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A technology review of pumped thermal energy storage based on CO_2 cycles

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ABSTRACT

Pumped thermal energy storage (PTES) is an innovative physical energy storage technology that converts surplus electricity into heat, stores it in thermal reservoirs, and reconverts it into electricity when needed. When CO_2 is employed as the working fluid, PTES can offer advantages of potentially high round-trip efficiency, compact system equipment, and good operational flexibility without significant geographical limitations, which make it superior for applications in large-scale energy storage scenarios. However, there remain technical challenges to be addressed before the technology can be widely adopted: Selection of most appropriate thermodynamic configuration; design and operation of the main components, such as expanders, compressors, heat exchangers, thermal energy storage materials and storage tanks; and design of control systems to maximise control system efficiency and reliability. This review paper provides the first comprehensive technology review focused exclusively on PTES systems based on CO_2 cycles. Unlike previous studies that have addressed PTES more generally or considered CO_2 only as one working fluid among many, this review aims to provide insightful information on recent advancements in PTES systems based on CO_2 cycles, and the technical and operational issues related to the main components and control systems. Following description of working principles and characteristics of thermodynamic cycles, this review discusses the current research and development status, technical challenges and risks, and future research trends of the main components and control approaches. By identifying technical challenges and research gaps, this work provides a foundation for advancing PTES technologies toward commercial readiness.

1. Introduction

Renewable energy plays a crucial role in the transition to less carbon-intensive and more sustainable energy systems. Electricity production from renewable sources, such as solar, wind, geothermal and hydroelectric power, can significantly reduce the greenhouse gas emissions and help to mitigate climate change issues [1,2]. Driven by policy support and cost reductions of solar panels and wind turbines in particular, production capacity from renewable sources has grown rapidly in recent years. In the UK, electricity generation from renewable sources reached a record 135.8 TWh in 2023, accounting for 46.4 % of total electricity generation [3]. However, renewable energy sources like solar and wind are intermittent, hence they cannot produce electricity consistently. Furthermore, large-scale grid connection brings significant challenges to the power grid system and introduces significant wastage due to imbalances in energy demand and supply [4,5]. Therefore, the successful deployment of renewable energy critically requires support from energy storage. Energy storage systems can periodically store excess energy generated during periods of low demand and release it during peak electricity demand, which can help to smooth the fluctuations of renewable energy production. Consequently, renewable energy production integrated with energy storage systems can reduce the dependence on fossil fuels, improve grid stability and flexibility, enhance energy security, and facilitate power transmission and distribution [6–8].

At present, only pumped hydro energy storage (PHES) and compressed air energy storage (CAES) have been commercially established for large-scale energy storage. PHES offers the benefits of large energy storage capacity, relatively fast response, long storage time, and high system efficiency, but they are restricted by special geographical conditions, long construction period, large initial investment, and damage to the ecological environment [9–11]. The CAES also offers advantages of high energy storage capacity, long storage period, and high efficiency. However, traditional CAES systems do not recover the thermal energy

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generated during compression process and requires external energy from combustion of fossil fuels and are also restricted by special geographical environments, such as underground caves, salt caves and rock formations [12–15]. To improve the viability and efficiency of energy storage and mitigate its dependence on special geographical environments, advanced CAES systems and thermal energy storage (TES) have been proposed in the last two decades, including adiabatic CAES, isothermal CAES, liquid air energy storage (LAES), supercritical CAES, and pumped thermal energy storage (PTES) [16,17]. Adiabatic CAES stores the heat generated during compression and reuses them during expansion, which significantly enhances the overall system efficiency [18,19]. Isothermal CAES employs a liquid (water) piston or water droplets injection to reduce the temperature rise during compression and minimize the energy loss [20,21]. LAES uses liquefied air or nitrogen to store energy so that it has large energy storage density, but the cryogenic air separation and liquefaction processes result in large system cooling exergy loss [22–24]. Supercritical CAES use supercritical air or CO_2 to store energy more efficiently, due to the unique thermodynamic properties of supercritical fluids, such as high density, low viscosity, and low diffusion coefficient [25,26]. PTES uses electricity to store both heat and cold energy during the charging process with the stored energies converted back to electricity during the discharging process. In the literature, PTES is often used interchangeably with pumped thermal electricity storage, electro-thermal energy storage, pumped heat electricity storage, or Carnot batteries. Among the advanced energy storage technologies under development, PTES is recognized as one of the most promising solutions for large-scale, long-duration, low environmental impact energy storage technologies [17,27,28]. Furthermore, PTES systems can be built at different scales, ranging from small industrial installations to large grid-level storage systems, and can be installed almost anywhere with no requirement for specific geographic conditions, such as mountains or large bodies of water. The working fluid in PTES systems plays a critical role in transferring thermal energy between the hot and cold reservoirs and enabling the stored energies to be converted back to electricity [29]. The selection of working fluids significantly affects the system efficiency, capital cost, and scalability of the storage system. It is dependent on the specific design, temperature range, and application scenarios. The working fluids used in PTES systems include air, argon, helium, and CO_2. PTES systems using air, argon and helium can potentially operate at high temperatures up to 1000 °C, depending on the compressed pressure, and have round-trip efficiency up to around 60 % [30–33]. However, air, argon and helium have a relatively low energy density and specific heat capacity compared to CO_2, which make the systems less efficient at transferring and storing heat and lead to larger, bulkier systems for the same energy capacity. CO_2 has excellent heat transfer properties and high energy density and has the potential to lead to better thermodynamic performance than compressed air [34,35]. The use of CO_2 can also enable aboveground storage at less extreme temperatures than compressed or liquid air. CO_2 PTES systems are also more efficient due to lower compression and pumping energy requirements, as well as reduced thermal losses during energy transfer. CO_2 cycles, including supercritical Brayton and *trans*-critical Rankine cycles, can also be operated over a wide range of temperatures, from near-ambient temperature to hundreds of degrees Celsius, which makes it possible to design systems with large temperature differences between the hot and cold reservoirs, improving energy storage capacity and overall efficiency [17,28,36]. Additionally, CO_2 is non-toxic, non-flammable, and readily available, which makes it an environmentally friendly working fluid for power generation and energy storage systems [37–39]. External heat supply such as waste heat from industrial processes or solar thermal storage can also be used to further increase the overall energy efficiency of the systems [40,41].

PTES systems based on CO_2 cycles potentially offer a high-efficiency, scalable, and environmentally friendly solution for energy storage. However, there remain technical challenges that need to be addressed for wide adoption of such systems. Components operating at high pressures and high temperatures, such as turbomachinery and heat exchangers, require advanced alloys and engineering solutions to ensure long-term reliability [37,39]. Maintaining efficient heat transfer between CO_2 and the TES medium and maintaining the quality of insulation of the TES tanks can be technically challenging [42,43]. Turbines and compressors are facing significant technical and economic challenges associated with their development and deployment due to the extreme operating conditions [44–48]. Further, proper control is essential for ensuring the system's efficiency, stability, safety, and longevity. Controlling CO_2 based PTES systems presents several unique challenges due to the extreme and variable operating conditions, as well as the complex thermophysical behaviour of CO_2 near its critical point [49,50]. To help in accelerating the development of CO_2 PTES systems, this review paper provides the first comprehensive technology overview focused exclusively on PTES systems based on CO_2 cycles. Unlike previous studies that have addressed PTES more generally or considered CO_2 only as one working fluid among many, this review aims to provide insightful information on recent advancements and the technical and operational issues related to the main components and control systems. The paper fills a clear gap in the literature and establishes a foundation for future research and development. In this review, the working principle and characteristics of implemented thermodynamic cycles are firstly demonstrated. The current research and development progress, technical challenges and risks, and research trends on turbines, compressors, heat exchangers, and TES materials and storage tanks are addressed. Control system design and control strategies for the optimisation of CO_2 based PTES systems are also discussed.

2. Introduction of PTES systems

2.1. Working principle

PTES system is an energy storage technology that stores electrical energy in the form of thermal energy and later converts it back to electricity when needed [51]. A schematic diagram of PTES systems is shown in Fig. 1. The main components contain expanders, compressors, heat exchangers, and TES medium and tanks. The operation processes in PTES systems involve charging, standby, and discharging. During the charging process, electrical energy is used to drive the compressor to produce thermal energy via a heat pump. The fluid is compressed, and its temperature rises significantly through position 1 to position 2. This hot thermal energy is delivered to the hot TES tank, where it releases heat to the storage medium. On the cold side, the working fluid expands and cools down through position 3 to position 4, the cold thermal energy is delivered to the cold TES tank and drops the temperature of storage medium. The storage medium used in the hot tank typically includes molten salts, concrete, rocks, or advanced phase change materials. The storage medium for the cold tank is often water, ice, or other medium [52,53]. Once the heat and cold thermal energy have been stored in their respective tanks, the system is in standby mode until energy is needed. The stored thermal energies can be maintained for a long time with minimal energy loss, depending on the insulation quality of the tanks. During the discharging process, when electricity is required, the stored thermal energy is used to generate electricity via a heat engine. The thermal energy from the hot tank is delivered to the working fluid to increase its internal energy. The high temperature working fluid expands and drive expanders to produce mechanical work through position 2′ to position 1′, which is converted into electricity using a generator. After passing through the expander, the working fluid is cooled by the cold thermal energy from the cold tank, completing the cycle. The difference in temperature between the hot and cold TES tanks drives the heat engine, allowing it to produce electricity efficiently. The two heat exchangers (HX1 and HX2) are required to deliver heat and cold thermal energies. The involved thermodynamic cycle could be *trans*-critical Rankine cycles, supercritical Brayton cycles or other types

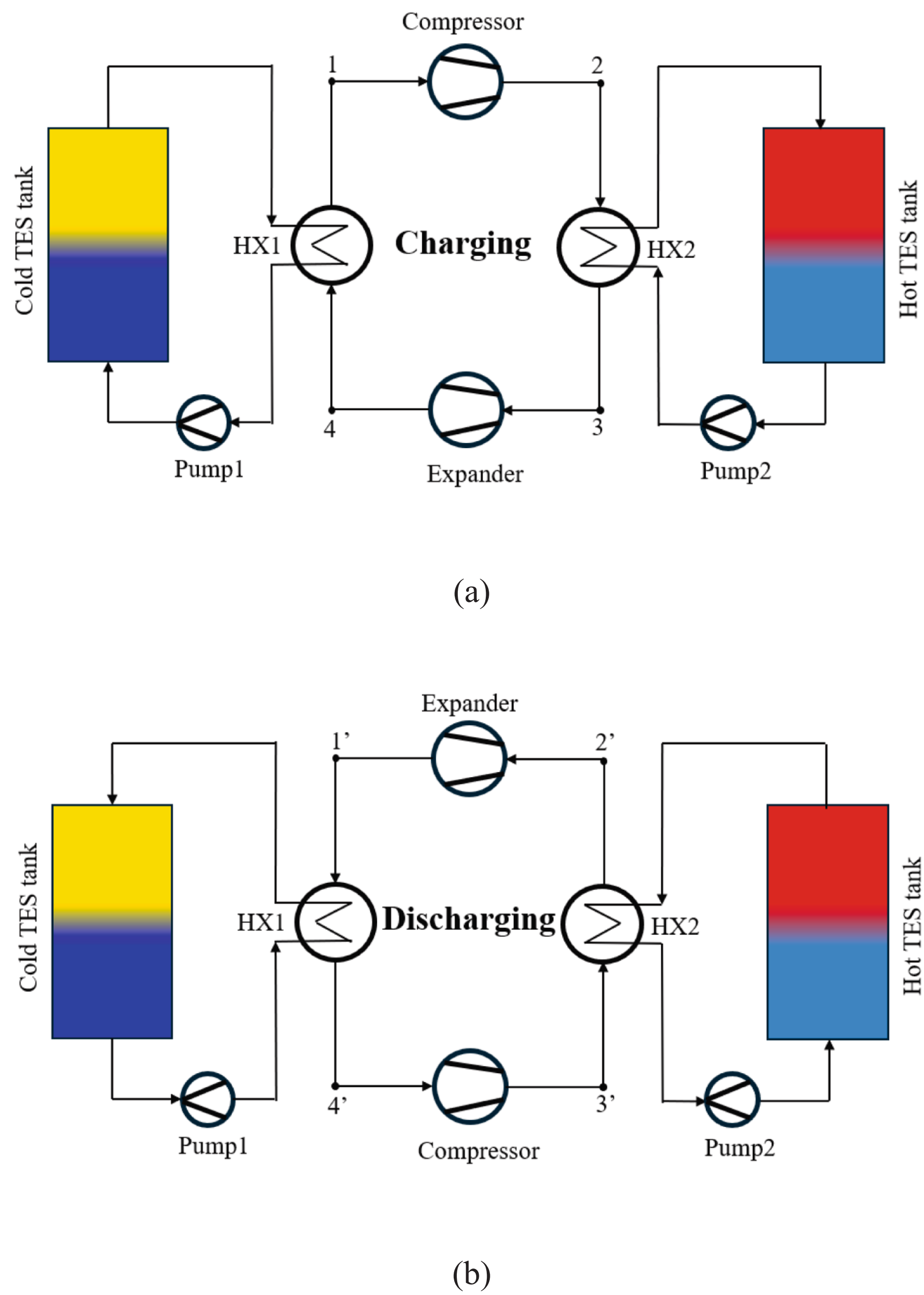

Fig. 1. Schematic diagram of PTES systems. (a) Charging mode and (b) Discharging mode.

depending on the design of the systems and the working fluids [28,54,55].

White et al. [51] investigated the thermodynamic behaviours of PTES systems with argon as working fluid, identified the main sources of irreversibility, and analysed their impact on overall system efficiency. They found that highly efficient compression and expansion processes resulted in larger overall system efficiency. For fixed compression and expansion efficiencies, the cycle performance was found to be primarily governed by the temperature difference between the two TES tanks. White [31] also examined energy losses in the two TES tanks arising from irreversible heat transfer and friction, and emphasized the impacts of operating temperatures, reservoir geometry and mode of operation on the losses. Improve the design of TES tank to limit the heat loss and retain the stored energy is therefore crucial for enabling large-scale, long-duration storage solutions. Recently, Rabi et al. [28] reviewed different thermodynamic cycles applied in PTES systems. The round-trip efficiency was found to be primarily influenced by the isentropic performance of compressors and expanders, the thermal effectiveness of the TES tanks, pressure losses within the circuit, unwanted heat transfer to or from the system, and the efficiency of the electrical machines. Brayton cycles using air, argon, helium, or CO_2 as the working fluid reach round-trip efficiencies between 34 % and 82 %, and *trans*-critical Rankine cycles using CO_2 achieve efficiencies ranging from 30 % to 73 %.

