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Review

Status and Development Perspectives of the Compressed Air Energy Storage (CAES) Technologies—A Literature Review

Marcin Jankowski *, Anna Pałac, Krzysztof Sornek, Wojciech Goryl, Maciej Żołądek, Maksymilian Homa and Mariusz Filipowicz *

Department of Sustainable Energy Development, Faculty of Energy and Fuels, AGH University of Krakow, 30-059 Krakow, Poland; anna.palac@agh.edu.pl (A.P.); ksornek@agh.edu.pl (K.S.); wgoryl@agh.edu.pl (W.G.); mzoladek@agh.edu.pl (M.Ż.); maksymilian.homa@agh.edu.pl (M.H.)
* Correspondence: mjankowski@agh.edu.pl (M.J.); filipow@agh.edu.pl (M.F.)

Abstract: The potential energy of compressed air represents a multi-application source of power. Historically employed to drive certain manufacturing or transportation systems, it became a source of vehicle propulsion in the late 19th century. During the second half of the 20th century, significant efforts were directed towards harnessing pressurized air for the storage of electrical energy. Today's systems, which are based on storing the air at a high pressure, are usually recognized as compressed air energy storage (CAES) installations. This paper aims to provide an overview of different technologies that take advantage of the energy accumulated in the compressed air. Particular attention is paid to the CAES installations that are working as electrical energy storage systems (EESs). These systems, developed originally as large capacity (>100 MW_e) and fuel-based installations, may soon become fully scalable, highly efficient, and fuel-free electrical energy storage systems. To present this opportunity, a thorough review encompassing previous and up-to-date advancements in their development was carried out. In particular, CAES concepts, such as diabatic (D-CAES), adiabatic (A-CAES), and isothermal (I-CAES), are described in detail. This review also provides the detailed characteristics of the crucial elements of these configurations, including compressors, expanders, air storage chambers, and thermal storage tanks. Knowledge of these components and their role allows us to understand the main challenges behind the further development of the mentioned CAES setups. Apart from the CAES systems that are designed as EES systems, this paper describes other prospective technologies that utilize the energy of pressurized air. Accordingly, compressed air cars and their key elements are explained in detail. Moreover, the technology renowned as wave-driven compressed air energy storage (W-CAES) is described as well, indicating that the utilization of pressurized air represents a viable option for converting ocean energy into electrical power.

Keywords: CAES; compressed air; energy storage

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1. Introduction

The International Renewable Energy Agency (IRENA) reports that global power generation could potentially reach 89.8 PWh_e by 2050, indicating a substantial rise from the 2020 level of 27.0 PWh_e [1]. The rapid expansion of global energy consumption underscores the need for the advancement of technologies that ensure energy savings as well as the robust supply of electrical power. Compressed air represents a multi-application thermodynamic medium that can serve both as the energy accumulator and the source of power utilized to drive certain types of machines, such as turbogenerators or vehicle engines. Today's systems, which are based on the conservation and utilization of pressurized air, are usually recognized as compressed air energy storage (CAES) systems.

The practical use of compressed air dates back to around 2000 B.C. when bellows were used to deliver a blast of air for the metal smelting process [2]. In 1762, classical bellows began to go out of use due to the invention of the first mechanical air compressor that was developed by J. Smeaton [3]. Nearly a century later (1861), compressed air at a pressure of 6 bar was employed to power pneumatic drills during the construction of the Mont Cenis Tunnel, linking Italy with France [4]. From 1881 to 1994, the city of Paris distributed air at a pressure of about 6 bar through a 900 km city-wide pipeline system. At some point, compressed air was distributed to about 10,000 end users, and employed to power clocks, sewing machines, and workshop devices [5]. Another interesting concept utilizing compressed air has become known as the Urban Pneumatic Mail System (or pneumatic tube mail). This was a historical communication system utilized in urban areas for the rapid transmission of mail and small parcels through a network of pneumatic tubes. This innovative system was prevalent in the late 19th and early 20th centuries, revolutionizing urban communication and postal services. An exemplary deployment of this concept was the pneumatic tube mail system installed in Prague, Czech Republic. This system featured five main lanes arranged in a star topology, with lanes of a total length of about 55 km [6].

In the first half of the 20th century, the idea of using compressed air as electrical energy storage was proposed. The first such concept was developed in 1943 when F.W. Gay submitted his patent entitled: 'Means for storing fluids for power generation' [7]. Already at that point, the author proposed to store off-peak electrical energy by compressing air with an electric-driven compressor and storing it in a special underground chamber. During on-peak demand, the pressurized air would be reheated and expanded in the turbine to drive the electric generator. Although not commercialized for the next 20 years, the technology described in the patent formed the foundation for developing electrical storage systems that utilize the CAES concept.

Most of the currently studied CAES concepts refer to their application as electrical energy storage (EES) systems. These systems are designed to optimize the production of electricity in both conventional large-scale power plants and renewable power systems. The efficiency enhancement of the power plants supplied with fossil or nuclear fuels typically involves modernizing the components of the plant or recovering waste heat within the plant. However, the performance of the power plant can also be improved by implementing an EES system that is based on the CAES concept. This involves storing inexpensive off-peak power from the baseload generation and transferring it back during peak-load hours [8]. The conservation of electrical energy during low-demand periods also allows a reduction in the adverse effect of negative energy pricing, which increases the economic performance of the power plant. The usage of the CAES electrical storage system can also improve the performance of renewables, such as wind turbines (WTs) or solar photovoltaic panels (PVs). This is because both wind and solar energy feature diurnal and seasonal intermittency [9], making the energy supply from WTs and PVs discontinuous and volatile. By saving the electrical output of WTs and PVs in a CAES-based EES system, the surplus energy that would otherwise be wasted during off-peak hours can be conserved and deployed later during periods of peak demand.

Among other EES technologies that can be applied at grid-scale (>1 MWh), pumped hydroelectric energy storage (PHES) maintains a dominant position, representing 99% of all electrical storage plants, with a total installed power output exceeding 181 GW [10]. The insights gained from the operation of existing PHES plants demonstrate their long lifespan (20–40 years) and ability to achieve a round-trip efficiency of up to 90% [11]. However, the application of PHES installations is constrained to mountainous areas, where there are substantial elevation differentials and sufficient water reservoir volumes. Another option for a grid-connected EES system is electrochemical batteries (EBs), with a significant focus currently placed on those based on Lithium-Ion (Li-Ion) technology. Li-Ion batteries offer several advantages, such as a high energy density (150 Wh/L–500 Wh/L), excellent round-trip efficiency (up to 95%), and fast charging capabilities [12]. It must be noted, however, that they are also prone to leakage and electrolyte evaporation, which can pose safety risks and reduce their life span. Moreover, the materials used in Li-Ions, such as lithium, cobalt, or nickel, can be expensive and subject to price fluctuations [13]. Other EES technologies, such as supercapacitors, flywheels, and superconducting magnets, also represent an interesting option. However, they are all characterized by low storage capacities (<1 MWh) and short discharging times [6], making them applicable mainly for short-term energy storage applications. Meanwhile, CAES technology presents a great prospect in terms of scalability, enabling the storage of electrical energy at both grid-scale levels (>1 MWh) and in small-scale energy systems (<1 MWh) [12].

The implementation of a CAES that was adapted to store electrical energy began in 1969 [14] with the decision to develop the diabatic CAES (D-CAES) installation in northern Germany (Huntorf). The project was aimed at storing off-peak baseload power and providing black start capability for the local grid [15]. The installation was successfully commissioned in 1978 and is operating to this day. However, due to the significant heat losses that are generated during the air compression and a need for combusting natural gas to heat up the pressurized air, the round-trip efficiency of the Huntorf plant is relatively low (42%). In the mid-1970s, the American Department of Energy (DOE) launched an R&D program that was aimed at decoupling CAES systems from fossil fuels [16]. Within the project, newer configurations, such as adiabatic (A-CAES) and isothermal (I-CAES) systems, were proposed with the purpose of minimizing the dependence on external fuel and increasing the storage cycle efficiency. However, their development was eventually suspended, mainly because D-CAES was considered a feasible and near-term technology [2]. Consequently, the first CAES system that was launched in the USA was a D-CAES plant located at the McIntosh site [17]. Compared to the Huntorf installation, the McIntosh plant incorporated heat recuperation in its design, resulting in fuel savings and an improved round-trip efficiency of 54%. Both Huntorf and McIntosh utilized huge underground salt caverns in order to store the pressurized air. Despite significant interest in D-CAES technology that followed the successful completion of the Huntorf and McIntosh projects, they remain the only large-scale D-CAES plants currently in operation.

The Huntorf and McIntosh are both large capacity (>100 MW_e) CAES systems designed to perform baseload shifting and provide a reserve power supply. Meanwhile, with the development of systems that are based on variable renewable sources (solar and wind), the focus is on mitigating their intermittency, providing significant energy preservation and a better viability of PV and WT plants. Furthermore, these systems can be constructed at various scales, covering a wide range of installed power outputs. The latter raises the need for a scalable CAES technology with a broad spectrum of potential power outputs. The cycle efficiency must also be increased, bringing it closer to the levels achieved in PHES or EBs. These objectives can be achieved by a more rational use of the fuel in a D-CAES configuration (see Section 4.1) or through the application of the already-mentioned A-CAES and I-CAES concepts. A-CAES systems operate by saving the otherwise wasted heat of compression, which substantially increases the cycle efficiency (see Section 2.2). The crucial component influencing the A-CAES performance is the thermal energy storage (TES) tank, which accumulates the heat generated during the air compression. Designing a TES tank for an A-CAES presents a significant challenge, prompting extensive investigation and research activities. With regard to I-CAES installations, the compression and expansion of air occur under near-isothermal conditions, significantly enhancing the thermodynamic performance of these processes and ultimately improving the overall efficiency of the CAES system. The methods that are investigated for conducting isothermal compression and expansion are described in detail in Sections 4.1 and 4.2. Regardless of the type of the CAES electrical storage plant, the key component is the chamber that stores the pressurized air. As already mentioned, Huntorf and McIntosh utilized solution-mined salt caverns of a large volume (>300,000 m^3) [18]. Partly for this reason, the CAES has historically been perceived as a technology that strongly depends on suitable geographical conditions, much like PHES systems. To overcome this problem, scholars and engineers have suggested alternative air storage chambers, such as aboveground pressure vessels, underwater containers, or small lined rock caverns (LRCs). Owing to these solutions, the variety of potential locations for CAES systems has substantially expanded, allowing for a more flexible and location-independent design of the CAES plants.

Ongoing studies focus primarily on the more efficient use of pressurized air as electrical energy storage. In particular, significant efforts are directed into the development of a fuel-free, highly efficient, and scalable CAES electrical storage plant. This study describes the existing solutions, current advancements, and future prospects related to the development of these installations. Apart from a thorough description of the CAES systems that work as EES systems (D-CAES, A-CAES, and I-CAES), the detailed characteristics of their individual components are also presented. In particular, various types of compressors and expanders are elucidated, including conventional dynamic units and extensively researched isothermal machines. Past experiences and future perspectives for A-CAES systems are also given, with a focus on the potential techniques for storing waste heat from the compression. Alternative technologies for storing the pressurized air are discussed as well, indicating that storing electrical energy with a CAES technology does not have to be constrained by specific location requirements. Additionally, this review underscores that pressurized air also has other prospective applications, including automobile propulsion systems and wave-driven compressed air energy storage (W-CAES) systems.

