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Review

Comprehensive Review of Compressed Air Energy Storage (CAES) Technologies

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Abstract: As renewable energy production is intermittent, its application creates uncertainty in the level of supply. As a result, integrating an energy storage system (ESS) into renewable energy systems could be an effective strategy to provide energy systems with economic, technical, and environmental benefits. Compressed Air Energy Storage (CAES) has been realized in a variety of ways over the past decades. As a mechanical energy storage system, CAES has demonstrated its clear potential amongst all energy storage systems in terms of clean storage medium, high lifetime scalability, low self-discharge, long discharge times, relatively low capital costs, and high durability. However, its main drawbacks are its long response time, low depth of discharge, and low roundtrip efficiency (RTE). This paper provides a comprehensive review of CAES concepts and compressed air storage (CAS) options, indicating their individual strengths and weaknesses. In addition, the paper provides a comprehensive reference for planning and integrating different types of CAES into energy systems. Finally, the limitations and future perspectives of CAES are discussed.

Keywords: compressed air energy storage; adiabatic compressed air energy storage; advanced adiabatic compressed air energy storage; ocean compressed air energy storage; isothermal compressed air energy storage

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1. Introduction

By 2030, renewable energy will contribute to 36% of global energy [1]. Energy storage systems provide crucial performance options for improving energy efficiency and therefore facilitate the integration of renewable energy [2] by mitigating renewable energy fluctuations [3]. A variety of energy storage technologies are available, based on the type of energy that is being stored. These include mechanical, electrochemical, electrical, chemical, and thermal energy storage. Since these technologies are so diverse and varied, they are further separated and subdivided [4]. There are several types of mechanical storage technologies available, including compressed air energy storage, flywheels, and pumped hydro; chemical storage includes conventional battery technologies (lead acid, lithium-ion), flow cells, and fuel cells; electrical storage includes capacitors, supercapacitors, and magnetic storage; thermal storage includes phase change materials and cryogenic storage. Storage technologies from different categories may be combined under certain circumstances, such as the integration of thermal stores into CAES technology [5]. Chen et al. [6] compared the economics and technical characteristics of many popular energy storage systems. Figure 1 shows a comparison between the key characteristics of the common energy storage technologies.

In contrast to the other energy storage technologies listed in Figure 1, mechanical storage systems have a significantly lower capital cost and a relatively higher lifetime and power/energy rating. Thus, they are suitable for load shaving, load levelling, time shifting, and seasonal energy storage. Large-scale commercialised Compressed Air Energy Storage (CAES) plants are a common mechanical energy storage solution [7,8] and are one of two large-scale commercialised energy storage technologies capable of providing rated power capacity above 100 MW from a single unit, as has been demonstrated repeatedly in large-scale energy management [9,10]. This paper provides a comprehensive study of CAES technology for large-scale energy storage and investigates CAES as an existing and novel energy storage technology that can be integrated with renewable and alternative energy production systems and waste heat storage.

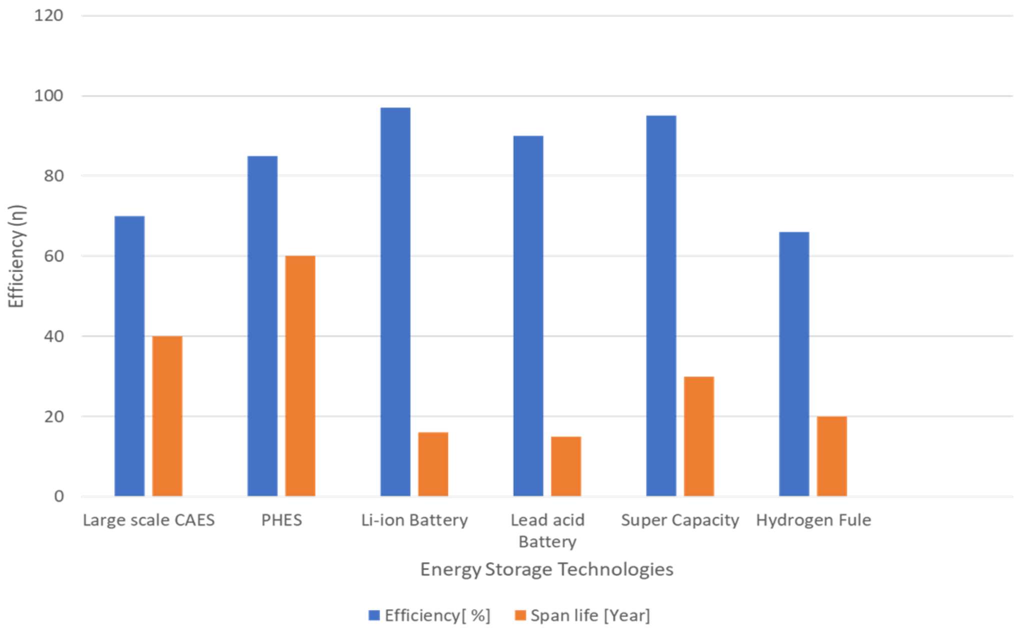

Figure 1. The main characteristics of energy storage technologies.

2. CAES History and Basic Principles

The concept dates back to the 1940s [6], but the technology was not applied to industry until the 1960s. In the 1960s, existing power plants faced a number of challenges. A significant amount of low-cost, off-peak power was wasted, while an increasing amount of power was required during peak hours. CAES research was motivated by the need to balance these fluctuations [11]. In the mid-1970s [12,13], CAES technology became increasingly attractive. Using this technology, compressed air is used to store and generate energy when needed [14]. It is based on the principle of conventional gas turbine generation. As shown in Figure 2, CAES decouples the compression and expansion cycles of traditional gas turbines and stores energy as elastic potential energy in compressed air [15].

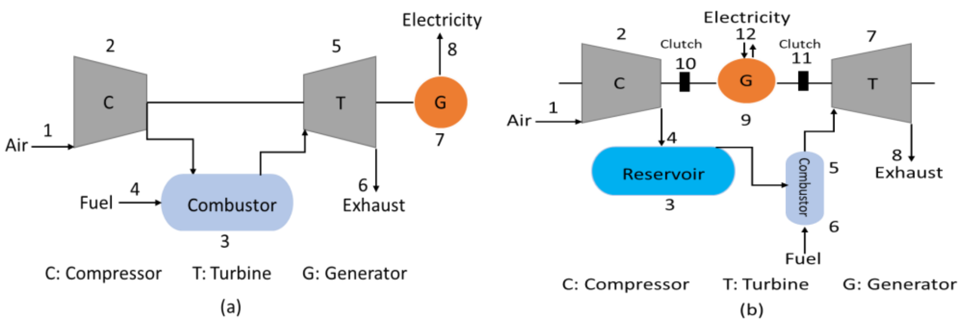

Figure 2. Gas turbine and CAES schematic diagram: (**a**) schematic diagram of gas turbine system; (**b**) schematic diagram of storing energy in gas turbine system.

During times of low demand, energy is commonly captured by compressing and storing air in an airtight location (typically between 4.0 and 8.2 MPa, such as in an underground cavern), and then using the gas to generate energy at times of higher demand [16].

During this process, compressed air is drawn from the storage vessel, mixed with fuel, combusted, and then expanded through a turbine to extract the stored energy to produce electricity through a generator. Using a recuperator, waste heat from the exhaust can be captured before it is released into the atmosphere (Figure 3).

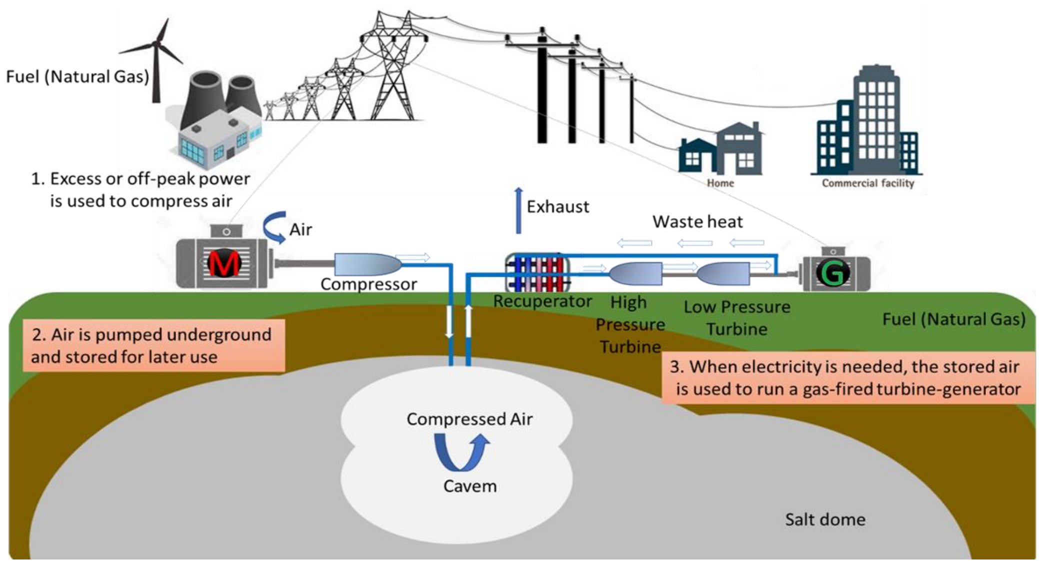

Figure 3. Components of the CAES system.

