui, China	Operation	10 MW/80 MWh	VL-CCES, RTE ⩾ 60%, utilizing low-grade industrial waste heat from cement kilns; coupled with carbon capture
Feicheng 100 MW Novel CO_2 Molten Salt Energy Storage Demonstration Project	Feicheng, Shandong, China	Construction	100 MW/400 MWh	CCES+(high-temperature) molten salt thermal storage, RTE ⩾ 63%
Huadian-Dongfang Electric Mulei CO_2 Energy Storage Project	Changji Prefecture, Xinjiang, China	Construction	100 MW/1000 MWh	Non-supplementary combustion, integrated with cold and thermal storage system
Energy Dome Sardinia Pilot Plant	Sardinia, Italy	Operation	2.5 MW/4 MWh	VL-CCES
Energy Dome Ottana Project	Sardinia, Italy	Construction	20 MW/200 MWh	VL-CCES
Energy Dome Columbia Project	Columbia, Wisconsin, USA	Plan	20 MW/200 MWh	VL-CCES

During peak demand, the stored heat generates steam to drive turbines to generate electricity. This system simultaneously provides electricity, heating, cooling, and steam, greatly improving overall energy utilization efficiency. The project currently achieves an electrical-to-electrical conversion efficiency of ⩾ 63% and an overall conversion efficiency of ⩾ 85%. Upon completion, it will supply approximately 125 million kWh of dispatchable electricity and 634000 GJ of heating annually.

The Huadian-Dongfang Electric Mulei CO_2 energy storage project, planned for full operation by the end of 2025, is currently the world's largest CO_2 energy storage project. With 1000 MWh storage capacity coupled with 600 MW of wind power and 400 MW of PV power [54], it employs CO_2 gas–liquid phase-change energy storage technology, which can achieve an electrical energy conversion efficiency of up to 60.4% by leveraging CO_2 physical phase transitions during compression, liquefaction, and gasification. Upon completion, this project will effectively alleviate peak-load regulation pressures on the power grid of Xinjiang Uyghur Autonomous Region, reduce curtailment of wind and solar power, resolve large-scale renewable energy grid integration challenges, and enhance grid stability and reliability.

Analysis of the projects listed in Table 2 reveals several key trends in the early commercial deployment of CCES technology.

Scaling up and growing confidence: There is a clear progression from small-scale pilot demonstrations such as Energy Dome's 4 MWh unit, to large-scale commercial projects like the 1000 MWh Mulei facility. This trend reflects increasing confidence in the viability and maturity of CCES systems.

Application-specific technical pathways: Project design choices are highly tailored to application needs. For example, the Wuhu Conch CCES project utilizes industrial waste heat and adopts VL-CCES configuration to optimize efficiency. In contrast, standalone energy storage projects such as Energy Dome's tend to prioritize technical simplicity and lower capital costs, favoring VL-CCES configuration with flexible gas holders to simplify storage infrastructure.

Integration with thermal storage for enhanced performance: The Feicheng project exemplifies the integration of compressed CO_2 storage with molten salt with thermal storage, aiming for higher RTE and multi-energy outputs (electricity, heat, steam, cooling). This hybrid approach represents a promising direction for increasing the overall utility and efficiency of energy storage systems.

Early performance indicators: While detailed operational data from commercial-scale projects remain largely proprietary, available public performance data offer valuable insights. For instance, the Wuhu Conch project reports a RTE exceeding 60%, which aligns well with the thermodynamic models for systems utilizing low-grade waste heat. Energy Dome claims an expected efficiency of 75%−80% and a target LCOE of 50–60 $/MWh for its commercial units. Demonstrating these performance targets in real-world operations is critical for establishing CCES's competitiveness among long-duration energy storage technologies.

Engineering challenges in commercial deployment: The path from laboratory to commercial site introduces engineering challenges not always evident in simulations. For CCES, these include the long-term integrity of materials in contact with high-pressure and potentially impure CO_2, the development of high-efficiency compressors and expanders operating with supercritical or phase-changing CO_2, and the real-time control strategies for managing cyclic loading and transient operation. Lessons learned from these first-of-a-kind projects are invaluable for de-risking future deployments and guiding subsequent R&D efforts.

Storage infrastructure considerations: Current CCES demonstration projects primarily rely on above-ground storage vessels. The commercial validation of underground storage options such as salt caverns and saline aquifers remains an important future milestone, potentially enabling larger-scale and cost-effective CO_2 energy storage.

Overall, the aforementioned demonstration projects reveal a clear development trajectory for CCES technology. CCES demonstration projects are currently transitioning from pilot-scale trials to the early stages of commercialization, with individual project capacities steadily increasing. These initiatives predominantly explore applications within specific scenarios, such as supporting large-scale wind and solar power bases, utilizing industrial waste heat, and integrating with CCUS technologies. In the future, as CCES technology continues to mature and cost decline, it is poised to play an increasingly significant role in long-duration energy storage, helping power grids accommodate higher shares of renewable energy and supporting the broader energy transition.

4 Challenges and cutting-edge research of CCES

As a cutting-edge physical energy storage technology, numerous studies on CCES have been conducted to date. Although CCES systems demonstrate superior performance of ESD, system efficiency, and environmental benefits, large-scale deployment still faces several key challenges, including optimization of CO_2-based mixed working fluids for improved thermodynamic performance, efficient and cost-effective liquefaction of low-pressure CO_2, development of low-cost, safe, and scalable CO_2 storage facilities, system performance enhancement of CCES through integrated design improvements, and accurate evaluation of dynamic system behavior under real-world operating conditions. Addressing these limitations will be critical to advancing CCES toward widespread commercial application.

4.1 CO_2-based mixtures working medium

The favorable thermodynamic properties nominally position CO_2 as an ideal working fluid for CGES systems. However, its practical implementation confronts two key technological bottlenecks: the demands of hyperbaric operation and the challenges of harsh condensation conditions [55,56]. Recent advancements demonstrate that blending CO_2 with organic fluids, which have relatively higher critical temperatures and low pressures, offer a promising pathway for mitigating these imitations in CCES systems [57–60].

By adjusting critical parameters such as critical temperature and pressure, CO_2-based mixtures can be tailored to suit a wider range of operation conditions and environmental requirements. This has led to increased interest in employing CO_2-blended working fluid in CCES systems.

For instance, Liu et al. [61] demonstrated that blending CO_2 with R134a (1,1,1,2-Tetrafluoroethane) in a LCES system alleviated subcritical condensation challenges by shifting the vapor-liquid equilibrium curve relative to pure CO_2, resulting in a 22.7% increase in net power output, a 38% reduction in optimal charge pressure, and competitive ESD. Similarly, Ma and Liu [62] conducted a comparative assessment of CO_2 binary mixtures for low-pressure LCES systems, identifying CO_2/R161 (Fluoroethane) (70/30 wt.%) and CO_2/R1270 (Propylene) (82/18 wt.%) as optimal working fluids. The CO_2/R161 system achieved 52.95% RTE and 29.74 kWh/m^3 ESD, while the CO_2/R1270 system maintained 52.12% RTE and 29.83 kWh/m^3 ESD.

Tang et al. [63] engineered a CO_2/Propane (78/22 wt.%) binary mixture to enhance SC-CCES system performance in arid regions, achieving a 10.2% increase in RTE. Fu et al. [64] evaluated a non-cryogenic CCES system using CO_2 blended with six refrigerant additives, finding that blending CO_2 with 20% R32 (mass fraction) achieved the highest coefficient of performance and the lowest LCOE. Yan et al. [65] further identified CO_2/R32 (Difluoromethane) (65/35 wt.%) and CO_2/R161 (85/15 wt.%) as optimal working fluids for high-efficiency CCES system deployment.

To address CO_2 condensation challenges in high-temperature environments, Zhang et al. [66] showed that blending CO_2 with Propylene, R32, and R1234yf (2,3,3,3-Tetrafluoropropylene) at optimized mass ratios significantly enhanced CCES operational flexibility. Hou et al. [67] demonstrated that CO_2/R1270 and CO_2/R32 mixtures exhibited superior adaptability to environmental fluctuations in liquid CO_2 mixture energy storage systems synergistically integrated with coal-fired power plants (CFPPs).

Collectively, these studies highlight the integration of CO_2-based mixtures as an effective strategy to address thermodynamic limitations, enhancing system efficiency and scalability. The advantages include depressed critical parameters which enable near-ambient pressure operation without sacrificing ESD; CO_2 inerting effect which reduces the flammability limits of organic components [68]; and characteristic temperature glide of CO_2 mixtures which promotes thermal matching between working fluid and heat sources/sinks, and enhances phase-change heat transfer coefficients [69].

However, the application of CO_2-based mixtures in CCES systems is still in its infancy, with critical gaps to be addressed, such as thermodynamic optimization, economic and environmental trade-offs, and validation under dynamic operational conditions. Additionally, there is currently no standardized methodology for screening or optimizing working fluid mixture ratios, making it challenging to balance system efficiency and cost. Future research should prioritize developing a comprehensive database for CO_2-based mixture to support systematic design and optimization efforts.

4.2 Low-pressure CO_2 condensation of CCES

To enhance ESD, extensive research has focused on liquid CO_2 energy storage (LCES) systems. However, the performance LCES is limited by phase transition challenges during subcritical CO_2 liquefaction that occurs at the turbine outlet during the energy discharge phase [70].

Figure 6 illustrates the latent heat change of CO_2 vaporization as a function of saturation temperature. As saturation pressure decreases, the saturation temperature drops, while the latent heat of vaporization gradually increases, reaching 303.5 kJ/kg at a saturation pressure of 1.43 MPa.

During energy release phase, simultaneously operating a refrigeration unit to cool and liquefy CO_2 at the expander outlet leads to substantial power consumption, which seriously reduces system efficiency and complicates meeting peak load regulation requirements.

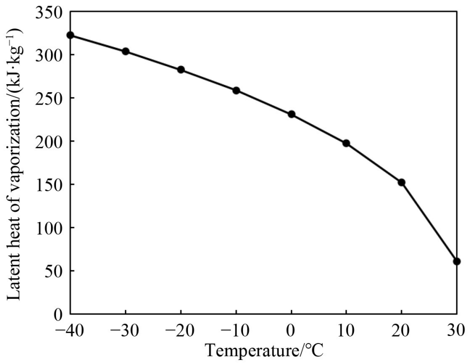

Fig. 6 Temperature and latent heat of vaporization at the CO_2 saturation state.

Therefore, achieving high-efficiency liquefaction of low-pressure CO_2 during discharging is critical for advancing the performance of LCES systems.

To achieve liquefaction of low-pressure CO_2 without relying on additional cold sources, Liu et al. [31] proposed an ejector condensing cycle to lower cooling temperatures and broaden operation range of LCES systems. Similarly, Zhao et al. [71] developed a self-condensation LCES system using a vortex tube. However, regardless of the self-condensation approach, excessively high system pressures pose safety risks, and the resulting complex system configurations result in higher capital cost, hindering large-scale application.

An alternative way is to incorporate external cold sources to liquefy low-pressure CO_2. The regasification of liquefied natural gas (LNG) at atmospheric pressure (~−162 °C) releases substantial cold energy (830−860 kJ/kg) [72], providing an opportunity for cryogenic energy recovery when coupled with LCES systems [73]. However, the large temperature difference between CO_2 liquefaction (~−40 °C) and LNG regasification (~−162 °C) causes severe cryogenic exergy destruction during direct heat exchange. Thermodynamic modeling reveals that the LNG cold exergy is irreversibly lost during direct heat transfer. Although integration with additional components can improve LNG-CCES system performance, it also increases system complexity and imposes geographical limitations on LCES application.

Efficient liquefication of CO_2 at the expander outlet and gasification at the compressor inlet requires both cold energy and heat energy during energy release and storage phases. Consequently, a high-efficiency refrigeration system, acting as an advanced heat exchanger, is essential for energy-saving peak regulation by storing and releasing cold energy. The use of advanced composite phase change materials (PCMs) to achieve cascaded thermal matching is an effective pathway to enhance refrigerator performance.

For instance, Wang et al. [74] employed two-stage cool storage devices filled with crystalline hydrated salt and small pebbles for effective heat transfer. Zhang et al. [75] suggested utilizing steel pipe-packed bed regenerators containing appropriate thermal storage materials. Sun et al. [76] adopted liquid methanol combined with phase-change cold storage to separately capture sensible and latent cold energy. Fu et al. [64] developed a phase-change coupled system integrating calcium chloride aqueous solution with ice slurry to sequentially liquefy and vaporize low-pressure CO_2.

Currently, regenerators represent the most efficient method for low-pressure CO_2 liquefaction. However, many recent relevant studies treat regenerators as simple heat exchangers without detailed simulations and experimental validation. Zheng et al. [14] proposed an LCES system integrating a Linde-Hampson liquefaction cycle with a dual-stage cold/heat storage mechanism. Their comprehensive thermal transfer dynamics analysis, including temperature-heat transfer diagrams and exergy assessments, provide optimized design guidelines for enhanced heat exchanger performance.

Thermal (or cold) energy storage methods are primarily categorized into: ① sensible heat storage, which involves temperature changes of the storage medium without phase transitions; ② latent heat storage, which utilizes the large energy (known as latent heat) absorption or release during phase transitions of the storage medium (such as from solid to liquid or liquid to gas); and ③ thermo-chemical heat storage, which employs reversible chemical adsorption or reactions for energy storage and release.

For LCES systems, a two-stage thermal (or cold) storage scheme typically combines a solid or liquid medium sensible heat storage with a phase-change material for latent heat storage. Yet, few studies have focused on phase-change cold energy storage media tailored for low-pressure CO_2 liquefaction. Therefore, it is of great importance to identify or develop phase-change materials with congruent phase transition temperatures aligned with CO_2 properties, elucidate coupled heat and mass transfer mechanisms, and analyze transient system behaviors. Establishing a graded cold storage system that exploits multistage utilization of both sensible and latent thermal energy will be a crucial technological breakthrough, enabling energy-efficient liquefaction of low-pressure CO_2 and advancing the performance of LCES systems.