2. CAES Available Technologies

2.1. Diabatic (Fuel-Supplied) CAES

CAES electrical storage technology was first introduced as early as the second half of the 20th century [2]. The reason for increased research into this type of energy storage was the pursuit for alternatives to pumped storage power plants [19], which are subject to specific geographical restrictions. The aim of such systems is to store the energy produced during off-peak hours and release it at times of peak demand. Additionally, such installations can be used to restart the country's energy system in the event of a possible blackout [20]. In the first studies on CAES, numerous suggestions for improving its operation were considered [21,22], including adiabatic or isothermal operation concepts. Due to significant technological and economic difficulties, it was decided to implement a basic solution, which is currently known as diabatic compressed air energy storage (D-CAES)—see Figure 1. The D-CAES structure can be compared to a classical gas turbine (GT) system consisting of a compressor, combustion chamber, and expander (turbine). In contrast to the GT installation, the D-CAES operation is divided into two operation cycles, with the system charging that is performed in the compressor and the discharging that is completed in the turbine. Between the charging and discharging cycles, there is a phase of storing the compressed air in a cavern or any other type of chamber. Detailing the subsequent processes, the air is first compressed in the compressor. Before storing it in a cavern, it is cooled down in the heat exchanger. During peak energy demand, the pressurized air is directed to the combustion chamber to be mixed with fuel that is then combusted. The high-pressure and high-temperature flue gas can then be expanded in the expander to drive the electric generator that is mounted on the expander shaft.

In the case of D-CAES, the air is compressed outside the turbine system and stored in appropriate tanks [23] or, more often, in underground caverns [24] to be later fed to the turbine in the event of an energy requirement. When assuming the use of D-CAES systems for the above-mentioned purposes, it is important to bear in mind the requirement for a very high energy capacity (>500 MWh) and a short response time (of minutes) of the storage plant [6]. As air has a relatively low energy capacity, the requirement for large storage spaces arises. For this reason, the use of aboveground artificial reservoirs will very often be uneconomic for large-scale systems. As mentioned, the operation of D-CAES systems is divided into the processes of charging and discharging. When analyzing these stages, special attention should be paid to energy losses. During charging, the compressor increases the pressure of the medium up to 8 MPa [25,26]. As the air is compressed, a significant increase in its temperature is observed. When considering the options of using natural rock voids or aboveground tanks, the compressed air must be cooled. If this is not achieved, there is a high risk of damage to the reservoir and, thus, a reduction in the lifetime of the entire system. D-CAES assumes that the medium is cooled by exposing it to the ambient. Typically, heat exchange takes place using one or more intercoolers during the compression process and an aftercooler after leaving the compressor [18]. This means that thermal energy is practically completely lost in the process of charging the storage. In existing installations, the temperature of the air inside the tank is close to ambient conditions. When energy is required, the discharge process is initiated. Before the stored air is fed into the turbine rotor, it must be heated. This procedure is usually carried out by combining it with natural gas in the combustion chamber. As a result of the combustion of the mixture, high-pressure, high-temperature flue gases are emitted, which can then be directed to the turbine. This is where another disadvantage of D-CAES comes in, which is the need to supply additional heat to the working medium. This will usually be fossil fuel, the use of which is not optimal these days due to carbon dioxide emissions. For this reason, such systems are often called supplementary-fueled compressed air energy storage (SFCAES). Due to the requirement of supplying additional heat to the system, D-CAES is sometimes referred to as hybrid energy storage.

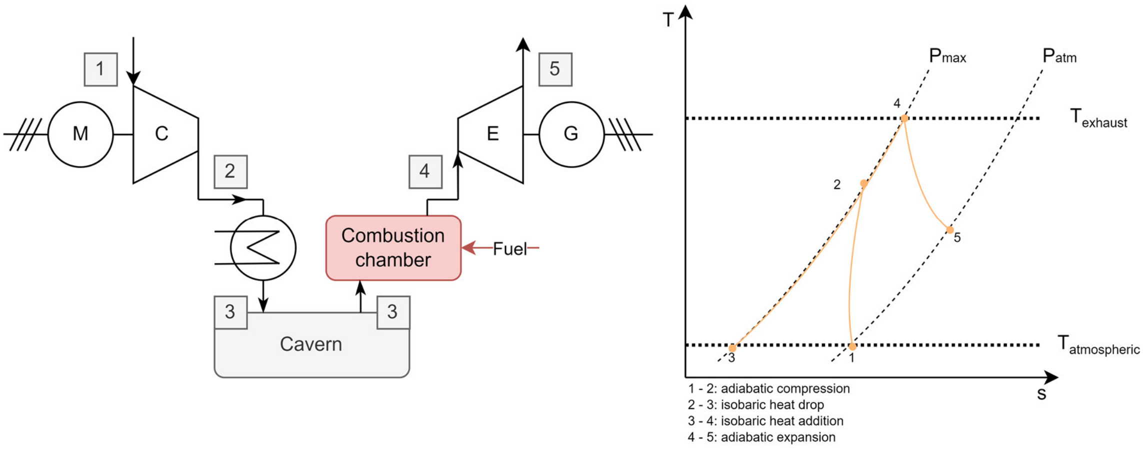

Figure 1. Schematic of the classical D-CAES system, where M—motor, C—compressor, E—expander, and G—generator.

Assessing the energy efficiency of D-CAES relative to other energy storage methods requires a special approach. There are two possible methods for determining the efficiency of D-CAES (Equations (1) and (2)) [27].

$$\eta_1 = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} \quad (1)$$

$$\eta_2 = \frac{E_{out,el} - E_{in,th} \cdot \eta_{ref}}{E_{in,el}} \quad (2)$$

where $E_{in,el}$ and $E_{in,th}$ represent the input electrical and thermal energies, respectively; $E_{out,el}$ is the output electrical energy; and η_{ref} represents the reference efficiency.

Equation (1) can be labeled as the basic approach. Both energy sources used throughout the process are then taken into account. The second formula assumes the use of the reference efficiency of a virtual system with the same source and energy input. If it is assumed that the D-CAES system operates on natural gas, the reference efficiencies will come from a system based on natural gas, such as a combined cycle gas turbine. When comparing different CAES technologies, Equation (1) should be used, while Equation (2) is applied when referring to other energy storage systems. The presence of heat loss during the charging process results in relatively low round-trip efficiencies. For the currently operating systems [25,26], it does not exceed 60%.

2.2. Adiabatic CAES

In adiabatic CAES, the heat generated during the compression cycle is not released into the atmosphere as in a diabatic CAES setup but is recovered and stored in a thermal energy reservoir (see Figure 2). While discharging the compressed air from the air storage chamber, the previously stored thermal energy is utilized to preheat the air and maximize the harnessed energy. The adiabatic CAES may recover the compression heat at different air temperatures (100 °C–600 °C), depending on the applied configuration of the compression system (see Section 4.2), as well as on the adopted TES and CAES technologies. Some A-CAES systems cool down the air after the compression to the temperature range of 30 °C to 50 °C [28]. This is a temperature level tolerated by the underground salt caverns, which have been considered as potential air storage chambers for the A-CAES installation. The literature also highlights advanced adiabatic CAES (AA-CAES) plants. These systems are usually referred to as A-CAES plants, in which the waste heat from the compression is recovered with a very high efficiency using specially designed heat exchangers [6].

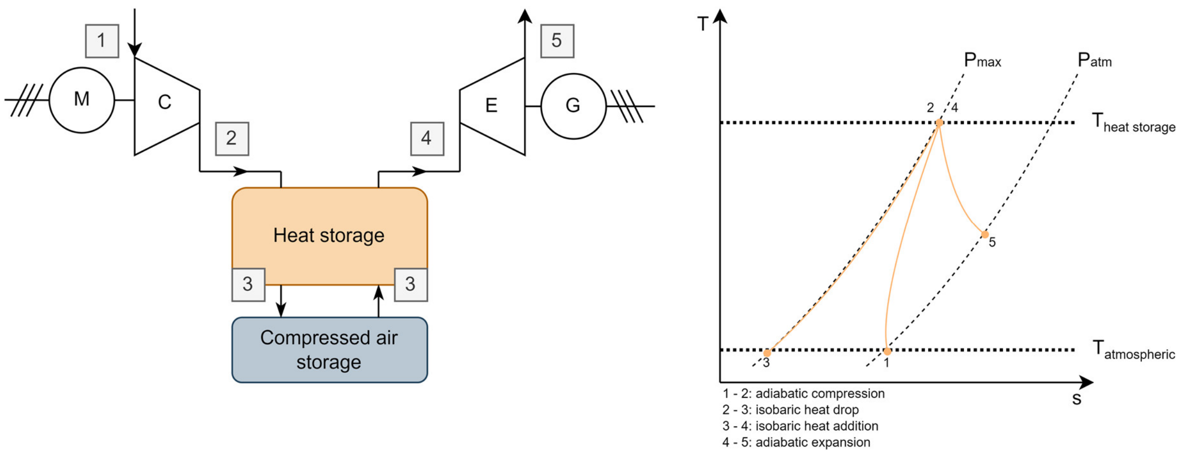

Figure 2. Simplified scheme of an adiabatic CAES, where M—motor, C—compressor, E—expander, and G—generator.

The calculation of the efficiency of adiabatic CAES differs from diabatic CAES, as no additional energy is delivered to the system during the discharge. The efficiency is simplified to the ratio of output energy to the input energy delivered to the system (Equation (3)).

$$\eta = \frac{E_{out,el}}{E_{in,el}} \tag{3}$$

The efficiency of A-CAES can be directly compared to other energy storage systems. The typical efficiency of its cycle ranges from 55% to 75%, peaking in A-CAES systems [29]. As the adiabatic CAES includes thermal energy storage (TES), the combined efficiency of both systems adds to the final value. This is one of the factors implying the importance of the selected TES. During the operation of any adiabatic CAES, large amounts of energy in the form of heat are transported from the compressor to the thermal storage and then to the expander. Due to the high operating temperatures of these processes and the induced thermal stresses, typical adiabatic CAES plants require additional time to reach their maximum efficiency after startup. For example, it took up to 40 min in a test A-CAES plant built by ALACAS [30].

A-CAES extends the typical CAES system with the addition of thermal storage and a heat exchange system. The typical A-CAES is composed of the following elements [30–32]:

- A compression unit, composed of single or multiple compressors, capable of withstanding high temperatures of up to 700 °C;
- A cooling unit, absorbing the heat from the compressed air, reducing it to the required low-level temperature, and transferring the heat to thermal storage;

- Thermal storage capable of withstanding high temperatures;
- Compressed air storage, typically operating in the range of 40 to 90 bar;
- A heating unit, preheating the air before expansion;
- An expansion unit, composed of a single or multiple expanders.