Generally, the wide variation in round-trip efficiencies reported for PTES systems in the literature arises from several interrelated technical and design factors. Different working fluids exhibit distinct thermo-physical and thermodynamic properties, such as specific heat capacity, critical temperature, thermal conductivity, and viscosity, which influence compression, expansion, and heat transfer processes. Fluid stability at high temperatures, compatibility with storage materials, and ease of achieving near-isothermal heat transfer also affect system performance. High-performance turbomachinery can significantly increase efficiency, while less advanced or scaled-down prototypes often exhibit large losses. A larger temperature difference between the two TES tanks enables higher exergy availability and improves the thermodynamic cycle performance. However, the larger temperature difference can increase irreversibility due to greater entropy generation during heat transfer process, which conversely reduces the available work output. Systems with well-designed heat exchangers and effective insulation reduce thermal losses, while imperfect designs or long-duration storage may suffer from serious heat leakage and degradation. Moreover, practical considerations, including system scale, operating temperature levels, and the efficiency of electrical machinery used for energy conversion, create additional efficiency variations.

2.2. Comparison with other storage technologies

Characterization criteria of PTES systems involve assessing key parameters that define their performance, efficiency, scalability, and economic viability. The critical criteria and metrics to evaluate PTES systems include round-trip efficiency, energy density, scalability, response time, system operability, cycle life and durability, capital cost and environmental impact [36,56]. Round-trip efficiency is the ratio of the electric energy recovered during the discharging process to the energy used in the charging process [57]. Higher round-trip efficiency indicates a more effective storage system with minimal energy losses during the charging and discharging processes. Typical PTES systems aim for efficiencies in the range of 60–70 %, although some advanced designs target higher efficiencies. Energy density refers to the amount of energy stored per unit volume of the system [58]. A higher energy density allows for a more compact and space-efficient system, reducing the footprint required for thermal storage tanks. Scalability measures how easily the system can be scaled up or down for various applications [8]. PTES systems need to be easily scalable to suit different energy storage needs, from small applications to large grid-scale systems. Response time refers to how quickly the PTES systems can start producing electricity after a demand signal is received [59,60]. Fast response times are critical for balancing grid supply and demand, especially when integrating intermittent renewable energy sources like wind or solar. System operability refers to the PTES system's ability to operate under different load profiles, including start-up, shutdown, partial load operation and varying charge–discharge cycles [61]. Flexible operation is essential for responding to fluctuations in energy demand and integrating with intermittent energy sources. Cycle life and durability refers to the number of charge–discharge cycles the system can undergo before its performance significantly degrades [62]. A longer life reduces maintenance costs and increases the overall economic viability of the system. Capital cost is the upfront investment required to build and deploy the PTES system [63,64]. Lower capital costs make PTES systems more attractive compared to other energy storage technologies like batteries or CAES systems. Environmental impact of PTES systems refers to its effect on the environment, both during construction and operation [65,66]. A lower environmental impact is desirable for achieving sustainability goals and reducing greenhouse gas emissions.

A comparison of PTES systems with other storage technologies is shown in Table 1. At present, systems like CAES and PHES are competitive in large-scale applications but face geographical limitations. Batteries are suitable for short-duration storage with fast response times but at a higher capital cost. Hydrogen storage is promising for long-term energy storage but is currently hindered by low efficiency and infrastructure costs. PTES systems offer medium energy density and can handle long discharge durations at a relatively low cost but with moderate round-trip efficiency. They can provide not only electricity storage but also combined hot and cold thermal energies, which can enhance energy system integration. Their response time is competitive with existing grid requirements. And with appropriate design, PTES systems can support ancillary services such as frequency regulation and inertia through rotating machines. Unlike PHES and CAES, PTES systems are not constrained by geography; and unlike flow batteries, it is not constrained by expensive electrochemistry. PTES systems also offer superior sustainability, as its core components can be composed of non-toxic, abundant, and recyclable materials. Cycle life is measured in decades, with performance degradation mainly limited to insulation quality and equipment wear rather than irreversible chemical or geological factors.

Benato and Stoppato [17] also compared PTES systems with other energy storage technologies. The advantages of PTES systems they found include long cycle life, independence from geographical constraints, and the absence of fossil fuel requirements during operation. PTES can also be retrofitted or integrated with existing fossil-fuel power plants and offers a pathway for more sustainable energy transition. Considering these benefits, they concluded that PTES systems employing reversible Brayton cycles represent a highly suitable option for large-scale energy storage applications. In recent years, the simplicity of their configuration and relatively low investment costs have attracted significantly growing interest.

3. Thermodynamic CO_2 cycle for PTES systems

The high heat transfer efficiency of CO_2 due to its favourable thermodynamic properties is particularly advantageous for thermal energy storage and release. The ability to operate at high pressures and temperatures leads to higher specific power outputs and thus smaller expanders and compressors. The most used CO_2 cycles in PTES systems are *trans*-critical Rankine cycle and supercritical Brayton cycle. These cycles are selected based on the specific requirements of the storage system and the operating conditions, including temperature range, pressure range, storage medium, scalability, system efficiency, and with or without external heat source. The temperature and pressure ranges of the cycle must match the characteristics of the thermal storage medium to minimize irreversibility. Scalability is also crucial, because different cycles

Table 1
A comparison of PTES system with other energy storage technologies [56,67,68,69].

Storage Technology	Round-trip Efficiency	Energy Density	Discharge Duration	Capital Cost ($/kWh)	Scalability	Response Time	Cycle life (year)	Environmental impact
PTES	40 – 70 %	~0.5–1.5 MJ/m^3	Hours to days	50–150	MWh–GWh	Minutes	30–50	Low
PHES	70 – 85 %	~0.5–2 MJ/m^3	Hours to days	50–200	GWh–TWh	Minutes	50–100	High
CAES	40 – 60 %	~0.5–2 MJ/m^3	Hours to days	30–150	MWh–GWh	Minutes	30–40	Medium to high
Lithium-ion batteries	85 – 95 %	~250–700 Wh/kg	Minutes to hours	200–400	kWh–MWh	Milliseconds	10–20	Medium
Flow batteries	60 – 80 %	~10–100 Wh/kg	Hours to days	150–300	kWh–MWh	Seconds to minutes	12–20	Medium
Supercapacitors	90 – 95 %	~5–10 Wh/kg	Seconds to minutes	300–1000	kWh	Milliseconds	8–7	Low
Hydrogen	30 – 50 %	~120–142 MJ/kg	Days to weeks	200–1000	MWh–GWh	Hours	20–50	Low

perform optimally at different power and energy capacities. The presence or absence of an external heat source can further determine cycle selection, since certain configurations require specific cycle adaptations. Overall, selecting the most appropriate CO_2 cycle is essential to maximize round-trip efficiency, ensure reliable operation, and optimize both the capital and operational costs of PTES systems. Schematic temperature-entropy diagrams of PTES systems based on CO_2 cycles are shown in Fig. 2, respectively with *trans*-critical Rankine cycle and supercritical Brayton cycle. A summary of CO_2 cycles used for PTES systems are shown in Table 2.

During the charging process, the *trans*-critical Rankine cycle allows CO_2 to transition from subcritical to supercritical states. Their operations cover a temperature range of approximately –20 °C to 200 °C for thermal storage and subsequent discharge. Kim et al. [74] proposed employing water controlled by a pump as an isothermal liquid piston as shown in Fig. 3 to compress or expand the supercritical CO_2. By maintaining the compression and expansion processes close to isothermal conditions, these cycles minimize irreversibility associated with temperature differences during heat transfer, which results in higher round-trip efficiencies compared to conventional adiabatic cycles. A high round-trip efficiency of 74.5 % were reported, though the presence of water raises concerns about internal corrosion. In comparison, the supercritical Brayton cycle maintains CO_2 above its critical point throughout charging, avoiding phase changes and eliminating the need for precise phase control. It accommodates higher temperatures up to 600 °C and pressures up to 250 bars, which can provide greater operational flexibility for some occasions, practically at the presence of external heat sources.

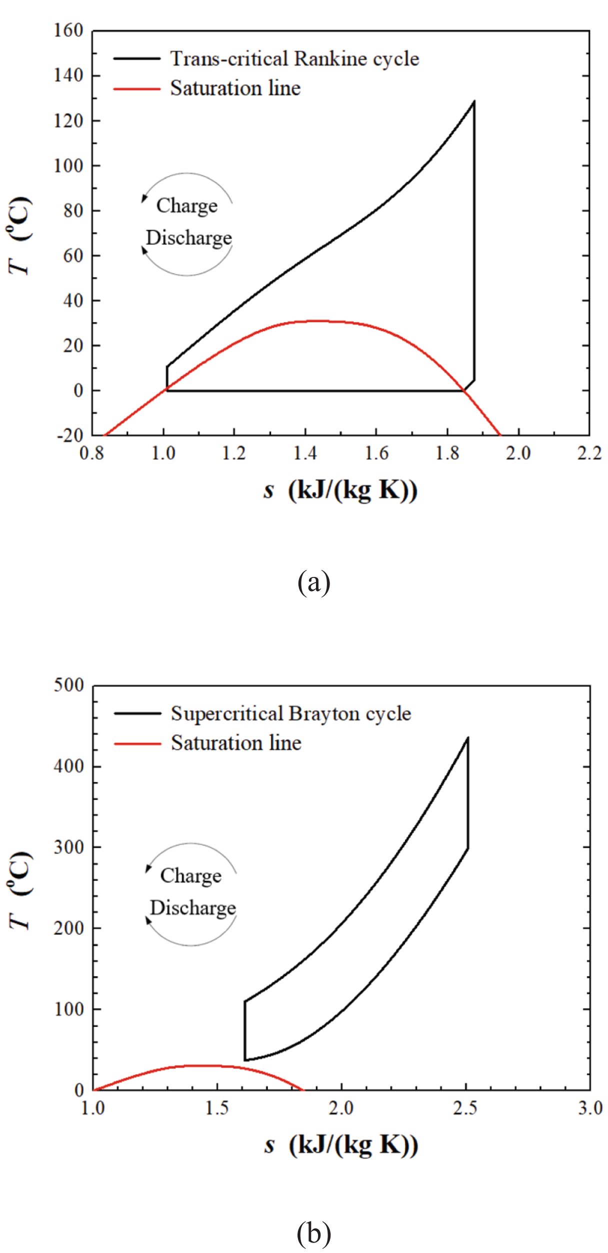

Fig. 2. Schematic temperature-entropy diagrams of PTES systems based on CO_2 cycles. (a) *Trans*-critical Rankine cycle and (b) Supercritical Brayton cycle.

During the discharging process, the *trans*-critical Rankine cycle transits CO_2 from supercritical to subcritical states. Performance improvement methods include reheated and splitting cycle variations proposed by Morandin et al. [72]. The reheating of CO_2 after expanding was expected to increase the efficiency by keeping the fluid at a higher average temperature during the expansion process. The split Rankine cycle was expected to be more efficient in use of the stored thermal energy. However, those improved configurations result in lower round-trip efficiency and show less promising performance compared to the base *trans*-critical Rankine cycle configuration. The supercritical Brayton cycle operates entirely above the critical point of CO_2, where the working fluid remains in a supercritical state during the discharging process. The supercritical Brayton cycles are usually associated with increased cost due to the need for high-temperature materials. Recuperation and recompression are the most common method to improve performance of supercritical Brayton cycle [39]. Recuperation employs a heat exchanger to recover thermal energy from the high-temperature CO_2 leaving the expander and transferring it to the CO_2 exiting the compressor. This improves the cycle's thermal efficiency and reduces fuel or energy consumption. Recuperation also lowers the temperature difference between heat source and working fluid, minimizing irreversibility during heat transfer. Recompression further improves efficiency by splitting CO_2 flow on low-pressure side after recuperation and compressing a portion separately before mixing it back. This reduces the temperature rise during compression, which lowers the work required by the main compressor and minimizes the entropy generation. The combination of recuperation and recompression allows supercritical CO_2 Brayton cycles to maintain a relatively high round-trip efficiency across wide temperature ranges.

From Table 2, the supercritical Brayton cycle is generally used for compressed pressure larger than 200 bars, while the *trans*-critical Rankine cycle and its variants are usually for compressed pressure lower than 200 bars. When the *trans*-critical Rankine cycles are employed, they show a broad range of round-trip efficiencies from 29.2 % to 74.5 % depending on the specific configuration and operating conditions, but most of them lies in the range of 50 % to 60 %. The lowest efficiency 29.2 % is from the study of Baik et al. [77]. The main reason is the relatively high pressure 48.7 bars into the compressor, which leads to a low ratio 2.4 of expander inlet pressure to the outlet. When the expansion ratio is small, the expander produces less work output, which directly reduces the round-trip efficiency of the system. The low expansion ratios also restrict the temperature drop across the expander, which decreases the exergy utilization from the working fluid. Therefore, optimizing the pressure ratio of a PTES system is essential to maximize power generation and improve the overall efficiency. The largest efficiency of 74.5 % is from the study of Kim et al. [74], which employed the isothermal compression and expansion processes to improve system efficiency. For the supercritical Brayton cycles, they show round-trip efficiency ranging from 22.34 % to 45.5 %. He et al. [82] investigated a PTES system with basic supercritical CO_2 Brayton cycle and gives the lowest efficiency 22.34 %, mainly caused by the lower temperature into the expander during the discharging process, which is only 73 °C. A lower inlet temperature reduces the enthalpy drop across the expander, which directly decreases the amount of mechanical work that can be recovered. Since the expander is responsible for

Table 2
A summary of thermodynamic cycles used for PTES systems based on CO_2 cycles.