As shown in Figure 3, CAES systems store and dispatch energy using technology and natural geological formations [15] using six key components:

1. A motor or generator with clutches for alternate engagement with the compressor or turbine train.
2. An air compressor with two or more stages, inter-coolers and after-coolers, to achieve compression efficiency and reduce compressed air moisture content.
3. The turbine train that includes both high-pressure and low-pressure turbines.
4. Controls for the combustion turbine, compressor, and auxiliaries, as well as for the regulation and control of the changeover from generation to storage mode.
5. Auxiliary equipment for the facility's operation, including fuel storage and handling, as well as mechanical and electrical systems for various heat exchangers.
6. The underground component mainly consisting of a cavity for compressed air storage.

There are numerous advantages associated with large-scale CAES systems that are integrated with the grid network, including peak shaving, load shifting, frequency, and voltage management [15,17]. Additionally, CAES plants can also be integrated with intermittent renewable energy sources, such as wind and solar, to smooth out the output power [17]. According to Bouman, CAES facilities also have a lower environmental impact than natural gas power plants [18]. Nevertheless, the geographical requirement of a cavern as well as the combustion of fossil fuels during the discharge process are the major limitations of the CAES system [6,17].

Modern CAES systems store compressed air either in man-made containers at ground level or underground (e.g., salt caverns, hard rock caverns, saline aquifers) [17,19]. Additionally, offshore and underwater storage systems have been tested and are in the process of rapid development [15].

To evaluate the CAES system's process performance, components, and integrated system, several researchers used simulation tools such as CFD (computational fluid dynamics), Aspen Plus [20–24], and MATLAB/Simulink [15,25,26]. A number of methodologies have been proposed to improve the round-trip efficiency of CAES systems in the literature, with an emphasis on the recovery of waste heat from compressors during the charging process and turbines during the discharging process. A CAES system can be classified into three categories as shown in Figure 4.

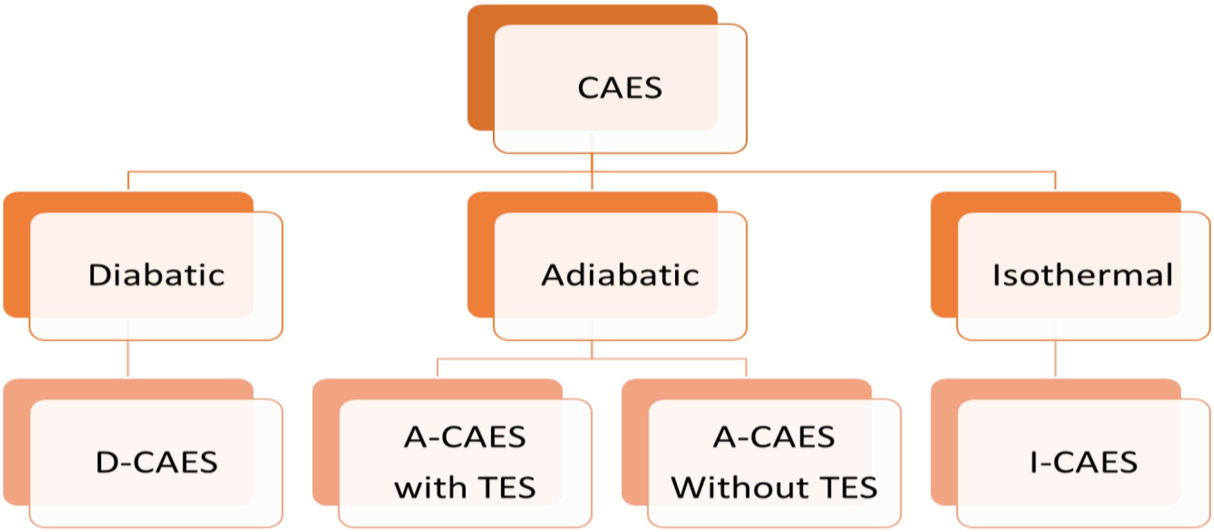

Figure 4. CAES classification.

A diabatic CAES, an adiabatic CAES, and an isothermal CAES are the three main types of CAES. When a diabatic CAES system is used, the heat of compression is wasted on the environment. External energy sources, such as a natural gas burner, are necessary to compensate for the wasted energy and preheat the air before expansion. In order to address this issue, adiabatic CAES systems are being developed. In this system, thermal energy is stored and absorbed via a thermal energy reservoir. During discharge, this energy is returned to raise its temperature. A CAES with an isothermal design was proposed and developed to reduce energy loss. In this system, the air is compressed and stored using an isothermal air compression method. When electricity is required, isothermal air expansion releases air from the storage cavern to generate power [27].

2.1. Diabatic CAES Systems (D-CAS)

Over the past 40 years, CAES has been used at the grid level [28]. During the charging process, electricity from the grid powers a motor that drives a turbine that compresses air into an underground cavern while rejecting the heat of compression into the environment [13] During discharge, the high-pressure stored air is combined with gas to allow combustion which powers one or more turbines which drive generators to produce electricity [19].

There are two large-scale D-CAES plants in operation: the 290 MW Huntorf plant in Germany and the 110 MW McIntosh CAES plant in the USA. Both facilities use natural gas as a primary heat source and store high-pressure air in salt caverns [21,29–31]. Using a two-stage air compression/expansion system, the Huntorf plant operates at a pressure range of 46 to 72 bars with an efficiency rate of 42% [27]. Due to the lack of a heat storage mechanism, 25% of the energy supplied to the air compressors is wasted, despite inter-cooling between the two-stage compressors.

The McIntosh plant uses three compressors and two expanders to provide pressures between 46 and 75 bars. An efficiency of 53% is achieved by pre-heating the air before using the energy extracted from the hot exhaust air from the expander. The loss of compression heat energy and the usage of fossil fuels to preheat the air before expansion, contribute to the low efficiency of these two plants [32,33]. Based on the analysis performed by Kim et al. [34], Figure 5 illustrates the heat and energy flows in the McIntosh plant used to produce 1.0 kWh of output.

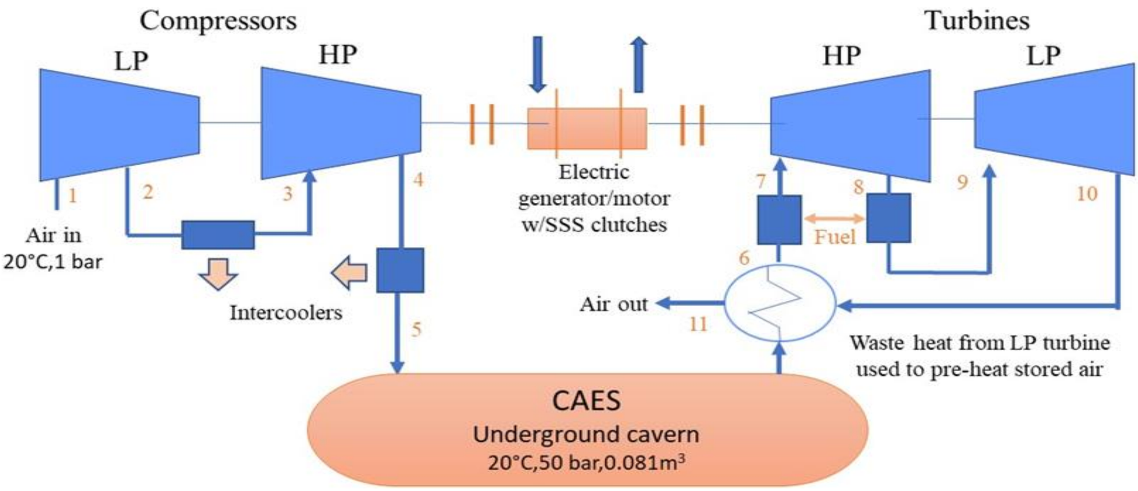

Figure 5. Heat and energy fluxes at the McIntosh CAES plant, adapted from [35].