The key element in an A-CAES facility is the thermal storage unit, which eliminates the need for the extra fossil fuel heat that occurs in diabatic facilities. Depending on the chosen thermal storage system, cooling and heating units can be combined with the storage, i.e., in solid storage medium regenerators [33]. In adiabatic CAES, the thermal storage must meet specific technical requirements. These include the following [28,34]:

- Cooling the compressed air to the lowest possible outlet temperature during the charging process and heating the compressed air to the highest possible outlet temperature during the discharge process;
- Maintaining a low-temperature variation of the air leaving the thermal storage.
- Minimizing the pressure loss during the operation,
- Low idle state losses.

These requirements are met by a variety of thermal storage technologies, further described in Section 4.3. As indicated there, these systems can be categorized by how the air comes into contact with the thermal storage medium. The contact is either direct or indirect. The systems can be further classified by the type of heat transfer and storage medium [34]. In A-CAES systems, typically, a solid or liquid medium is used as they require a high thermal capacity of the storage [35].

Solid-state media with direct contact storage systems are frequently used in A-CAES. Such a system has the form of a pressurized chamber filled with a rock or ceramic material, allowing the air to pass through (Figure 3). During the compression cycle, hot air passes through the system, heating the solid medium. The flow of air is reversed through the decompression cycle, and the air is preheated before the decompression [36]. This type of thermal storage has the advantage of combining the heat exchanger and the storage into a single unit and does not require an additional heat transfer system. However, controlling the temperature of the exiting air is more challenging.

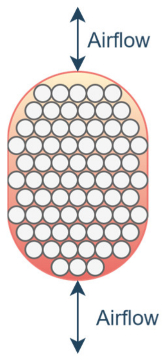

Figure 3. Vertical flow regenerator filled with a solid storage medium.

Another approach is an indirect contact, liquid medium system, such as the two tank system. Both the air and the heat transfer medium flow through the pipes layered in the heat exchanger. This system has two separate tanks, storing hot and cold media [37]. This approach eliminates the problem of the media mixing in the liquid storage, which may occur in the solution with a single tank. The pumps available in this type of system control the flow of the media, allowing a more precise control over the temperature of the heat exchanger; however, they require additional energy to operate [38].

In a high-temperature A-CAES design, the operating compressor heats the air to a high temperature of around 700 °C. The challenge faced here is that most of the widely available industrial compressors operate up to the temperature of around 400 °C [39]. While the compressors required by the system are being developed, new designs for an A-CAES plant are proposed (see Section 4.2). They utilize two or more compressors in a series layout, compressing the air in steps. At each intermediate point, the air is cooled, and the heat is transferred to the storage. With this approach, the temperature of the storage is lower, but it does not influence the efficiency of the storage, as this is determined by how well the collected heat is utilized, not by the storage temperature. However, the overall efficiency of such an A-CAES plant is reduced because of the transmission losses of both the air and media flowing through a complex system [40].

By comparison, A-CAES systems have a clear advantage over D-CAES systems as they contain and utilize the thermal energy generated during the compression process. Minimal additional energy is required to preheat the air during discharge, contrary to a diabatic CAES system [25]. Additionally, the stored air in an A-CAES system may have a low temperature, and there might be a wide range of possible storage solutions, which is an advantage over uncooled CAES. The cost of air storage is reduced as they do not require thick thermal insulation to prevent the loss of heat; moreover, natural underground cavities can be adopted [41].

A limiting factor in the applicability of the A-CAES is the time required to reach full operational efficiency for both charging and discharging. An A-CAES facility is best suited to operate in conditions that do not require frequent switching between cycles [42]. However, these systems compensate for this drawback with a very high energy capacity compared to battery storage, for example. Additionally, its capacity is relatively cheap to expand, especially when utilizing underground cavities like salt caverns or decommissioned mines [43].

A-CAES systems encounter operational challenges at the component level, restricting the use of readily available components. The high temperatures present in the cycles of the single-stage A-CAES facilities require specially designed components. As mentioned, the additional stages of both compression and expansion can overcome the issue with selecting components, but in exchange for a reduced overall system efficiency [44]. Subsequent research efforts should prioritize enhancements in compressor and heat exchanger designs, delve into isobaric systems, and undertake experimental investigations under authentic operational conditions.

One of the notable projects of the A-CAES plant was the ADELE (Adiabater Druckluftspeicher für die Elektrizitätsversorgung) pilot plant, which was started in 2010 by STRABAG, General Electric, and RWE. The plant was designed with a compressor and turbine operating on air with temperatures over 600 °C and compressing the air into underground storage with a pressure of up to 100 bar. These conditions require a significant development in the area of turbomachinery, which was partially a goal of the project. The air would flow through a solid material TES, a pressure-resistant vessel filled with rock material. Unfortunately, the plant was never operational, and it was only a simulated expected efficiency that was provided, which was around 70%. The project finished in 2017 [45,46].

An A-CAES pilot plant with a similar construction was finished by ALACAES in 2016 and was tested until 2018. The system consisted of cylindrical underground air storage in a tunnel, which was a thermocline TES filled with rocks and a compressor. The system did not include a turbine. It was used to validate a simulated performance of the system and monitor the behavior of the TES and the air storage. The estimated efficiency of the plant was between 63% and 74%. Additional conclusions were that the structure of the cavern and the concrete TES withstood the temperature and pressure cycling, with leakage appearing only on the sealed end of the cavern [30].

The TICC-500, an A-CAES pilot plant completed and tested in 2016, is well documented in [47]. It used piston compressors in a five-stage compression cooling layout, requiring 1357 kWh of energy to raise the pressure in the 100 m air tank to 93.4 bar. The system used water heat exchangers and a TES tank. The water was stored at 108.6 °C. The turbine installed in the system was providing 326 kWh of energy at the mentioned parameters of the system. The combined efficiency of the plant during testing was around

22.7%. The conclusion after the test was that the higher-than-expected energy draw was due to the unsteadiness of the operation of the piston compressors and the small air tank. The installation of an axial-flow turbine and improved thermal insulation of the system would enhance the overall efficiency.

The RICAS 2020 project, funded by the EU, is a design study for an underground research infrastructure situated in an abandoned Austrian mine. Its purpose is to assess and enhance the performance of advanced adiabatic compressed air energy storage (AA-CAES) technology. The project focuses on creating a durable sealing membrane capable of withstanding the high temperatures and pressures within the cavern. Additionally, their efforts are directed toward optimizing the overall efficiency of the AA-CAES system. Currently, the project is in the design phase and has not progressed to the construction stage [48].

Aside from research and pilot plants, Siemens Energy has had CAES plants in their offer since 2023. These include both diabatic and adiabatic CAES, with the latter being combined with their own TES solution. The claimed round-trip efficiency of their offered solution is in the range of 65–70%, with a power train of 50 MW up to 250 MW [49].

In 2022, an A-CAES power station designed by CECH Jiangsu Institute (Jiangsu Jintan Salt Cave CAES) was successfully connected to the grid, passed an operational test at full capacity, and became operational [50]. The plant has an installed maximum power generation of 60 MW, and the air stored in the underground salt cavern has an energy capacity of 300 MWh [51].

2.3. Isothermal CAES

Unlike A-CAES systems that store and utilize generated heat, isothermal compressed air energy storage (I-CAES) aims to limit the change in the temperature of the compressed gas, ideally maintaining a constant temperature throughout the whole cycle, implying a thermodynamically isothermal change of state. Preferably, the temperature is maintained as low as 30 °C–40 °C to reduce heat loss during storage, which makes it easier to adapt underground cavities as air reservoirs [41].

What is important is to mention that in I-CAES, the heat generated during the compression and the heat removed from the compressor must remain in equilibrium. The same is true for the expansion cycle, where heat is added to the expander. However, the I-CAES system does not use separate heat exchanger units to manage the compression waste heat, as in a low-temperature storage A-CAES [52].

During the operation of the I-CAES system, the rate of pressure change in the compressor or expander is decisive, as the heat transfer between the air and its surroundings is a limiting factor. Because of the reduced compression speed in the I-CAES, reciprocating engines are frequently used as compressors and expanders. They have a good efficiency factor at a low volumetric flow. This compression rate constraint effectively reduces the maximum power delivered by a single unit; hence, they are frequently used in series [53].

The main components of I-CAES are similar to those used in A-CAES systems, as follows [54]:

- Low-temperature air storage, either in an underground cavern or a tank;
- A compression unit, commonly a reciprocating engine with additional mechanisms to improve the heat transfer;
- An expansion unit with the same properties as the compressor.

The key difference is the absence of thermal energy storage and heat exchangers. An early design of the I-CAES plant tested in 2006 used a reciprocating engine with an oil column instead of pistons, which increased the engine efficiency. Additionally, such a solution creates a direct contact between the compressed air and oil, enhancing the heat transfer process. This way, the oil absorbs part of the heat generated in the process. In this solution, however, the heat transfer is limited by the diameter of the oil column and, in turn, by the piston size [55]. A schematic diagram of such a plant is presented in Figure 4.

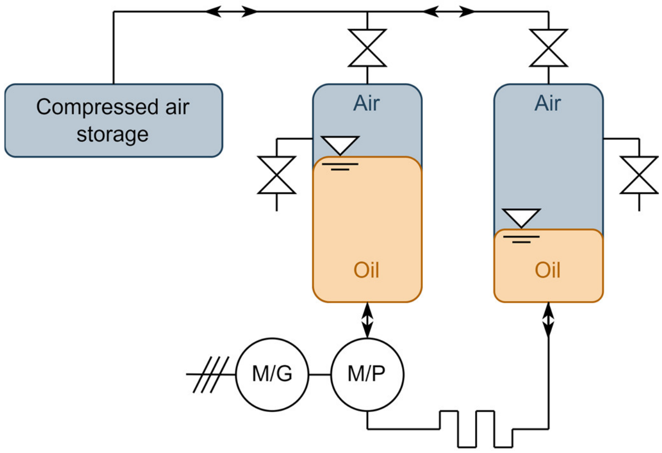

Figure 4. Simplified scheme of I-CAES plant, where M—motor, G—generator, and P—pump.

Aside from introducing modifications to the piston chamber of the mentioned system, another proposed design is to greatly increase the heat transfer between the air and liquid by spraying water into the piston chamber. An additional benefit of this solution is increasing the heat capacity of the air, making it easier to maintain a constant temperature [56]. After the compression process, the water is either separated from the air or remains compressed together in the storage. It is then sprayed again into the air during the expansion.

Similarly to A-CAES, a large advantage of the I-CAES is the low storage temperature, which allows for safe storage of the air in underground cavities, like salt caverns or decommissioned mines, without the need for using additional cooling equipment. In the case of I-CAES designs with direct liquid–air contact in the compressor, the stored air has a higher humidity, which increases its heat capacity. However, it also increases the risk of corrosion or sludge deposition in the storage [57].