Reference	Charging process	Discharging process	CO_2 cycle	Hot energy storage	Cold energy storage	Round-trip efficiency	Additional note
Mercangöz et al. [70]	32.4 bars to 140 bars, −3.0 °C to 122.3 °C	132.5 bars to 36.0 bars, 118 °C to 17.4 °C	*Trans*-critical Rankine	Pressurized water	Ice	51 %	
Morandin et al. [71]	18.0 bars to 188.7 bars, 3.8 °C to 176.8 °C	174.2 bars to 20.8 bars, 176.8 °C to 3.8 °C	*Trans*-critical Rankine	Pressurized water	Ice	60 %	Ammonia refrigeration cycle integrated
Morandin et al. [72]	18.1 bars–197.1 bars	165.9 bars to 21.6 bars, 177 °C inlet	Reheated Rankine	Pressurized water	Ice	56.4 %	
	17.9 bars to 146 bars	145.3 bars to 20.7 bars, 151 °C inlet	Split Rankine	Pressurized water	Ice	59.4 %	Ammonia refrigeration cycle integrated
	21.7 bars to 186.4 bars	188.6 bars to 26.9 bars, 166 °C inlet	Vapor draw split Rankine	Pressurized water	Ice	48.1 %	Throttling valve instead of expander
Kim et al. [73]	35 bars to 160 bars, 0 °C to 122 °C	160 bars to 35 bars, 600 °C inlet	Split Rankine	Pressurized water	Ice	63.2 %	External high temperature heat source
Kim et al. [74]	35 bars to 160 bars, 0 °C to 122 °C	160 bars to 35 bars, 122 °C inlet	*Trans*-critical Rankine	Pressurized water	Water	73.3 %	Isothermal liquid piston compressor
	35 bars to 160 bars, 0 °C to 150 °C	160 bars to 35 bars, 150 °C inlet	*Trans*-critical Rankine	Pressurized water	Water	74.5 %	Isothermal liquid piston compressor
	35 bars to 300 bars, 0 °C to 150°C	300 bars to 35 bars, 150 °C inlet	*Trans*-critical Rankine	Pressurized water	Water	69.9 %	Isothermal liquid piston compressor
Morandin [75]	18.5 bars to 188.6 bars, 3 °C to 175 °C	137.8 bars to 20.3 bars, 175 °C inlet	*Trans*-critical Rankine	Pressurized water	Salt water brine	64 %	
Wright et al. [76]	32.6 bars to 140 bars, −2.7 °C to 119 °C	131.8 bars to 37 bars, 116 °C inlet	*Trans*-critical Rankine	Pressurized water	Ice	60.2 %	
Baik et al. [77]	48.7 bars to 203.5 bars, 13.3 °C to 139.8 °C	143.8 bars to 59.6 bars, 113.6 °C inlet	*Trans*-critical Rankine	Pressurized water	Water	29.2 %	
Ayachi et al. [78]	35.2 bars to 119.8 bars, 25 °C to 135 °C	113.4 bars to 45.5 bars, 125 °C inlet	*Trans*-critical Rankine	Superficial bedrock	Ice or water	44.1 %	Heat regeneration
	39.5 bars to 134.8 bars, 25 °C to 135 °C	128.1 bars to 50.6 bars, 125 °C inlet	*Trans*-critical Rankine	Superficial bedrock	Ice or water	49 %	Two-stage discharge
	42.8 bars to 147.1 bars, 25 °C to 135 °C	140.4 bars to 54.7 bars, 125 °C inlet	*Trans*-critical Rankine	Superficial bedrock	Ice or water	55.8 %	Two-phase turbine, two-stage discharge
Pan et al. [79]	20 bars to 200 bars, −20 °C to 180 °C	150 bars to 22.1 bars, 180 °C inlet	*Trans*-critical Rankine	Pressurized water	NaCl brine	56.9 %	
Blanquiceth et al. [80]	31.6 bars to 200 bars	200 bars to 31.6 bars, 538 °C inlet	*Trans*-critical Rankine	Molten salt		51.7 %	Recompression, solar heat input
Trevisan et al. [81]	45 bars to 220 bars, −10 °C inlet	220 bars to 45 bars, 440 °C inlet	*Trans*-critical Rankine	Molten salt		33.13 %	
	73.8 bars to 250 bars, 32 °C inlet	250 bars to 73.8 bars, 440 °C inlet	Supercritical Brayton	Molten salt	Water	27.26 %	
He et al. [82]	75 bars to 221 bars, −37 °C to 76 °C	212 bars to 76.5 bars, 73 °C inlet	Supercritical Brayton	Water	Water	22.34 %	
Rindlt et al. [83]	80 bars to 240 bars	240 bars to 80 bars, 513 °C inlet	Supercritical Brayton	Solar salt	Thermal oil	38.9 %	Double recuperated and recompressed and dual expansion
McTigue et al. [84]	80 bars to 250 bars	250 bars to 80 bars, 563 °C inlet	Supercritical Brayton	Molten salt	Water	45.5 %	Recuperated and recompressed, external high temperature heat source
Maccarini et al. [85]	95.5 bars to 250 bars	250 bars to 83 bars, 440 °C inlet	Supercritical Brayton	HITEC XL	Water	38.8 %	

converting thermal energy back into electricity, insufficient inlet temperature results in lower power output and reduced round-trip efficiency. Rindlt et al. [83] investigated a PTES system based on the recuperated and recompressed supercritical layout. The modelled system operated with low pressure of 80 bars and high pressure 240 bars. A temperature range was between 16 °C and 513 °C, and a round-trip efficiency of 38.9 % was achieved. McTigue et al. [84] also studied a PTES system with a recuperated and recompressed supercritical CO_2 Brayton cycle. The low pressure was 80 bars and high pressure 250 bars. The temperature range was between 20 °C and 563 °C. For the discharging process, external high temperature solar thermal energy was added to the system as shown in Fig. 4, leading to the higher round-trip efficiency 45.5 %.

The difference in round-trip efficiency between *trans*-critical Rankine cycles and supercritical Brayton cycles in PTES systems is mainly attributed to thermodynamic characteristics, heat transfer behaviour, and system design requirements. In a *trans*-critical Rankine cycle, CO_2 undergoes subcritical states during both charge and discharge processes. The near-isothermal heat transfer during evaporation in charging process and condensation in discharging minimizes temperature differences between CO_2 and the TES medium, which reduces the entropy generation and irreversibility during the heat transfer process. Consequently, more of the stored thermal energy is converted back into mechanical work for electricity generation, which leads to higher round-trip efficiency. In contrast, the supercritical Brayton cycle operates entirely above CO_2's critical point. While this simplifies component design by avoiding vapor–liquid transitions, it results in less favourable heat transfer characteristics. Heat exchange between supercritical CO_2 and TES medium typically involves larger temperature differences, which increases exergy destruction. However, when PTES systems are coupled with high-temperature external heat sources, such as concentrated solar power or high-grade industrial waste heat, supercritical Brayton cycles present several advantages over *trans*-critical Rankine cycles. At elevated temperatures, supercritical Brayton cycles achieve higher thermal efficiencies because of larger enthalpy drops across the expander and more effective utilization of the available temperature gradient. Overall, the *trans*-critical Rankine cycle is advantageous for smaller to medium-scale systems with smaller temperature differences

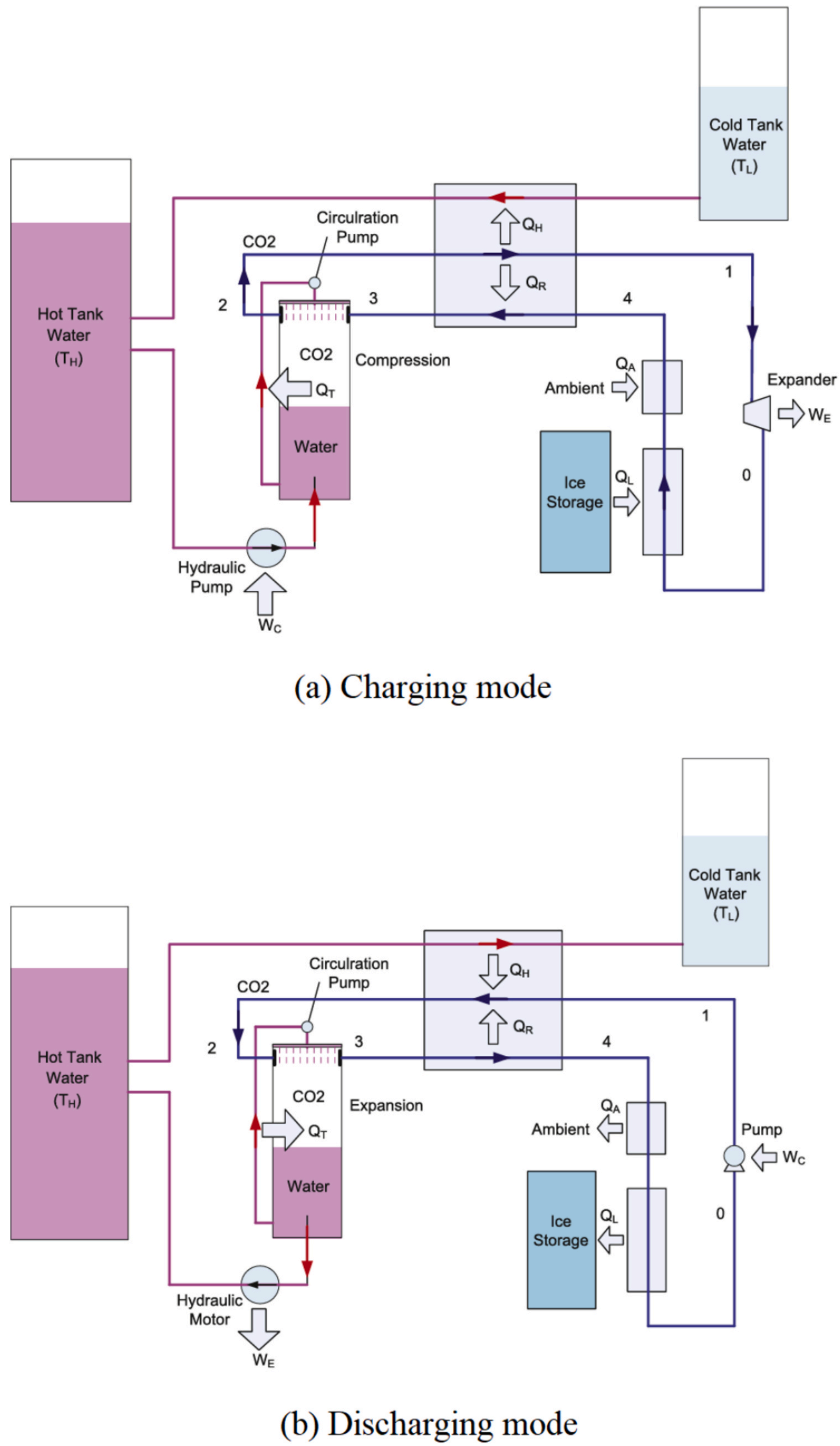

Fig. 3. Schematic of isothermal PTES systems with a *trans*-critical CO_2 cycle by Kim et al. [74]. (a) Charging mode and (b) Discharging mode.

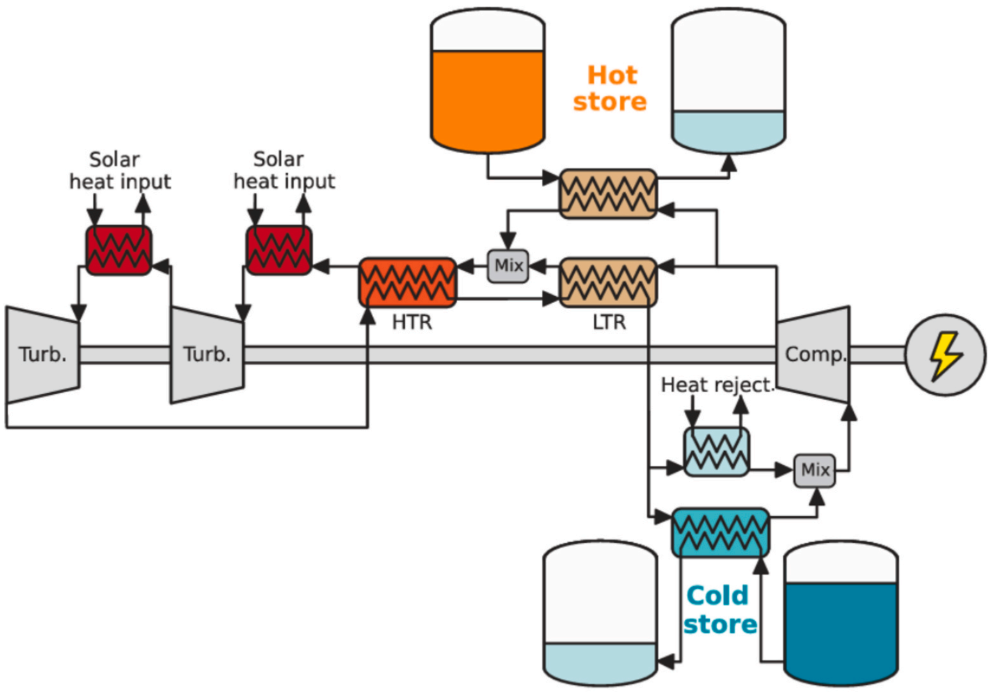

Fig. 4. Schematic of PTES system based on a recuperated and recompressed supercritical CO_2 Brayton cycle and combined high temperature solar heat input from McTigue et al. [84].

due to simplicity and integration ease, whereas the supercritical Brayton cycle is better suited for large-scale, high-temperature PTES systems.

Until now, the PTES remains an emerging technology, with most research and development still at the modelling, simulation, or pilot scale stage, and practical implementation at a large scale remains challenging and has yet to be realized. The practical efforts are concentrated in experimental setups and demonstration projects funded by academic institutions, government programs, and industry consortia. Among them, the Isentropic project in the UK and the SELECO$_2$ project in Europe have built prototype systems to validate theoretical models and test component performance. Isentropic project employs argon as working fluid, while SELECO$_2$ project uses CO_2. The SELECO$_2$ project employs *trans*-critical Rankine cycle for both charging process and discharging processes [86]. The experimental setup includes a scaled-down heat exchanger, replicating real-world dynamics, with operating conditions ranging from 40-130 °C and pressures of 80–120 bars. Preliminary results show the round-trip efficiency of 30–35 % and highlight the challenges posed by energy losses and irreversibility occurring in heat exchangers and turbomachines. In practice, large temperature differences often occur at the heat exchanger interfaces and lead to significant exergy destruction. The large variations in CO_2 properties near the critical point further make it difficult to maintain optimal heat transfer and cycle efficiency. Compressors and expanders in *trans*-critical CO_2 systems must handle wide pressure ratios and variable fluid properties. Mechanical inefficiencies, leakage, and off-design operation contribute to lower isentropic efficiencies than those assumed in theoretical models. Matching the dynamic temperature profile of the CO_2 cycle with sensible or latent storage materials is also difficult, which often leads to incomplete utilization of stored heat. Thermal losses due to imperfect insulation and energy degradation during long storage periods further reduce round-trip efficiency.