4.3 CO_2 storage facility

As a critical component of CCES systems, the CO_2 storage facility significantly impacts overall system performance. Traditional isochoric gaseous storage incurs throttling losses, leading to partial exergy loss during energy cycles [46]. Consequently, developing efficient methods for storing both compressed and expanded CO_2 remains an urgent challenge. Above-ground artificial CO_2 storage tanks offer an attractive alternative by eliminating reliance on large natural underground caverns, thereby promoting broader CCES deployment. To enable surface-level low-pressure isobaric CO_2 storage, several researchers have proposed utilizing flexible gas holders [30,38,78]. However, these systems typically require large storage volumes and complex designs.

To achieve high-density low-pressure CO_2 storage, Peng et al. [79] introduced an adsorption-based CO_2 storage device which enhanced CO_2 storage density by approximately 24.8 times compared to conventional isochoric storage. Nevertheless, efficient heat exchange during charging and discharging is essential to maintain rapid system responsiveness.

Because CO_2 in CCES systems is typically maintained at high pressures (generally 10–25 MPa), storage tanks on the high-pressure side must meet stringent safety standards that conventional steel pressure vessels often cannot satisfy. Additionally, vessels require a considerable amount of excess capacity to ensure stable operation during energy release, increasing material cost and reducing the economics of CCES systems.

Given these challenges, underground natural formations such as salt caverns, saline aquifers, depleted gas/oil reservoirs, and coal bed seams present promising options for large-scale CO_2 storage [80]. For instance, Liu et al. [29] designed a CCES system using two saline aquifers at different depths as CO_2 reservoirs. Jiang et al. [81] investigated the feasibility of storing CO_2 in deep post-combustion underground coal gasification cavities, while Cao et al. [82] developed a CCES system incorporating an underground coal seam for CO_2 storage.

The dynamic behavior of CO_2-water-rock interactions during underground storage has also been studied. For example, Li et al. [83] investigated hydrodynamic and thermodynamic properties of CO_2 storage in aquifers through numerical simulations. Shi et al. [84] demonstrated the feasibility of storing supercritical CO_2 (SC-CO_2) in aquifers, finding that fewer operational cycles and higher temperature improve system efficiency. Subsequent research [85] developed predictive models for mineral trapping capacity during geochemical interactions in subsurface CO_2 sequestration. Li et al. [86] created a multiphase flow numerical framework for geological CO_2 storage systems, simulating cyclical operation dynamics in vertical wells and saline aquifer formations. Pressure decay analysis reveals a 38.7% reduction (from 15.96 to 9.78 MPa) in storage reservoir pressure over 200 operational cycles.

In different CCES application scenarios, CO_2 storage is generally categorized into above-ground storage and underground storage. Above-ground storage suits regions lacking geological storage conditions or small-scale energy storage scenarios. Flexible gas bags, while mature, are bulky; artificial tanks provide flexibility but must address thermodynamic stability challenges during the charging and discharging process, such as low-temperature phase change control of liquid CO_2. Supercritical CO_2 storage tanks require materials capable of withstanding high temperature and pressure. Underground storage enables large-scale CCES development but is constrained by the availability of suitable geological reservoirs (e.g., saline aquifers, salt caverns), imposing stringent site-specific limitations that may restrict widespread deployment.

4.4 CCES system integration

Beyond advancements in the CCES system itself, recent research has increasingly focused on enhancing performance and optimizing configurations through synergistic integration with diverse energy systems, enabling multi-stage energy utilization and poly-generation capabilities.

4.4.1 CCES integration with waste heat recovery

Due to the asynchronous nature of compression and expansion processes in CCES systems, TES has emerged as a widely adopted strategy for capturing compression heat during charging phases and reusing it during discharge cycles. However, recent advances in CCES have revealed a critical limitation in TES implementation—significant thermal energy losses occur, which substantially compromise the overall system performance [18]. This identified energy recovery gap has driven considerable research interest toward CCES system optimization through synergistic integration with complementary technologies including organic Rankine cycles (ORC), Kalina cycles, and absorption heat pump systems.

Among waste heat recovery (WHR) technologies, ORC, which employed organic working fluids is the most commonly applied due to its suitability for low to medium temperature heat sources typical in CCES systems [87–89]. A typical integration scheme for the CCES system with an ORC cycle is illustrated in Fig. 7. The generated compression heat during charge process is stored in a thermal storage tank. During discharge, this heat is either utilized either for reheating CO_2 before expansion or serves as a low-grade heat source to drive ORC cycle, thereby generating additional work and enhancing the overall system efficiency.

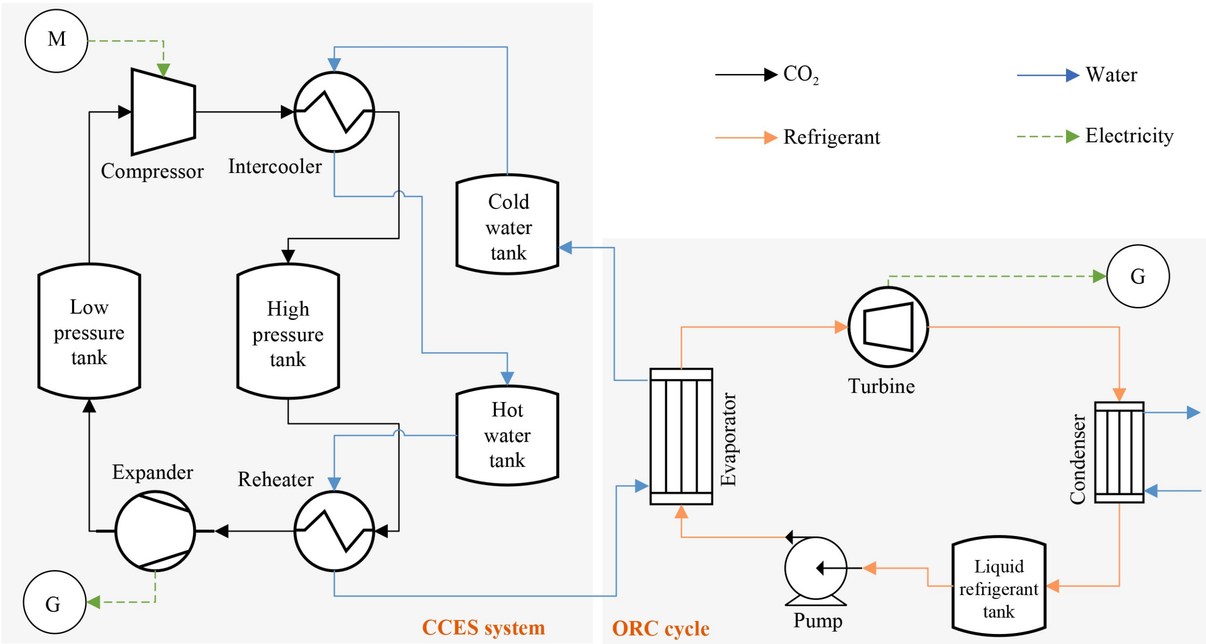

Fig. 7 Schematic diagram of CCES integrated with ORC cycle.

Numerous studies have focused on the thermodynamic analysis of CCES system integration with ORC from both energy and exergy perspectives. For example, Wang et al. [18] employed an ORC with R245fa as the working fluid to recover waste heat from compressors and expanders in a LCES system with a high-pressure ratio, yielding a system RTE of 56.64%. Zhang et al. [90] developed a TC-CCES system coupled with an ORC using propane, demonstrating an exergy efficiency of 34.62%. Ghorbani et al. [91] designed an integrated LCES system with a dual-stage ORC utilizing R142b and R290 as working fluid, achieving a RTE of 41.22%, a TEE of 83.84%, and a LCOS of 8.55 cents/kWh. Zhang et al. [49] presented a hybrid CCES system with ORC-based WHR, yielding a TEE of 72.6%, a total exergy destruction cost of 452.35 $/h, and a product unit cost of 18.49/GJ through multi-objective optimization.

The Kalina cycle, which employs an ammonia-water (NH_3-H_2O) as the working fluid, is another promising thermodynamic solution for low-grade WHR applications [92]. Introduced by Alexander Kalina in 1980, it reduces exergy destruction in low-temperature cycles. Zhang et al. [93] designed a hybrid CCES-Kalina system to enhance performance in low-grade TES applications, as presented in Fig. 8. This integrated system, operating with thermal storage temperatures below 200 °C, achieved a specific exergy efficiency of 58.17%, an RTE of 59.38%, and an ESD of 6.32 kWh/m^3 through thermodynamic optimization.

Furthermore, high-temperature heat pump systems, commonly applied in industrial heating and thermal regeneration processes requiring precise temperature control, have been integrated with CCES to improve thermodynamic performance [94]. Hao et al. [95,96] employed a heat pump system to reheat compression heat in a TC-CCES system, as illustrated in Fig. 9, resulting in improved performance across multiple indicators. Qiao et al. [97] developed a novel heat pump-integrated SC-CCES system with multi-stage compression heat recovery without reliance on external heat source, achieving an impressive RTE of 80.1%.

4.4.2 CCES integration with renewable energy

Considering the potential of solar energy to address the challenge of insufficient heating, some researchers have integrated solar thermal energy into CCES systems to improve overall performance. For example, Xu et al. [98] developed a hybrid LCES system that combined solar thermal energy with wind-generated electricity for pumping operations. Chen et al. [99] proposed two SC-CCES systems coupled with concentrating solar thermal storage and investigated their thermodynamic and economic performance. Fu et al. [100] designed TC-CCES and SC-CCES systems incorporating trough solar heat storage for auxiliary heating. Afterwards, Fu et al. [101] introduced a photothermal-assisted LCES system aimed at increasing the inlet temperature of the expander to improve efficiency. To reduce conventional fossil fuel consumption, Gao [102] employed a solar tower system

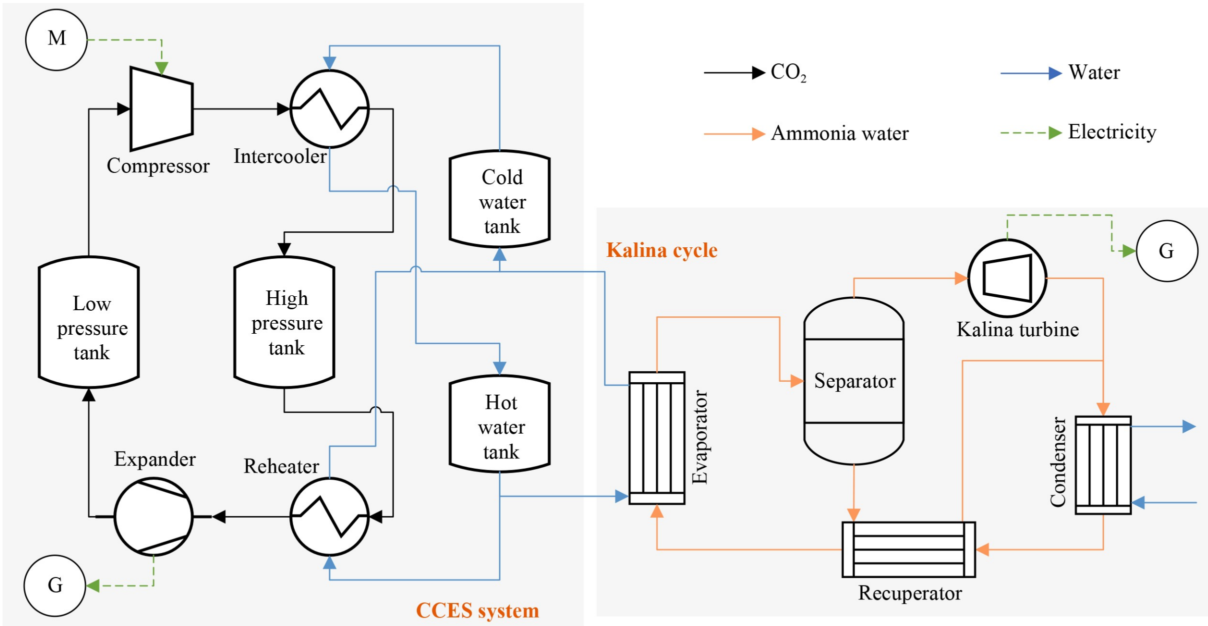

Fig. 8 Schematic diagram of CCES integrated with Kalina cycle.

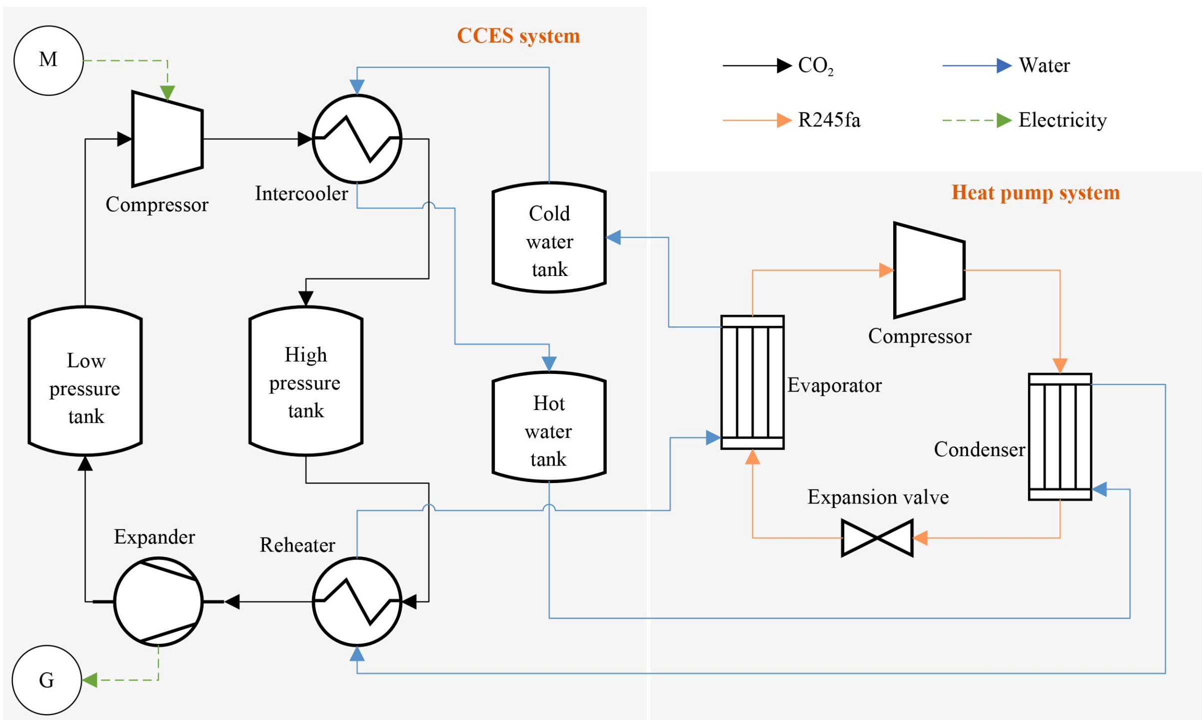

Fig. 9 Schematic diagram of CCES integrated with heat pump system.

to increase CO_2 temperature of turbine inlet in an SC-CCES system. The results indicated that the coupled system effectively improved electrical energy storage efficiency compared to conventional CCES systems.