Another advantage of I-CAES over adiabatic and diabatic CAES is the range of available components that can be used in the plant. Owing to the low temperature maintained throughout the whole cycle, the components like compressors and piping do not have to withstand high-temperature stresses. Additionally, insulating these components to prevent energy loss due to heat transfer outside of the system is less important and easier to achieve [58]. Importantly, since the compressor is modified to increase the rate of heat dissipation from the air, no additional cooling or heat exchangers are required, reducing the number of components in the system [59].

However, since I-CAES compression and expansion units are based mainly on piston-derived technologies, the compressors and expanders feature low-power outputs. Low power levels reduce the charging rate of this type of storage. This is connected to another factor that reduces the charging and discharging rates of the cycle, which is the limited space in the pistons of the compressor and expander units.

In real applications of the I-CAES plants, a certain temperature change in the air is still inevitable, even with the isothermal system. Thus, it is worth mentioning that there exists a polytropic transformation, which is between the adiabatic and isothermal transformations [60].

An American startup, LightSail, started working in 2008 on an I-CAES plant. Their idea was to spray water in the piston chamber of a custom-built compressor. They predicted achieving a 60% efficiency in the first year of operation. However, the company faced difficulties in the development of the system components, as they could not adapt anything readily available. They closed in 2018 and failed to deliver a product [57].

Another similar project was led by SustainX, starting in 2013. They used a pneumatic piston compressor with a spray-based air–water interface. After running tests on a small scale (in a 40 kW plant), the company built a commercial-level test plant with a 1.5 MW power output in 2013. The prototype was operating in both compression and expansion cycles. Tests run that were performed in 2014 have demonstrated a prototype round-trip efficiency of 54%, with the air operating temperature ranging between −20 °C and 40 °C. However, the efficiency did not take into account any thermal or electrical losses during standby. To measure the efficiency, the storage was charged to a full capacity and immediately discharged. The final report provided by SustainX in 2015 deemed the plant commercially viable [61].

A different approach to an I-CAES plant was proposed by the company SEGULA Technologies in a project called Remora. In their solution, the energy delivered to the system during charging powers a 15 MW hydraulic turbine that drives the water into a pressurized container filled with air. The water rises from the bottom, compressing the air that is then fed into a 90 MWh underwater storage tank. The ideal placement of the storage tank is 70 m to 200 m below the surface, making this solution suited to operate with offshore wind turbines. The predicted overall efficiency of the proposed system is 70%. In 2020, SEGULA built an onshore demonstrator called Odysea. It has four quasi-isothermal air compression–expansion chambers installed, powered by three centrifugal turbines, two of which are compressing the water to a high pressure in turns with the other powering the generator during the discharge. SEGULA is working on a sea-based demonstrator, with completion planned for 2023 [62].

2.4. Compressed Air Cars

Climate change and energy security require looking for technology innovations in the transport sector. Among different innovative solutions based, for example, on the usage of hydrogen [63,64] and solar energy [65,66] to power cars, boats, and planes, vehicles using energy stored in compressed air produced by a compressor have also been suggested, being perceived as environmentally friendly and prospective vehicles [67].

The idea of using compressed air to power vehicles dates back to the middle of the 19th century [68]. Before the invention of gasoline and diesel engines, compressed air engines were used as the power source in locomotive transportation for over half a century (they were extensively developed, especially during the 1880s and 1890s). The use of compressed air in transport applications began to shrink in the 1930s due to the emergence of highly efficient fossil-fueled internal combustion engines (ICEs). Finally, the development of ICE technology after World War II caused the disappearance and replacement of compressed air-driven engines from the road [69]. Nowadays, this technology is gaining in popularity again because compressed air vehicles can be considered a low-cost, easy-to-operate, and environmentally friendly alternative to ICEs [70]. This type of vehicle could be used in places where the production of gas emissions is undesirable, e.g., in production halls, enclosed spaces, and town centers [71].

The operation of compressed air engines used in the automotive sector is based on the usage of high-pressure air stored in the chambers. The process of air compression causes a rise in the total or stagnation pressure of the air with an increment in its temperature. During this process, the energy of the working engine is transferred to the air. This energy is then converted by the engine into mechanical power through the expansion of compressed air in the cylinder (the compressed air is converted into the rotational motion of the vane driving the air motor connected to the axle). This work produces the torque required to propel the vehicle forward [69]. The exemplary working process of a reciprocating piston compressed air engine is shown in Figure 5.

In recent years, different versions of compressed air engines have been developed. The majority of constructed prototypes come from modifications of conventional ICEs. For example, Zhai et al. [72] carried out studies with a modified single-cylinder diesel engine, and they created a unit powered by compressed air with a maximum power of 2.6 kW at an air pressure of 0.8 MPa. Huang et al. [73] developed compressed air engines based on a conventional 100 cm^3 motorcycle engine. A modified unit reached a maximum power of 0.95 kW under an air pressure of 0.9 MPa and at 1320 rpm. Furthermore, Nabil [74] modified the 150 cm^3 Dayun petrol engine and obtained 245 W of power under an air pressure of 0.8 MPa and at 300 rpm. The efficiency of the developed engine reached 9.6%.

Moreover, vehicle manufacturers developed and tested pneumatic engines, including, for example, Tata Motors of India [75] and the EngineAir of Australia Company [76].

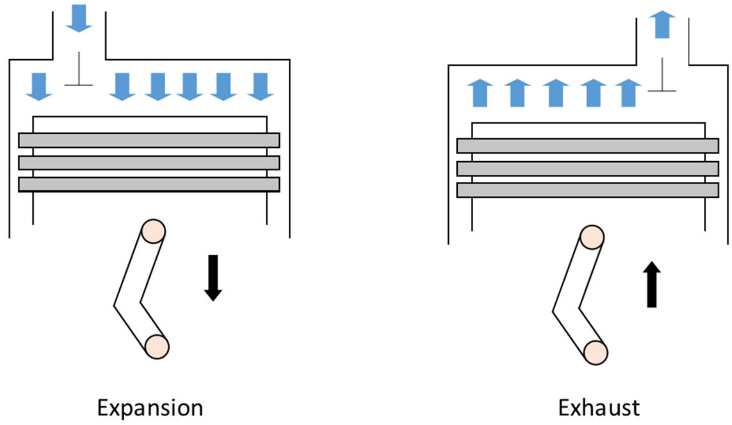

Figure 5. Working process of a reciprocating piston compressed air engine [69].

Furthermore, the worldwide literature includes several examples of testing compressed air engines integrated with vehicles. For example, Evrin et al. [77] developed and tested a prototype of a pneumatic vehicle. The experiments showed that the maximum torque varied from 21 Nm to 44 Nm, and the total energetic efficiency was observed at a level of 59.5%. Suranjan et al. [78] designed a vehicle dedicated to short distance applications such as golf carts, mall taxis, etc. The car model was developed using Solid Works 2017 software and then tested in an ANSYS workbench environment. The designed car could reach speeds ranging between 10 km/h and 20 km/h while being eco-friendly and sustainable at the same time. Xu et al. [79] analyzed the power performance, economy, and energy conversion efficiency of compressed air engines under different road conditions. The experimental results showed that the compressed air consumption rate of the pneumatic motor with reverse rotation was higher than that with forward rotation. The maximum power output and energy conversion efficiency of the pneumatic motor were about 1220 W and 13.23%, respectively. The team from the Brno University of Technology developed a vehicle powered by compressed air stored in the air reservoirs, which was able to run a 7 km track at a speed of 50 km/h [80]. Another example of a vehicle powered by compressed air was developed at the Technical University of Košice. This vehicle was equipped with a three-cylinder engine and a 10 L air reservoir. The maximal pressure of the compressed air was 20 MPa [81]. Also in Poland, students of the Faculty of Energy and Fuels at the AGH University in Krakow developed a prototype of an innovative vehicle powered by compressed air—the Zephyr AGH (see Figure 6) [82]. Furthermore, Teli et al. [83] designed a pneumatically powered bicycle, with an overall efficiency of 54.4% reported when operating on compressed air.

Alternatively, despite a few disadvantages, compressed air engines can be integrated as a part of hybrid systems. Such hybrid systems may be considered as a transition vehicle power system between fossil-fueled combustion engines and ecological-friendly electric propulsion systems [84]. Brown et al. [85] discussed a hybrid drivetrain concept based on compressed air energy storage. Yi et al. [86] proposed a hydro-pneumatic energy storage system for hybrid mining trucks. The results showed that the volume and weight could be reduced by 24.8% and 15.4%, respectively, when compared with a compressed air energy storage system. Bravo et al. [87] tested hydraulic–pneumatic hybrid powertrains. It was discovered that the discussed system can store 69% of the available energy.

The prominence of vehicles powered by compressed air (including hybrid units) will increase in popularity. There are many applications in which such types of vehicles can be introduced, including, for example, production halls, enclosed spaces, and town centers. However, one of the main challenges before the potential commercialization of the developed prototypes is to provide higher ranges of operation. Another problem faced by compressed air vehicles is that their energy density is too low. In future research, compressed air could be replaced with liquid nitrogen [79].

Figure 6. An example of a compressed air powered vehicle—the Zephyr AGH [82].

2.5. Wave Energy Conversion through Air Compression

Harnessing wave energy has emerged as a compelling avenue in the pursuit of renewable energy sources, owing to the perpetual nature of oceanic motion. Waves represent an omnipresent and dynamic force, offering significant potential for sustainable energy generation. Within the spectrum of wave energy conversion technologies, the utilization of air compression stands as a promising method, wherein the mechanical energy inherent in oceanic waves is transduced into compressed air for subsequent power generation [88].

The process involves the conversion of mechanical energy from oceanic waves into pneumatic energy through air compression. A pivotal exemplar of this mechanism is illustrated in the Liquid Piston Compressor system. Herein, the oscillatory motion induced by waves actuates a piston submerged in a liquid medium, thereby initiating the compression of air within the system. The resultant compressed air is then stored under high pressure, poised for utilization in diverse applications, such as electricity generation via gas turbines or for various industrial purposes.

The Liquid Piston Compressor signifies a paradigmatic advancement in wave energy conversion technologies. Its operational framework revolves around the principle of leveraging wave-induced motion to impel a liquid-immersed piston, thereby facilitating the air compression. The resulting compressed air reservoir serves as a versatile energy reservoir adaptable for an array of applications ranging from power generation to mechanical propulsion.

Beyond the Liquid Piston Compressor, a spectrum of alternative systems exists, each harnessing air compression as a conduit for wave energy conversion. These encompass pneumatic chambers designed to capture wave energy, subsequently channeling it towards driving gas turbines or electric generators. Furthermore, certain methodologies directly utilize compressed air for mechanical propulsion or ancillary industrial processes.

The utilization of compressed air derived from wave energy conversion has multifarious applications. It serves as a viable means for electricity generation, particularly in coastal regions or offshore installations. Moreover, compressed air finds usefulness in pneumatic tools, mechanical drives, and a spectrum of industrial processes, thereby accentuating its versatility and efficacy as a renewable energy resource.

The designated nomenclature for such systems is 'wave-driven compressed air energy storage' (W-CAES), which combines a heaving buoy wave energy converter with compressed air energy storage. The operational principle involves waves driving the heaving buoy, converting wave energy into mechanical work to pump water into a water–air compression chamber, forming a liquid piston compressor. The air compression in the chamber thus converts mechanical energy into compressed air energy.