4. Technology review of key components of CO_2 cycles

4.1. Expanders

The expander expands high-pressure, high-temperature CO_2 to lower pressures and temperatures, and the thermal energy is converted into mechanical work during the expansion process [87]. This mechanical work is then used to drive a generator, producing electricity. The CO_2 expander can be classified into two categories based on their working principles: volumetric turbines and turbine expanders.

Volumetric expanders produce work by changing the volume of the expansion chamber, which include piston expanders, swing rotor expanders, screw expanders, sliding vane expanders, and scroll expanders. In a piston expander, the compressed CO_2 enters the expansion chamber and expands through pushing the piston, and the expansion converts the high-pressure energy into mechanical energy [88]. The piston moves in response to the expanding CO_2, and the expander works in a cycle of intake, expansion, exhaust, and compression. Piston expanders are effective in high-pressure environments and can be designed with tight seals, making them a selection for supercritical CO_2 systems, but challenges such as material durability need to be addressed for longevity [89,90]. Screw expanders consist of two or more intermeshing helical rotors housed in a casing. As the supercritical CO_2 enters the expander, the fluid occupies the spaces between the rotors and expands as the rotor space increases along the expander. This expansion results in the generation of torque, which is used to drive a generator for electricity production. Screw expanders are particularly efficient in small to medium-sized systems and their efficiency drops when operating below certain power thresholds [91]. The design and manufacturing of screw expanders require high precision, particularly in the rotor profiles and housing, and limit their applications in high pressure scenarios [92]. Swing rotor expanders operate based on the principle of expanding high-pressure CO_2 as it moves through an eccentric rotor mechanism. The design features a rotor that swings or oscillates as CO_2 enters the expander, allowing it to expand and do work [93]. While simpler in terms of moving parts, the design and manufacturing of swing rotor expanders can be complex due to the need for precise rotor geometries and motion control mechanisms. Sliding vane expanders operate based on the principle of expanding high-pressure CO_2 in a rotating assembly of vanes that slide within a cylindrical chamber. These expanders do not require intake or exhaust valves, which simplifies their design and operation, and can accommodate both liquid and gas phases [94–97]. This lack of valves eliminates potential issues related to wear and leakage associated with traditional valve systems. Scroll expanders consist of a static scroll and a rotating scroll that create a crescent-shaped closed chamber. High-pressure CO_2 enters the chamber through the centre, expands as the scrolls rotate, and exits through an exhaust port [98]. Their design enables effective conversion of thermal energy into mechanical energy, making them suitable for supercritical CO_2 applications [99]. Like sliding vane expanders, scroll expanders do not require intake or exhaust valves, eliminating potential issues related to wear, leakage, and throttling losses, and challenges are also related to friction, wear, and material durability [100,101].

Turbine expanders use high-speed rotation of the impeller to expand CO_2 from high pressure to low pressure while producing work and can be axial or radial turbines. Radial turbines use a radial flow path, where the working fluid moves perpendicularly to the axis of rotation. Radial turbines are typically smaller and suitable for compact systems and applications with lower or moderate power outputs. Their radial flow design allows for efficient energy conversion in high-pressure and high-temperature environments, typically for supercritical CO_2 systems [102–104]. Radial turbines have the advantages of compact size, relatively simple design, and good efficiency at smaller scales, making them suitable for applications that require effective thermal-to-mechanical energy conversion, and allow for smaller installations and reduced material requirements, but are limited by the scalability for large power outputs [105,106]. Axial turbines are more common in high-power applications and can handle larger mass flow rates and higher power outputs. The working fluid inside flows parallel to the axis of rotation. The axial configuration allows for effective energy extraction from the expanding supercritical CO_2 [107,108]. Axial turbines hold the benefits of highly efficient for large-scale power generation, capable of handling high temperatures and pressures, but are more complex and expensive to manufacture compared to the radial turbines. A comparison of different potential expanders used for PTES systems based on CO_2 cycles are shown in Table 3. Only piston expanders, radial turbines and axial turbines have the qualification to be used in the PTES systems, due to the relatively high-pressure requirement.

The selection of the expander depends on the temperature range, pressure range, scalability, and system efficiency. The piston expanders are generally suitable for *trans*-critical CO_2 Rankine cycle, and the radial turbines and axial turbines are more suitable for supercritical Brayton cycle. Patel et al. [88] designed a small-scale twin-cylinder piston expander as shown in Fig. 5. The twin cylinders are in an inline configuration. The inlet pressure and temperature are respectively 172.3 bars and 85 °C to the piston expander. The generated power is only 4.5 kW for assumed fully isentropic condition, and the overall thermal efficiency of the cycle was estimated to be only 12.75 %. Jiang et al. [89] fabricated and tested a prototype of two-rolling piston expander. Tests were carried out with the inlet temperature 35 °C and pressure 90 bars. For the rotational speed ranges between 850 to 1000 rpm, the isentropic efficiency was only about 28 %–33 %. Therefore, designing CO_2 expanders for PTES systems with *trans*-critical Rankine cycle presents significant technical challenges. At low inlet temperatures (below 180 °C as shown in Table 2), the working fluid typically has high density and relatively low enthalpy drop across the expander, which restricts the amount of recoverable power. This results in smaller expansion ratios and lower efficiency compared to high-temperature expanders. Furthermore, conventional turbine or piston expander designs often suffer from excessive mechanical and frictional losses when operating with CO_2 at low-temperature conditions, which further reduce the isentropic efficiency. Additionally, leakage between moving components becomes particularly problematic due to the high-pressure differential and small clearances required, thus lubrication systems must be carefully managed to avoid fluid contamination or corrosion, while still providing adequate sealing and wear protection. To improve the performance of this CO_2 expander, a static seal and a high-pressure resistant rubber O-ring were used to block the leakages by Hu et al. [90].

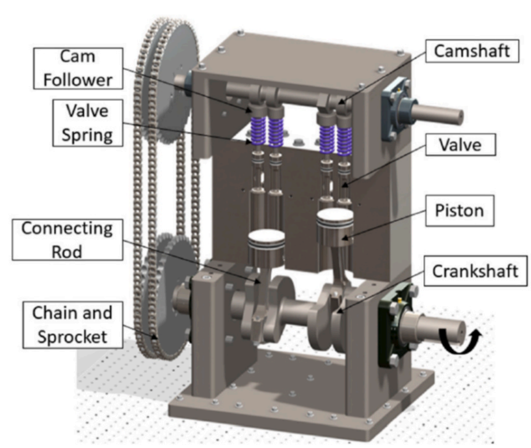

Fig. 5. Schematic of a twin-cylinder CO_2 piston expander from Patel et al. [88].

Table 3
A comparison of potential expanders used for PTES systems based on CO_2 cycle [116].

Type	Power (kW)	Pressure	Efficiency	Speed (rpm)	Advantages	Disadvantages
Piston	Low to medium (tens to hundreds)	Up to 200 bars	50–80 %	Hundreds to thousands	Low leakage, good sealing, high pressure resistance	Requires intake/exhaust valves, poor balance, large size, noisy and prone to vibration
Screw	Low to medium (tens to thousands)	Up to 120 bars	50–80 %	Hundreds to thousands	No unbalanced mass forces, low vibration, low maintenance costs, suited for small and medium-size systems	Difficult to manufacture screws, high cost, not suitable for high pressure, limited power output
Swing rotor	Low (lower than ten)	Up to 120 bars	50–60 %	Hundreds to thousands	No sealing or lubrication issues, suitable for high pressure ratio	High friction loss between the roller and the cylinder, not suitable for high pressure, limited power output
Sliding vane	Low (up to tens)	Up to 100 bars	50–80 %	Hundreds to thousands	Simple structure, high reliability, low cost	High friction between vanes, rotors, and cylinders, large leakage loss, not suitable for high pressure, limited power output
Scroll	Low (up to tens)	Up to 150 bars	50–80 %	Hundreds to thousands	Fewer moving parts, low friction, simple manufacturing	Complex geometry, large gaps, difficult to seal, limited power output
Radial turbine	Medium (hundreds to thousands)	Up to 300 bars	60–90 %	Higher than thousands	Compact structure, suited for small and medium-size power systems	Not suitable for large power units compared to axial turbine
Axial turbine	High (higher than thousands)	Up to 300 bars	60–90 %	Higher than thousands	Compact structure, suitable for large-scale power systems	Expensive, not suitable for small power units compared to radial turbine

An oil supply system was also adopted to improve the lubrication of the expander. The improved expander was reported to achieve a maximum efficiency of 77 % at the revolution speed of 867 rpm.

When CO_2 flows through turbines in supercritical Brayton cycles, it operates at high pressures (above 200 bars) and high temperatures (above 500 °C), which poses significant engineering challenges for expander design. Under such conditions, the materials used for turbine blades, casings, and seals must maintain structural integrity, creep resistance, and corrosion resistance over prolonged operation. Conventional steels are inadequate, leading to the reliance on advanced nickel-based superalloys, ceramic coatings, and other high-performance materials. Key candidates include Inconel 718, Inconel 625, Rene 41, Mar-M247, CMSX-4 and CMSX-10. However, these materials are costly and often difficult to manufacture into the complex geometries required for turbine components [109]. Thermal stress is another major obstacle. Rapid temperature fluctuations during start-up, shutdown, or load changes can induce severe thermal fatigue, cracking, and distortion in turbine parts. Effective thermal management is therefore essential, requiring advanced blade cooling strategies and robust insulation techniques. The higher density of supercritical CO_2 compared to steam allows for more compact turbomachinery, but this increases the design complexity of high-speed turbines, as small flow passages and tight tolerances heighten susceptibility to leakage and mechanical losses. Maintaining efficiency across a wide range of operating conditions is also a key challenge. Turbines must sustain high aerodynamic performance under partial loads, variable inlet conditions, and off-design scenarios, which necessitates precise blade profile optimization [110]. Advanced computational fluid dynamics (CFD) is widely employed for this purpose, but experimental validation remains limited due to the high cost and difficulty of replicating extreme CO_2 conditions. Moreover, long-term durability is threatened by material degradation under high pressures and temperatures, combined with CO_2-induced corrosion and oxidation. All these challenges highlight the need for further advances in material science, cooling technologies, and robust system design before high-temperature CO_2 expanders can be reliably implemented in large-scale supercritical Brayton PTES systems.

So far, several supercritical CO_2 power generation systems have been constructed and the developed turbines from these projects have the potential to be employed in the large-scale PTES systems. Wright et al. [111] from Sandia National Laboratories (SNL) designed and tested two turbomachinery units (main-compressor and the re-compressor) with a maximum speed of 75,000 rpm, a pressure ratio of 1.8, and a maximum power generation capacity of 125 kWe for a turbine inlet temperature of 538 °C. As shown in Fig. 6, all the rotating machinery was mounted on a single shaft, which simplified the structure but required the compressor and turbine to rotate at the same speed and be matched appropriately.

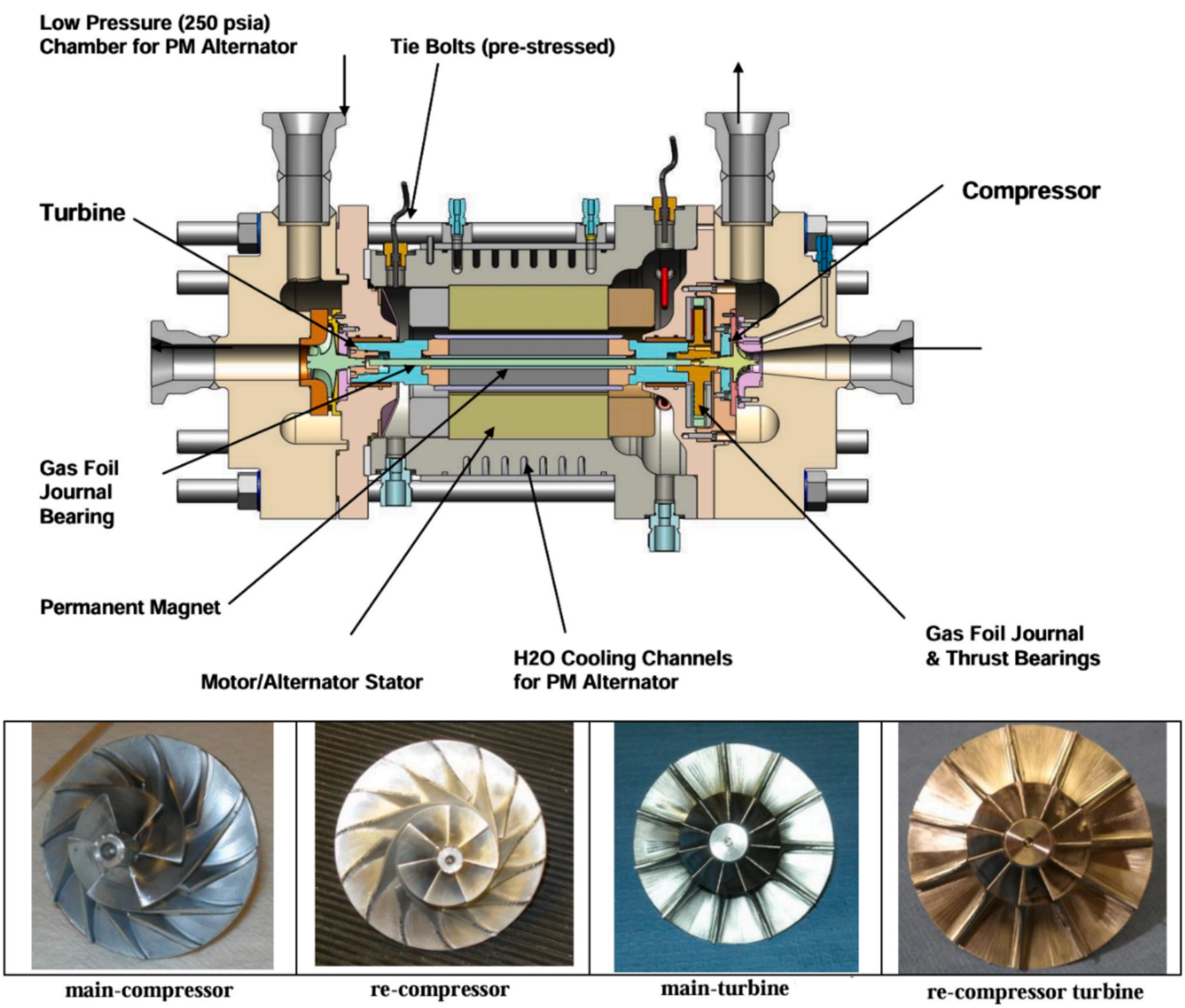

Fig. 6. Schematic of turbo-alternator-shaft design for the SNL S-CO_2 test loop from Wright et al. [111].