Moreover, recent research emphasizes advanced system coupling strategies to expand CCES configurations via renewable integration and waste heat cascading, thereby maximizing exergy recovery. Liu et al. [103] designed an enhanced CCES system integrating solar energy and ORC to increase CO_2 temperature before expansion and recover waste heat, resulting in increased net system power output and overall system performance. To enable cascading utilization of energy, Jiang et al. [104] proposed a LCES system assisted by multi-mode solar thermal and coupled with ORC (STS-ORC-LCES system). This system incorporates three weather-adaptive operation and demand modes to enhance environmental compatibility and operational flexibility of the system.

4.4.3 CCES integration with poly-generation

Currently, CCES systems have evolved from unidirectional power delivery to integration with poly-generation systems, leveraging their inherent multi-energy synergies. As shown in Fig. 10, during the charging and discharging processes, CCES not only outputs electricity but also generates compressor heat and cold CO_2 streams that can serve as input energy sources for other applications. For instance, waste heat can be utilized for district heating or to drive absorption refrigeration; electricity can be employed in the power-to-methane (PtM) process; and the system can simultaneously satisfy diverse user demands for multiple energy forms such as cooling, heating, electricity, and gas. This technological advancement follows two strategic development pathways: synergistically integrated with thermal power or combined heat and power (CHP) units within energy hub architectures, and coupling with poly-generation plants, which demonstrate enhanced thermodynamic flexibility and the cross-sectoral decarbonization potential of CCES.

CFPPs remain vital for grid stability due to their mature operations and precise frequency regulation [105]. Retrofitting CFPPs with energy storage systems not only enhances their operational flexibility but also facilitates integration of renewable energy into the grid [106,107]. Several studies have explored practical implementations of CCES systems in combination with thermal power

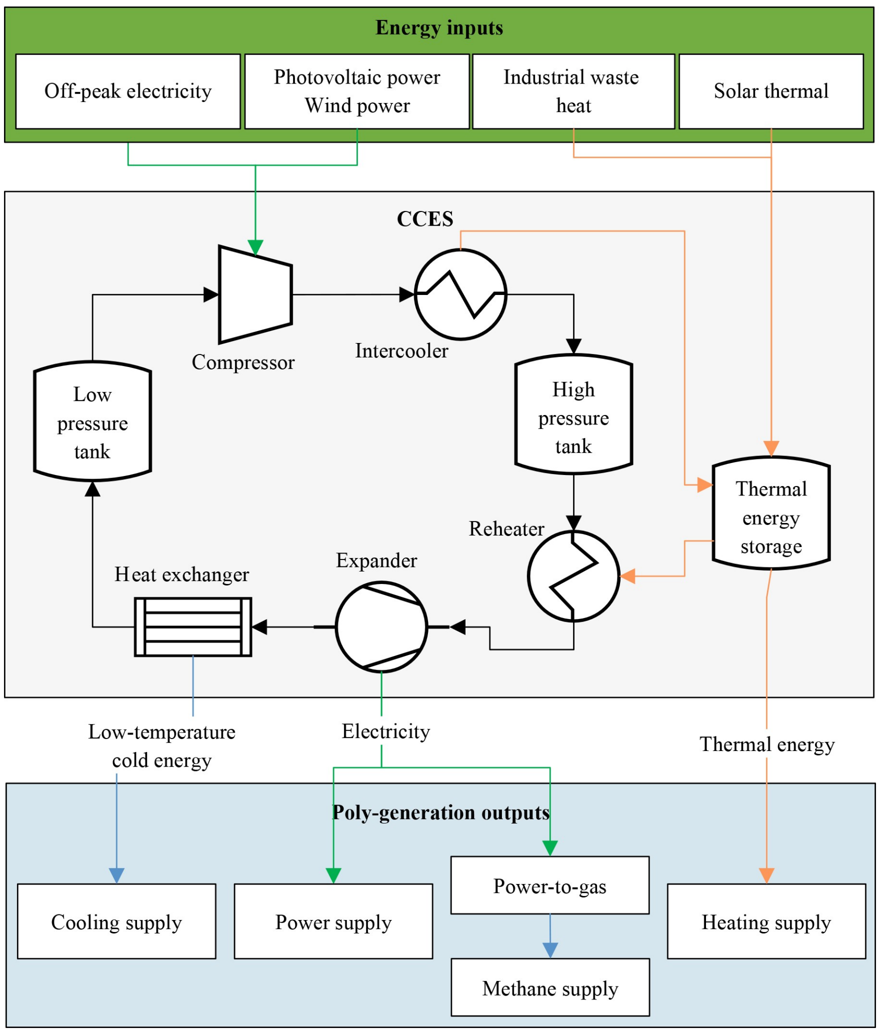

Fig. 10 Schematic diagram of CCES integrated with poly-generation system.

plants. For instance, Cao et al. [108] retrofitted a 660 MW CFPP with a SC-CCES system and analyzed system performance under varying conditions. The findings revealed that RTE positively correlated with SC-CO_2 mass flow rate and pressure ratio, while counterintuitive RTE degradation occurs with increased steam temperature due to regenerator pinch point exacerbation. To improve flexible operation of thermal power plants, Chae and Lee [109] performed a techno-economic optimization of four hybrid CCES/LCES configurations for CFPP integration, identifying an optimal layout with 46% RTE and 36 kWh/m^3 ESD. He et al. [110] proposed a coupled CHP-CCES system that demonstrated significant performance enhancements compared to standalone CCES system. Zhang et al. [111] proposed a ternary integrating CCES and steam ejectors into a CHP unit to enhance flexibility and efficiency of CFPPs. Their findings demonstrated that SE significantly improve low-grade heat utilization, while CCES integration enhances system adaptability, offering a viable pathway for retrofitting coal plants to support renewable grid integration with reduced carbon emissions. Hou et al. [112] designed an LCES system integrated with a CFPP, recovering compression heat via condensation water and preheating CO_2 with extraction steam, thus eliminating the need for heat storage tanks. This system achieved an electricity storage efficiency of 55.04%, an 8.04% improvement over pre-integration.

Recently, research has shifted to operational strategies and performance analyses of integrating CCES with poly-generation systems. Specifically, Liu et al. [113] developed an integration system, combining CCES with cooling, heating and power (CCES-CCHP), which outperformed conventional CAES-CCHP in thermodynamic efficiency. Qi et al. [114] combined an LCES system with renewable energy in a power to methane (PtM) system, simultaneously producing power and methane with a 41.3% overall system energy efficiency. Xu et al. [115] developed an LCES-CCHP system utilizing flash evaporation for CO_2 phase separation, achieving optimized metrics: 64.97% RTE, 17.46 kWh/m^3 ESD, and a competitive LCOE 0.07 $/kWh. Zhang et al. [116] designed an intensified CCHP system synergistically integrating wind-generated electricity and turbine exhaust heat recovery through TC-CCES, attaining a power conversion efficiency of 0.48, comprehensive energy efficiency of 1.19, and ESD of 11.51 kWh/m^3 under design conditions. A hybrid poly-generation system combining solar energy, CCES, an ejector-driven power cycle, and multi-effect distillation was proposed by Zhang et al. [117]. Their analysis showed that solar collector mass flow rate significantly influenced thermal energy and warm exergy, which leads to a significant impact on key performance indicators except electrical efficiency. The system achieved a comprehensive energy efficiency of 128.1%, an ESD of 22.216 kWh/m^3, and an adjusted LCOE of 0.131 $/kWh under optimized operating conditions.

The diverse integration pathways discussed in this section are synthetically summarized in Fig. 11. This schematic conceptualizes the CCES system as a versatile energy hub, highlighting its core capability to interact with a wide array of external energy systems. As analyzed, waste heat from industrial processes or the compression stage can be recovered and upgraded through cycles like ORC and Kalina, or directly utilized for heating and cooling. Furthermore, integration with renewable sources such as solar thermal energy effectively mitigates the issue of inadequate heating, thereby elevating the system's overall performance. Most importantly, by coupling with poly-generation systems, CCES transcends its traditional role as a mere electricity storage technology, enabling efficient, cascaded utilization of energy to simultaneously satisfy diverse end-user demands for electricity, heating, cooling, and synthetic fuels. This synergistic integration is pivotal for enhancing the overall energy efficiency, operational flexibility, and economic viability of CCES, underscoring its potential as a cornerstone technology for future integrated energy systems.

However, several gaps in research remain and warrant further attention. First, more work is needed on designing multi-energy systems coupled with CCES to realize regional multi-energy complementary synergistic operation mode, thereby accommodating varied application scenarios and energy demands. Furthermore, most existing studies have focused primarily on investigating CCES performance under steady-state conditions. In reality, system behavior evaluation under variable loads is fundamental for optimizing scheduling and assessing system feasibility. Therefore, operation characteristics under off-design conditions and dynamic behavior of CCES integration system should be further investigated based on preliminary steady-state theoretical analyses.

4.5 Dynamic behavior of CCES

Most recent studies on CCES systems have focused on system configuration and performance analysis under steady-state, design-point conditions. However, steady-state models fall short of accurately representing system operation characteristics in real-world applications. The integration of renewable energy sources, like wind and solar, demands that CCES systems dynamically manage intermittent power generation and varying load demand. This requires CCES to operate dynamically during

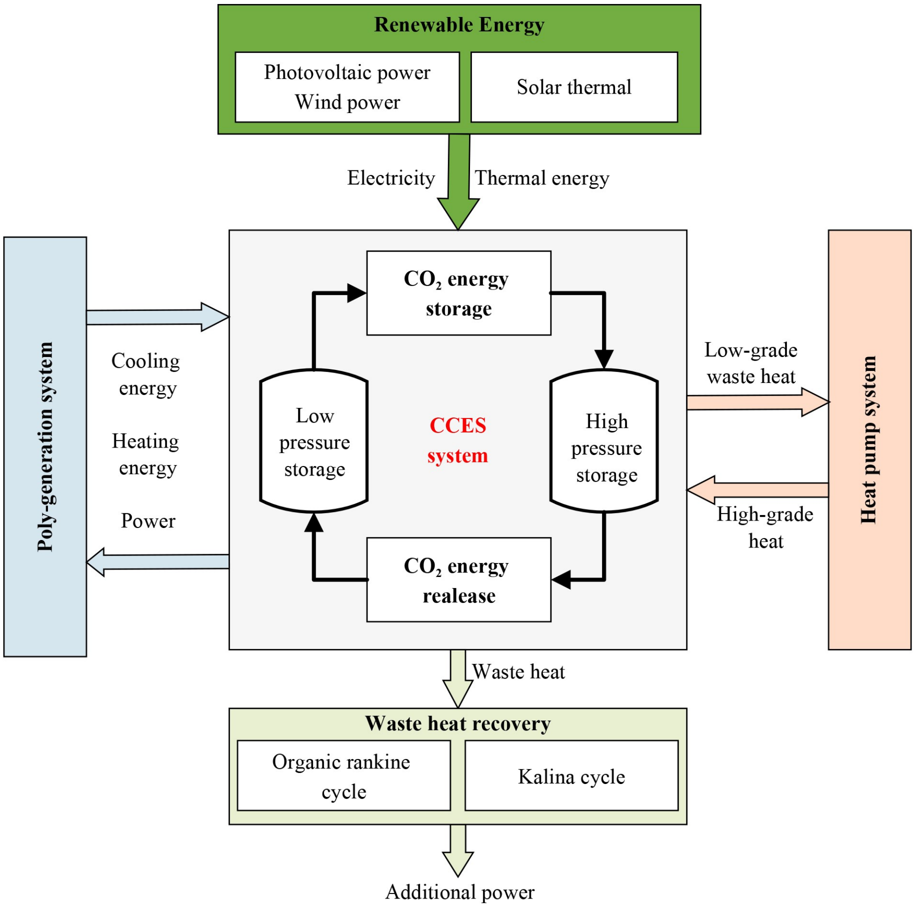

Fig. 11 Schematic diagram of CCES integration.

charging and discharging cycles, adapting to unsteady-state conditions. Therefore, to optimize such integration, key challenges related to process design and operational strategies must be addressed to enhance both energy efficiency and economic viability of CCES technology.

Given that real-world operation involves frequent load fluctuations and off-design conditions, research efforts have extended to comparative analyses of design and off-design behaviors, with scholars exploring both standalone CCES system performance and the coupled operational characteristics of hybrid CCFP-CCES configurations. For example, Zhao et al. [70] analyzed two operational strategies for CCES: constant pressure (CP) and sliding pressure (SP), finding that the SP mode demonstrated superior energy retention with a 67.37% RTE over a 2.88-h discharge duration, compared to 64.96% RTE over an extended 3.64-h discharge cycle in CP mode. Xu et al. [118] evaluated operational dynamics of a low-grade-heat-integrated LCES system across both design and off-design regimes, showing that RTE critically depends on operating parameters, varying from 22.16% to 63.60% in off-design conditions, with peak efficiency under design conditions. Wan et al. [119] developed an off-design performance prediction model for LCES under two operational strategies: CP charging and CP discharging (CP-CP), and CP charging with SP discharging (CP-SP), revealing that CP-SP outperforms at 70% to 100% load, while CP-CP is advantageous at 100% to 120%. Zhao et al. [120] investigated off-design performance of an SC-CCES system employing bi-objective optimization to maximize RTE and optimize ESD. He et al. [121] evaluated a SC-CCES system integrated with CHP under off-design scenarios, finding that speed regulation-throttling regulation demonstrates superior operational efficacy and broader operational flexibility over dual-speed regulation, with ESD positively correlated to discharge load but unaffected by charging load fluctuations.