The general idea of such systems is shown in Figure 7. The system consists of a floating buoy, a bidirectional hydraulic cylinder, a rectifier with four check valves, a four-way directional valve, two water–air compression cylinders, four pneumatic check valves, a cooler, and a compressed air storage tank. Compared to the conventional hydraulic accumulator, the open accumulator substantially increases the volumetric energy storage density for the same peak pressure and total volume.

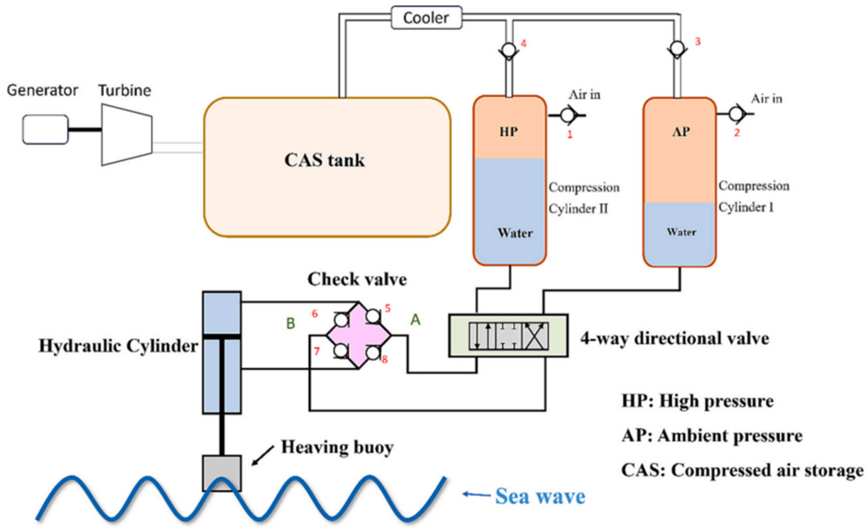

Figure 7. Schematic diagram of the proposed W-CAES. The air is regarded as the energy storage medium and the power transmitting medium is water (based on [89]).

In this context, the development of reliable wave-driven air compressors has been paramount, as evidenced by various patents such as [90], presenting multistage constructions capable of operating at varying depths.

An intriguing application of wave-compressed air appears in reverse osmosis desalination systems, where compressed air aids in achieving the requisite pressure for transporting saline water through a membrane.

A notable company involved in the development of such systems is AOE—Accumulated Ocean Energy Inc., as described in [91], which has patented the AOE Ocean Buoy Array System (AOE OBAS). The AOE OBAS, after 15 years of development, is commercially available for various applications, boasting capacities exceeding 100 kW of continuous power generation, along with the capability to desalinate over 280 million L of water annually without any fuel costs or adverse environmental impacts. The OBAS utilizes compressed air as the energy storage medium, distinguishing it from other wave energy devices that face limitations due to the electrolysis in water-based electricity generation.

3. Air Storage Solutions

3.1. Underground Storage Chambers

The green evolution of energy storage technology can be exemplified by underground space energy storage, including compressed air energy storage systems. Underground storage systems are one of the most popular systems for storing compressed air. In underground CAES, off-peak or excess power is used to compress and store air within an underground storage cavern. When needed, this high-pressure compressed air is released and expanded in a gas turbine to produce electricity during peak demand hours [92]. The installation of the underground storage of compressed air requires a favorable location and favorable geology conditions. A number of underground structures and techniques can be employed for storage, including the following four types: rock salt caves [93], abandoned mines [94], artificially excavated hard rock caverns [95], and aquifers [96]—see Figure 8.

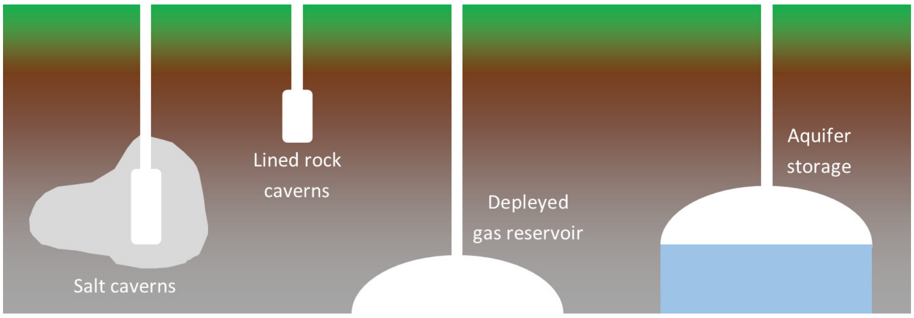

Figure 8. Types of underground energy storage chambers.

Salt rock caverns (SRCs) are artificial cavities located in underground formations that are created by injecting water through an access well and dissolving the salt [97]. They are considered a good underground energy storage medium. Depending on the depth, they can be operated with a pressure of up to 200 bars and thus allow the storage of very high volumes of gas [98]. SRCs have the advantages of a moderately high strength, a low permeability, and good self-healing properties. Therefore, salt caverns can remain stable for very long geological periods [99]. They are well-suited for the flexible operation and regular cycling that CAES plants operate under [100]. For example, the first commercial CAES facility—the Huntorf CAES plant (1978)—and the second commercial CAES facility—the McIntosh CAES plant (1991)—utilized underground salt caverns to store compressed air [101].

Furthermore, a number of studies on rock caverns created by excavating hard rock formations have been performed in terms of the feasibility of its application for compressed air storage. The CAES built by the transformation of abandoned coal mines can be divided into unlined rock caverns (URCs) and lined rock caverns (LRCs) according to their support form. The design method of the URCs is derived from the concept of salt cavern gas storage. Although this method is simple, the irregular, discontinuous surface and layered rock mass can lead to the directional leakage of high-pressure air [102]. On the other hand, the concept of the LRCs includes the installation of a lining structure to bear the greater part of the internal pressure load and to transfer the rest of the internal pressure load to the surrounding rock structure. These two structures cooperate to ensure safety. Furthermore, the polymer sealing layer blocks the transmission of high-pressure air in case of partial failure under a long-term fatigue load [103]. In addition to abandoned coal mines, it is possible to use depleted oil or gas reservoirs [98]. The natural gas reservoirs meet the requirements for high-pressure air storage in terms of porosity and permeability [104]. Using underground coal mine space and depleted oil or gas reservoirs for energy storage has become an effective means to promote the development of low-carbon clean energy due to the advantages of a large space and low mining cost [105]. Taking into account the potential of such formations, two Japanese pilot tests of CAES were conducted in an abandoned mine [92,106].

An alternative to salt caverns and abandoned coal mines is the excavation of new rock caverns. It provides more possibilities for site selection close to energy sources, including solar and wind farms. On the other hand, this option would be more expensive compared to the previously discussed possibilities [92].

The worldwide literature consists of a number of examples of works related to the examination of recent and ongoing CAES projects, including both small-scale (<1 MW_e) and large-scale (>100 MW_e) installations. For example, King et al. [107] presented candidate methods of storing high-pressure air using underground features in large-scale applications. The authors assessed the overall potential for CAES in India by examining geological features and locations with the greatest potential for CAES plants. As specific site screening criteria are applicable to each of these reservoir types and technologies, determining the viability of the reservoir itself and of the technology for that site, Matos et al. [99] reviewed the criteria applied to identify suitable technology–reservoir couples. Wang et al. [108] built a mathematical model used to predict the debrining parameters for a salt cavern used for

CAES. This model was based on the pressure equilibrium principle. Combined with the sonar survey data of a salt cavern, the equations were deduced for calculating the debrining parameters. Wei et al. [93] developed a correlation model between salt cavern energy storage and CO_2 emission. Furthermore, a method for the comprehensive utilization of salt cavern energy storage was proposed. The potential for CO_2 reduction in China by the comprehensive utilization of the salt cavern was estimated at 28.3% for the compressed air energy storage, 13.3% for natural gas storage, 10.3% for oil storage, 6.6% for a liquid flow battery, 24.8% for hydrogen storage, and 16.8% for carbon dioxide storage. Ozarslan [109] investigated large quantities of underground gas storage methods and the design aspects of salt caverns. A pre-evaluation was made for a salt cavern gas storage field in Turkey. Parkes et al. [110] described a technique using Esri's ArcGIS® Geographic Information System software to derive potential storage cavern locations and volumes that might be used for CAES systems. The authors defined the methods, which included the spatial distribution, thickness, and insoluble content of the halite beds, together with an estimate of the potential physical volumes of the solution-mined caverns. Menendez et al. [111] developed three-dimensional CFD numerical models and investigated the thermodynamic performance of underground reservoirs in CAES systems at operating pressures from 6 to 10 MPa. The results of the numerical model were used to estimate the preliminary energy balance and the round-trip energy efficiency. As was summarized, the power generation and the round-trip energy efficiency increased when the variations in air temperature were reduced and when the air mass flow rate was reduced. Chen et al. [112] proposed an integrated energy system consisting of a CAES system and a precooling system to decrease the energy consumption of the compression trains in the charging process and to enhance the round-trip efficiency of the system. The results of the thermodynamic analysis showed that the round-trip efficiency of the proposed system was improved by more than 3% compared to the conventional CAES system.

3.2. Underwater Containers

One of the most prominent renewable energy technologies are onshore and offshore wind farms. As systems whose operation is strongly linked to weather conditions, their operation is characterized by fluctuations related to the time of day and season. Underwater compressed air-based energy storage (UWCAES) can help with this problem. They are considered to be one of the most promising technologies to improve wind energy production [27,113].

There are different types of the described technology. All of them, however, take advantage of the high pressure present at the bottom of the sea. The main idea is to balance the pressure in the reservoir with the surrounding water. Unlike, for example, compressed air storage in underground rock voids, the air pressure in the reservoir is approximately constant with changes in volume, so it can be called isobaric storage. It is worth noting that the operation of the tank under ideal isobaric conditions is not possible. Some pressure differences will always be present between the areas of the tank that are submerged at different depths. Nevertheless, an approximate isobaric character is possible due to the presence of seawater in the tank itself during the system operation and/or the flexible walls of the tank. As the storage charging process begins, the tank fills with seawater. The volume of the compressed air tank is, therefore, limited by the water surface. As more and more compressed air is supplied, the water leaves the tank, thereby increasing the resulting volume occupied by the compressed air. In the process of discharging the storage, the water fills the tank again.

Two methods of the charging process can be distinguished. This process can be performed similarly to classic ground-based systems, which utilize the compressor. However, there is an approach involving the use of tank water in the form of a liquid piston [114]. In this case, excess electricity from, for example, a wind farm is transferred to hydrostatic pumps that directly draw down the stored water in the reservoir by increasing the prevailing pressure in the reservoir. Maisonnave et al. [115] obtained a high efficiency in the modeled system using this approach. It is worth noting that this process only replaces the compressor operation. The whole process is divided into shorter stages of compressing smaller portions of air, which are then transferred to the target tank.