A comparison of the technical properties of the Huntorf and McIntosh plants is presented in Table 1. The McIntosh facility was designed primarily to shift the load on a weekly basis, while Huntorf's priority is to shift power on an hourly basis and high efficiency is not a high priority [36].

Table 1. Technical specifications for the Huntorf and McIntosh D-CAES plants [28,30,34,36].

Specifications	Unit	Huntorf Plant	McIntosh Plant
Operation year	-	1978	1991
Capacity	[MW]	290	110
Charging period	[h]	8	40
Discharging period	[h]	2	26
Start-up time	[min]	14	12
Charging time	[h]	8	40
Discharging time	[h]	2	26
Efficiency of plant	[%]	42	53
Efficiency of compressor	[%]	80	80
Minimum/Maximum energy	[MWh]	Min. 0, Max. 480	Min. 200, Max. 2000
Number of caverns	-	2	1
Pressure range of cavern	[bar]	46–72	46–75
Cavern volume	[m^3]	310,000	538,000
Air mass flow of compression	[kg/s]	107	93
Air mass flow expansion	[kg/s]	455	154
Temperature of exhaust gas	[°C]	480	370 [1]

[1] Before recuperator.

There are several conventional CAES plants currently in the research and development stage, such as the 2700 MW Norton Plant in Ohio and the 300 MW PG&E Plant in California [37]. Several D-CAES projects have failed as a result of geologic constraints, low cycle efficiency, and noticeable energy losses, including the 150 MW Seneca Plant in New York, the 270 MW Iowa Stored Energy Park in the USA, and the 1050 MW Donbas Plant in Ukraine [28,35].

2.2. *Adiabatic/Advanced Adiabatic Compressed Air Energy Storage (A-CAES)/(AA-CAES)*

The adiabatic compressed air energy storage (A-CAES) system has been proposed to improve the efficiency of the CAES plants and has attracted considerable attention in recent years due to its advantages including no fossil fuel consumption, low cost, fast start-up, and a significant partial load capacity [38].

The A-CAES system utilizes Thermal Energy Storage (TES) to recover and store heat produced during the compression stage, which is then reused during the expansion stage, eliminating the need for fossil fuel heating [38], as illustrated in Figure 6a. A heat discharge from state 2 to state 3 is stored in TES and used to increase the temperature of the air from state 3 to state 4, as shown in Figure 6b. Compared to a D-CAES system, an A-CAES system uses only off-peak/renewable electricity [4,39]. A-CAES is expected to achieve an efficiency of 70–75% [12,40–43]. Grazzini and Milazzo [42], for instance, report a 72% efficiency in a 16,500 MJ A-CAES system with a variable configuration. Garrison and Webber reported a system using A-CAES technology driven by wind energy and concentrated solar power (CSP), achieved an A-CAES subsystem energy efficiency of 46% [44].

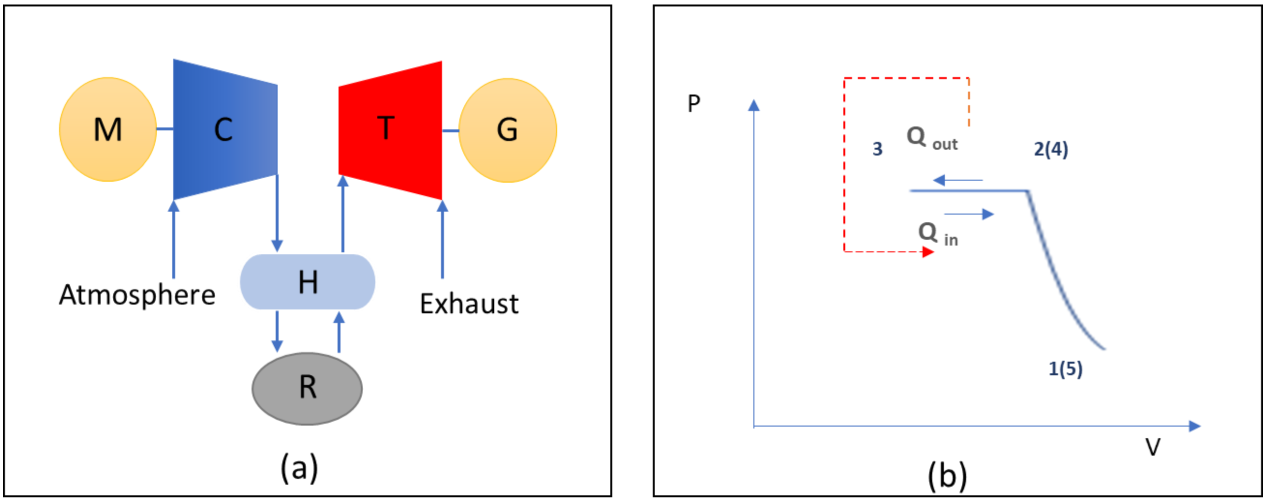

Figure 6. A-CAES system: (**a**) A-CAES system diagram; (**b**) A-CAES P-V diagram, adapted with [4,5].

To improve the performance of an A-CAES system, ejector technology was employed. The A-CAES system with an ejector increased power output from 31.10 MW to 32.81 MW and roundtrip efficiency (the ratio of power output during discharge to the electrical input during charging) from 61.95% to 65.36% [45]. Minutillo et al. [46] used a small-scale A-CAES unit and photovoltaic (PV) power system to power a small-scale off-grid base transceiver station, followed by a TES unit to cool and reheat the air.

Several large-scale advanced adiabatic-CAES plants are being developed and are on the verge of becoming commercially available. In Germany RWE Power is developing the ADELE project [47] with a capacity of up to 200 MW, the cycle efficiency is estimated to be 70% [47,48] by using 1 GWh storage capacity, although due to unforeseen business conditions the project has been put on hold [4]. The Chinese Academy of Science Institute of Engineering Thermo-physics has constructed a 1.5 MW A-CAES pilot plant and is currently constructing a 10 MW A-CAES pilot system, and relevant studies of the realistic performance of A-CAES are ongoing [1,4].

A-CAES performance is greatly influenced by a number of factors; a summary of the studies and developments is summarised in Table 2. At this time, it does not appear that AA-CAES plants exist on a utility-scale, but details of pilot and theoretical studies are included. A range of 63% to 74% cycle efficiency was estimated based on measured and estimated data. King et al. [19] state that several other AA-CAES plants are operating or have been commissioned, but no data is available.

Table 2. Summary of studies and developments of A-CAES performance.

Reference	System Evaluated	Outcome
[49]	A-CAES: Effectiveness and pressure loss of heat exchangers in A-CAES systems	Improved heat exchanger efficiency during charging or discharging significantly improved system efficiency
[50]	CAES: Configurations	High-temperature thermal storage (>600 °C) with temperature-resistant compressor materials improved efficiency
[51]	A-CAES: Multi-stage compressors and expanders and TES at 95–200 °C	Low round-trip efficiency (52–60%), fast start-up, and a wide range of partial load capability
[52]	A-CES: Low-temperature TES	Cycle efficiency (68%) and heat energy cycle efficiency (60%),
[25,50–55]	A-CAES	Developed advanced adiabatic compressed air energy storage options
[56,57]	T-CAES: trigeneration compressed air energy storage	Developed advanced CAES system
[21]	A-CAES: variable configuration system	System for variable fluctuations, e.g., from wind power
[58]	CAES, A-CAES: Thermodynamics analysis	Efficient compressed heat utilization contributed significantly to energy conversion efficiency during charge/discharge. Electrical efficiency of 71.8%
[38,59,60]	CAES: Integration with various renewable energy sources	Specific system for renewable sources
[61]	AA-CAES: Above-ground pilot with air storage (100 m^3 tanks) and TES (pressurized water)	Efficiency of 22.6%
[62,63]	AA-CAES: Underground Swiss pilot with 1942 m^3 rock cavern	Sensible and latent TES at temperatures as high as 550 °C
[36,41,50,52, 64,65]	AA_CAES: Theoretical modelling	Incorporated phenomena such as real gas effects, variable turbomachinery efficiency, and temperature-dependent thermophysical properties
[54]	A-CAES: Environmentally friendly system. Examined thermodynamic and economic aspects as well as transient models of the TES tanks.	Using low-cost, off-peak electricity for charging and generating during peak demand gave round trip energy efficiency (61.5%) and exergy efficiency (68.2%) with a payback period of 3.5 years

A-CAES systems have the potential to increase efficiency while emitting fewer greenhouse gases [38,38,66]. The development of A-CAES demonstration plants is currently in its early stages worldwide [52,67].