The test results show the turbomachinery operated as expected while a significant challenge related to the use of gas-foil bearings due to the high-power density of the turbomachinery. SNL also installed a large turbomachinery unit (designed by Peregrine Turbine Technologies) with operating speed of 118,000 rpm for 750 °C turbine inlet temperature and with an expected power generation capacity of 1 MWe [46]. However, the test capabilities could not match the design point of the machine. Clementoni et al. [112,113] from Bechtel Marine Propulsion Corporation developed and tested a turbomachinery comprised of a variable speed turbine-compressor with a nominal power generation capacity of 100 kWe. The test results show peak isentropic efficiencies of 83.6 % and 85.2 % at power outputs of 56.8 and 52.6 kW respectively. Held [114] from Echogen Power Systems tested the turbomachinery EPS100 unit, which contents a constant speed turbine-generator and a variable speed turbine-compressor and has a design power output of 8 MW for a turbine inlet temperature of 485 °C. The test results show an isentropic efficiency over 80 % for the turbine-compressor and ranging 20 % to 75 % for the turbine-generator. Allison et al. [115] from Southwest Research Institute tested a SunShot axial expander with power generation capacity of 10 MWe for an inlet temperature of 715 °C. The expander comprises of a four-stage shrouded axial turbine (as shown in Fig. 7) with a rotational speed of 27,000 rpm and the isentropic efficiency was expected to be over 85 %.

4.2. Compressors

Compressors increase the pressure of CO_2 in PTES systems before it is heated for expansion in expanders. Compressing CO_2 is more energy-efficient than compressing gases such as air, argon, and helium, due to its higher density, which can significantly reduce the compressor work and increase the power regeneration of PTES systems [117,118]. CO_2 compressors have been widely used in industrial refrigeration systems and are generally classified into two categories based on the method of compressing: volumetric and turbo-typed compressors. In a volumetric compressor, the pressure of CO_2 is increased by changing the volume within the compressor chamber, while in a turbo-typed compressor, the pressure is increased by spinning the fluid at high-speed using a rotating impeller.

Depending on the volume alteration method, volumetric compressors can be divided into reciprocating compressors and rotary compressors. Piston compressor is a type of positive displacement compressor and use reciprocating pistons within cylinders to compress the CO_2 gas. For CO_2 in *trans*-critical Rankine cycles, semi-hermetic piston compressors are widely used because they can handle the pressures (often above 100 bars) and the temperature of CO_2 better than many other designs. The semi-hermetic designs integrate the motor and compression unit within a sealed housing, which eliminates shaft seals and reduces leakage of high-pressure CO_2. One major advantage of semi-hermetic compressors is their ability to handle the high density and large volumetric flow rates of CO_2 while maintaining compactness and reliability. The sealed motor environment allows direct cooling by suction gas and ensures stable thermal management under high compression ratios. In addition, this design minimizes external contamination and improves operational safety, which is critical when dealing with high-pressure CO_2 systems. However, the high operating pressures and discharge temperatures (sometimes above 150 °C) demand advanced lubrication systems and effective internal cooling strategies. CO_2's low viscosity exacerbates wear and leakage risks in bearings and piston-cylinder clearances, which requires precise manufacturing tolerances and oil management systems [119]. Efficiency losses can arise due to suction gas overheating and motor heat dissipation within the housing. On the other hand, designing CO_2 compressors for low inlet temperatures (typically between –20 °C and 0 °C) also presents several technical challenges that directly affect the performance and reliability of PTES systems. At low suction temperatures, the gas density decreases, which reduces the mass flow rate of CO_2 entering the compressor. This leads to a lower volumetric efficiency and requires the compressor to operate at higher speeds or larger displacements to achieve the desired capacity, increasing mechanical stress and energy consumption. Another challenge is lubrication at low temperatures. The viscosity of lubricating oils increases significantly at sub-zero conditions, which can result in poor oil circulation, inadequate film formation, and higher wear of moving parts. Low inlet temperatures can also lead to condensation and two-phase flow at the suction port if the refrigerant is not adequately superheated. This can cause liquid slugging, which damages valves, pistons, or scroll elements inside the compressor. Proper suction gas superheating and effective heat exchanger design are therefore critical. Main manufacturers of semi-hermetic CO_2 compressors include GEA Bock, Copeland, Frascold, Dorin, and Bitzer. Rotary compressors include screw compressors, scroll compressors, sliding vane compressors, and rolling rotor compressors. Screw compressors use two interlocking helical rotors (also known as screws) to compress the gas. Scroll compressors consist of two spiral-shaped scrolls to compress the gas [120]. Sliding vane compressors is characterized by a rotor with several vanes

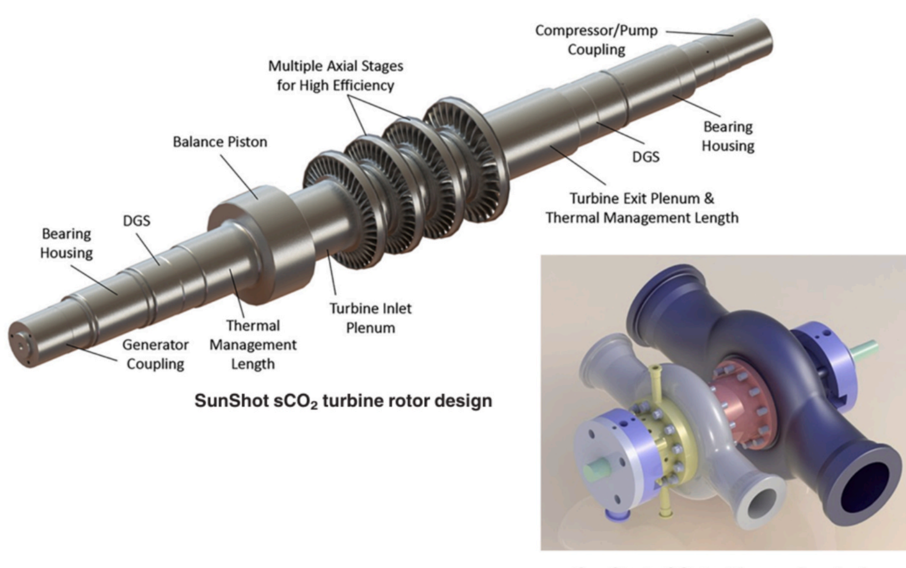

Fig. 7. Schematic of SunShot axial expander from Allison et al. [115].

that slide in and out of slots, creating varying volumes for gas compression. Rolling rotor compressors utilize rolling rotors to compress CO_2 gas. Rotary compressors are generally more efficient than reciprocating compressors, particularly at full load, making them suitable for applications requiring constant and efficient gas delivery [121]. Rotary compressors have been widely used in commercial and industrial refrigeration systems, particularly in *trans*-critical CO_2 refrigeration applications. However, in PTES systems, the charging process requires CO_2 to be compressed at very high pressures, typically ranging from 100 to 250 bars. Under such conditions, rotary compressors are generally unsuitable. The extreme pressure requires the critical components, such as vanes, rollers, and housings, to intense mechanical stress, to employ advanced materials and precise manufacturing techniques to prevent deformation, leakage, and potential failure.

The turbo-typed compressors include centrifugal compressors and axial compressors. Centrifugal compressors increase the pressure by forcing the working fluid radially outward through rotating impellers and are the most used in supercritical CO_2 systems due to their ability to handle large volumes of fluid and high pressures [45,122]. Centrifugal compressors demonstrate high efficiency in compressing supercritical CO_2, capable of achieving high pressure ratios in a single stage and maintaining efficient performance across a wide range of operating conditions, but performance may degrade if the fluid properties change significantly, such as near the critical point of CO_2 [123]. The sharp variations in density and compressibility near its critical point complicate the aerodynamic design. These rapid property changes can lead to flow instabilities such as surge and choke, which can reduce compressor efficiency and reliability [124,125]. Additionally, CO_2 has a much higher density than traditional working fluids like air or steam, which allows for more compact compressor designs but also demands higher rotational speeds to achieve the necessary pressure ratios [126]. Operating at such high speeds imposes mechanical stresses on impellers, bearings, and seals, requiring robust structural design. Temperature fluctuations during start-up, shutdown, and load changes can also induce thermal stresses and fatigue. Furthermore, sealing high-density CO_2 at pressures often exceeding 200 bars is technically challenging and may result in leakage or friction losses if not properly addressed [124]. Furthermore, achieving high isentropic efficiency in compact, small-scale centrifugal compressors for PTES systems requires precise aerodynamic optimization. Major manufacturers of CO_2 centrifugal compressors include Danfoss, Mitsubishi Heavy Industries, and Atlas Copco. Axial compressors work by compressing the fluid through multiple stages of rotating and stationary blades, with the fluid flowing parallel to the axis. They are also used in very large-scale systems where high flow rates and efficiencies are critical and have the advantages of high efficiency for large flow rates and good scalability but require more complex design and advanced control systems to optimize performance, especially in applications with variable loads, compared to centrifugal compressors [127]. However, unlike conventional air-based axial compressors, those designed for supercritical CO_2 must operate at very high pressures and sometimes at elevated temperatures depending on system configuration. The high fluid density of CO_2 compared to air significantly reduces the required flow area, which in turn leads to very compact blade geometries. This creates difficulties in manufacturing precision blades and maintaining aerodynamic efficiency in such small flow passages. The CO_2 properties near the critical point can destabilize the flow, increase the risk of stall and surge, and reduce overall compressor efficiency [128]. Additionally, the high operating pressures place substantial mechanical stresses on blades, disks, and casings, requiring advanced materials with high fatigue resistance and corrosion protection. Thermal cycling during start-up and shutdown further adds to the mechanical stress, potentially shortening component lifespan [129]. The primary manufacturers of CO_2 axial compressors include MAN Energy Solutions in Germany and Howden in the UK. A comparison of CO_2 compressors used for PTES systems are shown in Table 4.

One key recommendation for future CO_2 compressor designs is the use of advanced materials with high strength-to-weight ratios, excellent fatigue resistance, and corrosion tolerance to withstand pressures exceeding 200 bars and frequent thermal cycling. Materials such as nickel-based superalloys, coated steels, or novel composites could improve durability while allowing compact designs. Isothermal or near-isothermal compression techniques, including multi-stage intercooling and enhanced heat transfer, can reduce the work input and improve round-trip efficiency. For rotary, centrifugal, or axial compressors, optimizing blade and rotor geometries with advanced CFD and additive manufacturing can enhance aerodynamic performance while minimizing leakage and flow instabilities near the critical point of CO_2. Sealing and lubrication technologies also need advancement, particularly for semi-hermetic and piston compressors, to reduce leakage and wear at high pressures. Advanced control strategies that modulate the inlet temperature and pressure and accurate real-time monitoring of fluid properties are also required to ensure that the CO_2 remains within an optimal range for compression [131,132]. When there is insufficient mass flow through the compressor, surge may occur and result in flow reversal and potentially damaging the compressor. Surge control systems, variable inlet guide vanes, and compressor bypass systems can be considered to help mitigate surge risks by adjusting the flow rate and pressure conditions dynamically [133].

4.3. Heat exchangers

Heat exchangers in PTES systems facilitate the heat transfer between

Table 4
A comparison of compressors used for PTES systems based on CO_2 [130].

Type	Efficiency	Temperature	Pressure	Advantages	Disadvantages	Key Manufacturers
Piston	70–85 %	Up to 150 °C	Up to 200 bars	Good efficiency at small scales	Higher maintenance due to many moving parts, limited flow rate, noisy and vibration-prone	Burckhardt Compression, Siemens Energy, Howden
Screw	60–80 %	Up to 120 °C	Up to 100 bars	Compact and durable, lower noise and vibration, lower maintenance	More complex design, requires of oil injection in some designs for lubrication and sealing	Bitzer, BOGE, GEA
Scroll	70–85 %	Up to 100 °C	Up to 150 bars	Compact and quiet, fewer moving parts, smooth operation	Limited pressure capability, low capacity in large-scale applications	Danfoss, Emerson Climate Technologies, Panasonic
Sliding vane	60–75 %	Up to 100 °C	Up to 100 bars	Simple design and lower maintenance	Limited pressure capability, not suitable for large-scale applications	Gardner Denver, CompAir, Mattei
Rolling rotor	60–75 %	Up to 80 °C	Up to 80 bars	Small and compact, lower noise and vibration	Limited to low pressures, low flow rate, shorter lifespan	Daikin, LG Electronics, Hitachi
Centrifugal	70–85 %	Up to 180 °C	Up to 200 bars	High flow rate, efficient for large-scale operations, good efficiency at high pressure ratios, low maintenance costs	Expensive initial investment, less efficient in small-scale or intermittent power applications	Atlas Copco, Siemens Energy, Ingersoll Rand
Axial	80–90 %	Up to 300 °C	Up to 300 bars	High flow rate, compact design for large capacities, suitable for continuous high-volume applications	Complex design, leading to high costs, not efficient at lower flow rates, high maintenance requirements	Mitsubishi Heavy Industries, Siemens Energy, MAN Energy Solutions

CO_2 and thermal storage medium. Operating conditions such as high temperatures and pressures can lead to thermal expansion issues, so careful design considerations are required to prevent mechanical failure. Heat transfer effectiveness also directly impacts the efficiency and overall performance of the PTES systems. Shell and tube heat exchangers, plate heat exchangers, printed circuit heat exchangers (PCHE), and microchannel heat exchangers are candidates in PTES systems [37,134]. Shell and tube heat exchangers are durable, capable of handling high pressures and temperatures, and suitable for systems where high-pressure differentials exist between the two fluids [135]. However, they are usually bulkier than other types of heat exchangers and may have lower surface-area-to-volume ratios. Plate heat exchangers have the advantages of high heat transfer efficiency, compact size, and low material costs, and are ideal for systems with moderate temperature and pressure ranges, providing compact configuration and efficient heat transfer. Challenges of plate heat exchangers for CO_2 applications related to pressure drop, fouling, and limit of operating conditions [136]. PCHE is a type of ultra-compact heat exchangers made by chemically etching channels into metal plates and then diffusion-bonding the plates together (as shown in Fig. 8). PCHEs can operate at very high pressures (up to 300 bars), making them suitable for supercritical CO_2 applications. Constructed from high-strength materials, they are less prone to corrosion and fatigue. However, they are more expensive to manufacture, and challenges are related to manufacturing complexity, design limitations, and sensitivity to operating conditions [137]. Microchannel heat exchangers (as shown in Fig. 9) involve multiple small channels that provide very high heat transfer per unit volume. The small channels lead to efficient heat transfer in a small footprint, while they may be sensitive to clogging or fouling which can reduce heat transfer efficiency over time [138].