Flexible tank walls are a relatively new idea (see Figure 9) [116]. The first proposals to use flexible material date back to 1989 [117]. Such tanks are very often referred to as Energy Bags [116,118]. They have an advantage over rigid tanks because of the stresses associated with varying pressures prevailing in different areas of the tank. With the use of a flexible casing, the loads are distributed over the tensile material and the bending stresses are virtually non-existent.

Figure 9. Energy Bags immersed in the tank during experimental tests [116].

The performance of underwater compressed air energy storage is closely related to the depth at which the tank is located [119]. This fact is both a major disadvantage and an advantage of these systems. This dependence allows the location of the tank to be adjusted depending on the required air pressure at the turbine inlet. In contrast to storage in rock voids, for example, no manual adjustment of the pressure of the medium is required during the discharge process. Unfortunately, the strong relationship with the depth also translates into strong geographical limitations on the use of the systems described. The diagram (Figure 10) shows the dependence of the energy density and storage pressure of subsea storage on the depth of its location [116]. It is worth noting that, unlike storage pressure, energy density grows non-linearly with increasing depth.

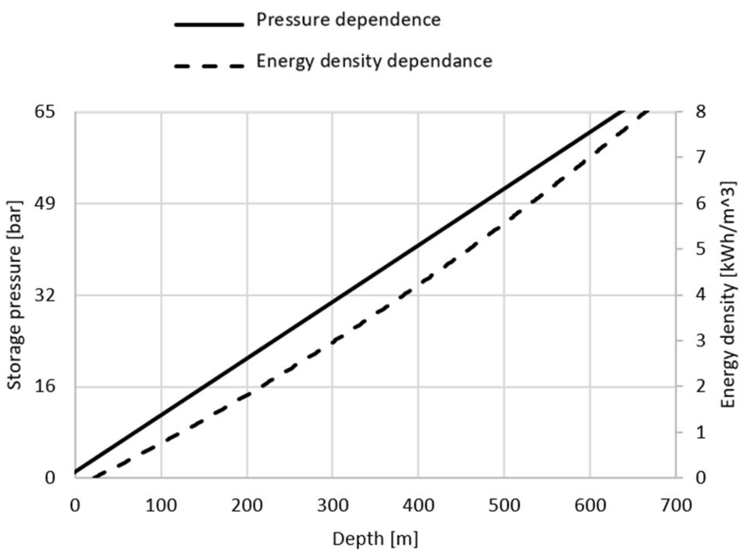

Figure 10. Graph showing the dependence of UWCAES energy density on the depth of the reservoir location [116].

Underwater CAES is assumed to be applied mainly in cooperation with systems of renewable energy sources [120]. Unfortunately, due to the relationship shown in Figure 10, the application of this technology for offshore photovoltaic or wind farms is very limited. The optimum storage pressure is achievable at depths of less than 500 m (~50 bar). For this reason, it is not feasible to use UWCAES for wind turbines fixed to the seabed. For these systems, a maximum depth of 50 m is claimed. Above this value, the construction is much less cost-effective [121]. These limitations translate into the greatest potential for UWCAES in floating wind and photovoltaic farms or wave energy generation. In addition, when comparing a classic CAES system with a rock hollow reservoir to UWCAES, higher efficiencies are theoretically obtained [122].

3.3. Aboveground Vessels

Another type of compressed air storage for CAES systems is aboveground storage. Systems using this type of storage are referred to as short-term systems with an operating capacity of no more than 24 h and an electrical capacity of less than 10 MW_e [123]. This is due to the fact that the storage vessels are usually of a limited capacity and operating pressure for material reasons [2]. The most common solutions are air storage tanks, gas cylinders, and gas storage pipelines [124] made of steel or composite materials. Their design is very similar, differing only in dimensions—length or diameter and possible mobility. It is also possible to use concrete storage volumes when low air pressures are considered [2].

Compressed air systems have been used successfully for many years. They are commonly used in large and small manufacturing plants. They are also often found in the equipment of artisanal workshops, automotive workshops, paint shops, or carpentry workshops. One of the key elements of such a system is the air storage tank, which is usually stationary or mobile in the form of gas cylinders. This part of the system is used to store pressurized air (or other gases) that are pumped into it by a compressor. Air storage tanks are mostly used at temperatures from -10 °C to 50 °C, but it should be noted that condensate freezes at sub-zero temperatures, especially if there is no constant flow of the medium through the tank and the system. In this case, it is necessary to heat the underside of the air tank (especially for outdoor tanks).

Air storage tanks are available in a variety of shapes and sizes to meet the needs of different applications. They can be spherical (see Figure 11), cylindrical, or oblong, and their capacity can range from a few liters to several thousand liters. Pressure vessels can be made from a variety of materials, including plastics, carbon steel, stainless steel, aluminum alloys, or carbon fiber composite [125]. An important feature of the pressure vessels is their ability to store compressed air at a high pressure. With increasing energy efficiency requirements, the materials of the pressure vessel are critical to their successful performance, especially in high-pressure and high-temperature applications. The advances in composite materials with a higher strength, good thermal insulation, and corrosion resistance make them ideal for building pressure vessels operating in extreme conditions. To be safe and effective, compressed air vessels must be made of materials and designs that are strong enough to withstand large amounts of pressure. It is important to remember that pressure vessels in many countries are subject to special regulations, must be certified and periodically monitored by, for example, authorized institutions, and should meet safety standards such as ASME, PED, or TUV.

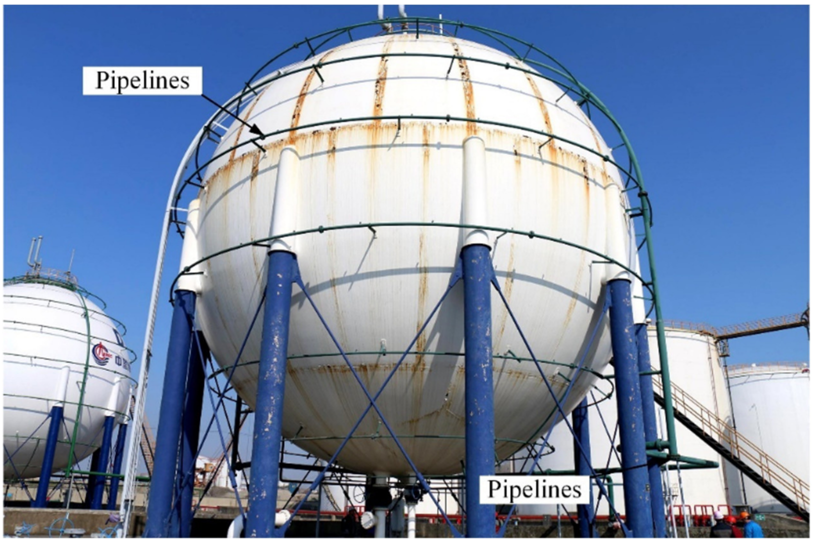

Figure 11. Spherical storage tank [126].

Aboveground storage systems have the advantages of scalability and modularity [127], as well as the possibility to be used at any location. The individual vessels can be connected in series or in parallel to increase the usability of this type of compressed air storage. Such connections allow the pressure stabilization of the system or the extension of the system operating time. The disadvantages compared to underground compressed air storage include a high variability of the operating pressure, the need for large areas for appropriately sized tanks for a comparable system capacity, the need for cyclical pressure and safety testing [2], and high investment costs—even more than 10 times higher than for salt caverns [128].

Few aboveground compressed air storage facilities have been built worldwide, so the technology is still in the development phase.

In the United States, a start-up company called SustainX was established in 2007 with the aim of developing I-CAES technology using tanks or other aboveground structures to store the compressed air. The plan was to develop the technology on an I-CAES basis because of the potential for higher efficiencies [129]. In 2013, the world's first and so far only MW-scale I-CAES plant based on pre-mixed foam to achieve quasi-isothermal compression was commissioned [130]. The 1.5 MW system achieved an efficiency of 54%, a significant improvement over D-CAES systems [107].

The New York Authority developed a 10 MW_e D-CAES solution with enough capacity to run the system for 4.5 h. The system was to be based on steel tube ground tanks [2].

In 2014, as part of the TICC-500 project implemented at Tsinghua University, a 500 kW_e adiabatic demonstration system was developed. It was based on air storage consisting of two parallel metal tanks, each with a volume of 50 m^3. The operating pressure was between 25 bar and 100 bar, allowing the system to operate for 1 h [131]. During the testing of the system, an efficiency of 33.3% was achieved [15], while, with further improvements to the system, an efficiency of at least 37% is possible [131].

In 2013, Macaoenergy Industrial Park Development Co., Ltd. (Bijie, China) and the Institute of Engineering Thermophysics of the Chinese Academy of Sciences developed a 1.5 MW_e supercritical CAES demonstration system. This system successfully operated for at least 3000 h and achieved an efficiency of about 55% [15]. Based on the experience gained, a 10 MW_e AA-CAES system was developed, operating at a 62.3% efficiency and 70 bar operating pressure [107]. This plant is in operation and has the potential to be scaled up to 100 MW_e [18].

4. Components of CAES Systems

4.1. Expanders

As already mentioned, the efficiencies of the charging and discharging processes in the electrical storage CAES system are one of the most influential factors affecting the performance of the entire CAES setup. To conduct an efficient discharging process in a CAES plant, it is essential to select the appropriate expander technology. One of the factors that influence the expander choice is the expected discharge power of the system. Meanwhile, the high scalability of the CAES technology results in a broad spectrum of potential discharging powers. For micro-CAES installations, the power output may be of the order of tens of kW_e, whereas for large-scale units, it can be as high as several hundred MW_e. Moreover, depending on the CAES technology applied, the expander working fluid may expand as a single-phase (D-CAES and A-CAES) or a two-phase (I-CAES) substance. These aspects make the expander choice a non-trivial task that must be performed with the greatest care. Overall, the machine that is finally selected must not only align with the specific requirements of the CAES system but also deliver a high expansion efficiency. Figure 12 presents the types of expanders that can be potentially used as expansion units in the CAES installation. In the figure, they are classified into positive displacement (volumetric) and dynamic (turbines) machines. The criteria for selecting the specific expander type are described in the following paragraphs.

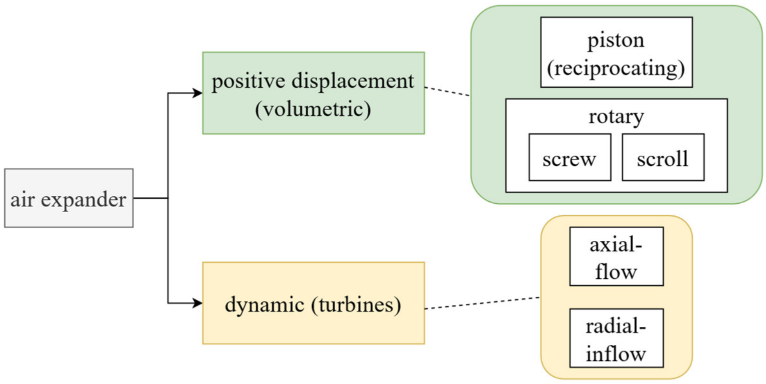

Figure 12. Air expander types.