2.3. Isothermal Compressed Air Energy Storage (I-CAES)

To improve CAES round-trip efficiency and reduce costs, it has been proposed to use isothermal or near-isothermal processes for compressed air energy storage and expanded air energy release, respectively [68].

Several studies have investigated novel strategies to minimize thermal energy loss in CAES systems. For example, General Compression, Sustain X, and Light Sail Energy [27,69] have recently developed the concept of achieving isothermal CAES (I-CAES) cycles by using an advanced compressor and expander design where heat is continuously removed from and added to air during compression and expansion, respectively [70], as illustrated in Figure 7.

Several methods have been used to enhance heat transmission as part of CAES systems, including liquid droplets, liquid piston air compressors/expanders, porous inserts, and hollow spheres. Since liquids are hardly compressible and gases heat during compression, a perfect isothermal plant is nearly impossible; however, a number of options have been recommended. SustainX built a 1.5 MW I-CAES prototype in 2013 [19]. During compression, water droplets were sprayed into the piston to capture heat. Several studies have attempted to improve the reversibility of gas compression and expansion by developing a liquid piston with a structure similar to reciprocating machines [19,71], excluding studies that used conventional volumetric expanders for achieving isothermal or quasi-isothermal compression and expansion [4,72–74].

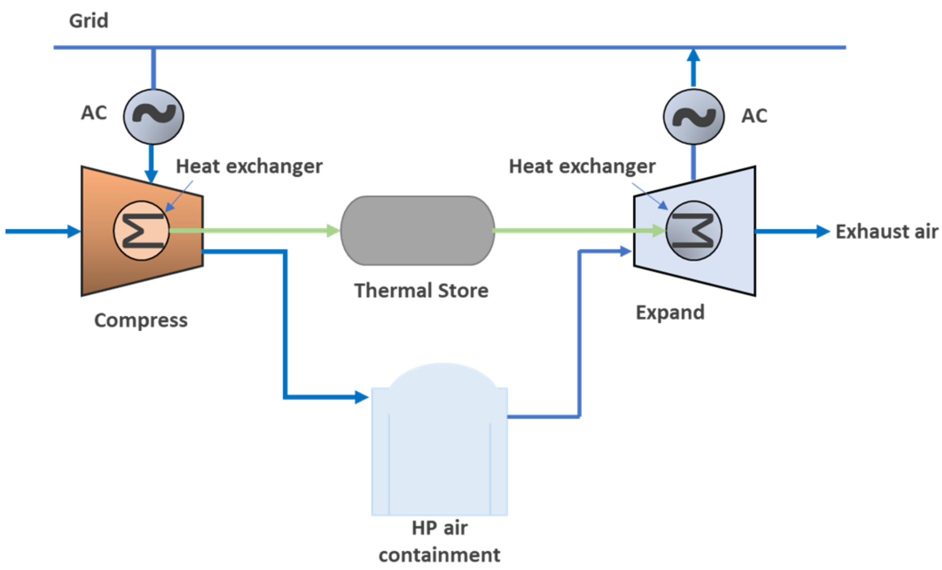

Figure 7. Schematic diagram of I-CAES.

By compressing or expanding gas within a fixed volume chamber using a liquid column, the proposed liquid piston optimizes the surface area-to-volume ratio, minimises thermal dissipation, and achieves near-isothermal operation in a gas chamber [4,75].

In order to improve the isothermal operation of CAES, drop spray injection heat transfer was introduced and combined with the liquid piston [33], which was shown to be effective at reducing air temperature and maintaining a near isothermal operating condition [76]. A new I-CAES for wind turbines was also developed by Saadat et al. [77] based on a liquid piston, in addition Yan et al. [78] performed experimental research on porous inserts utilizing a liquid piston-based I-CAES with a compression-to-expansion ratio of 10:6. Furthermore, heat transfer can be improved by injecting a water spray or droplet into the airflow in addition to using a liquid piston. Using a mechanical link within pneumatic cylinders, SustainX developed a two-stage, mixed-phase (water-in-air) heat transfer system [4,71].

LightSail Energy developed an I-CAES system that uses reciprocating machines to inject a dense mist spray that rapidly absorbs/emits heat energy during the charge and discharge periods [4,71]. Besides reciprocating machines, other options such as screws [79] and scrolls [80], have been investigated.

Rizos [81] evaluated the feasibility of a CAES system that is integrated into an offshore wind turbine's foundation, using the NREL offshore 5 MW baseline wind turbine as an example. Using a three-stage centrifugal compressor with a pressure ratio of 43:1, an axial multistage expander (12 stages) was employed at the pressure ratio of 43:1 and LHS PCM AlSi12 was used to absorb and release heat from and to the air.

Chen. et al. [82] designed and analysed a pumped hydro compressed air energy storage system (PH-CAES) and determined that the PH-CAES was capable of operating under near-isothermal conditions, with the polytrophic exponent of air = 1.07 and 1.03 for power generation and energy storage, respectively, and a roundtrip efficiency of 51%. Further, high system round-trip efficiency depends on system components with high individual efficiencies. For example, PH-CAES can reach 63% efficiency when the efficiency of the hydro turbine generator units is 90%.

As a result of the difficulty of proving such a concept, there are currently no commercial applications [71].

2.4. Droplet-Based I-CAES

To achieve near-isothermal, high-efficiency CAES systems, spray cooling with liquid droplets has been proposed [27]. This method significantly increases the heat transmission rate. This system is improved by increasing the surface area of the heat transfer system by using a large number of tiny droplets [27,83]. Figure 8 shows an example of a CAES system that uses liquid droplets to manage air temperature changes. A liquid (water or oil) is injected into the chamber during air compression; then, the liquid is separated from the gas and collected in a TES for later use; lastly, the warm liquid is injected back into the air flow during expansion [84].

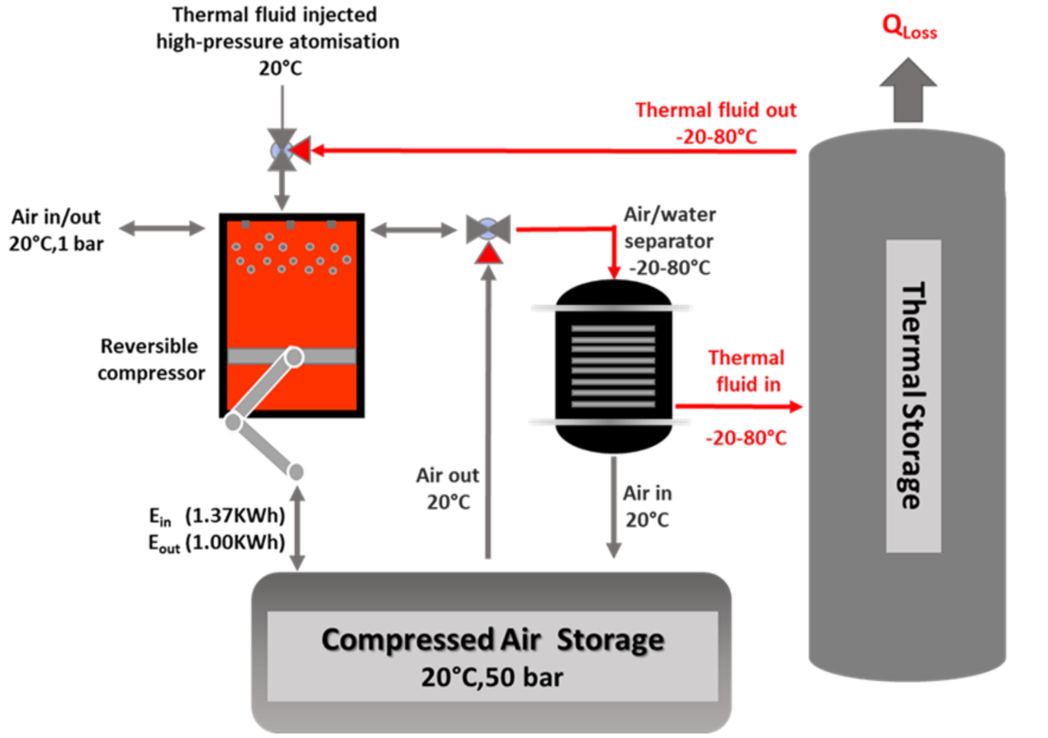

Figure 8. Schematic diagram of a droplet-based isothermal CAES (I-CAES) system producing 1.0 kWh output power, adopted from [84].