A comparison of CO_2 heat exchangers having the potential to be used for PTES systems are shown in Table 5. For high-pressure CO_2 systems, PCHEs and microchannel heat exchangers are the best choices due to their high efficiency and pressure tolerance. In less demanding applications, shell and tube and plate heat exchangers are reliable and commonly used, while fin and tube heat exchangers are cost-effective but limited to lower-pressure systems. Chai and Tassou [137] provided a comprehensive review on performance of PCHEs for supercritical CO_2 power generation applications. The material selection, manufacturing and assembly, heat transfer and pressure drop characteristics, and optimization of channel geometric design are presented. The knowledge gaps are also identified for a wider range of applications based on the heat exchangers currently available on the market. Further, Chai and Tassou [134] summarized and analysed high-temperature (temperature range 350 to 800 °C) and high-pressure (pressure range 150 to 300 bars) heat exchangers which have the potential to be employed in supercritical CO_2 power generation and conversion systems. The heat exchangers investigated included PCHEs, diffusion-bonded plate-fin heat exchangers, microtube heat exchangers, 3D printed metallic heat exchangers, investment cast heat exchangers, and ceramic heat exchangers. Main advantages and drawbacks of these heat exchangers for supercritical CO_2 applications were presented. Potential technologies on material selection, design, manufacture, and operation for such heat exchangers were explored. Technology gaps and further research to accelerate the development of such heat exchange technologies were also identified.

Designing and operating CO_2 heat exchangers near the critical point also presents several unique challenges that significantly affect the performance of PTES systems [140]. CO_2 heat exchangers operating

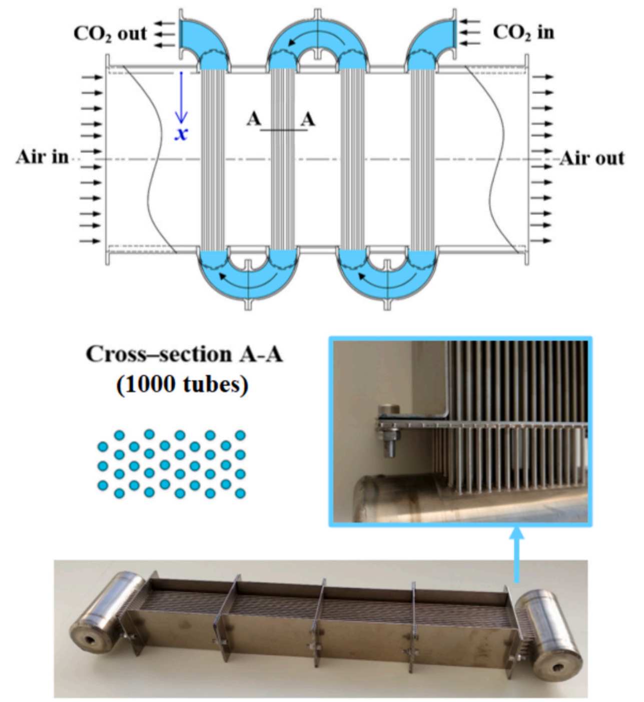

Fig. 9. Schematic of microchannel heat exchanger (courtesy of Reaction Engines Ltd).

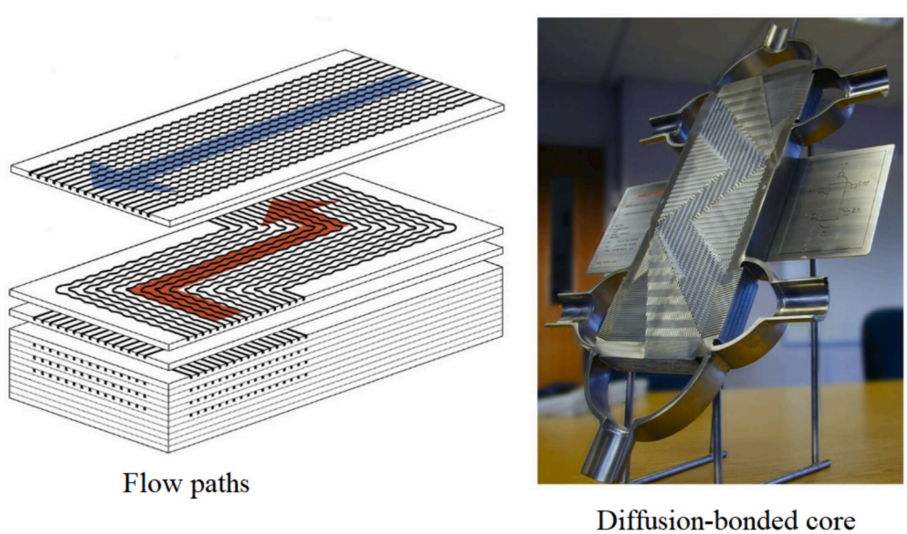

Fig. 8. Schematic of PCHE (courtesy of Heatric Meggitt UK).

Table 5
A comparison of heat exchangers used for PTES systems based on CO_2 cycles [139].

Heat Exchanger Type	Design/Working Principle	Pressure	Temperature	Advantages	Challenges
Shell and tube	Tubes enclosed within a cylindrical shell	Up to 300 bars	Up to 600 °C	Reliable and robust	Large footprint, potential for leakage at high pressure
Plate	Corrugated plates stacked together	Up to 200 bars	Up to 400 °C	Compact, high heat transfer efficiency	Limited by pressure, fouling in certain fluids
Printed circuit	Microchannels etched into metal plates	Up to 500 bars	Up to 900 °C	Compact, high heat transfer efficiency, high-pressure tolerance	Relatively high pressure drops, expensive, complex manufacturing
Microchannel	Dense array of small channels	Up to 400 bars	Up to 650 °C	Compact, high heat transfer rate per unit volume	Relatively high pressure drops, expensive
Fin and tube	Tubes with extended surfaces	Up to 200 bars	Up to 650 °C	Economical, widely used	Limited to lower pressures

near the critical point face a major challenge related to the pinch point issue, which occurs when the temperature difference between the hot and cold fluids becomes extremely small, particularly around the pseudo-critical temperature of CO_2 [141]. This narrow temperature difference limits the overall driving force for heat transfer, causing larger heat exchanger surface areas to be required to achieve the same thermal duty. In dynamic operating conditions, especially during charging and discharging transitions, the pinch point can shift with pressure and temperature fluctuations, making it difficult to maintain effective thermal coupling between the CO_2 and the thermal storage medium. To address these challenges, innovative heat exchanger designs such as multi-stream, segmented, or printed circuit heat exchangers, along with careful operating condition optimization, are required to mitigate pinch point effects and enhance system performance.

In PTES systems with supercritical Brayton cycles, especially those operating at temperatures above 500 °C, heat exchangers experience large temperature gradients between hot and cold streams, causing thermal expansion mismatch, warping, or cracking of plates, tubes, or shells. A range of structural alloys, such as low-alloy steels, austenitic steels, nickel alloys, and titanium alloys, can be considered as candidates. However, at temperatures exceeding 650 °C, nickel-based or titanium-based alloys become necessary to withstand oxidation in the supercritical CO_2 environment and maintain pressure containment without requiring excessively thick walls. While these high-performance alloys ensure reliability and durability under extreme conditions, they significantly increase capital costs [142]. Supercritical CO_2's high density and low viscosity exacerbate pressure drop issues and may lead to localized flow instabilities, which affect heat transfer uniformity and overall system efficiency. Designing heat exchangers for PTES systems with supercritical Brayton cycles requires balancing material limitations, mechanical stresses, thermal performance, and cost, while ensuring long-term reliability and minimal exergy losses. Advanced modelling, additive manufacturing, and novel heat exchanger architectures, such as printed microchannel or plate-fin designs, are increasingly explored to meet these challenges [134]. The PTES systems also require sophisticated control of heat exchanger operation, adjusting flow rates, pressures, and temperatures to optimize performance based on real-time demand and system conditions [143]. Efficient coupling between high-temperature storage medium and the working fluid requires careful selection of interface materials and geometries to reduce irreversibility. Fouling, corrosion, and thermal fatigue from repeated charge–discharge cycles also threaten long-term durability. For instance, designing heat exchangers for molten salts at temperatures above 500 °C presents multiple engineering challenges due to the unique thermal, chemical, and mechanical properties of molten salts [144,145]. At such high temperatures, molten salts like nitrate or chloride mixtures exhibit high thermal stability but are chemically aggressive, posing significant corrosion risks to conventional metallic materials. Corrosion can lead to wall thinning, pitting, or even catastrophic failure over extended operation, necessitating careful selection of corrosion-resistant alloys such as high-nickel or high-chromium steels. However, these materials are expensive, increasing overall system costs. Additionally, solidification risks during start-up or shutdown must be mitigated, as molten salts typically solidify above ambient temperatures, potentially blocking flow passages.

5. Development of thermal energy storage medium and storage tanks

5.1. Thermal energy storage medium

For thermal energy storage in PTES systems, heat is transferred from CO_2 to the storage medium during charging and is extracted from the storage medium to generate power during discharging. The thermal energy in PTES systems is typically stored at two different temperatures, one for the hot reservoir and the other for the cold. Storage materials must withstand repeated thermal cycling without cracking, sintering, or chemical degradation, while containment structures must tolerate thermal expansion and high pressures if integrated with CO_2 cycles. Mainly three categories of TES technologies are employed, including sensible heat storage, latent heat storage, and chemical heat storage [42,70]. Sensible heat storage stores energy by increasing the temperature of a storage medium (such as water, molten salts, or solids like concrete or rocks) and is used in most PTES systems due to the simplicity and wide availability of materials. However, the sensible heat storage requires large volumes for high-capacity storage due to lower energy storage density [146]. Sensible heat storage also relies on maintaining high temperature differences, often several hundred degrees Celsius, which can lead to substantial heat losses through insulation, piping, and other interfaces. Latent heat storage stores energy by taking advantage of the phase change (e.g., from solid to liquid) of a material and heat is absorbed or released during the phase transition at a nearly constant temperature. Latent heat storage has the advantages of high energy density, compact storage, and constant-temperature storage, but limited selection of phase change materials (PCMs), due to phase segregation and material degradation over multiple thermal cycles as well as poor thermal conductivity, restrict their large-scale applications [147,148]. Many PCMs experience volume changes, supercooling, or chemical decomposition, which can lead to reduced storage capacity, loss of reliability, and increased maintenance requirements. Containment and compatibility with construction materials also pose difficulties, as high operating temperatures and chemical interactions can corrode containers or heat exchanger surfaces. Low thermal conductivity can result in slow energy transfer, reducing system responsiveness and overall round-trip efficiency [149,150]. Thermochemical energy storage stores energy by driving an endothermic chemical reaction. During discharge, the reverse reaction occurs, releasing heat. Thermochemical energy storage has the potential of relatively high energy density and for long-duration energy storage, but limited material options (only a few materials such as metal oxides, carbonates, and hydrates are currently available) and degradation over repeated cycles restrict their applications for energy storage [151,152]. The reactive chemicals must maintain stability over thousands of charge–discharge cycles without significant degradation, which limits the choice of suitable compounds. Additionally, containment materials must resist corrosion and chemical attack, especially under high-temperature conditions typical of PTES systems. Many thermochemical reactions require precise temperature and pressure control to proceed efficiently, and deviations can lead to incomplete reactions, reduced energy recovery, or material degradation. Thermochemical reactions also often involve solid reactants or phase changes, which can limit reaction rates due to slow diffusion or poor contact between reactants. Designing reactors and heat exchangers that maximize reaction kinetics while minimizing pressure drops and thermal losses is technically challenging and can increase system complexity and cost. A comparison of TES technologies potentially used for PTES systems are shown in Table 6 and a summary of applicable TES medium are shown in Table 7.

So far, numerous comprehensive review papers have been published for analysing various TES materials and their applications. Faraj et al. [153] reviewed the use of PCMs in domestic heating and cooling systems. Alva et al. [154] discussed and analysed the properties of various TES materials in solar energy applications. Paul et al. [155] reviewed high temperature sensible materials for TES application above 500 °C. Ding et al. [156] reviewed hybrid TES materials used for advanced hybrid storage technologies. Badenhorst [157] presented a review of the application of graphitic materials (including synthetic and natural graphite, graphitic fibres, graphitic foams, expanded graphite, graphite nano-platelets, graphene, carbon nanotubes and amorphous carbons) in solar thermal energy storage. Gasia et al. [158] reviewed latent and sensible materials for relatively high temperature (>150 °C) storage applications. Palacios et al. [159] summarized the TES materials demonstrated and deployed in thermal power plants and concentrated solar power plants. Prasad et al. [160] explored and discussed high-temperature solid–gas, gas–gas, and other advanced thermochemical energy storage materials and systems that operate above 300 °C. Xu et al. [161] surveyed various phase change materials and manufacturing techniques in concentrated solar thermal power plants. Nazir et al. [162] reviewed organic, inorganic and eutectic PCMs and discussed the influence of melting point, temperature range, thermal conductivity, energy density on TES applications. Zalba et al. [163] explored the PCMs together with their thermophysical properties and their heat transfer performance and application scenarios. Pielichowska and Pielichowski [164] reviewed PCMs for TES applications and provided methods for enhanced performance and safety by improving thermal conductivity, encapsulation methods and shape stabilization. Jurczyk et al. [165] reviewed the single-phase and phase-change materials for different storage temperature ranges: low-temperature (<100 °C), medium-temperature (100–300 °C) and high-temperature (>500 °C), and emphasized the importance of selecting optimal heat storage materials based on process parameters and heat transfer methods including storage temperature ranges, material thermophysical and chemical properties, economic cost, and the operational parameters of the heat source.