Turbines provide the output power through the continuous change of the angular momentum of the working fluid. During the first stage of this process, the fluid's momentum is substantially increased by decreasing the fluid's pressure in the stationary nozzle rows. Next, the momentum of the fluid is transferred to rotating rotor blades, generating the power output that can then be received on the turbine shaft. The uninterrupted flow of the working fluid through the turbine vanes allows these machines to operate at high fluid flow rates [44]. Moreover, the so-called turbine stages (where the turbine nozzle rows are followed by the turbine rotor blades) can be connected one after another, forming a compact multi-stage structure that can work efficiently with significant pressure ratios. Such a design refers primarily to the axial-flow machines [132] and is widely applied to the turbines that operate with high-pressure and high-temperature working fluids (steam and gas turbines). Owing to the multi-stage arrangement (see Figure 13), the power output may even reach several hundred MW_e, with the isentropic efficiency of the entire machine being as high as ~90% [133]. Radial-inflow turbines (see Figure 14) also feature a high expansion efficiency (~90%) [134], but they are typically constructed as single-stage machines [135] with a power output of less than 1 MW. Overall, turbines are perfectly tailored for large-scale CAES installations, for which expanders must provide very large power outputs (1 MW_e–500 MW_e). It does not preclude the use of turbines in smaller CAES units (<1 MW_e), but the investment cost may likely be higher than that incurred for volumetric machines.

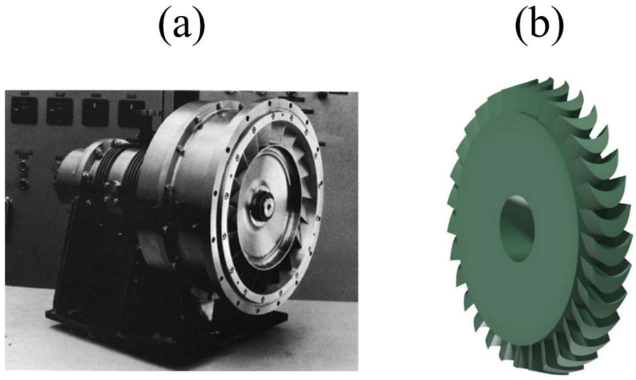

Figure 13. (**a**) Multi-stage axial-flow turbine unit [132], and (**b**) axial-flow turbine rotor [133].

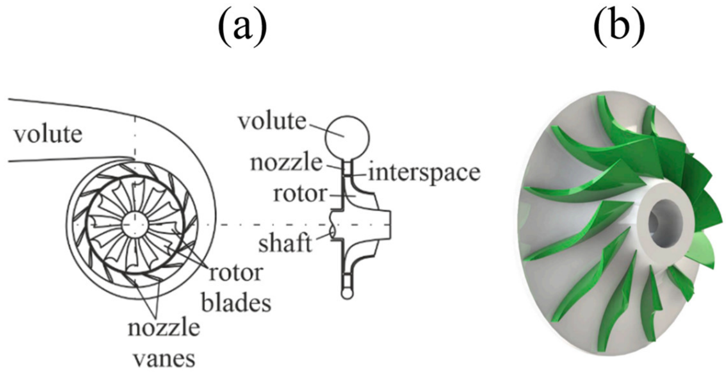

Figure 14. (**a**) Single-stage radial-inflow turbine unit [134], and (**b**) radial-inflow turbine rotor [135].

Taking into account that the stored air pressure fluctuates during the discharging of the CAES (particularly when isochoric storage chambers are applied), special control strategies are needed to meet the specific power output requirements. The control methods, which are derived from other turbine applications, include setting a constant turbine inlet pressure (using the throttling valve), operating the turbine on sliding pressure mode, adjusting the guide vane, or adjusting the ejector pressure [114].

In designing the discharging system for the CAES installation, it is possible to combine the application of different turbine types in order to create a more compound expansion system. For this purpose, turbines with different internal flow arrangements can be used, including axial- and radial-type units. Moreover, CAES turbines can be designed according to the engineering practice that has been applied through the years with respect to steam or gas power units [136]. Such approaches have been adopted while designing CAES installations located in Huntorf (Germany) and McIntosh (USA).

The Huntorf CAES system provides a discharge power capacity of 321 MW_e through the combined application of the high- and low-pressure turbine units [137]. Placed one after the other, the turbine units create the so-called turbine train. Before entering the first expansion unit, the pressurized air is mixed with natural gas that is combusted in the combustion chamber. Then, the hot gas (~550 °C) at the pressure of 46 bar is directed to a high-pressure turbine to be expanded to 11 bar. The partially expanded gas is then reheated in the second combustion chamber to reach a temperature of ~850 °C. The reheated gas flows to the low-pressure turbine and is expanded further to the ambient (1 bar) pressure. Significantly, in the design of the high-pressure expansion unit, steam turbine design principles were adopted [136]. This was due to the fact that steam turbine elements are designed to withstand much higher working fluid pressures than gas turbine components. Meanwhile, the low-pressure expander was adapted to work under much lower air pressures (<15 bar), making its design more similar to a typical gas turbine unit [54].

A very similar design of the discharge power system was adopted in the McIntosh CAES installation. This system provides a power output of 110 MW_e while expanding the hot air in the high- and low-pressure turbine units. Compared to the Huntorf CAES installation, the McIntosh system operates with an improved round-trip efficiency (54%—McIntosh, 42%—Huntorf). The increase in the McIntosh performance was achieved owing to the heat recovery of the gas leaving the turbine train [138]. This solution, adapted from stationary gas power plants, consists of preheating the pressurized air that flows from the storage chamber with the hot gas that leaves the low-pressure turbine unit.

The previous applications of the turbine units have been presented with respect to the D-CAES installations. However, it was reported that the turbine technology could also be applied to an A-CAES configuration. Such a solution has been adopted in the TICC-500 small-scale CAES project developed by the China Electric Power Research Institute and Tsinghua University [131]. The system discharge power of 500 kW_e is provided by the turbine train that consists of three expansion units, each featuring an isentropic efficiency of more than 80% [131]. The turbine wheels of the TICC-500 rotate at the speed of 30,000 r/min. To synchronize this speed to the rotation rate of the turbine-coupled electric generator, a high-speed gear reducer was utilized [131]. As underlined in [139], the high rotational speeds of the small turbine units utilized in small-scale CAES (<1 MW_e) systems may pose challenges, as the use of speed reducers is linked to additional energy losses in the system. Promising and more effective solutions for utilizing high rotational speeds may be based on high-speed generator technology [139].

As described above, turbine technology features a number of advantages, including great scalability, a very high efficiency, and a long operating lifetime. However, turbines cannot expand two-phase working fluids since the turbine blades would be eroded with time. This precludes the use of turbines in an I-CAES system, where the expanded air typically undergoes mixing with liquids or dispersed compounds. Moreover, the application of turbines for a very small (micro) CAES installation may be economically unprofitable. For such applications, positive displacement expanders may be a better choice, and their characteristics are described in detail in the following paragraphs.

Positive displacement (volumetric) expanders are machines that produce their power output through a cyclic increase of the volume that is occupied by the working fluid. In such an expander, the pressurized fluid applies force on a certain moving element (e.g., piston), causing an increase in the occupied volume, which, in effect, leads to its expansion. The displacement of the moving element can then be transferred to the machine shaft to extract the useful mechanical work. As Figure 12 presents, there are several types of volumetric expanders that can be applied as discharging units in a CAES installation. The operating aspects and selection criteria of these machines are explained below.

The reciprocating piston expanders (see Figure 15) have the longest and most documented history of application, being used as expansion units in steam, internal combustion, or Stirling engines. In these machines, the extraction of the useful work is accomplished through the reciprocating motion of the piston within the space of a cylinder. The pressurized gas flows through the intake valve to the cylinder. Inside the cylinder, the gas is expanded to a lower pressure, setting the piston into a reciprocating motion. After expansion, the gas is discharged through the outlet valve [140]. Due to the intermittent nature of the fluid flow and a limited built-in volume ratio, the piston expanders feature relatively low flow rates [44]. Hence, the piston expanders can be applied as low-power expansion units in small- (<1 MW_e) or micro-scale (<100 kW_e) CAES installations. Studies on applying these engines in steam Rankine cycle systems [141] or internal combustion units [142] showed that they are capable of expanding two-phase working fluids, indicating their potential use in an I-CAES system. Furthermore, the rotational speeds of these machines are typically low, allowing for the direct connection to an electric generator without requiring a speed reduction gearbox. However, their isentropic efficiencies typically do not exceed 70% [143], with values often falling below 50% [144].

number	part name
1	valve
2	piston
3	connecting rod
4	crank shaft
5	timing parts
6	cam shaft
7	timing gears

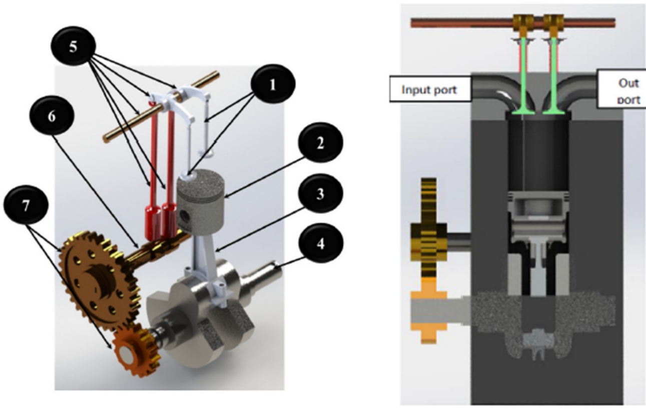

Figure 15. Component parts of reciprocating piston expander [140].

In response to the significant energy losses that occur during the expansion of the fluid in the piston engine, Van de Ven and Li [145] introduced the concept of a liquid piston. This idea, which was originally developed for the compression process, can be easily adapted for the expansion of the fluid [145]. By making use of the column of liquid that fills the piston chambers, the heat loss can be minimized. Therefore, the expansion process can be carried out at near-isothermal conditions, making this expansion machine an ideal choice for an I-CAES technology.

Recently, rotary expansion machines (both screw and scroll) have gained increased attention. Compared to piston expanders, screw and scroll machines are characterized by such advantages as a better isentropic efficiency, a lighter weight, a lower vibration, and a more silent operation [44]. Up to the present time, many studies on these expanders have been conducted with the aim of applying them in organic Rankine cycles (ORCs) [146,147] or super-/trans-critical carbon dioxide [148] power plants. Both screw and scroll expansion units are often restructured from compressors, which are much more widely applied and commercially available than expanders. Importantly, both screw [149] and scroll [150] machines tolerate the two-phase expansion of the fluid, and, hence, they are also a feasible solution for an isothermal CAES system. The revolution speed of the rotary expanders is usually higher than that of the piston engines [44], and a speed reduction gearbox may be necessary for coupling the machine with the electric generator. In comparison to piston engines, screw and scroll machines usually feature lower pressure ratios, with the lowest values (1.5–5.0) being attributed to the scroll expanders [44].