Compressing the air within the cylinder while injecting water droplets into the cylinder was found to reduce compressor work while increasing the output power of the gas turbine [85,86]. Zhang et al. [87] proposed a quasi-isothermal expander in which water droplets are injected into the expansion cylinder based on numerical modelling of reciprocating adiabatic expanders. In comparison with the adiabatic expander, numerical simulations indicate that the quasi-isothermal expander increases output work by 15.7% and decreases cylinder height by 8.7%.

2.5. Liquid Piston Air Compressor/Expander (LP-CAES)

A liquid piston air compressor/expander was proposed in 2009 by Van de Ven and Li [75] to reduce thermal energy losses during the gas compression and expansion processes. Figure 9 shows the operation of a liquid piston compressor/expander.

The liquid piston compresses gas directly in a vertically oriented chamber with a fixed volume using a water column. Due to the heat transfer between the gas and the liquid, gas compression and expansion are quasi-isothermal. The proposed liquid piston can be integrated into wind turbines to utilise seawater as a heat sink [27,33].

A liquid piston compressor/expander offers a number of advantages, including reduced air leakage due to a liquid column. Secondly, water sprays are more effective when using a liquid piston to compress a gas because they can simply fall into the interface with the water when compressing the gas. Additionally, as the liquid can conform to any irregularity in the chamber, the surface area to volume ratio, and hence heat transfer, can be maximized. It is possible to optimize heat transfer even further by placing porous inserts or longitudinal tubes above the solid piston within the compression region. Furthermore, air–liquid interfaces can be shaped in any irregular way [88]. CAES systems with closed storage chambers can minimize dead volume and improve pressure ratios and system efficiency by forming the top region of the chamber into a tapered cone rather than a cylinder. Consequently, the temperature and air pressure in the chamber fluctuates dramatically during the operation of the system [27]. A liquid piston CAES system with an open accumulator was developed by Li et al. [71] which can be integrated with wind turbines. In this process, seawater was used as a heat source/sink in order to reduce air temperature variations during compression and expansion as well as improve system performance. An analysis of a novel CAES system using a dual liquid, piston-open accumulator chamber was conducted by Saadat and Li [89], which can be integrated to wind turbines. Simple controls have also been developed to optimise the required output power, control system pressure, and capture of as much wind energy as possible. The use of porous media inside the liquid piston compressor/expander has been presented as a promising option for increasing heat transfer and thus improving system efficiency. Yan et al. [78] conducted a complete experimental study (10 bar) to examine the influence of porous inserts on the heat transfer mechanism in a liquid piston compressor/expander at low pressures. Three different types of interrupted ABS inserts and two different types of aluminium inserts were compared with a control case without inserts. Incorporating porous media into the liquid piston was found to improve heat transfer during air compression as well as expansion, improving the efficiency–power density trade-off. Air compression using porous inserts increases the power density by 39 times at a 95% efficiency, and when the power density remains constant at 100 kW/m^3, it increases by 18%.

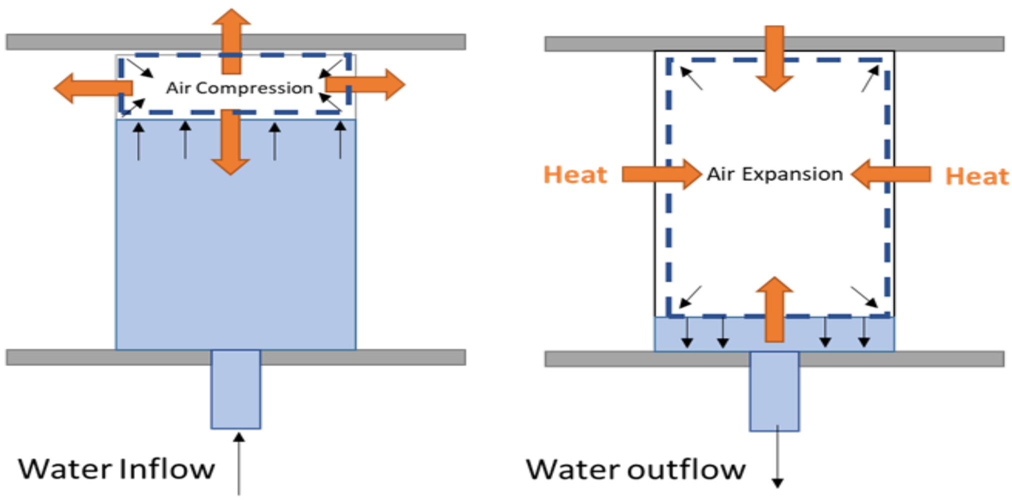

Figure 9. Schematic diagram of a liquid compressor/expander.

Wieberdink et al. [90] examined the effectiveness of porous media in enhancing liquid piston compressor/expander performance at high pressures between 7 and 210 bar. When compressed and expanded, uniformly distributed porous inserts with 93% efficiency increased power density by 10 and 20 times, respectively. Porous media can also increase efficiency during air compression and expansion by 13% and 23%, respectively. Zhang et al. [87] investigated the effect of porous media on the thermal behaviour of air inside a liquid piston compressor/expander by using computer simulations.

2.6. Ocean CAES (OCAES)

Ocean CAES (OCAES) is another form of CAES system, in which the air temperature remains close to constant during compression and expansion [27]. Isothermal or quasi-isothermal process produces the least amount of thermodynamic work during compression while producing the most work during expansion [4], and thus a higher efficiency. There has been little attention paid to underwater compressed air storage due to the limited number of commercial-scale systems. The components of this system are a fixed storage site in the ocean or a lake and a compressor located on land that supplies pressurised air to the storage site [91]. The technology has been studied in several research projects [92–94] with one recently implemented in Toronto, Canada [95].

The hydrostatic pressure in the ocean is employed in an Ocean CAES (OCAES) system to keep compressed air in the storage vessel, located at a fixed ocean depth at a constant high pressure. By operating at constant pressure, an OCAES system is more efficient than a constant-volume CAES system operating with large pressure gradients [34,96]. There are three kinds of OCAES systems according to how the compression heat is handled: adiabatic, diabatic, and isothermal. Figure 10 provides a schematic of these configurations. During the cooling process in the diabatic OCAES, the compressed air wastes heat through the surrounding environment. This heat must be compensated for prior to expansion by burning fossil fuels or other external sources of heat. In an adiabatic OCAES, the air thermal exergy is absorbed by a reliable TES at the compression outlet. This stored thermal exergy is used to pre-heat the air prior to the expander producing power. This near-isothermal OCAES system is achieved by using the liquid piston compressor/expander concept. Figure 10 lists an example of an isothermal OCAES system based on the liquid piston concept [97].