There is extensive consensus that dynamic operational behaviors diverge fundamentally from steady-state operational behaviors in energy storage systems, with transient characteristics emerging as critical factors for both design optimization and real-time control. Recent research has begun multidimensional investigations into dynamic response mechanisms of CCES systems. For example, Chaychizadeh et al. [122] modeled CCES coupled with distributed wind farms, incorporating synthetic wind power profiles to achieve an RTE of 57.55% in real-world wind conditions.

Zhang et al. [123] conducted sensitivity analysis of CCES dynamic behavior, identifying trade-offs: storage chamber volumetric expansion exhibited a positive correlation with RTE enhancement, yet inversely impacts ESD; while higher CO_2 mass flow rated lower RTE but boost ESD; a larger pinch point temperature differentials of heat exchangers decreased RTE. Jafari et al. [124] analyzed a hybrid PV/linear Fresnel reflector S-CCES system across four seasons, validating the feasibility of combining solar thermal and electrical generation for stable energy storage and highlighting the potential for optimization in component design to minimize losses. Zhang et al. [125] evaluated dynamic performance of a CO_2-based binary mixtures in CGES systems, demonstrating that CO_2/R32 and CO_2/R161 showed stable performance under varying tank volumes and ambient temperatures, with RTE reductions of 0.68%−11.97% but improved pressure stability and compressor efficiency. Huang et al. [126] reported that steady-state models overestimated RTE by 23.9% compared to dynamic model, highlighting the necessity of including transient effects in CCES system design. Jiang et al. [127] established two dynamic SC-CCES systems without auxiliary cold and heat sources, identifying compressor and heat exchanger as dominated exergy losses and validating dynamic operational characteristics and optimization pathways. Zhang et al. [128] conducted transient analysis of a two-stage CCES system, systematically investigating eight distinct operational modes, quantifying state-dependent efficiency characteristics, identifying an 8.22% efficiency variation between 48.48 and 56.70% across different operational modes, highlighting state-dependent performance.

Table 3 summarizes key performance differences between dynamic and steady-state CCES models based on these findings. Steady-state models, though useful for initial design, are limited to fixed operating conditions and often overestimate RTE and underestimate losses. In contrast, dynamic models capture real-world variability and transient responses, enabling more accurate analysis of operational strategies amid renewable energy fluctuations, and providing critical guidance for system control and grid integration. However, significant gaps remain in this field, particularly in developing high-fidelity dynamic models, multi-parameter coupling optimization, trade-offs between system economics and performance, and dynamic control strategies to realize system stable operation.

4.6 Challenges and future prospect for CCES

Having reviewed the working principles, system configurations, performance metrics, and integration strategies of CCES technology, it is imperative to synthesize the key challenges that hinder its large-scale commercialization and to outline the promising directions for future research.

4.6.1 Major challenges

At present, CCES technology is still in its infancy and faces several significant challenges that must be addressed to achieve large-scale application.

1) One major issue is the absence of a unified theoretical framework or standardized methodology for selecting and optimizing CO_2-based mixed working fluids. Although blending CO_2 with organic working fluids can improve thermodynamic properties and operational stability, determining the optimal mixing ratios while balancing system efficiency, safety, and cost remains challenging. Future research should prioritize developing comprehensive databases of CO_2 mixtures and multi-objective optimization methods techniques.

2) Liquefaction of low-pressure CO_2, especially under subcritical conditions, presents another critical challenge. Current self-condensation methods often lead to high

Table 3 Performance differences between dynamic and steady-state models for a CCES system

Item	Dynamic model	Steady-state model
Model characteristics	Captures transient behavior, load fluctuations, and real-time responses	Based on fixed design points; assumes constant operating conditions
Operational strategies	Evaluates strategies like CP-SP, SR-TR under varying loads	Optimized for specific design parameters only
RTE	Generally lower; reflects real-world variability (e.g., 48.48%−56.70%)	RTE was overestimated (e.g., by up to 23.9%)
ESD	Shows correlation with discharge load; insensitive to charging load	May not accurately reflect ESD under variable operation
Exergy loss	Identifies dominant loss sources (e.g., compressor, heat exchanger)	May underestimate loss due to lack of transient effects
Parameter sensitivity	Reveals trade-offs (e.g., volume vs. RTE, mass flow vs. ESD, heat exchanger pinch vs. RTE)	Less capable of capturing parameter interactions under off-design conditions
Applicability	Suitable for integration with renewables and grid stability analysis	Limited to ideal or design-phase analysis

system pressures and increased complexity, while relying on external cold sources such as LNG is constrained by geographical factors and entails considerable exergy losses. There is an urgent need for advanced regenerators and phase-change materials with tailored transition temperatures to facilitate more energy-efficient liquefaction processes.

3) Regarding CO_2 storage, traditional constant-volume gas storage suffers from throttling losses, while constant-pressure storage requires large storage volumes and complex infrastructure. Although underground storage options like salt caverns and saline aquifers hold promise, their applicability is highly dependent on specific geological conditions. Above-ground storage systems require materials that can withstand high-pressure and low-temperature, significantly increasing costs. Novel approaches such as adsorption-based storage remain experimental and lack industrial validation.

4) While the integration of CCES with waste heat recovery, renewables, and poly-generation systems has shown potential to improve overall efficiency, most current studies are based on steady-state models that fail to capture the dynamic behavior of real-world operations. Real-world applications require robust dynamic modeling to manage intermittent renewable inputs and fluctuating load demands. Research on transient responses, off-design performance, and advanced control strategies remain insufficient, constraining the system’s regulation capabilities and operational reliability.

4.6.2 Future prospect

Although substantial progress has already been made in various aspects of CCES technology, the several key research trends have been identified for future studies.

1) To address challenges in working fluid optimization, future research should prioritize the screening and fine-tuning of CO_2-based mixtures, focusing on improving critical thermodynamic properties and system compatibility through advanced theoretical modeling and rigorous experimental validation. In addition, research and development of PCMs and thermochemical storage materials tailored for CO_2 temperature ranges will be instrumental in achieving efficient cold storage and hierarchical energy utilization. Integrated designs combining cold and heat storage hold promise for significantly reducing exergy losses and improving system flexibility.

2) In terms of CO_2 storage facilities, two main pathways warrant attention. In regions suitable for geological storage, intensified research on the dynamic characteristics of multi-cycle injection and extraction, rock-fluid interactions, and long-term geological stability is essential. For above-ground storage, innovative adsorption technologies and composite-material pressure vessels are expected to become focal points for development. Concurrently, advances in high-performance compressors, expanders and highly efficient heat exchangers will be critical to enhancing overall system efficiency and operational reliability.

3) Future CCES systems should emphasize intelligent coupling strategies that enable multi-energy complementary operations to maximize overall energy utilization. The development of high-fidelity dynamic models and real-time control algorithms is imperative to optimize CCES performance under variable and intermittent operating conditions. Emerging technologies such as machine learning and digital twin offer promising avenues for predictive maintenance and operational optimization.

4) Finally, supportive government policies and electricity market mechanisms are crucial for the commercialization of CCES. Large-scale demonstration projects, comprehensive operational data collection, and establishment of industry standards are fundamental for cost reduction and widespread deployment.

In summary, despite distinct technical and economic challenges, CCES potential for high efficiency, compact energy storage, and environmental friendliness remains highly compelling. By addressing these research priorities through concerted efforts, CCES can evolve from conceptual and pilot-scale demonstrations to a cornerstone technology that supports high-renewable energy penetration and contributes significantly to global carbon neutrality goals.

5 CCES integration with CCUS

Facing the global energy transition toward decarbonization and the mission of carbon neutrality, power systems are confronted with the dual challenges of efficient energy storage and stringent constraints on CO_2 emission. CCUS stands as a vital climate change mitigation technology, enabling large-scale CO_2 emission reduction from the energy sector. As both CCES and CCUS play pivotal roles in advancing the energy transition and achieving carbon neutrality, their integration represents a transformative synergy, forming a closed-loop carbon-energy management system that enhances both energy storage capabilities and carbon mitigation effectiveness.

5.1 Mechanism and synergistic advantages of CCES integration with CCUS

As a typical CO_2 utilization scenario, CCES can be integrated into all segments of CCUS chain, establishing a closed-loop carbon-energy synergy. This integration leverages the complementary nature of the two technologies: CCUS provides a continuous stream of captured CO_2, while CCES utilizes this CO_2 for grid stability and energy arbitrage. The core of this integration lies in the meticulous management of material (CO_2) and energy flows, which operate on fundamentally different characteristics and timescales. Figure 12 presents a schematic overview of the material and energy flows involved in the CCES integration with CCUS.

A critical distinction must be made between the circulating working fluid within the CCES system and the captured CO_2 produced from industrial sources. CCES operates primarily on a closed-loop principle regarding its working fluid. After the initial charge that fills the system's inventory, the ongoing "consumption" of CO_2 is negligible, limited mainly to fugitive leaks from seals, valves, and connections, which necessitate make-up gas. Industry data from high-pressure gas systems suggest annual leakage rates typically remain below 1% to 2% of the total inventory [129]. In contrast, a typical CCUS facility attached to an industrial emission source captures a massive and continuous flow of CO_2, often amounting to millions of tonnes annually. Therefore, the vast majority (> 99%) of this captured CO_2 cannot be consumed by the CCES system itself. The material flow follows a clear pathway: Initial charge: a significant portion of initially captured CO_2 fills the CCES working inventory; make-up: a tiny fraction (< 1%) of the ongoing captured CO_2 compensates for system leaks; allocation: the overwhelming majority of captured CO_2 is intelligently dispatched to external utilization pathways, such as conversion to synthetic fuels, chemicals, or building materials, or directed to permanent geological sequestration sites. This allocation is dynamically optimized based on real-time economic and operational constraints, such as electricity prices, demand for CO_2 utilization, and storage site availability.

Simultaneously, the energy flow enables optimal cross-utilization of energy across different stages of both processes: Charging (energy input): off-peak or surplus renewable electricity drives compressors, converting electrical energy into the potential energy of high-pressure CO_2; waste heat recovery: compression heat generated during charging is captured and stored. This thermal energy can be utilized to preheat CO_2 before expansion during discharge, significantly enhancing RTE, or supply low-grade thermal energy for solvent regeneration in capture plants (e.g., amine-based processes), thereby reducing the parasitic energy penalty associated with CO_2 capture; discharging (energy output): during peak electricity demand, high-pressure

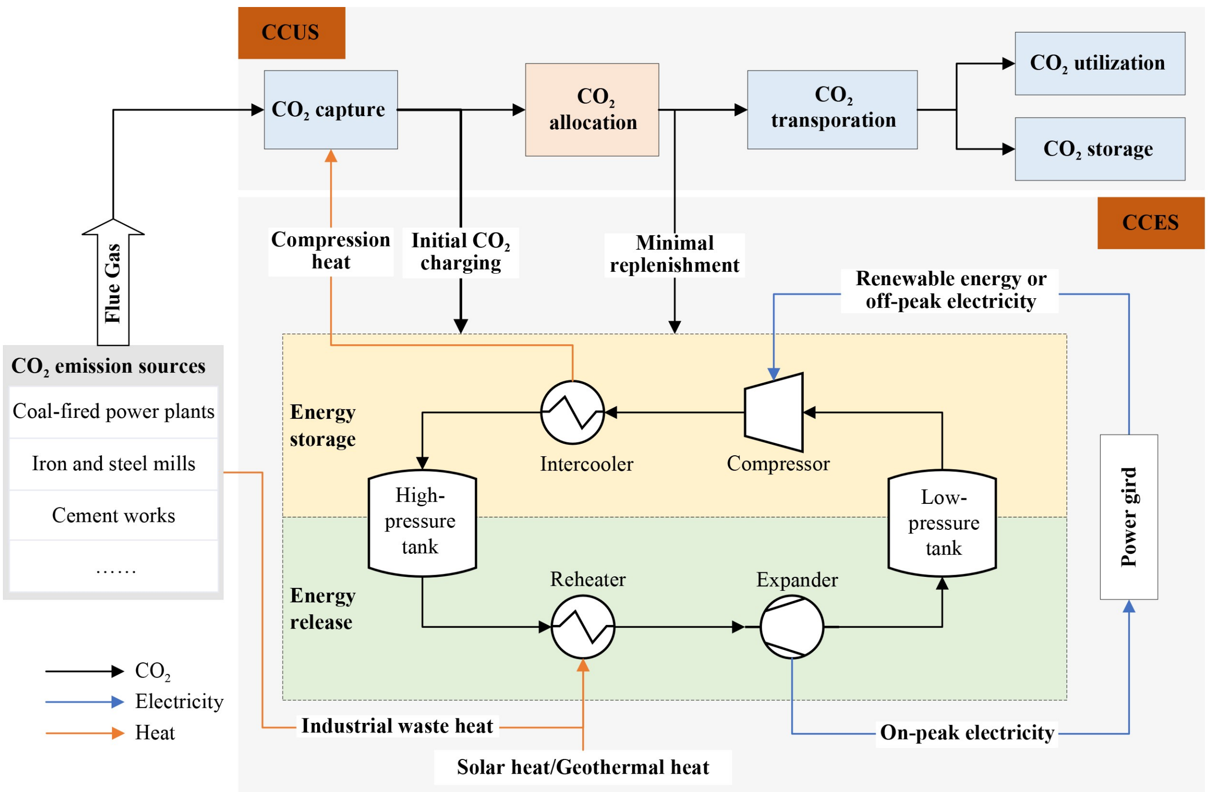

Fig. 12 Schematic diagram of CCES integration with CCUS.

CO_2 is expanded through turbines to generate and dispatch electricity to the power grid.