For low-cost, large-scale storage, sensible heat storage is often the best option, while latent heat and thermochemical storage provide more energy-dense potentials for applications requiring compact storage or high-efficiency long-duration energy storage. Selecting the appropriate TES medium for PTES systems depends on factors like the temperature range, energy density, and cost, and the identified materials should provide high energy density, stability, and cost-effectiveness, especially for phase change or thermochemical storage materials. However, integrating latent heat storage with CO_2 cycles requires precise thermal management to match the temperature range of the working fluid, as mismatches can significantly reduce energy conversion efficiency. Advanced heat exchanger designs, such as metal foams, embedded fins or encapsulated PCMs, are often necessary, but these increase system complexity and capital cost. Integrating thermochemical energy storage with CO_2 cycles requires careful matching of reaction temperatures with cycle operating conditions. The need for high-temperature operation, rapid charging/discharging, and cycle durability makes scaling thermochemical energy storage for large-scale PTES systems particularly demanding. For low-temperature storage, water and PCMs (like paraffin wax) offer cost-effective solutions [166]. So far, most PCMs that are already commercialized are paraffin-based, while others such as bio-based, inorganic, and eutectic mixtures are emerging in the market. For high-temperature applications, molten salts, nitrate salts, and ceramics are ideal [167]. Rocks, sand, and concrete provide low-cost, scalable options for industrial applications where energy density is less critical. Molten salts offer good thermal conductivity and heat capacity and are the potential candidate in high-temperature PTES systems [168]. However, one of the major challenges associated with molten salts is their corrosive nature, especially for applications requiring long-term durability and exposure to high temperatures, making material selection and operational control critical. The choice of molten salt depends on the target operating temperature, thermal stability, corrosivity, cost, and compatibility with heat exchangers and system materials. Several candidates have been identified depending on the temperature range and operational requirements. Nitrate-based salts, such as the widely used solar salt ($NaNO_3$–KNO_3, typically 60:40 wt%), offer a melting point around 220 °C and maximum operating temperatures up to 600 °C [169]. These salts are stable, cost-effective, and have extensive experience from concentrated solar power applications. Nitrite-containing salts, such as $NaNO_2$–KNO_3 mixtures, provide slightly improved thermal conductivity and moderate temperature operation (250–500 °C) [170]. Carbonate-based salts, including Li_2CO_3–Na_2CO_3–K_2CO_3 ternary mixtures, are suitable for higher temperature ranges (450–750 °C) due to their excellent thermal stability and heat capacity [171]. Chloride-based salts like NaCl–KCl or $MgCl_2$–NaCl–KCl mixtures offer very high thermal stability, suitable for operation above 700 °C, but are more corrosive and challenging to handle [172].

Table 6
A comparison of TES technologies used for PTES systems [42].

TES Technology	Storage Medium	Operating Temperature	Energy Density	Advantages	Disadvantages
Sensible Heat Storage	Solid (rocks, concrete), liquid (water, molten salts)	Up to 1400 °C	Specific heat 0.5–2.6 kJ/(kg K)	Mature technology, simple design and operation, cost-effective, suitable for large-scale TES systems	Low energy density, large volume needed
Latent Heat Storage	PCMs like salts, paraffin wax, metals	Up to 900 °C	Heat of fusion 50–800 kJ/kg	High energy density, efficient use of space, stable temperature during phase changes, suitable for medium scale	High cost, limited to specific temperature ranges, complex design for effective heat transfer, degradation of materials over time
Thermochemical Storage	Reversible chemical reactions such as metal oxides, ammonia-based systems	Up to 1600 °C	Reaction enthalpy up to 1400 kJ/kg	Very high energy density, durable storage medium, long-duration storage	High cost, complex systems and processes, slow response time, technical challenges in reaction management

Table 7
A summary of TES medium used for PTES systems [42,53,154].

Storage medium	Type	Temperature range (°C)	Energy density (kWh/m^3)	Cost ($/kWh)	Scalability	Challenges
Rocks/Gravel	Sensible	200–1000	20–40	1–10	High	Requires large volumes
Water	Sensible	0–100 (liquid); up to 200 (pressurized)	50–100	1–10	High	Low temp applications
Molten salts	Sensible	200–565 (nitrates); up to 750 (chlorides)	80–150	30–60	High	Solidifies at lower temps, corrosive
Paraffin waxes	Latent	30–200	100–200	50–100	Medium	Low thermal conductivity
Salt hydrates	Latent	30–150	150–350	20–50	Medium	Phase separation, corrosive
Metal Alloys	Latent	200–1000	300–600	100–200	Low-Medium	Expensive
Thermochemical (Sorption)	Thermochemical	50–1000	400–1000	50–150	Medium-High	Complex, expensive

5.2. *Thermal energy storage tanks*

Thermal energy storage tanks can be categorized into single-tank, double-tank, and multi-tank configurations based on energy requirements. Single tank systems are generally simpler and more cost-effective. They typically use a thermocline approach, where a single tank is charged with heat at one end and discharged at another, creating a gradient of temperature (thermocline) within the tank [173,174]. This configuration allows for straightforward thermal management but may suffer from issues like thermal mixing, which can reduce overall efficiency. Two-tank systems involve separate tanks for charging and discharging [175]. This configuration helps maintain thermal stratification better than single-tank systems, as each tank can be optimized for specific functions. Multi-tank configurations utilize several tanks to further enhance the thermal storage capacity and efficiency and provide enhanced thermal stratification and flexibility compared to single-tank systems [176]. These systems can be arranged in series or parallel, depending on the operational requirements, and are particularly advantageous in large-scale applications, where higher energy storage capacity and better temperature control are required [177]. The primary challenge with multi-tank configurations is the increased cost and complexity due to multiple tanks and the associated infrastructure needed for effective management. Mao [178] summarized the TES tanks and focused on the shape of storage tank and provided a good reference for designing, operating, and energy saving of TES systems. The storage tank is mainly cylinder and rectangle, and the rectangular configuration is popular for sensible heat storage in large-scale system while the cylinder storage tank is more extensive for latent heat storage in lab-scale system. A comparison of TES tanks can be used for PTES systems are shown in Table 8.

For the design of TES tanks, there are many technical challenges that should be addressed [179]. Compact geometries, such as packed beds or modular tank arrays, provide good heat transfer but may cause non-uniform temperature distribution, which leads to thermal mixing and reduced round-trip efficiency. Conversely, large cylindrical tanks minimize surface-to-volume ratios and reduce thermal losses but suffer from poor heat transfer rates, requiring advanced internal heat exchanger design. Different fin geometries are used to increase the heat transfer performance of the storage tank as shown on Fig. 10 by Suresh and Saini [180]. The fins were employed to enlarge the heat transfer surface area of the storage medium within the tanks. Another effective approach to improving heat transfer performance, particularly in PCMs, is the incorporation of additives that enhance the thermal conductivity of the storage medium. Graphitic carbons have been reported to be highly effective in addressing the inherent low thermal conductivity of PCMs by Badenhorst [157]. Particulate additives can increase the thermal conductivity of PCMs up to ten times, whereas matrix-based materials such as compressed expanded graphite and graphitic foams can deliver enhancements exceeding 100 times. Furthermore, TES systems in PTES operate under high pressures and wide temperature ranges, sometimes up to 600 °C. TES tanks must withstand thermal expansion, cyclic stresses, and pressure gradients without compromising integrity. Large-scale tanks face issues of wall thickness, welding integrity, and thermal fatigue, while compact modular geometries demand precision manufacturing to ensure sealing and long-term durability. Geometries suitable for laboratory-scale prototypes may not be practical for large-scale applications. Minimizing heat loss by maintaining clear separation between temperature layers during storage, especially over long durations, is also a major challenge. Advanced insulation materials are required to minimize thermal losses. Storage tank materials must withstand the temperature range of the stored medium, resist corrosion, and maintain structural integrity under thermal cycling. Large-scale PTES systems require massive storage volumes, especially for sensible heat storage, which increases material and land use costs. Some thermal energy devices use modular thermal storage tanks that can be added or removed to scale the system based on demand, improving flexibility and reducing initial costs.

Table 8
A summary of thermal energy device used for PTES systems.

Configuration	Advantages	Limitations
Single tank	Simple design and operation, lower initial investment, suitable for smaller applications.	Less efficient due to thermal mixing, limited storage capacity for large-scale applications, challenges in maintaining thermal stratification
Two tanks	Improved efficiency with better temperature management, greater operational flexibility, separate functions for charging and discharging	Higher capital costs due to the second tank, increased system complexity
Multi tanks	Optimal thermal management with enhanced stratification, scalability for larger energy needs, reduces thermocline losses	Increased capital and operational costs due to multiple tanks, complexity in control systems for managing multiple tanks

6. Potential control strategies and control system design

Controlling PTES systems based on CO_2 cycles presents a unique set of challenges due to the extreme and variable operating conditions, as well as the complex thermophysical behaviour of CO_2 near its critical point [49]. Essential state parameters for control in PTES systems include temperature for managing thermal efficiency and preventing overheating or freezing, pressure for the thermodynamic cycle's efficiency and safety, flow rate for heat transfer rates and system responsiveness, and energy level for optimizing charging and discharging cycles based on energy availability. The control system must dynamically adjust temperatures, pressures, and mass flow rates in response to changes in energy demand or input. Without accurate control, fluctuating loads can cause temperature or pressure overshoots, leading to thermal stress, efficiency losses, or safety concerns.

During compression process, CO_2 undergoes rapid changes in

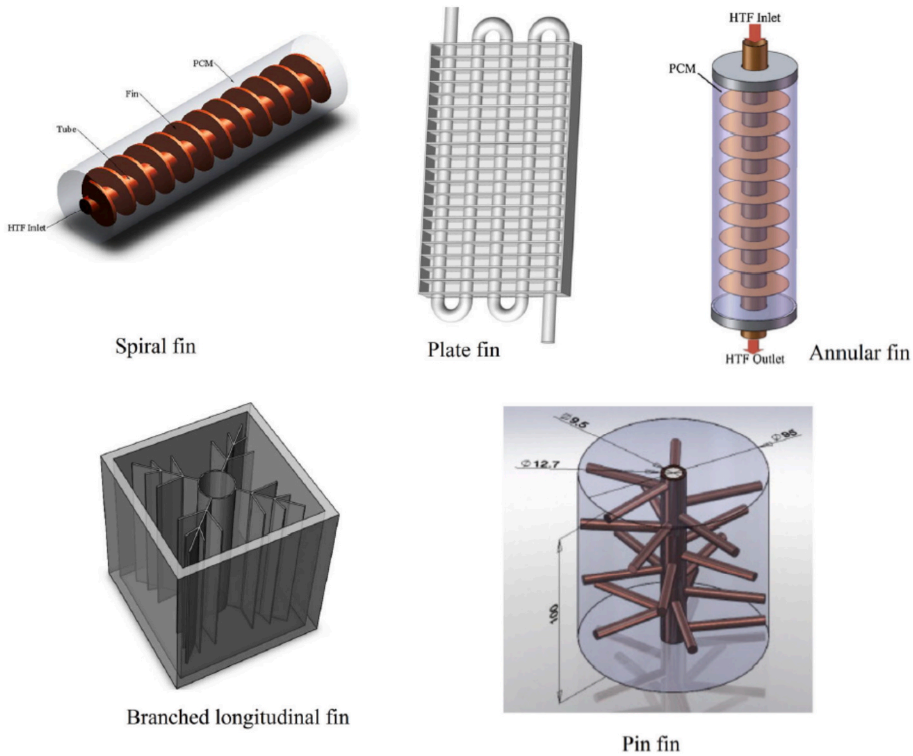

Fig. 10. Different fin geometries used to increase the heat transfer surface of the storage tank by Suresh and Saini [180].

density, viscosity, specific heat, and other properties near its critical point. Small deviations in temperature or pressure can cause large changes in the fluid state, making the system difficult to stabilize. These non-linear variations make controlling the system particularly difficult [181,182]. The challenge of compressor control is mainly for handling rapid temperature and pressure fluctuations during transitions through the critical region to avoid inefficiencies, operational instability, or damage to components. Advanced, real-time monitoring systems with highly responsive control algorithms are usually required to adjust parameters dynamically based on near-critical fluid behaviour. Precise thermal management of heat exchangers is also necessary to maintain efficiency. Controlling heat transfer rates, particularly during start-up, shutdown, or when switching between heating and cooling modes, can be complex [183,184]. Poor control on heat exchangers can lead to inefficiencies, thermal fatigue, or mechanical failure. Inadequate control can also lead to excessive temperature gradients, which may damage the heat exchangers or other system components. Highly responsive heat exchange control systems, including dynamic flow control and temperature management, are necessary. The control of start-up and shutdown sequences is complex due to the need to carefully manage the transition to operational conditions [185,186]. During these periods, large fluctuations in temperature, pressure, and fluid properties can occur, leading to mechanical stress and operational risks. If not properly controlled, start-up and shutdown transients can result in mechanical damage, loss of efficiency, or even catastrophic failure. Using pre-programmed start-up and shutdown sequences, along with real-time monitoring and adjustments, can help mitigate the risks associated with these transients. This includes the use of safety valves, pressure relief systems, and emergency shutoff controls that are automatically activated if the system detects any unsafe conditions.

In applications such as grid-connected energy storage, the PTES systems must be integrated with external systems such as electricity grids or industrial processes [187,188]. This integration requires synchronization and control across multiple systems, which may have different dynamic behaviours. Poor coordination between the PTES system and external systems can lead to inefficiencies, grid instability, or failure to meet demand. The control system must manage the PTES system while also responding to signals from the grid or external process controllers. Integrated control systems that optimize power cycle performance using multi-variable control algorithms are required. These systems should be able to adjust key parameters such as turbine speed and flow rates to maintain peak efficiency under varying conditions. During the control process, by allowing compressors and sometimes expanders to operate at variable rotational speeds, variable speed drives can offer the ability to continuously adjust mass flow rate, pressure ratio, and heat transfer characteristics to match real-time operating conditions. For example, in the charging stage, a compressor equipped with variable speed drive can modulate its speed to adapt to the available renewable electricity input, thus avoiding frequent on/off cycling and reducing mechanical stress. Similarly, during discharging, a variable-speed turbine or expander can be tuned to align with the grid's power demand profile, improving both efficiency and flexibility. Meanwhile, unlike conventional power plants that are designed for relatively stable baseload operation, PTES systems inherently face fluctuating load conditions. Operating at part load often leads to efficiency penalties due to off-design behaviour of compressors, turbines, and heat exchangers. For example, compressors may experience reduced isentropic efficiency and higher relative losses at lower flow rates, while turbines may suffer from reduced expansion efficiency at diminished load levels. Heat exchangers may exhibit deteriorated performance under reduced flow and temperature differences, which can lower round-trip efficiency. Control strategies should be able to modulate energy storage or power generation in response to fluctuating grid conditions [189].