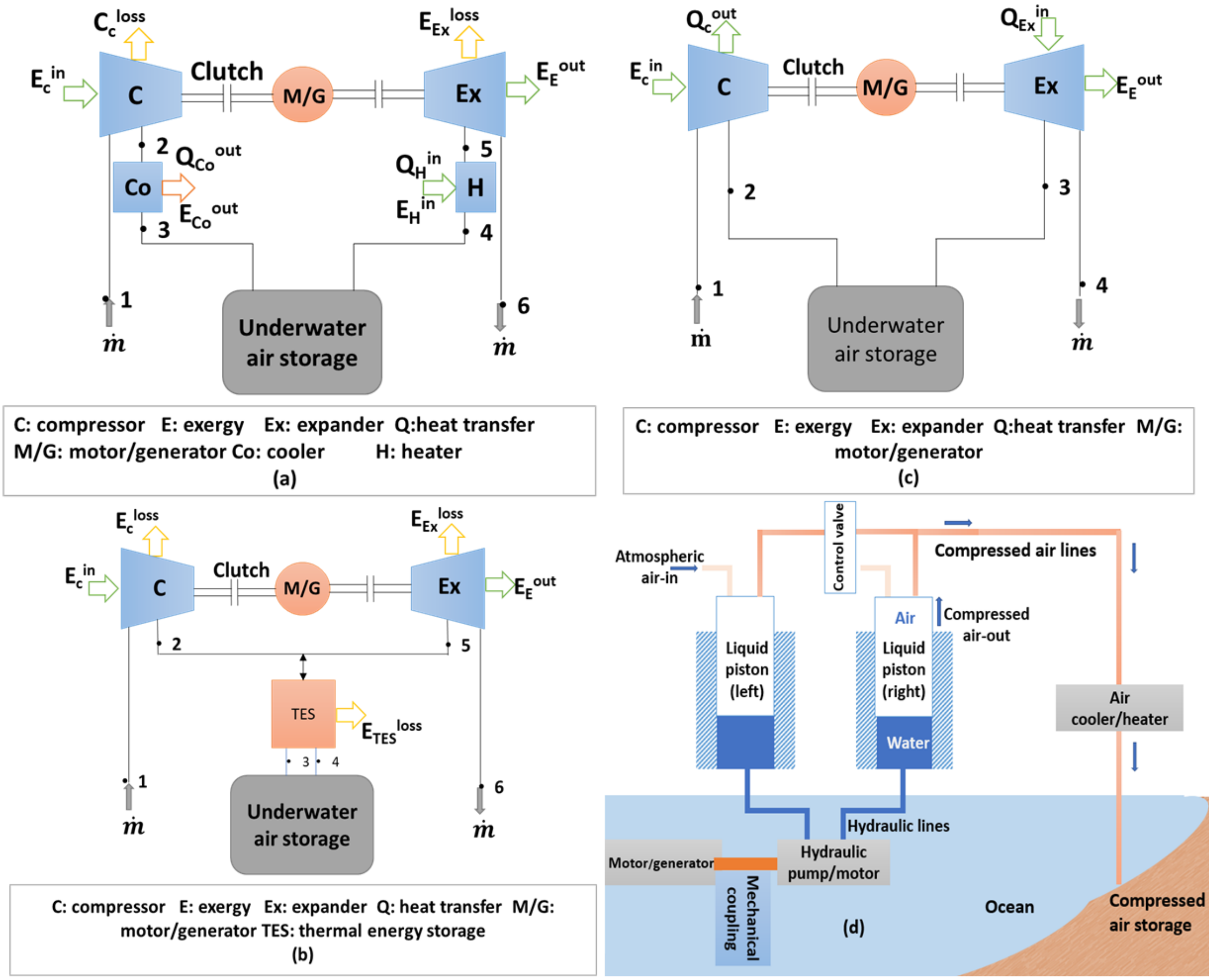

Figure 10. OCAES system: (**a**) diabatic OCAES, (**b**) adiabatic OCAES, (**c**) isothermal OCAES, (**d**) isothermal OCAES system based on the liquid piston concept.

Pumps/motors, electric motors/generators, compressed air storage, connecting lines, control valves, air coolers/heaters, and liquid piston compressors/expanders are the most important components of this system. The hydraulic pump is utilized in an isothermal OCAES to flow a column of liquid into the liquid piston (right), compressing the air as a result and transferring it to an underwater air storage chamber. In the power-generating phase, air is sent back to the liquid piston to drive the liquid out of the piston. After the liquid leaves the piston, it flows into the hydraulic motor that is mechanically connected to the generator [27].

Seymour [98,99] introduced the concept of an OCAES system as a modified CAES system as an alternative to underground cavern. An ocean-compressed air energy storage system concept design was developed by Saniel et al. [96] and was further analysed and optimized by Park et al. [100]. A first approach, described in "Ocean Energy On Demand Using Under Ocean Compressed Air Storage" [98], could produce 1 GWhr of electricity, while a second approach, described in "Undersea Pumped Storage for Load Levelling" [96], could produce 230 MW of electricity during the course of 10 h. In an exergy and energy analysis, Patil and Ro [97] evaluated several types of OCAES systems, including diabetic, adiabatic, and isothermal.

An OCAES system with a maximum power of 0.5 MW and an energy storage capacity of 2 MWh was evaluated at a depth of 100 m with a constant pressure of 10 bar. As shown in Figure 11, the isothermal OCAES had the highest overall exergy efficiency of 70%, while the diabatic OCAES had the lowest overall exergy efficiency of 55%. Patil and Ro [97] conducted an exergy analysis to examine the exergy flow and efficiency of different OCAES systems. Patil et al. [101] examined the end-to-end efficiency of an OCAES by using analytical and numerical models to examine how the polytropic index and pressure ratio affect an air compressor/expander. The OCAES system efficiency may be increased from 24% to 72% by lowering the polytropic index from 1.4 to 1. In addition, it was discovered that decreasing the pressure ratio can improve the efficiency of air compression and expansion.

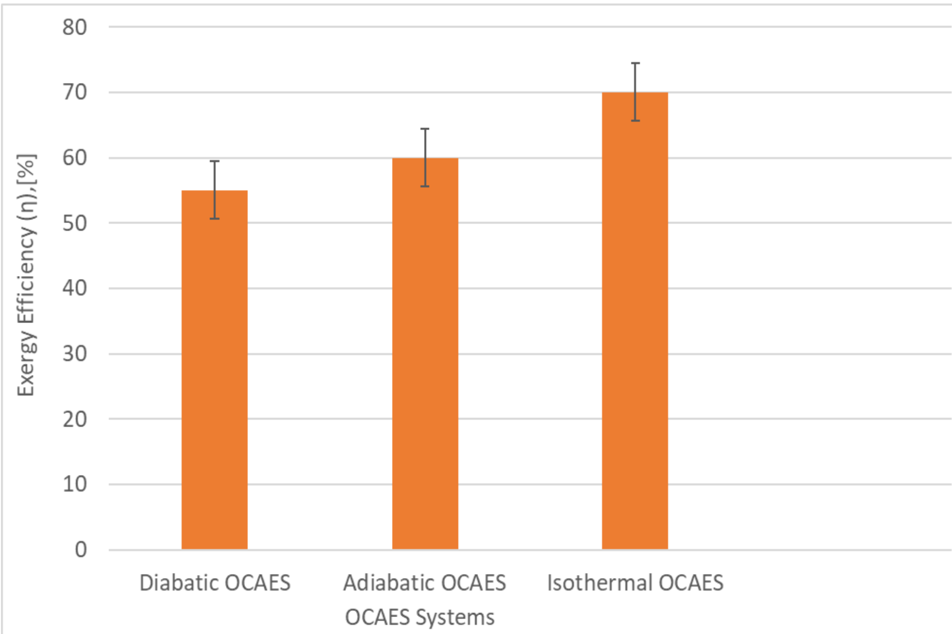

Figure 11. Exergy efficiency of various types of OCAES.

Patil et al. [101] investigated various heat transfer enhancement techniques to a liquid piston-based OCAES system. They found increases in the end-to end efficiency from applying an optimal trajectory during compression (5%); introducing hollow spheres (9%); introducing porous inserts (17%); and spray cooling (17%).

Sheng et al. [102] investigated a hybrid Marine Current Turbine (MCT) farm-OCAES to fulfil a stand-alone island's main power supply using tidal marine resources. Each component of the proposed hybrid system was modelled in this study, and the system was then analysed using various test scenarios. The cycle efficiency of the simplified OCAES was found to be 60.6% [96]. Additionally, the findings indicated that the proposed hybrid system is capable of operating effectively and continuously even under extreme load conditions.

Table 3 below summarizes the various methods used to enhance the performance of the CAES system by increasing the amount of heat transferred during the compression and expansion of air.

Table 3. Review of the various methods used to improve heat transfer [78,88,90,93,95,102].

Method of Enhancing Heat Transfer	Impact
A process of injecting small liquid droplets into the air at a high mass flow rate while being compressed.	The compression efficiency can be increased by up to 98%.
Compressing air using Pareto's optimal trajectory in a liquid piston.	An increase of 10–40% in power density.
Inserting porous inserts into a liquid piston at low pressures.	Increased power density by 39 times and increased efficiency by 18%.
Inserting porous inserts into a liquid piston under high pressure.	20 times increase in power density and a 23% increase in efficiency.
Utilization of hollow spheres.	The peak air temperature of the system was reduced by 32 °C and the end-to-end efficiency of OCAES was increased by 9%.
The OCAES uses spray cooling and porous media.	End-to-end efficiency improved by 17%.

Recently, a concept has been proposed for isothermal air compression that has a high efficiency. The Air Battery is illustrated as a unique CAES system for storing air isothermally by displacing air with water, with a round-trip efficiency of 81% [103–105]. As the isothermal compressor tanks fill with water, a pump pressurizes the water. As the air pressure rises, compressed air is pushed into one of the compressed air storage tanks. Using compressed air, water is pushed into a hydropower turbine, which generates electricity. This system has the highest round-trip efficiency of any operating CAES system to date. There are, however, two major disadvantages to this technology: (a) the high cost of storing air in pressure tanks (estimated at $250 per kWh) and (b) the variable pressure from the storage tanks lowers the system's storage capacity; Hunt et al. attempted to address these issues in their latest research [103].