The intricate coupling of energy and material flows enables CCES integration with CCUS to deliver significant synergistic benefits across three main dimensions. First, resource and facility sharing: Captured CO_2 provides a reliable and low-cost gas source for energy storage cycle of CCES system, and post-energy-release CO_2 can be used as a product output. Major infrastructure components of CCUS, such as CO_2 compression equipment, high-pressure transportation pipelines, and underground storage reservoirs (e.g., salt caverns or saline aquifers), can be shared in a CCES system, significantly reducing redundant capital investments and simplifying the overall system footprint. In terms of economic benefit, this coupling enhances the viability of a project by distributing substantial capital costs of infrastructure across two revenue streams: grid services (e.g., energy arbitrage, ancillary services) provided by CCES, and the value derived from permanent CO_2 sequestration. This dual-purpose utilization of captured CO_2 as both working fluid and sequestered product lowers the levelized cost of both electricity storage and carbon abatement compared to standalone technologies. Furthermore, the integrated approach improves system flexibility and energy efficiency: the storage facility dynamically transitions between acting as an energy buffer (charging during low-cost, high-renewable periods by compressing CO_2 and discharging during peak demand by expanding it to generate power) and serving as a secure carbon sink. Importantly, the cross-utilization of waste heat and compression heat between CCUS and CCES processes reduces overall energy penalties, enhancing the resilience and responsiveness of the coupled system.

5.2 CCES integration with CCUS

5.2.1 CCES integration with CO_2 capture

CO_2 capture is widely recognized as an effective approach for reducing CO_2 emissions from energy industries [130]. However, the high cost of energy consumption, often termed the energy penalty, associated with CO_2 capture processes remains a significant challenge. Coupling CO_2 capture with energy storage presents an opportunity to reduce costs by optimizing the use of electricity and heat [131]. Based on this concept, numerous studies have explored the integration of CCES with CO_2 capture systems.

Huang et al. [132] proposed a CCES system integrated with an oxy-fuel combustion CO_2 capture system (Oxy_CCES). During off-peak periods, CO_2 produced from oxy-fuel combustion is pressurized and stored, while during peak periods, the high-pressure CO_2 is expanded to generate electricity. Techno-economic analysis showed this Oxy_CCES system enhances net efficiency (34.1%) and exergy efficiency (57.5%), while reducing net present value and LCOE compared to conventional oxy-fuel power plants. Notably, although compression heat recovery partially offsets energy demands, supplementary fuel combustion remains necessary to elevate the CO_2 temperature to optimal operational threshold.

Xu et al. [133] developed an integrated system combining a LCES system, an oxy-fuel combustion gas turbine (oxy-GT) capture unit, and a natural gas pressure reduction station (PRS). The oxy-GT combustion products, CO_2, H_2O and O_2, are cooled to provide working fluid for LCES subsystem, while the PRS supplies cold exergy for low-pressure CO_2 condensation. Compared to a basic LCES system, this integration increased power output from 5 to 16.23 MW, improved net energy efficiency from 19.84% to 63.44%, and decreased LCOE from 0.1657 to 0.0872 $/kWh.

Yin et al. [134] designed a TC-CCES system leveraging LNG cold energy for CO_2 liquefaction and cryogenic CO_2 capture, as illustrated in Fig. 13. Low-pressure CO_2 is compressed using off-peak electricity or renewable energy and stored in high-pressure tanks (HPT). During peak hours, high-pressure CO_2 is heated via organic Rankine cycle (ORC2) and expanded to generate electricity. ORC1 recovers compression heat, while ORC2 utilizes high-temperature flue gas from natural gas combined cycle (NGCC). LNG cold energy serves as cold source for both ORC1 and cryogenic capture processes. Techno-economic analysis of two cases revealed that Case 2 (liquid CO_2 storage in low-pressure tanks) achieved the highest electric RTE of 68.49%, energy efficiency of 72.25% and exergy efficiency of 59.30%.

Song et al. [135] developed a hybrid system integrating CCES with dry reforming of methane (DRM) and carbon capture. During charging, CO_2 captured from a power plant is pressurized via isobaric compression and interstage cooling. During discharging, CO_2 is heated by the off-gas from solar-driven DRM system before expanding through a turbine to produce electricity. The high-temperature CO_2 after energy release is blended with methane in a DRM reactor to produce syngas (H_2 and CO). This system achieves an energy efficiency of 77.09% and reduced CO_2 capture heat requirement by 43.33%.

5.2.2 CCES integration with CO_2 storage

Injecting captured CO_2 into geological reservoirs for

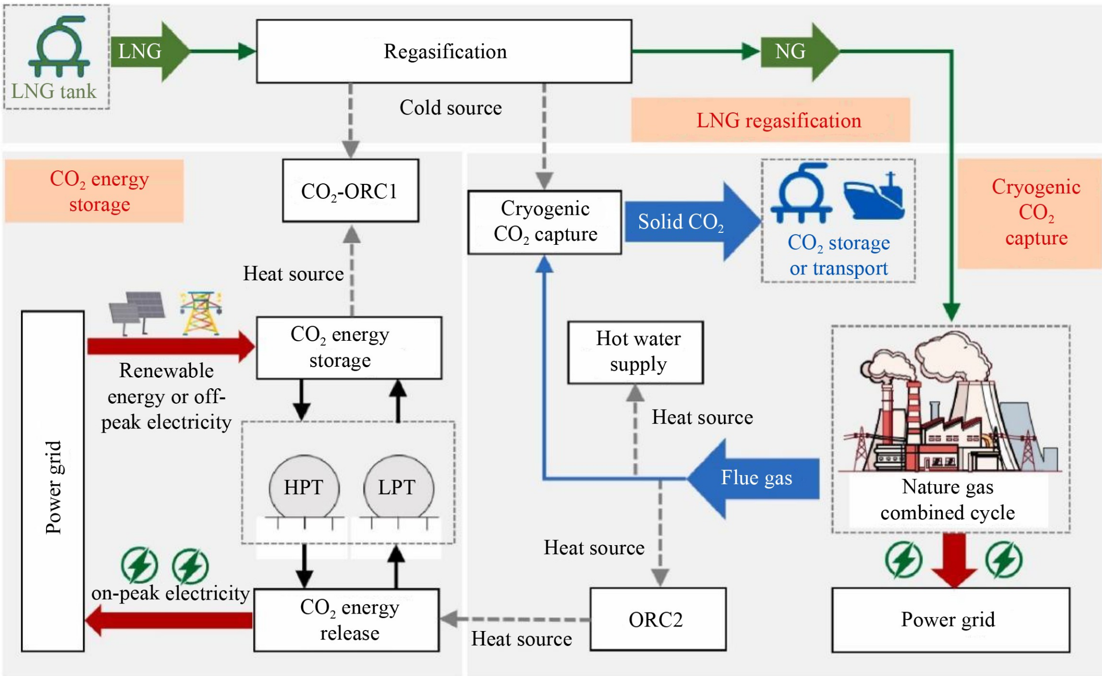

Fig. 13 Conceptual flowchart of CCES integration with carbon capture proposed by Yin et al. [134] (adapted with permission from Yin et al. [134], copyright 2024, Elsevier).

sequestration provides a viable approach for long-term CO_2 reduction. Additionally, utilizing deep geological formations as CO_2 storage site in CCES systems offers an alternative to manufactured storage tanks, thereby reducing the capital costs associated with working fluids storage. The geothermal heat present in deep formations can heat the stored low temperature CO_2 in storage time, further reducing the cost of heating prior to expansion. Recently, several studies have investigated the development of CCES systems integrated with geological sequestration of CO_2.

Cao et al. [82] reported a CCES system coupled with CO_2 storage in an antiquated mine goaf. Captured gaseous CO_2 is compressed to SC-CO_2 and injected into the mine goaf. Injection of CO_2 ceases once the optimal storage pressure for energy storage is reached. During peak hours, the SC-CO_2 expands through multistage turbines to generate electricity, and the depressurized CO_2 is stored in an abandoned cave. The results indicate that this coupling system can achieve an optimal RTE of 53.75% at a 21.9 MPa storage pressure. Economically, the integrated CCES-CCS system outperforms a stand-alone CCES system when the carbon tax exceeds 47 $/tonne.

Minkley et al. [136] designed a geological energy storage system integrating an SC-CO_2 cycle with CO_2 storage in salt cavern reservoirs, thereby eliminating the need for manufactured CO_2 container. During renewable energy power surplus periods, CO_2 is compressed isentropically from low-pressure buffer tanks into high-pressure salt formations, with reverse turbomachinery used during discharge. Their results indicate cycle efficiencies exceeding 50%.

Jiang et al. [137] developed a porous media adiabatic CCES system (PM-ACCES) employing dual aquifer reservoirs at different depths, enabling *in situ* thermo-geological storage of compression heat. Simulations show a 3.05 MW discharge power and a 12.16 MWh discharge capacity with a 51.93% RTE. However, the turbine outlet pressure is limited by the formation's injectivity pressure threshold, and solar-augmented operations increase turbine exhaust, causing thermal losses.

Stepanek et al. [138] proposed a CCES system utilizing solution-mined salt domes as CO_2 geological storage reservoirs. This system uses two salt caverns at different pressures (high-pressure: 7−12 MPa; low-pressure: 1−3 MPa) and employs gravel as a thermal capacity medium. Thermodynamic simulations indicate that this system can achieve over 60% RTE and power outputs exceeding 100 MW, with stable energy storage capacity up to 600 MWh under optimal pressure cycling conditions.

These studies collectively confirm the feasibility of integrating CCES with underground CO_2 storage. Ideal locations for such integration feature excess electricity—preferably from renewable sources—geologically suitable formations capable of storing high-pressure CO_2, and infrastructure for electrical grid interconnection. Saline aquifer, salt caverns, abandoned mine goafs are all viable geological CO_2 storage options for CCES, meeting both energy storage demands and geological sequestration requirements. Furthermore, deep reservoirs offer promising sites for combined storage of high-temperature thermal energy and high-pressure CO_2 [139], simplifying CCES system design and reducing initial capital investment for surface equipment.

5.3 Applications of CCES integration with CCUS

The segment of the CCUS chain integrated with CCES can be dynamically adjusted to meet specific requirements across various scenarios, aiming to enhance overall energy efficiency and reducing costs. This flexibility allows CCES-CCUS integration to adapt to diverse future needs effectively.

5.3.1 Thermal power plants

As major sources of CO_2 emissions, thermal power plants can achieve flexible low-carbon transformation by integrating CCES with CCUS. Direct CO_2 emission from thermal power generation can be reduced by adding CO_2 capture system to tail gas. CCES enhances power output flexibility and peak-shaving capacities by converting off-peak electricity into dispatchable on-peak electricity. Additionally, waste heat from flue gas and steam in thermal power plants can be utilized as an external heat source for the CCES system, boosting energy storage efficiency. The existing grid-connected infrastructure (e.g., substations, transmission lines) in thermal power plants further lowers investment costs. For LCES systems, thermal power plants can facilitate the commercial-scale output of liquid CO_2.

5.3.2 High-emission industrial sectors

High-emission industries such as steel, cement, and chemicals can leverage CCES to store captured CO_2 *in situ*, enabling regulation of industrial electricity consumption. An operational mode of “CO_2 capture-energy storage-peak regulation-sequestration/utilization” helps reduce industrial carbon emission intensity while providing an energy storage solution that alleviates electricity cost pressures. CO_2 released from energy storage can be used as a feedstock for producing high-value-added chemicals through co-production of electricity, carbon, and chemicals. In addition, coupling with industrial waste heat recovery further enhances overall system energy efficiency. For example, the Wuhu Conch 10 MW/80 MWh CO_2 energy storage demonstration project in China successfully applied CCES integration with CCUS in the cement industry using low-temperature waste heat from the cement kiln (direct flue gas below 90 °C) to promote CO_2 evaporation and expansion.

5.3.3 Renewable energy power stations and industrial clusters

CCES integration with CCUS can also be deployed in wind and PV power stations. These stations can serve as hubs, connecting industrial clusters (such as iron and steel mills, chemical plants) via CO_2 pipelines, forming a network for “CO_2 capture-transportation-energy storage-sequestration/utilization”. Captured CO_2 compressed for energy storage effectively balances grid fluctuations and increases renewable energy consumption. Use of underground space, such as saline aquifers and salt caverns, can realize combined temporary pressurized CO_2 storage and long-term sequestration. In addition, modular deployment of distributed carbon-negative power plants based on CCES integration with CCUS can replace traditional thermal power peaking units, delivering stable green power directly to industrial parks or remote areas without relying on grid infrastructure.

5.3.4 Integration with SC-CO_2 pipelines

Another cutting-edge advancement involves integration of CCES system with SC-CO_2 pipelines. This integration supports multifunctional applications such as cross-regional CO_2 dispatch, power grid peak shaving, frequency regulation, peak-valley arbitrage, and utilization of abandon electricity. This synergy not only enhances the industrial value chain of CCUS but also provide a secure, cost-effective, long-duration energy storage solution, supporting grid stability and renewable energy integration. A landmark project in Jilin Oilfield in China features a 390 km SC-CO_2 pipeline, designed for a pressure of 14.5 MPa. Leveraging pipeline’s high-capacity, high pressure, and SC-CO_2 working fluid, the system generates electricity through expansion of 9 MPa SC-CO_2, while low-pressure CO_2 (0.1 MPa) is compressed and injected into the high-pressure pipeline for subsequent enhanced oil recovery and geological sequestration. This breakthrough marks China’s first integrated application of SC-CO_2 pipeline technology with CCES.

5.3.5 CCUS hubs and carbon-energy synergy

CCUS hubs acts as central nodes that collect CO_2, either gathering it from emission sources or distributing it to utilization or storage sites [140]. They coordinate CO_2 capture, transport, utilization, and storage resources via intelligent dispatch systems, enabling spatiotemporal optimization of CO_2 flow. When coupled with CCUS, a novel carbon-energy synergetic system emerges, as illustrated in Fig. 14. During off-peak time, surplus electricity compresses low-pressure CO_2 into a supercritical state, and the pressurized CO_2, combined with high-pressure CO_2 from capture sources, is injected into underground storage reservoirs (e.g., salt caverns or depleted gas fields). During peak time, high-pressure CO_2 is extracted from the underground reservoir; after fulfilling external utilization or sequestration, residual CO_2 expands through turbines to generate electricity fed back to the power grid. Underground reservoirs in CCUS hubs serves dual purposes: short-term high-pressure CO_2 buffer and permanent long-term CO_2 storage. Dynamic optimization prioritizes grid peak shaving, with excess CO_2 directed toward chemical utilization, enhanced oil recovery (EOR), or dedicated geological storage, maximizing underground resource value.