For the control strategies, proportional-integral-derivative (PID) control remains a foundational control design due to its simplicity and effectiveness in various applications. It adjusts system parameters such as pressure and temperature based on the difference between the desired setpoint and the actual state. PID controllers are straightforward to implement and can effectively handle dynamic responses in CO_2 cycles, ensuring optimal performance under varying operational conditions [190]. For PTES systems with CO_2 cycles, PID control can be applied to: Cycle pressures and CO_2 mass flow rate regulation to ensure that compressors and expanders operate within safe pressure limits while matching load requirements; turbomachinery speed control by regulating turbine or compressor shaft speed to maintain desired output power; heat exchanger outlet temperature control for stabilizing charging and discharging processes; grid synchronization to ensure that the generated power meets frequency and voltage stability requirements. Model predictive control (MPC) is increasingly favoured for its ability to handle multi-variable systems and forecast future system behaviour, making it suitable for grid energy management and optimizing energy dispatch [191]. MPC uses a dynamic model to forecast system behaviour and adjust control inputs accordingly and maintain efficient operation under varying conditions by minimizing energy losses and improving response to disturbances. This approach is particularly beneficial in integrating renewable energy sources, enhancing the overall performance of CO_2 cycles. In PTES systems, MPC can regulate both the thermodynamic cycle dynamics and the grid interaction. The controller uses a dynamic model of the CO_2 cycle, incorporating the behaviour of compressors, turbines, heat exchangers, and thermal storage units. At each sampling interval, MPC predicts the future evolution of system states, such as pressure levels, shaft speeds, turbine outlet temperatures, and storage state-of-charge, over a specified prediction horizon. Based on these predictions, MPC computes optimal control actions (e.g., compressor mass flow, turbine inlet guide vane position, or valve openings) to minimize cost function. This cost function typically balances cycle efficiency, round-trip performance, thermal stress minimization, and grid requirements. For grid-connected PTES systems, MPC can directly incorporate grid demand forecasts, frequency regulation signals, and market-based dispatch requirements. This allows the system to dynamically adjust charging and discharging power levels while respecting operational constraints such as maximum CO_2 pressures, turbine temperature limits, and heat exchanger capacity. Adaptive control is critical for dynamically adjusting to changing operational conditions, ensuring optimized performance in variable environments [192]. Adaptive control adjusts operational parameters in real-time based on current system performance and environmental conditions. This approach enhances efficiency and stability by continuously learning from data, allowing the system to respond to variations in load and operational demands. In PTES systems, adaptive control regulates compressor operation, turbine expansion, valve positions, and heat exchanger flows while ensuring that storage state as well as pressure and temperature limits remain within safe bounds. Adaptive control continuously updates its control laws, such as adjusting compressor mass flow regulation or turbine inlet control, to compensate for these shifts. This ensures stable operation without requiring extensive retuning that conventional controllers would need. For grid-connected operation, adaptive control provides additional benefits. As the system responds to fluctuating frequency regulation signals or demand-side dispatch, the adaptive controller modifies its parameters to maintain power balance while minimizing efficiency losses. Neural network control leverages machine learning capabilities to manage non-linear processes and improve predictive maintenance strategies [193,194]. Neural network control involves using artificial neural networks to predict system behaviour and optimize control strategies. This approach enhances the management of operational parameters such as pressure, temperature, and flow rates, improving efficiency and response to dynamic conditions. By learning from historical data, neural networks can adapt to fluctuations, making the system more robust and efficient. In PTES systems, neural network control can be applied to regulate compressor power, turbine expansion ratio, valve operations, and heat exchanger duty while considering the strong coupling between pressure, temperature, and mass flow in CO_2 cycles. During the charging process, neural network control can learn the relationship between compressor inlet conditions, CO_2 thermodynamic states, and storage tank response to maintain stability and efficiency. In the discharging process, they can optimize turbine output and thermal discharge to match real-time grid requirements, even under rapidly varying load demands. For grid-connected operation, neural network control offers predictive and adaptive regulation. Trained on historical operational data or high-fidelity simulations, the neural network can anticipate how changes in grid frequency, load fluctuations, or renewable energy availability will impact PTES operation. This allows the system to adjust setpoints dynamically, ensuring grid frequency support, peak shaving, and load balancing without significant efficiency penalties. Decentralized control is advantageous for large-scale systems, allowing for independent operation while presenting coordination challenges [195]. Decentralized control for energy storage systems distributes decision-making across multiple controllers rather than relying on a central controller. This approach enhances flexibility, scalability, and reliability, allowing local systems to respond dynamically to changes in demand or supply. It is particularly effective in integrating renewable energy sources and managing grid interactions. In practice, decentralized control for PTES systems involves regulating pressure, temperature, and flow rates within each subsystem independently. For example, a compressor controller manages suction pressure and discharge temperature, while a turbine controller regulates expansion ratio and output power. Heat exchanger controllers maintain desired outlet temperatures on both CO_2 and storage sides, while storage tank controllers ensure proper charging and discharging rates. These local controllers use relatively simple algorithms such as PID or state feedback, which can operate with fast response and robustness against local disturbances. When connected to the electrical grid, decentralized control supports frequency regulation, peak shaving, and load following by coordinating local setpoints. A supervisory layer, though not centralizing all decision-making, communicates grid requirements, such as increased power output during peak demand or reduced operation during renewable surpluses, to the respective subsystem controllers. A summary of the control strategies potentially used for PTES systems based on CO_2 cycles are shown in Table 9.

7. Summary and future research trends

PTES systems based on CO_2 cycles are a highly promising candidate for large-scale energy storage, particularly in the context of increasing reliance on renewable energy sources. The properties of CO_2, including high density, low cost, and non-flammability, enable the development of systems of high energy densities, leading to compact designs, high efficiency and environmental performance. The ability of CO_2 based PTES systems to operate in both *trans*-critical Rankine and supercritical Brayton cycles can enable CO_2 operation across a broad temperature range of storage applications. However, substantial challenges still remain in the design of expanders, compressors, heat exchangers and controls for these systems can be widely applied in integrated power system decarbonisation approaches.

(1) CO_2's high density and excellent heat transfer characteristics enables compact design of turbomachinery and heat exchangers, which reduce system footprint and increase system efficiency. CO_2 cycles can efficiently operate across a wide range of temperatures and pressures, making them suitable for use in PTES applications. PTES systems based on CO_2 cycles can also provide grid-scale flexibility, with fast response times suitable for frequency regulation, peak shaving, and renewable energy integration. The adaptability to different cycle and configurations including reheated, split, and recuperated cycles, also allows optimization for specific operating conditions.
(2) From the literature review, PTES systems based on *trans*-critical Rankine cycles show a broad range of round-trip efficiencies from 29.2 % to 74.5 % depending on the specific configuration and operating conditions. Most efficiencies lie in the range of 50 % to 60 %, while those based on other supercritical Brayton cycles show round-trip efficiency ranging from 22.34 % to 45.5 %. The higher round-trip efficiency achieved by *trans*-critical Rankine

Table 9
A summary of control strategies used for PTES systems based on CO_2 cycles.

Control Design	Description	Main components	Advantages	Challenges	Applications
PID	Proportional-Integral-Derivative control for regulating system variables.	Sensors, actuators, and control algorithms	Simple to implement, widely used	Limited performance in non-linear systems	Temperature and pressure control
MPC	Uses a dynamic model of the system to predict future behaviour and optimize control actions.	Model of PTES system, optimization algorithm	Handles multi-variable control, anticipates disturbances	Requires accurate models, computationally intensive	Grid energy management, optimizing energy dispatch
Adaptive	Adjusts control parameters in real-time based on system performance.	Adaptive algorithms, feedback mechanisms	Continuously optimizes performance	Complexity in implementation	Dynamic operation in variable conditions
Neural network	Employs artificial neural networks to learn system behaviour and optimize control strategies.	Neural network models, training data	Ability to learn complex relationships	Requires significant training data, risk of overfitting	Non-linear process control, predictive maintenance
Decentralized	Each subsystem has its own controller, allowing for independent operation and control.	Local controllers, communication network	Scalability, flexibility in large systems	Coordination challenges, potential for suboptimal performance	Large-scale PTES systems, distributed energy resources

cycles is due to the more efficient energy exchange with the TES medium. The *trans*-critical CO_2 Rankine cycle is advantageous for smaller to medium-scale systems with smaller temperature differences due to simplicity and ease of integration, whereas the supercritical Brayton cycle is better suited for large-scale, high-temperature PTES systems, particularly with high-temperature external heat sources, such as concentrated solar thermal energy and high-grade industrial waste heat.

(3) While CO_2 cycles can theoretically achieve high efficiencies, optimizing the entire PTES system for various operating conditions remains a challenge. Detailed thermodynamic analyses and simulations to identify optimal operating parameters and cycle configurations are necessary. When CO_2 operates at high temperatures and high pressures (up to 600 °C and 300 bars), concerns exist on the compatibility of materials used in components such as expanders and heat exchangers. Development and testing of advanced materials, including high-temperature alloys and coatings that can withstand corrosive environments and maintain structural integrity, are necessary.

(4) PTES systems based on CO_2 cycles are still at the research and development stage, and large-scale commercial deployment has yet to be realized. Preliminary results from the SELECO$_2$ project show round-trip efficiency of 30–35 % for *trans*-critical Rankine cycle system and highlight the challenges posed by energy losses and irreversibility occurring in heat exchangers and turbomachines.

(5) Designing CO_2 expanders for PTES systems remains a challenge. For low-temperature *trans*-critical Rankine cycles, the high density and relatively low enthalpy drop across the piston expander restrict the amount of recoverable power, which results in lower system efficiency compared to high-temperature expanders. For high-temperature supercritical Brayton cycles, axial and radial turbines must withstand temperatures up to 600 °C and pressures above 200 bars. This necessitates the use of nickel-based super-alloys, advanced coatings, and novel blade cooling techniques. Furthermore, CO_2 expanders require careful optimization as they may experience flow instabilities at certain operating conditions, especially at start-up, shutdown and off-design operation.

(6) CO_2 compressors also present several challenges, primarily due to the unique properties of CO_2 near its critical point and the extreme operating conditions involved. These include handling rapid property changes and design for operation at relatively high pressures and temperatures. Relatively high operating pressures and temperatures also require advanced lubrication systems and effective internal cooling strategies. Sealing high-density CO_2 at pressures often exceeding 200 bars is another technical challenge and may result in leakage or friction losses if not properly addressed. In practical implementation, semi-hermetic reciprocating compressors are commonly adopted for CO_2, but their scalability to large PTES applications is not feasible due to the large number of compressors required. Innovative aerodynamic designs and optimization techniques that can handle the unique properties of CO_2 are essential to improve system performance and efficiency. Centrifugal and axial compressors, while more scalable, face aerodynamic instabilities at high density ratios and require advanced materials and precision manufacturing.

(7) Heat exchangers are also challenging components in PTES systems based on CO_2 cycles. In *trans*-critical Rankine cycles, heat exchanger irreversibility due to sharp property variations near the critical point reduce efficiency. For supercritical Brayton cycles with maximum temperatures above 500–600 °C, material selection becomes a major challenge. Nickel- and titanium-based alloys are required, dramatically increasing costs. Integration with molten salts or thermochemical storage adds further complexity, as it requires compatibility between CO_2 and high-temperature molten salt to ensure durability against corrosion and thermal cycling.

(8) The choice and integration of TES systems is important to PTES viability. Sensible heat storage with molten salts is the most mature technology but is limited by thermal stability and requires large volumes. Latent heat storage can provide higher energy density, but challenges of phase-change kinetics, material compatibility, and volume change need to be addressed. Thermochemical storage offers the highest potential energy density, but suffers from slow reaction kinetics, reversibility issues, and material degradation. Coupling CO_2 cycles with TES systems therefore requires careful thermal matching, stable operating ranges, and innovative system configurations.

(9) Heat losses can significantly reduce the overall system efficiency. Development of advanced insulation materials and designs for thermal storage tanks to minimize heat losses are essential. Materials used in heat exchangers, storage tanks, and piping systems also must withstand high temperatures and pressures while being resistant to corrosion and degradation. Research is required into advanced materials, such as high-temperature ceramics and coatings, to enhance the durability and longevity of system components. Efficient heat transfer is also critical to the overall efficiency. Development of novel heat exchanger designs is necessary to improve the heat transfer efficiency. The energy density of thermal storage materials determines the total energy that can be stored in a specific volume. Exploration of new thermal storage materials with higher energy densities, such as PCMs or advanced thermochemical storage solutions is important.

(10) PTES systems often involve multiple components that need to be controlled simultaneously, leading to increased complexity in control strategies. The start-up and shutdown processes need to be carefully managed to avoid thermal stress and other operational issues. Operation requires precise control of pressure and temperature to maintain stability. Advanced control algorithms and monitoring systems that can quickly respond to fluctuations and maintain optimal operating conditions are essential to ensure smooth system operation. The ability to respond quickly to fluctuations in energy demand or supply due to intermittent renewable sources can be limited in PTES systems. Research into hybrid systems that combine PTES with other energy storage technologies for improved responsiveness and flexibility. Effective integration of PTES systems into existing energy grids can be complex, particularly in coordinating with other generation and storage systems.

(11) To ensure stable grid-connected operation, PTES systems must be equipped with advanced controls. Conventional proportional-integral-derivative controllers can manage local variables such as compressor discharge pressure, turbine expansion ratio, or storage tank temperature, but can struggle with system-wide optimization. Model predictive control offers predictive capability and handles multivariable constraints but requires accurate models and high computational effort. Adaptive control can adjust parameters in real time to cope with uncertainties, but maintaining stability across wide load variations is difficult. Neural network controllers provide a promising pathway for complex, nonlinear dynamics, though their practical reliability remains unproven. Decentralized control architectures are gaining attention for their scalability and fault tolerance but require careful coordination to avoid instability between subsystems.

(12) High capital costs and the scalability of PTES systems can be barriers to widespread adoption, particularly for smaller capacity installations. Economies of scale can be achieved through the development of standardized components and modular system designs, reducing manufacturing and installation costs. Conducting comprehensive lifecycle assessments are recommended to evaluate the environmental footprint and improve sustainability through recycling and waste reduction strategies. Addressing these technical challenges is essential for the advancement of CO_2 based PTES systems to commercialisation stage. Ongoing research and development, coupled with collaboration among industry, academia, and government entities, will be critical to overcome these obstacles and unlock the full potential of PTES technologies.

CRediT authorship contribution statement

Lei Chai: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Savvas A. Tassou:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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