A unique solution developed by Hunt et al. [103] combines isothermal compression with the use of high-pressure compressed air storage tanks in the deep ocean (IDO-CAES). As a result of the study, it was found that the IDO-CAES is especially effective for storing significant amounts of energy over extended periods of time, such as seasonal or pluri-annual storage cycles. Moreover, the study examined the technology's techno-economic feasibility in comparison with other EES systems. In addition, the study analysed the global potential of IDO-CAES using GIS-based analysis, providing the first assessment of its potential contributions.

3. Performance and Operating Conditions of D-CAES, A-CAES and I-CAES

CAES systems are operated with a variety of expansion machines. A high-quality performance can only be achieved when appropriate compressors and expanders are used [106]. A CAES system's performance is significantly affected by the effectiveness of its compression and expansion processes since these processes are the "interfaces" by which different energies are transferred, and where significant exergy losses are typically experienced. Several studies have indicated that the compressor and expander/turbine isentropic efficiencies have the greatest overall influence on CAES performance [52].

Traditionally, the efficiency of conventional D-CAES is determined by the maximum operating temperature, based on the Carnot efficiency of heat engines. Conversely, theoretically, the cycle efficiencies of storage systems with a single electrical input associated with A-CAES and I-CAES are not affected by the maximum operational temperature or storage temperature [51]. Table 4 contains information about the reported CAES systems, along with the operational conditions and important parameters associated with them including the highest operating temperatures found in D-CAES systems [4,7,28,72,77,107–112]. In practice, current advancements in compressors and expanders have restrictions on the limiting temperature of D-CAES. Due to the availability of gas turbine trains operating at a pressure drop of 11-1 bar, the air temperature at the inlet of the LP (low-pressure) turbine can reach more than 800 °C [51].

Table 4. Operating details of selected CAES systems.

System	Temperature [°C]	Pressure in Cavern/Tank [MPa]	Round-Trip Efficiency [%]	Ref(s)
D-CAES	Inlet temperature for LP [1] $\geq$ 850. Inlet temperature for HP [2] $\geq$ 550	$P_{max,cavern}$ = 7.2 P $o_{peration}$ = 4.8–6.6	η = 42	[17,113]
D-CAES (With recuperator)	Inlet temperature for LP ≈ 870 Inlet temperature for HP ≈ 540	P $o_{peration}$ = 4.5–7.4	η = 54	[113,114]
D-CAES	The maximum temperature is 1050. Outlet temperature of LT is 583. Exhaust temperature from HRSC 95	P = 6	η = 51.1 (CAES-CC) η = 53.4 (Recuperated CAES)	[24]
D-CAES	Inlet temperature of HP is 550 Inlet temperature of LP is 827 Temperature of exhaust gas is 204, Air temperature in cavern is 25	P $o_{peration,min}$ =4.2 P $o_{peration,max}$ = 7.2	η ≈ 45	[109]
A-CAES	Operating temperature range is 90–200	Two configurations were considered: one is 7.2 and the other is 15	η = 56	[51]
A-CAES & I-CAES	Max. temperatures for A-CAES are 623 and 239 For single-stage and two-stage compression, respectively. Maximum temperature is 80 for I-CAES systems for both configurations	Two pressure ratios: for single-stage compression/expansion the ratio is 50 & (~5); for two-stage compression/expansion the ratio is 7.1 and 7.1 (~5)	A-CAES (Single-stage) η = 23.6 A-CAES (Two-stage) η = 48.6 I-CAES (Single-stage) η = 70.6 I-CAES (Two-stage) η = 73.9	[34]
A-CAES	Max. temperature is 400	$P_{max,cavern}$ = 6.6 $P_{min,cavern}$ = 4.6	"Hypothetically" 79.2 if heat exchanger efficiency is 0.7	[115]
A-CAES	Exhaust temperature is 3 Air temperature at compressor outlet is 159. Air temperature at air turbine inlet 130.	$P_{max,tank}$ = 3.5 $P_{min,tank}$ = 2.5	ηs_{torage} = 57	[69]
A-CAES	Max. temperature is ≈150. Exhaust temperature is 15.	Pressure ratio 90	η= 50–75 [3]	[116]
I-CAES	Ideal isothermal constant temperature	P_{max} = 1	η ≥ 90	[33]
I-CAES	Isothermal constant temperature. Temperature difference ≤ 5.	P $o_{peration}$ = 20–35	η= 74.8 [4]	[77]

[1] LP: Law pressure. [2] HP: High pressure. [3] The typical cycle efficiency depending on the number of stages and the efficiency of the turbine. [4] For entire wind & CAES system.

The high HP (high pressure) gas turbines have a large pressure drop of 42-11 bars, so D-CAES systems, including the Huntorf plant, designed the HP turbine in accordance with "steam turbine engineering" principles [51]. As a result, the HP turbine's inlet temperature is only

550 °C, which is lower than the current standard for steam turbine operation. Foley et al. [117] analysed the comprehensive operations for these two plants, Huntorf and McIntosh.

In contrast, the listed A-CAES system performance can have a wide range of operating temperatures, usually 150 to 650 °C. The recent performance and availability of high-temperature TES usually place restrictions on the upper limit of the operational temperature [118]. It is predicted that the operating temperature of TES will increase significantly as a result of rapid TES development. Until now, different applications and groups have chosen different operating temperatures and TES types based on their requirements. The AA-CAES Project comprises 19 different partners and is thought to cover the complete spectrum of thermal storage devices, including phase change, high heat capacity solid and liquid media, and hybrid devices. As a result of the advantages of a high surface area for heat transfer and affordable storage materials, He and Wang [4] selected solid media (natural stone, concrete, fireproof material, and metal) for use as TES. They did, however, mention the need for expensive pressurised containers to contain the solid TES. Liu and Wang [119] conducted a sensitive analysis of compressed air temperature at the inlet of HP turbines using thermal oil as the sensible TES medium in a temperature range from 490 K to 580 K. According to their findings, the A-CAES improved total energy efficiency and round-trip efficiency. Yang et al. [115] developed a modified A-CAES system by analysing many sensible heat storage materials from the literature [4,120]. Using wind power, the system was called hybrid thermal–compressed air energy storage, which further increased the temperature of the heat storage (theoretical analysis indicated the maximum temperature of TES could reach 1273 °C) [115]. As compared to A-CAES integrated with a sensible TES, there is a limited number of published works using latent TES. A-CAES has been investigated by Peng et al. [121] using packed bed thermal energy storage (PBTES) loaded with PCM particles. Moreover, hybrid sensible/latent TES has been demonstrated in A-CAES systems that employ a packed bed of pebbles on top and encapsulated PCMs, where the stored temperature reached 600 °C [108]. As a promising method of storing heat with sensible (solid particles) or/and latent (PCMs), PBTES [122] appears to be an attractive and promising technology. It has been studied in energy-saving buildings and solar thermal energy [123–126].

Tian and Zhao [127] summarized and listed several commercial PCMs and inorganic salts, which are discussed in [127] which is based on [128]. These materials have latent heats ranging from 124 to 560 kJ/kg and phase change temperatures ranging from 100 to 897 °C. Consequently, the PCM's optimal operating temperature demonstrates the potential for use of the latent heat TES in A-CAES systems [128]. Moreover, the high energy density of latent heat storage means that a certain amount of heat can be stored within a smaller area in an ACAES system due to its high energy density. A PCM's behaviour of near isothermal heat transfer during the phase change period may improve heat transfer and provide optimal air temperature control when the PCM behaves in this manner. The studies of PBTES with a cascade of PCM filling [129] further demonstrated that performance enhancements may be achieved with the best PCM fillings in terms of material combinations and selections [4]. There is, however, a problem with the poor thermal conductivity of PCMs that must be addressed by new composite PCMs or by heat transfer improvement methods. An assessment of published literature indicates that there is no integration of thermochemical TES with A-CAES at present.

Furthermore, an isothermal CAES is expected to maintain a constant operating temperature from charging to discharging. I-CAES systems, however, are typically operated at near-isothermal temperatures due to the difficulty of achieving isothermal compression and expansion. During compression and expansion, temperatures rise and fall slightly, respectively. A variety of experimental or theoretical I-CAES systems have been studied using different operating pressures and temperatures in Table 4.