With the rapid expansion of data centers, both energy consumption and cooling demands are continuously increasing. Integrating CCES-CCUS systems with data centers offers an innovative solution to address these challenges. In the liquid cooling system of a data center, the coolant absorbs heat from the chips, causing its temperature to rise. During the energy release phase of the CCES system, the heated coolant circulates through pipelines to an evaporator, where it exchanges heat with CO_2. The cooled coolant then returns to the data center racks to continue dissipating heat from the chips, completing the cooling cycle. This cascaded energy utilization and integrated cycle approach significantly reduces the energy consumption of data centers while improving overall energy utilization efficiency. In the future, this coupling of CCES systems with data centers is expected to become a standard practice.

5.4 Challenges and future prospect for CCES integration with CCUS

CCES integration with CCUS represents a transformative shift from single-function energy storage toward a multi-functional system that combines energy storage with carbon reduction. This integration is expected to become a promising pathway for future energy system transformation, aligning energy resilience with climate goals. Despite its significant potential, practical implementation of CCES-CCUS integration still faces some challenges that must be addressed through focused future research.

5.4.1 Key challenges

1) System efficiency and design complexity: CCES

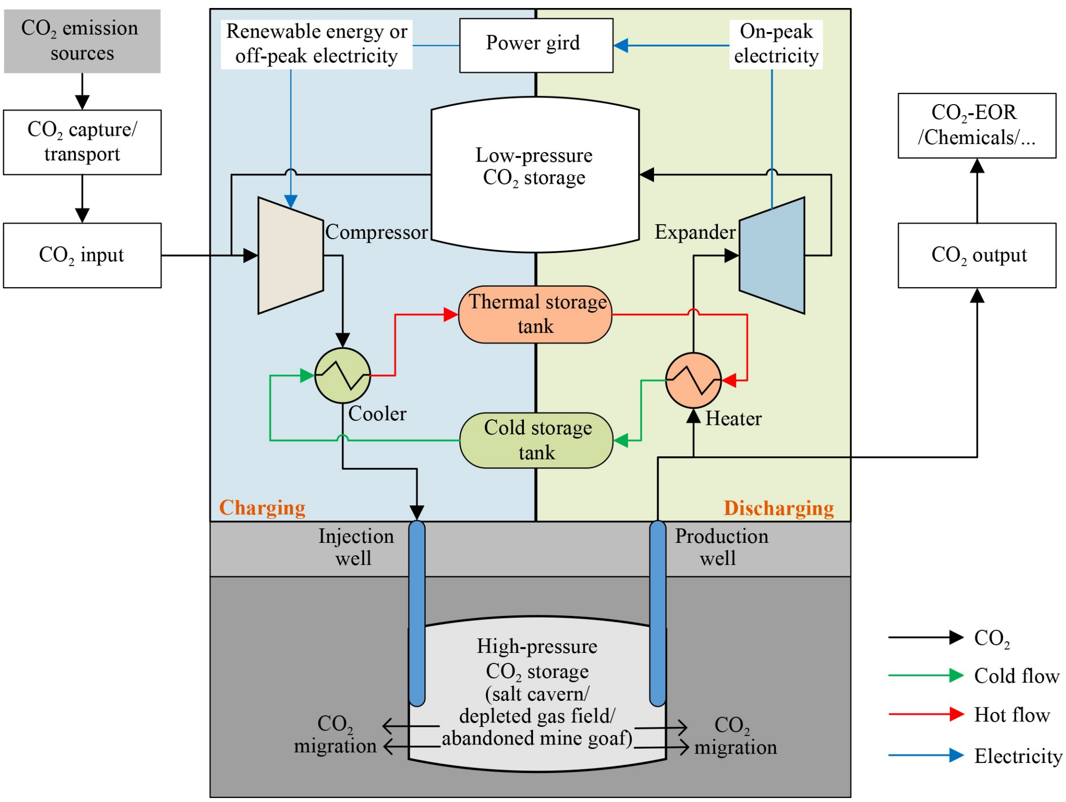

Fig. 14 Schematic diagram of CCES integration with CCUS hub.

operates as a closed-loop system and cannot continuously consume captured CO_2 [129], which necessitates complementary utilization pathways (e.g., chemicals or fuel production) or secure, permanent geological storage for excess CO_2. The high energy consumption associated with CO_2 capture processes, especially chemical absorption, can significantly reduce overall net energy storage efficiency of the integrated system [99,141]. Moreover, the multi-stage architecture of the integrated system (comprising capture, compression/storage, and power generation) combined with asynchronous operations across different phases results in significant technical complexity. Large-scale deployment also requires precise synchronization between the spatiotemporal profiles of industrial CO_2 emissions and fluctuations in grid electricity demand, imposing stringent constraints on system design and real-time control strategies. In addition, a fundamental challenge lies in optimizing the trade-off between maximizing energy storage efficiency and ensuring long-term integrity and security of CO_2 storage, which intensifies both engineering design and operational management demands.

2) Environmental and geological risks: High-pressure CO_2 storage presents leakage risks in both above-ground tanks and underground reservoirs, necessitating robust, continuous monitoring system to ensure containment integrity. Sustained high-pressure CO_2 injection in underground formations can significantly alter formation pressure regimes, increasing the risk of geo-mechanical issues such as fault reactivation or caprock failure [142]. Cyclic CO_2 injection and extraction may lead to pore pressure fluctuations and trigger rock fatigue damage. The coupling of long-term high pressure CO_2 storage with short-term pressure cycling during energy storage could accelerate plastic deformation of reservoirs. Additionally, complex geochemical reactions (e.g., mineral dissolution and precipitation) may alter reservoir petrophysical properties like porosity and permeability during underground CO_2 storage, potentially causing CO_2 depletion. Failure to maintain adequate subsurface CO_2 inventories would directly undermine CCES operational efficiency [143].

3) Techno-economic feasibility: CCES integration with CCUS entails substantial CAPEX for CO_2 capture, compression, expansion, injection, storage infrastructure, and monitoring devices, alongside significant operational costs (OPEX). The economic viability of projects faces uncertainty due to dependence on volatile revenue streams, including electricity arbitrage margins, fluctuating carbon credit prices, and unpredictable markets for CO_2 utilization. Crucially, costs associated with potential risks—particularly leakage risks and the need for long-term monitoring and potential environmental remediation—require robust quantification and financial provisioning to ensure project feasibility.

5.4.2 Future prospect

CCES integration with CCUS represents a dual-value innovation in power peak regulation and CO_2 emission reduction, offering a transformative potential for renewable energy grid stability and industrial decarbonization. It is poised to bridge the critical gap between achieving carbon neutrality and enhancing resilience of energy system. To transition CCES-CCUS from conceptual design toward experimental validation, project demonstration, and ultimately, widespread deployment, future research must prioritize overcoming the key challenges outlined previously. The main research directions should include, but not be limited to, the following aspects:

1) For CCES integration with CO_2 capture, it is necessary to develop source-specific carbon capture and energy storage coupling processes. These processes can be tailored to different CO_2 concentrations (e.g., 15%−25% in cement kilns, 5%−15% in CFPPs). Additionally, thermodynamic cascade models that effectively match compression heat supply with solvent regeneration heat demand can be established to reduce the capture energy penalty. Moreover, more attention should be paid to the development of dynamic synergistic scheduling of integrated CCES and carbon capture systems capable of synchronizing capture processes with power load fluctuations. For instance, in the amine-based absorption capture process, CO_2-rich amine obtained during on-peak power supply time can be stored and then de-absorbed and compressed during off-peak times.

2) For CCES integration with above-ground and underground CO_2 storage, comprehensive emergency response plans and risk management measures should be implemented to minimize leakage risks and their potential consequences. Above-ground storage prioritizes prevention of catastrophic instantaneous accidents, while underground storage focuses on ensuring long-term sealing integrity and monitorability of geological systems. Furthermore, it is critical to clarify feasibility constraints for multi-functional reuse of storage sites. It is suggested that research on the rock mass mechanical response of geological reservoirs under dual-mode operation of CO_2 energy storage and long-term sequestration be advanced, and integrity evaluation criteria for CO_2 injection-production switching be established. The rock mass mechanical response in geological reservoirs under dual-mode of CO_2 energy storage and sequestration involves multi-field coupling (flow-stress-chemical-thermal) effects. Correspondingly, future research should

place greater emphasis on developing cross-scale, multi-field coupling simulation models to support synergy of safety and efficiency management in CCSE and CO_2 storage integration systems.

3) In terms of CCES integration with full-chain CCUS processes, on the one hand, it is suggested that future research focus on developing multi-objective optimization models for energy storage and emission reduction, and designing carbon flow matching algorithms to achieve optimal allocation of CO_2 among energy storage cycles (working fluid), utilization (fuels/chemicals/EOR), and geologic storage. On the other hand, research should also entail establishing a robust techno-economic evaluation system to conduct rigorous cost-benefit analyses under multiple market scenarios, to quantify economic benefits, including CAPEX reductions from shared infrastructure and synergistic gains combining power arbitrage revenue and carbon credit returns, and to analyze break-even points for integrated project viability based on carbon and electricity price differentials using policy coupling models.

4) Future research should also aim to overcome materials bottlenecks, particularly the development of high-pressure and corrosion-resistant materials, to support the safe storage of high-pressure CO_2 and broaden the application scenarios of CCES. Based on the framework of CCES integration with CCUS, an extensible modular structure design should be conducted to explore adaptation solutions for different application scenarios and verify the feasibility of cross-industry coupling.

6 Conclusions

This paper presents a comprehensive literature review of technological advancements in CCES and offers a perspective on CCES integration with CCUS. It identifies several key challenges requiring further attention, including optimization of mixed working fluids, efficient and cost-effective liquefaction of low-pressure CO_2, development of low-cost, safe, and scalable CO_2 storage facilities, enhancement of CCES system performance, and evaluation of dynamic system behavior. In addition, it highlights the synergy mechanisms, industrial applications, and challenges of CCES-CCUS integration. Based on the analysis, the following key conclusions can be drawn:

1) The thermodynamic performance of CCES varies significantly across different system configurations. In comparison with the SC-CCES system, LCES and TC-CCES have significantly higher thermodynamic performance in terms of RTE and exergy efficiency, due to their high compression ratios. LCES outperforms other configurations in ESD. Compressors and turbines account for the major exergy loss in CCES systems, a loss that is further exacerbated by multi-stage designs. Additionally, heat exchangers in LCES system experience considerable exergy loss due to gas-liquid temperature mismatches.

2) To improve energy efficiency and enhance the environmental adaptability of CCES systems, CO_2-based mixtures are employed as working fluids to modify system operating conditions. However, a standardized working medium screening system is essential for optimizing the composition and thermodynamic properties of CO_2-based mixtures.

3) Regenerator-based liquefaction is the most effective method for low-pressure CO_2 condensation. The main challenge lies in identifying suitable cold energy storage media (e.g. PCMs) and designing a hierarchical process based on sensible heat storage and latent heat storage to reduce system cold energy loss.

4) In terms of CO_2 storage facilities, above-ground tanks are suitable for regions lacking geological storage resources, while underground reservoirs (e.g., salt caverns, saline aquifers) can facilitate large-scale deployment but face stringent site constraints.

5) The inherent thermal and electrical coupling in CCES systems offers significant opportunities for system performance improvement through integration with external energy sources, enabling energy cascade utilization and poly-generation of power, heating, and cooling.

6) CCES system efficiency exhibits high sensitivity to operating parameters. Additionally, system dynamic behavior modeling reveals that RTE is often overestimated in steady-state analyses. This highlights the need for transient modeling and high-precision dynamic control strategies, which are essential for performance optimization, system component design, and supporting CCES integration with renewable energy systems to enhance grid stability.

The integration of CCES with CCUS represents a transformative shift away from single-function energy storage toward synergetic carbon reduction and energy storage. CO_2 captured from industrial sources provides a low-cost working fluid for CCES. Geological reservoirs enable dual-function energy buffering and permanent CO_2 sequestration. Pipeline-coupled CCES supports cross-regional energy dispatch. The following research trends have been identified for future studies to enhance the integration of CCES and CCUS:

1) For more efficient, flexible, and multifunctional system integration, it is important to explore novel thermal energy recovery technologies for waste heat utilization, investigate effective coupling strategies between CCES and various energy systems, and design dual-function geological reservoirs capable of

simultaneous CO_2 storage and energy buffering during system operation.

2) To realize reliable operation of the integrated system under off-design conditions and to support its engineering demonstration and application, it is necessary to focus on developing advanced, high-precision simulation models for transient process (such as startup, shutdown, and load variation), and on researching dynamic optimization strategies and control algorithms based on the entire life cycle or full operating conditions.

3) Despite the proven feasibility of geologic formation for both energy storage and CO_2 sequestration, concerns about the long-term safety and stability of underground reservoirs under dual-mode operation have significantly slowed technology deployment. Therefore, there is an urgent need to develop a dual-mode operational integrity evaluation standard for geological reservoirs and to study the mechanical response of rock formations under CO_2 energy storage-long-term sequestration switching.

4) For further development of CCES integration with CCUS, it necessary to develop multi-objective optimization models for the integrated system (e.g. CCES integration with CCUS hubs) to balance techno-economic and environmental goals. Furthermore, establishing comprehensive techno-economic assessment frameworks is essential to evaluate the feasibility and impact of CCES-CCUS integration across technical, economic, environmental, and social dimensions.

Nomenclature

Abbreviations

CAES	Compressed air energy storage
CCES	Compressed CO_2 energy storage
CCUS	Carbon capture utilization and storage
CCHP	Combined cooling, heating and power
CFPP	Coal-fired power plant
CHP	Combined heat and power
CP	Constant pressure
CRF	Capital recovery factor
DR	Discount rate
ESD	Energy storage density
IFR	Inflation rate
IR	Interest rate
LCES	Liquid CO_2 energy storage
LCOE	Levelized cost of energy
LNG	liquefied natural gas
ORC	Organic Rankine Cycle
RTE	Round-trip efficiency
SC-CCES	Supercritical compressed CO_2 energy storage
SP	Sliding pressure
TC-CCES	Transcritical compressed CO_2 energy storage
TEE	Total exergy efficiency
TES	Thermal energy storage
WHR	Waste heat recovery
VL-CCES	Vapor-liquid compressed CO_2 energy storage

Symbols

C	Cost
$\dot{E}$	Exergy
h	enthalpy/(kJ·(kg·K)$^{-1}$)
i	Stage of compressor train
j	Stage of expander train
k	System component
m	Mass flow rate/(kg·s^{-1})
N	Number
OM	Operation and maintenance cost
P	Power/kW
Q	Heat exchange rate/kW
s	Specific entropy/(kJ·(kg·K)$^{-1}$)
t	Time/h
T_e	Temperature/K
V	Volume

Greeks

η	Efficiency
ε	Heat exchanger effectiveness

Subscripts

c	Compressor
cold	Cold fluid
ch	Charging
cyc	cycle
di	Discharging
e	Expander
he	Heat exchanger
hot	Hot fluid
tot	Total

Superscripts

in	inlet
is	isentropic
out	outlet

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References

1. Chaudhry N, Hughes L. Forecasting the reliability of wind-energy systems: A new approach using the RL technique. Applied Energy, 2012, 96: 422–430
2. Yan R, Saha T K, Modi N, et al. The combined effects of high penetration of wind and PV on power system frequency response. Applied Energy, 2015, 145: 320–330
3. Shen Z W, Ritter M. Forecasting volatility of wind power production. Applied Energy, 2016, 176: 295–308
4. Ziel F, Croonenbroeck C, Ambach D. Forecasting wind power - modeling periodic and non-linear effects under conditional heteroscedasticity. Applied Energy, 2016, 177: 285–297
5. Li F, Yu Y, Shu Y, et al. Study on characteristics of photovoltaic and photothermal coupling compressed air energy storage system. Process Safety and Environmental Protection, 2023, 178: 147–155
6. Wang L, Pan Y C, Der Lee J, et al. Experimental investigation in the local heat transfer of supercritical carbon dioxide in the uniformly heated horizontal miniature tubes. International Journal of Heat and Mass Transfer, 2020, 159: 120136
7. Perera M S, Ranjith P G, Viete D R. Effects of gaseous and super-critical carbon dioxide saturation on the mechanical properties of bituminous coal from the Southern Sydney Basin. Applied Energy, 2013, 110: 73–81
8. Avanthi Isaka B L, Ranjith P G, Rathnaweera T D. The use of super-critical carbon dioxide as the working fluid in enhanced geothermal systems (EGSs): A review study. Sustainable Energy Technologies and Assessments, 2019, 36: 100547
9. Sarkar J. Cycle parameter optimization of vortex tube expansion transcritical CO_2 system. International Journal of Thermal Sciences, 2009, 48(9): 1823–1828
10. Lyu Q, Tan J, Li L, et al. The role of supercritical carbon dioxide for recovery of shale gas and sequestration in gas shale reservoirs. Energy & Environmental Science, 2021, 14(8): 4203–4227
11. Shi L, Wang C, Liu S, et al. Energy optimization and economic study of an energy storage system based on a carbon dioxide-to-methanol process. Journal of Energy Storage, 2023, 62: 106846
12. Xue X, Lv J, Chen H, et al. Thermodynamic and economic analyses of a new compressed air energy storage system incorporated with a waste-to-energy plant and a biogas power plant. Energy, 2022, 261: 125367
13. Sciacovelli A, Vecchi A, Ding Y. Liquid air energy storage (LAES) with packed bed cold thermal storage—From component to system level performance through dynamic modelling. Applied Energy, 2017, 190: 84–98
14. Zheng P, Hao J, Zhang Z, et al. Analysis of heat transfer characteristics of a novel liquid CO_2 energy storage system based on two-stage cold and heat storage. Frontiers in Energy, 2024, 19(2): 193–204
15. Dewevre F, Lacroix C, Loubar K, et al. Carbon dioxide energy storage systems: Current researches and perspectives. Renewable Energy, 2024, 224: 120030
16. Kim Y M, Lee J H, Kim S J, et al. Potential and evolution of compressed air energy storage: Energy and exergy analyses. Entropy, 2012, 14(8): 1501–1521
17. Liu J L, Wang J H. A comparative research of two adiabatic compressed air energy storage systems. Energy Conversion and Management, 2016, 108: 566–578
18. Wang M, Zhao P, Wu Y, et al. Performance analysis of a novel energy storage system based on liquid carbon dioxide. Applied Thermal Engineering, 2015, 91: 812–823
19. Morosuk T, Tsatsaronis G, Zhang C. Conventional thermodynamic and advanced exergetic analysis of a refrigeration machine using a Voorhees' compression process. Energy Conversion and Management, 2012, 60: 143–151
20. Wang L, Yang Y, Morosuk T, et al. Advanced thermodynamic analysis and evaluation of a supercritical power plant. Energies, 2012, 5(6): 1850–1863
21. Ebrahimi M, Ca Rriveau R, Ting S K, et al. Conventional and advanced exergy analysis of a grid connected underwater compressed air energy storage facility. Applied Energy, 2019, 242(5): 1198–1208
22. Herrmann U, Kelly B, Price H. Two-tank molten salt storage for parabolic trough solar power plants. Energy, 2014, 29(5): 883–893
23. Dincer I. Exergy as a potential tool for sustainable drying systems. Sustainable Cities and Society, 2011, 1(2): 91–96
24. Belderbos A, Delarue E, Kessels K, et al. Levelized cost of storage—Introducing novel metrics. Energy Economics, 2017, 67: 287–299
25. Aldersey-Williams J, Rubert T. Levelised cost of energy—A theoretical justification and critical assessment. Energy Policy, 2019, 124: 169–179
26. Jülch V. Comparison of electricity storage options using levelized cost of storage (LCOS) method. Applied Energy, 2016, 183: 1594–1606
27. Tafone A, Ding Y, Li Y, et al. Levelised Cost of Storage (LCOS) analysis of liquid air energy storage system integrated with Organic Rankine Cycle. Energy, 2020, 198: 117275
28. Zhang J, Zhou S, Song W, et al. Performance analysis of a compressed liquid carbon dioxide energy storage system. Energy Procedia, 2018, 152: 168–173
29. Liu H, He Q, Borgia A, et al. Thermodynamic analysis of a compressed carbon dioxide energy storage system using two saline aquifers at different depths as storage reservoirs. Energy Conversion and Management, 2016, 127: 149–159
30. Zhao R, Liu Z. Thermo-economic performance of a compressed CO_2 energy storage system with a flexible gas holder. Journal of Energy Storage, 2023, 60: 106675
31. Liu Z, Liu Z, Xin X, et al. Proposal and assessment of a novel carbon dioxide energy storage system with electrical thermal storage and ejector condensing cycle: Energy and exergy analysis. Applied Energy, 2020, 269: 115067
32. Ma H, Liu Z. Techno-economic assessment on a multi-stage compressed carbon dioxide energy storage system with liquid

storage. Energy Reports, 2022, 8: 11740–11750

33. Zheng P, Zhang Z, Yang J, et al. Thermodynamic and economic analysis of compressed carbon dioxide energy storage systems based on different storage modes. Applied Thermal Engineering, 2024, 243: 122669
34. Zhang Y, Yang K, Hong H, et al. Thermodynamic analysis of a novel energy storage system with carbon dioxide as working fluid. Renewable Energy, 2016, 99: 682–697
35. Hao Y, He Q, Fu H, et al. Thermal parameter optimization design of an energy storage system with CO_2 as working fluid. Energy, 2021, 230: 120688
36. Zhang T, Gao J, Zhang Y, et al. Thermodynamic analysis of a novel adsorption-type trans-critical compressed carbon dioxide energy storage system. Energy Conversion and Management, 2022, 270: 116268
37. Zhang X R, Wang G B. Thermodynamic analysis of a novel energy storage system based on compressed CO_2 fluid. International Journal of Energy Research, 2017, 41(10): 1487–1503
38. Xu M, Wang X, Wang Z, et al. Preliminary design and performance assessment of compressed supercritical carbon dioxide energy storage system. Applied Thermal Engineering, 2021, 183: 116153
39. Hao Y, He Q, Zhou Q, et al. Modeling and techno-economic analysis of a novel trans-critical carbon dioxide energy storage system based on life cycle cost method. Journal of Energy Storage, 2020, 28: 101273
40. Yang Y, Wang L, Dong C, et al. Comprehensive exergy-based evaluation and parametric study of a coal-fired ultra-supercritical power plant. Applied Energy, 2013, 112: 1087–1099
41. Tsatsaronis G, Morosuk T. Advanced exergetic analysis of a novel system for generating electricity and vaporizing liquefied natural gas. Energy, 2010, 35(2): 820–829
42. Gungor A, Tsatsaronis G, Gunerhan H, et al. Advanced exergoeconomic analysis of a gas engine heat pump (GEHP) for food drying processes. Energy Conversion and Management, 2015, 91: 132–139
43. Chen J, Havtun H, Palm B. Conventional and advanced exergy analysis of an ejector refrigeration system. Applied Energy, 2015, 144: 139–151
44. Liu H, He Q, Saeed S B. Thermodynamic analysis of a compressed air energy storage system through advanced exergetic analysis. Journal of Renewable and Sustainable Energy, 2016, 8(3): 034101
45. Yamankaradeniz N. Thermodynamic performance assessments of a district heating system with geothermal by using advanced exergy analysis. Renewable Energy, 2016, 85: 965–972
46. He Q, Liu H, Hao Y, et al. Thermodynamic analysis of a novel supercritical compressed carbon dioxide energy storage system through advanced exergy analysis. Renewable Energy, 2018, 127: 835–849
47. Liu Z, Liu B, Guo J, et al. Conventional and advanced exergy analysis of a novel transcritical compressed carbon dioxide energy storage system. Energy Conversion and Management, 2019, 198: 111807
48. Liu Z, Liu Z, Yang X, et al. Advanced exergy and exergoeconomic analysis of a novel liquid carbon dioxide energy storage system. Energy Conversion and Management, 2020, 205: 112391
49. Zhang Y, Liang T, Yang K. An integrated energy storage system consisting of Compressed Carbon dioxide energy storage and Organic Rankine Cycle: Exergoeconomic evaluation and multi-objective optimization. Energy, 2022, 247: 123566
50. Sun L, Tang B, Xie Y. Performance assessment of two compressed and liquid carbon dioxide energy storage systems: Thermodynamic, exergoeconomic analysis and multi-objective optimization. Energy, 2022, 256: 124648
51. Smart Energy International. First CO_2 Long Duration Battery Storage Launched in Sardinia. Amsterdam, Netherlands, 2022
52. Clarion Energy Content Directors. The Expansion of Renewable Generation Spurs Investment, Innovation in Long-Duration Energy Storage. Tulsa, Oklahoma, US, 2025
53. Yang Y, Huang B, Meng X, et al. Research summary on the energy storage technologies based on carbon dioxide thermodynamic cycle. Thermal Power Generation, 2023, 52(6): 12–23 (in Chinese)
54. Wang S, Zhang G, Wei K. Key technologies and engineering application of carbon dioxide energy storage power station. Water Power, 2025, 51(08): 108–114+123 (in Chinese)
55. Chen H, Goswami D Y, Stefanakos E K. A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. Renewable & Sustainable Energy Reviews, 2010, 14(9): 3059–3067
56. Dai B, Li M, Ma Y. Thermodynamic analysis of carbon dioxide blends with low GWP (global warming potential) working fluids-based transcritical Rankine cycles for low-grade heat energy recovery. Energy, 2014, 64: 942–952
57. Kim J H, Cho J M, Kim M S. Cooling performance of several CO_2/propane mixtures and glide matching with secondary heat transfer fluid. International Journal of Refrigeration, 2008, 31(5): 800e6
58. Zhang X P, Wang F, Fan X W, et al. Determination of the optimum heat rejection pressure in transcritical cycles working with R744/R290 mixture. Applied Thermal Engineering, 2013, 54: 176e84
59. Sarkar J, Bhattacharyya S. Assessment of blends of CO_2 with butane and isobutane as working fluids for heat pump applications. International Journal of Thermal Sciences, 2009, 48(7): 1460e5
60. Xia J, Wang J, Zhang G, et al. Thermo-economic analysis and comparative study of transcritical power cycles using CO_2-based mixtures as working fluids. Applied Thermal Engineering, 2018, 144: 31–44
61. Liu Z, Liu X, Zhang W, et al. Thermodynamic analysis on the feasibility of a liquid energy storage system using CO_2-based mixture as the working fluid. Energy, 2022, 238: 121759
62. Ma H, Liu Z. Preliminary thermodynamic analysis of a carbon