According to Park et al.'s computational analysis of a quasi-isothermal thermodynamic cycle for an undersea CAES, the final mean temperature increased by just 26.6% as air pressure increased to 25 bar [100]. Yan indicated that shorter compression/expansion times lead to a higher temperature rise, which is more similar to the adiabatic process [78]. In order to overcome the trade-off between power density and thermal efficiency of I-CAES systems, porous media inserts have been employed to enhance heat transmission [130]. As a result of the computational findings, it has been shown that if the metal foam covers the entire chamber length, the bulk temperature remains below 360 K (575 K for adiabatic systems) [130]. Additionally, porous inserts increased power density by 39 times at 95% efficiency and improved efficiency by 18% at 100 kW/m^3 power density in compression; in expansion, power density increased three-fold at 99% efficiency and efficiency improved by 7% at 150 kW/m^3 power density [78].

Moreover, the operating pressure of the three CAES systems differs slightly in addition to the operating temperature. In a conventional D-CAES system, the compressed air pressure may be adjusted to an appropriate value to fulfil the energy and power requirements during the charge and discharge periods according to the integration of the gas turbine cycle and large cavern volume. In contrast, high pressure of the compressed air is usually applied because A-CAES and I-CAES are usually used in small- and micro-scale energy storage systems, such as the integrated CAES and wind turbine or other distributed energy generation systems, to ensure a high energy density of the storage and reduce the size of the electrical components [4].

In order to select the appropriate system type, system functionality (i.e., D-CAES, A-CAES, and I-CAES) and specific configurations/specifications, such as the rated power and energy capacity of the system, are considered. The D-CAES and A-CAES systems are suitable for grid-scale energy storage applications (100 MW and 1000 MWh), while the A-CAES and I-CAES systems may be selected for smaller CAES systems. A D-CAES system is the least expensive and has the highest level of technological maturity among the three system types. On the other hand, D-CAES systems are powered by fossil fuels and emit sulphur dioxide, nitrogen oxides, and carbon dioxide. However, D-CAES has been regarded as a technology with a generally minimal environmental impact [112]. According to local regulations, penalties for these emissions may increase the lifecycle costs of D-CAES systems. As A-CAES and I-CAES systems do not require burning fossil fuels, their implementation depends primarily on the configuration of the system and expanders. As A-CAES and I-CAES are still in the pre-commercialization stage, both technical performance and cost-effectiveness of these systems must be demonstrated [4]. The basic requirements for achieving cost-effectiveness over the duration of a life cycle are a high degree of reliability and stability of the system performance. Based on operational data from decades of operation, it has been demonstrated that large-scale DCAES systems have extremely high storage reliability and running reliability over both charging and discharging periods. In contrast to D-CAES, the efficiency of heat storage and heat transfer also affects the reliability of novel A-CAES and I-CAES systems. High exergy capacity and low power loss of heat and gas storage are critical requirements for the durable performance of these advanced CAES-TES systems.

According to Budt et al. [13], the CAES lifecycle economic cost has a significant influence on the selection of the system. Several factors contribute to the economic aspects of grid-connected energy storage applications, including country-specific market conditions, legislation, and political structures. Micro-grid, off-grid systems have a payback period determined by CAES capital and maintenance costs. In a scenario in which the CAES system cost is comparable to other technological solutions, it is commonly referred to as a cost-effective, off-grid CAES system. Because CAES systems require less maintenance, the capital cost of the system dominates the life-time cost. Despite the high capital cost associated with large-scale CAES systems, the system's long lifespan and minimal waste materials mitigate the negative effects of the high capital cost and reduce the system life cycle costs. In these CAES systems, high-pressure containment is a significant component of the capital cost. According to White et al. [7], containment costs are proportional to internal volume and pressure. This pressure-dependent containment cost governs the cost of vessel-based gas storage in all system types as well as for the high-pressure heat reservoirs used in A-CAES systems. Currently, Lightsail is working to reduce costs by using advanced carbon fibre tanks rather than steel pressure vessels [4].

4. CAES Variants and Integrating of CAES Systems with the Renewable Energy Storage Technologies

Most research on CAES systems has focused on the concept of integrated CAES systems or integrating CAES units with conventional or renewable power plants as part of this system [131], as the compressed air is generated using surplus power production and stored until being converted into electricity. For example, Arabkoohsar et al. [132] examined the technoeconomic of CAES units combined with solar energy in the north of Brazil and conducted a feasibility study involving a gas station [133].

A study conducted by Jin et.al [134] investigated the possibility of reducing wind power fluctuation by combining a CAES unit with a wind farm. The analysis revealed the possibility of supplying more wind power with greater stability to the local grid. Wang et al. [135] developed and optimized a combined cooling, heat, and power (CCHP) plant using CAES, solar energy, and gas. Later, the same team performed an off-design performance analysis in order to determine the impact of partial load operation on the hybrid system's productivity and efficiency [136]. The literature suggests combining CAES systems with other energy systems. The CAES-multi-effect seawater desalination (MED) system is an example of such a system [137].

The CAES technology is similar to several more recent and older energy storage designs that have similar characteristics, but do not follow the exact same principles as CAES systems. These include technologies for humidifying compressed air storage (CASH). A CASH system is a CAES system equipped with an air saturator (to humidify the airflow before expansion), thus improving round-trip efficiency. An overview of this technology can be found in [39].

It is also possible to store large amounts of energy at a smaller size than a CAES system with liquid air energy storage systems (LAES), which store liquid air (or liquid nitrogen) rather than compressed air [83]. This supercritical CAES (SC-CAES) system has been developed as a result of recent developments in LAES technology that aim to improve efficiency [138]. A SC-CAES system has a 70% higher efficiency than a LAES system while not being constrained by the constraints of current air liquefaction technology, and a significantly higher energy density than conventional CAES technologies (over 18 times greater) [83,138].

5. Conclusions

With excellent storage duration, capacity, and power, compressed air energy storage systems enable the integration of renewable energy into future electrical grids. There has been a significant limit to the adoption rate of CAES due to its reliance on underground formations for storage. This paper presents an updated review of the CAES, which focuses on comprehensive trends in technology development, CAES characteristics and main classifications, particularly in light of the different perspectives on designing and integration:

- CAES systems' high energy capacity, high power rating, and long life span of around 40 years make it suitable for stationary and large-scale applications.
- CAES suffers from relatively low energy efficiency (between 40 and 70%), and there is much interest in its integration with different cycles to recover waste heat and to reducing exergy destruction.
- It is also necessary to integrate CAES with renewable energy sources in order to increase renewable penetration and system reliability.
- It is necessary to improve the performance of CAES technologies in order to extend their competitiveness, affordability, and efficiency for large-scale applications.
- To avoid under-sizing, over-sizing, decreased profitability, or decreased reliability, optimum capacity for a given pressure range of the air reservoir is required.

- Figure 12 below provides a comprehensive summary of the main advantages and disadvantages of the CAES classifications.

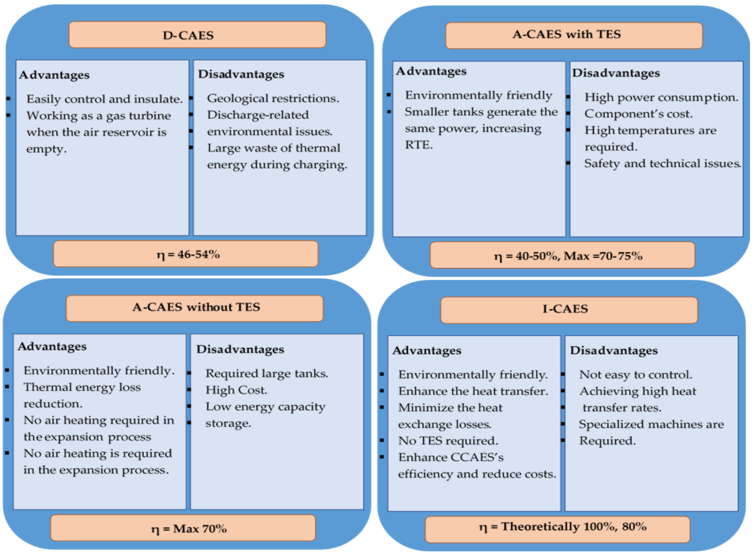

Figure 12. Main advantages and disadvantages of the CAES classifications.

Even when CAES is integrated with intermittent renewables and operates under off-design conditions, the integrated system may not operate at its peak performance without the optimal performance of its key components.

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