dioxide binary mixture cycled energy storage system with low pressure stores. Energy, 2022, 246: 123346
63. Tang B, Sun L, Xie Y. Design and performance evaluation of an energy storage system using CO_2-based binary mixtures for thermal power plant under dry conditions. Energy Conversion and Management, 2022, 268: 116043
64. Fu X, Yan X, Liu Z. Coupling thermodynamics and economics of liquid CO_2 energy storage system with refrigerant additives. Energy, 2023, 284: 128642
65. Yan X, Zhao R, Liu Z. Performance of a CO_2-mixture cycled energy storage system: Thermodynamic and economic analysis. Applied Thermal Engineering, 2023, 226: 120280
66. Zhang Y, Shen X, Tian Z, et al. 5E (energy, exergy, energy level, exergoeconomic, and exergetic sustainability) analysis on a carbon dioxide binary mixture based compressed gas energy storage system: A comprehensive research and feasibility validation. Energy Conversion and Management, 2023, 292: 117399
67. Hou K, Han N, Xue S, et al. Performance analysis and additive screening of a liquid carbon dioxide mixture energy storage system coupled with a coal-fired power plant. Journal of Cleaner Production, 2024, 473: 143525
68. Chen C C, Liaw H J, Wang T C, et al. Carbon dioxide dilution effect on flammability limits for hydrocarbons. Journal of Hazardous Materials, 2009, 163(2–3): 795–803
69. Chys M, van den Broek M, Vanslambrouck B, et al. Potential of zeotropic mixtures as working fluids in organic Rankine cycles. Energy, 2012, 44(1): 623–632
70. Zhao P, Xu W, Zhang S, et al. Components design and performance analysis of a novel compressed carbon dioxide energy storage system: A pathway towards realizability. Energy Conversion and Management, 2021, 229: 113679
71. Zhao P, Xu W, Gou F, et al. Performance analysis of a self-condensation compressed carbon dioxide energy storage system with vortex tube. Journal of Energy Storage, 2021, 41: 102995
72. Kanbur B B, Xiang L, Dubey S, et al. Cold utilization systems of LNG: A review. Renewable & Sustainable Energy Reviews, 2017, 79: 1171–1188
73. Bao J, He X, Deng Y, et al. Parametric analysis and multi-objective optimization of a new combined system of liquid carbon dioxide energy storage and liquid natural gas cold energy power generation. Journal of Cleaner Production, 2022, 363: 132591
74. Wang M, Zhao P, Yang Y, et al. Performance analysis of energy storage system based on liquid carbon dioxide with different configurations. Energy, 2015, 93: 1931–1942
75. Zhang Y, Yao E, Zhang X, et al. Thermodynamic analysis of a novel compressed carbon dioxide energy storage system with low-temperature thermal storage. International Journal of Energy Research, 2020, 44(8): 6531–6554
76. Sun W, Liu X, Yang X, et al. Design and thermodynamic performance analysis of a new liquid carbon dioxide energy storage system with low pressure stores. Energy Conversion and Management, 2021, 239: 114227
77. Liu Z, Wang M, Song Y, et al. Design and numerical analysis of recuperator for a liquid carbon dioxide energy storage system. Applied Sciences, 2023, 13(24): 13151
78. Zhang Y, Liu J, Yin S, et al. Design and performance analysis of a novel compressed air-liquid CO_2 energy storage. Energy Conversion and Management, 2024, 301: 118068
79. Peng Y, Gao J, Zhang Y, et al. Experimental study of adsorption CO_2 storage device for compressed CO_2 energy storage system. Journal of Energy Storage, 2023, 58: 106286
80. Zhou Q, Birkholzer J T, Tsang C F, et al. A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. International Journal of Greenhouse Gas Control, 2008, 2(4): 626–639
81. Jiang L, Chen Z, Farouq Ali S M. Feasibility of carbon dioxide storage in post-burn underground coal gasification cavities. Applied Energy, 2019, 252: 113479
82. Cao Z, Deng J, Zhou S, et al. Research on the feasibility of compressed carbon dioxide energy storage system with underground sequestration in antiquated mine goaf. Energy Conversion and Management, 2020, 211: 112788
83. Li Y, Yu H, Li Y, et al. Numerical study on the hydrodynamic and thermodynamic properties of compressed carbon dioxide energy storage in aquifers. Renewable Energy, 2020, 151: 1318–1338
84. Shi Y, Bai H, Rong Y, et al. Numerical simulation of cyclic performance of compressed carbon dioxide energy storage system in aquifer. Alexandria Engineering Journal, 2023, 62: 291–301
85. Shi Y, Lu Y, Rong Y, et al. Geochemical reaction of compressed CO_2 energy storage using saline aquifer. Alexandria Engineering Journal, 2023, 64: 679–689
86. Li Y, Yu H, Xiao Y, et al. Numerical verification on the feasibility of compressed carbon dioxide energy storage in two aquifers. Renewable Energy, 2023, 207: 743–764
87. Alsagri A S, Arabkoohsar A, Alrobaian A A. Combination of subcooled compressed air energy storage system with an Organic Rankine Cycle for better electricity efficiency, a thermodynamic analysis. Journal of Cleaner Production, 2019, 239: 118119
88. Safder U, Ifaei P, Yoo C K. Multi-objective optimization and flexibility analysis of a cogeneration system using thermorisk and thermoeconomic analyses. Energy Conversion and Management, 2018, 166: 602–636
89. Ahmadi A, El Haj Assad M, Jamali D H, et al. Applications of geothermal Organic Rankine Cycle for electricity production. Journal of Cleaner Production, 2020, 274: 122950
90. Zhang Y, Liang T, Yang C, et al. Advanced exergy analysis of an integrated energy storage system based on transcritical CO_2 energy storage and Organic Rankine Cycle. Energy Conversion and Management, 2020, 216: 112938
91. Ghorbani B, Mehrpooya M, Rooholamini S. Novel integrated structure of carbon dioxide liquefaction energy storage system using solar energy. Journal of Energy Storage, 2020, 31: 101641
92. Mokarram N H, Mosaffa A H. A comparative study and

optimization of enhanced integrated geothermal flash and Kalina cycles: A thermoeconomic assessment. Energy, 2018, 162: 111–125
93. Zhang Y, Lin F, Liu Z, et al. Energy and exergy performance evaluation of a novel low-temperature physical energy storage system consisting of compressed CO_2 energy storage and Kalina cycle. Journal of Energy Storage, 2023, 60: 106605
94. Arpagaus C, Bless F, Uhlmann M, et al. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy, 2018, 152: 985–1010
95. Hao Y, He Q, Liu W, et al. Thermodynamic analysis of a novel fossil-fuel-free energy storage system with a trans-critical carbon dioxide cycle and heat pump. International Journal of Energy Research, 2020, 44(10): 7924–7937
96. Hao Y, He Q, Du D. A trans-critical carbon dioxide energy storage system with heat pump to recover stored heat of compression. Renewable Energy, 2020, 152: 1099–1108
97. Qiao L, Pu W, Wu B, et al. Performance study of a supercritical carbon dioxide energy storage system with non-uniform graded compression heat recovery. Energy, 2024, 313: 133876
98. Xu M, Zhao P, Huo Y, et al. Thermodynamic analysis of a novel liquid carbon dioxide energy storage system and comparison to a liquid air energy storage system. Journal of Cleaner Production, 2020, 242: 118437
99. Chen K, Pu W, Zhang Q, et al. Thermodynamic and economic assessment on the supercritical compressed carbon dioxide energy storage system coupled with solar thermal storage. Journal of Energy Storage, 2021, 41: 102959
100. Fu H, He Q, Song J, et al. Thermodynamic of a novel solar heat storage compressed carbon dioxide energy storage system. Energy Conversion and Management, 2021, 247: 114757
101. Fu H, Shi J, Yuan J, et al. Thermodynamic analysis of photothermal-assisted liquid compressed CO_2 energy storage system hybrid with closed-cycle drying. Journal of Energy Storage, 2023, 66: 107415
102. Gao C. Performance investigation of solar-assisted supercritical compressed carbon dioxide energy storage systems. Journal of Energy Storage, 2024, 79: 110179
103. Liu Z, Guan H, Jin X, et al. Thermodynamic and economic analysis of a trans-critical CO_2 energy storage system integrated with ORC and solar energy. Energy, 2024, 313: 133667
104. Jiang H, Wang J, Xu H, et al. Thermodynamic performances of a novel multi-mode solar-thermal-assisted liquid carbon dioxide energy storage system. Journal of Energy Storage, 2024, 97: 112843
105. Wang C, Zhao Y, Liu M, et al. Peak shaving operational optimization of supercritical coal-fired power plants by revising control strategy for water-fuel ratio. Applied Energy, 2018, 216: 212–223
106. Zhang K, Liu M, Zhao Y, et al. Design and performance evaluation of a new thermal energy storage system integrated within a coal-fired power plant. Journal of Energy Storage, 2022, 50: 104335
107. Zhang L, Cui J, Zhang Y, et al. Performance analysis of a compressed air energy storage system integrated into a coal-fired power plant. Energy Conversion and Management, 2020, 225: 113446
108. Cao L, Li X, Wang D. A thermodynamic system of coal-fired power unit coupled S-CO_2 energy-storage cycle. Energy, 2022, 259: 125015
109. Chae Y J, Lee J I. Thermodynamic analysis of compressed and liquid carbon dioxide energy storage system integrated with steam cycle for flexible operation of thermal power plant. Energy Conversion and Management, 2022, 256: 115374
110. He T, Cao Y, Si F. Thermodynamic analysis and optimization of a compressed carbon dioxide energy storage system coupled with a combined heating and power unit. Energy Conversion and Management, 2023, 277: 116618
111. Zhang X, Zhang H, Zhao H, et al. Thermodynamic analysis of ternary coupled system based on combined heating and power unit, steam ejector and compressed carbon dioxide energy storage. Journal of Energy Storage, 2024, 104: 114748
112. Hou K, Wang Y, Han N, et al. Performance analysis of a liquid carbon dioxide energy storage system integrated with a coal-fired power plant. Journal of Energy Storage, 2024, 77: 109869
113. Liu Z, Cao F, Guo J, et al. Performance analysis of a novel combined cooling, heating and power system based on carbon dioxide energy storage. Energy Conversion and Management, 2019, 188: 151–161
114. Qi M, Park J, Landon R S, et al. Continuous and flexible renewable-power-to-methane via liquid CO_2 energy storage: Revisiting the techno-economic potential. Renewable & Sustainable Energy Reviews, 2022, 153: 111732
115. Xu W, Zhao P, Gou F, et al. Thermo-economic analysis of a combined cooling, heating and power system based on self-evaporating liquid carbon dioxide energy storage. Applied Energy, 2022, 326: 120032
116. Zhang Y, Lin Y, Lin F, et al. Thermodynamic analysis of a novel combined cooling, heating, and power system consisting of wind energy and transcritical compressed CO_2 energy storage. Energy Conversion and Management, 2022, 260: 115609
117. Zhang Y, Li C, Tian Z, et al. Energy, exergy, economic, and environmental analyses and optimization of a multigeneration system considering high-temperature island environment. Applied Thermal Engineering, 2024, 255: 124011
118. Xu W, Zhao P, Liu A, et al. Design and off-design performance analysis of a liquid carbon dioxide energy storage system integrated with low-grade heat source. Applied Thermal Engineering, 2023, 228: 120570
119. Wan Y K, Wu C, Liu Y C, et al. A technical feasibility study of a liquid carbon dioxide energy storage system: Integrated component design and off-design performance analysis. Applied Energy, 2023, 350: 121797
120. Zhao M, Zhu Y, Hu D, et al. Off-design performance of supercritical compressed carbon dioxide energy storage system. In: The 15th International Conference on Applied Energy, Qatar, Doha, 2023

121. He T, Cao Y, Si F, et al. Off-design characteristics and operation strategy analysis of a compressed carbon dioxide energy storage system coupled with a combined heating and power plant. Energy, 2024, 303: 131983
122. Chaychizadeh F, Dehghandorost H, Aliabadi A, et al. Stochastic dynamic simulation of a novel hybrid thermal-compressed carbon dioxide energy storage system (T-CCES) integrated with a wind farm. Energy Conversion and Management, 2018, 166: 500–511
123. Zhang Y, Wu Y, Yang K. Dynamic characteristics of a two-stage compression and two-stage expansion compressed carbon dioxide energy storage system under sliding pressure operation. Energy Conversion and Management, 2022, 254: 115218
124. Jafari S, Ameri M. Integrating photovoltaic/linear Fresnel reflector with supercritical carbon dioxide energy storage system: energy and exergy analysis. Journal of Energy Storage, 2022, 53: 105235
125. Zhang Y, Shen X, Tian Z, et al. A step towards dynamic: An investigation on a carbon dioxide binary mixtures based compressed gas energy storage system using energy and exergy analysis. Energy, 2023, 282: 128415
126. Huang Q, Feng B, Liu S, et al. Dynamic operating characteristics of a compressed CO_2 energy storage system. Applied Energy, 2023, 341: 120985
127. Jiang J, Zhang B, Chen W, et al. Investigation and optimization of the thermal performance of compressed supercritical CO_2 energy storage system based on dynamic modeling and transient simulation. Renewable Energy, 2025, 238: 121966
128. Zhang Y, Shen X, Tian Z, et al. Comparative study of operating modes on a gaseous two-stage compressed carbon dioxide energy storage system through energy and exergy analysis based on dynamic simulation. Energy, 2025, 316: 134521
129. Zhou A, Li X, Ren X, et al. Evaluation of the performance and economy for a hybrid energy storage system using hydrogen and compressed carbon dioxide as the energy carrier. Energy Conversion and Management, 2022, 264: 115700
130. Yun S, Lee S, Jang M G, et al. Techno-economic assessment of CO_2 capture integrated coal-fired power plant with energetic analysis. Energy, 2021, 236: 121493
131. Hu Y, Li X, Li H, et al. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. Applied Energy, 2013, 112: 747–754
132. Huang Q, Yao J, Hu Y, et al. Integrating compressed CO_2 energy storage in an oxy-coal combustion power plant with CO_2 capture. Energy, 2022, 254: 124493
133. Xu W, Zhao P, Gou F, et al. A combined heating and power system based on compressed carbon dioxide energy storage with carbon capture: Exploring the technical potential. Energy Conversion and Management, 2022, 260: 115610
134. Yin L, Ju Y, Lin Q. An integrated solution of energy storage and CO_2 reduction: Trans-critical CO_2 energy storage system combining carbon capture with LNG cold energy. Journal of Cleaner Production, 2024, 482: 144228
135. Song J, Fan Y, Wang F, et al. Thermodynamic analysis of a novel compressed carbon dioxide energy storage coupled dry methane reforming system with integrated carbon capture. Applied Energy, 2025, 377: 124769
136. Minkley W, Brandt M, Naumann D, et al. Energy storage in salt caverns with supercritical and transcritical CO_2. In ARMA/DGS/SEG International Geomechanics Symposium, Riyadh, Saudi Arabia, 2023
137. Jiang K, Huang S, Wang Y, et al. Simulation study of a novel approach to couple compressed CO_2 energy storage with compression heat storage in aquifers. Applied Thermal Engineering, 2025, 258: 124584
138. Stepanek J, Minkley W, Syblik J, et al. Thermodynamic analysis of compressed CO_2 energy storage in salt caverns with gravel stabilization. Journal of Energy Storage, 2024, 82: 110509
139. Jiang K, Huang S, Wang Y, et al. Feasibility study of a high-temperature thermal energy storage system using CO_2 as working fluid in horizontal aquifers. Journal of Energy Storage, 2024, 92: 112149
140. Global CCS Institute. The Global Status of CCS. Special Report: Understanding Industrial CCS Hubs and Clusters. Melbourne, Australia, 2016
141. Hadidi A. Thermodynamic design of the novel energy storage system based on liquid carbon dioxide for a 17 MW concentrated solar thermal power plant. Journal of Energy Storage, 2024, 83: 110761
142. Choi Y S, Young D, Nešić S, et al. Wellbore integrity and corrosion of carbon steel in CO_2 geologic storage environments: A literature review. International Journal of Greenhouse Gas Control, 2013, 16: S70–S77
143. Cui G, Ren S, Rui Z, et al. The influence of complicated fluid-rock interactions on the geothermal exploitation in the CO_2 plume geothermal system. Applied Energy, 2018, 227: 49–63