Screw expanders can be categorized as a single [146] or a twin screw [151] machine. The single screw expander is composed of a grooved rotor and two starwheels that are matched to the main rotor grooves (see Figure 16a). The expansion process of the working fluid occurs on both sides of the central rotor. An exemplary application of this type of machine has been shown by Ziviani et al. [152]. The authors first converted a single screw air compressor to a single screw expander. Then, they tested the expander performance in a small-scale ORC waste heat recovery system. The study outcomes revealed that, under different operating conditions, the expander efficiency can range from 40% to 80%.

The twin screw expander consists of a meshing pair of helical rotors (see Figure 16b). The working fluid is expanded in the working chamber that is formed in-between the rotating rotors. Dawo et al. [153] tested two twin screw expanders that were converted from volumetric screw compressors. They examined their application in an experimental ORC setup. By testing different operating conditions of the system, the authors achieved a maximum expander efficiency of 64%. In the same study, the authors highlighted that, among different types of volumetric machines, twin screw expanders feature the highest power outputs, the values of which may be up to several hundred kW.

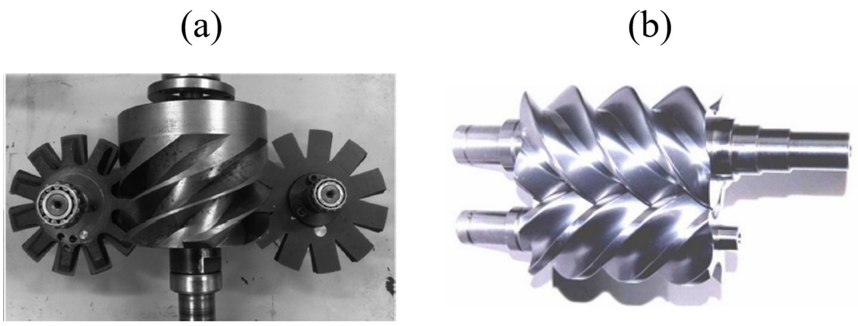

Figure 16. (**a**) Single screw expander [146], and (**b**) twin screw expander [151].

The features described above make screw machines a perfect choice for both small- (<1 MW_e) and micro-scale (<100 kW_e) CAES systems. The successful application of the screw expander in a CAES installation has been shown by Zhi et al. [154]. In their study, an oil–gas separator was applied to improve the performance of a 10 kW single screw expander. Through the application of the centrifugal oil–gas separator, the authors showed that the total expander efficiency (a product of the isentropic and mechanical efficiency) may achieve 80%.

The last expansion machine to discuss is a scroll expander. The scroll expander is made up of two interleaving scrolls (see Figure 17). One of the scrolls is fixed, while the other can move eccentrically around the fixed one. The pressurized fluid is directed to the space between the scrolls, known as the working chamber, and exerts force against the moving scroll. Owing to the rotary motion of the moving scroll, the working chamber expands in volume, causing the pressurized fluid to expand as well.

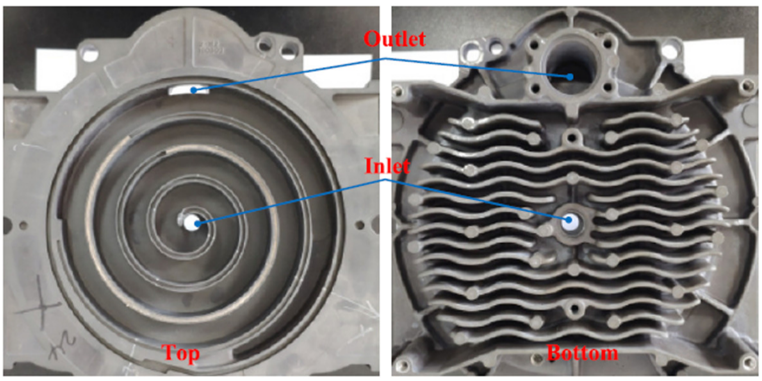

Figure 17. Scroll expander utilized in a micro-scale CAES installation [155].

As highlighted by Quoilin [156], the practice of deriving scroll expanders from existing compressor units (which, in general, also applies to the screw machines) may result in a significant deterioration of the expander efficiency. The latter is associated with such phenomena as the under- and over-expansion of the working fluid, the scale of which can be avoided or substantially reduced through the adjusted and optimized design of the rotary expansion unit. Du et al. [148] optimized the design of the scroll expander that was used in a trans-critical CO_2 power plant. They found that the expander isentropic efficiency can reach 87.4%. However, efficiencies as low as 44.8% can also be obtained if significant leakage losses are developed. In the study by Sun et al. [155], the performance of the scroll expander utilized in the CAES system was tested. By combining theoretical, experimental, and numerical studies, the authors noted that the expansion efficiency can be substantially improved by maximizing the air pressure at the expander inlet. Overall, the scroll expanders show great potential to be applied as compressed air expansion units. Nonetheless, it must be underlined that, due to their low built-in volume ratios, they can only be feasibly operated on relatively low airflow rates, making them appropriate mostly for micro-scale (<100 kW_e) CAES systems.

4.2. Compressors

As previously noted, the efficiency of the charging process significantly impacts the round-trip efficiency of the CAES electrical storage unit. Given that the charging of the CAES system relies on compressors, the appropriate selection of these machines is a key aspect in designing an efficient CAES installation. The working principle of the compressors is the exact opposite of that of the expanders. However, the main compressor types (see Figure 18) and their component assemblies are the same as those that were described for the expansion units. In compressors, the mechanical energy must be provided by the external prime mover in order to drive the compressor shaft. The rotational kinetic energy of the shaft can then be transferred to the working fluid in a way that is specific for a given type of compressor unit.

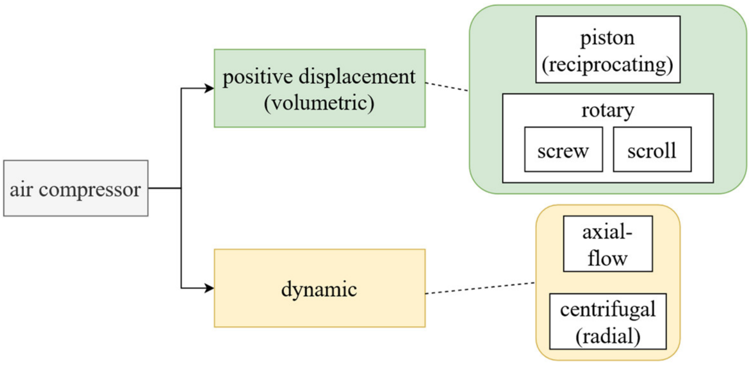

Figure 18. Air compressor types.

In positive displacement (volumetric) compressors, the increase in pressure is achieved by decreasing the volume occupied by the fluid. The latter is achieved by setting in motion the specific working element of the volumetric compressor (the piston, screw or scroll). Meanwhile, the energy transfer in dynamic compressors (centrifugal and axial) is a two-stage process. Firstly, the mechanical energy is transferred to the fluid by using either a radial or an axial rotor. Then, the fluid's kinetic energy is converted to the pressure energy in the stationary compressor elements. The latter may be designed as a set of divergently shaped vanes (in both axial and centrifugal machines) or as a single diverging channel (in centrifugal machines).

Both volumetric and dynamic compression units feature similar power ranges as their expander analogues. Accordingly, volumetric compressors will be better tailored to smaller CAES (small- and micro-scale) installations (<1 MW_e), whereas dynamic machines will be well adapted for medium- to large-scale CAES architectures (1 MW_e–500 MW_e). In terms of isentropic efficiency, positive displacement compressors feature similar efficiencies as those that are achieved by the corresponding expander units [157]. Meanwhile, dynamic compressors suffer from diffusing and decelerating flow in the vane channels [158]. Under such flow conditions, maintaining a steady flow without the separation of the boundary layer is much more difficult than in turbines where the fluid undergoes acceleration across the stator and rotor blade system. Hence, centrifugal and axial compressors typically exhibit lower efficiencies than their turbine counterparts. Much like axial-flow turbines, axial compressors can be designed as multi-stage units (see Figure 19) with the purpose of achieving high-pressure ratios. To the same end, centrifugal compressors may also be built as multi-stage machines (see Figure 20) [159]. As described later, a high-pressure ratio can also be attained by placing different compressor types (typically centrifugal and axial) one after the other, thereby creating a compressor train.

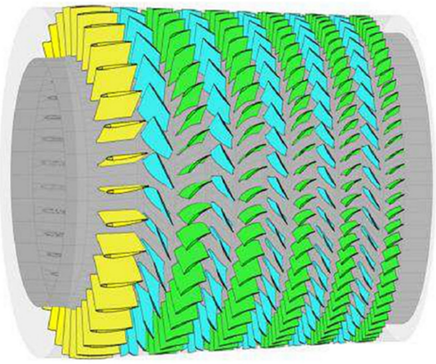

Figure 19. Three-dimensional model of a multi-stage axial-flow compressor [160].

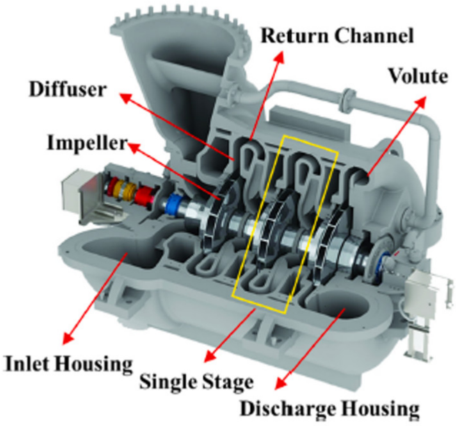

Figure 20. Cross section of multi-stage centrifugal compressor [159].

The CAES compressors usually operate at off-design conditions due to load fluctuations, which deteriorates the isentropic efficiency of the compression process. To alleviate the efficiency degradation, variable geometry assemblies can be implemented, including inlet guide vanes (IGVs), which are applied in axial [160] and centrifugal machines [161], and adjustable vaned diffusers (AVDs), which are employed in the centrifugal units [162]. With regard to the off-design control of the volumetric compressors, many regulation methods are in use, including throttling adjustments, recirculation controls, or intermittent machine operations [163].

The Huntorf and McIntosh CAES installations utilize dynamic compression units. In the Huntorf system, the compressor train comprises a low-pressure axial-flow compressor and a high-pressure centrifugal compressor. The axial compressor is placed at the front of the compression train as it is well adapted to be operated under high air volume flow rates. The ambient air is drawn into the suction line of the axial unit, where it undergoes compression and subsequently decreases in volume. In this state, it is directed to the centrifugal unit, which operates more efficiently with lower volume flow rates. Between the compression units, there is an intercooler that is used to cool down the air before subjecting it to further compression. The cooling of the pressurized air allows a reduction in the thermal stress in the compressor elements, resulting in a safe and robust operation of the entire machine. Moreover, compressing the gas at a lower temperature is generally linked to an enhanced compression efficiency [158]. In the McIntosh CAES plant, the same types of compressors are applied, but the entire process is performed with the use of four compression units. Both the Huntorf and McIntosh plants feature the same compression efficiency of 80% [28], whereas the rated power levels for driving their compressor trains are equal to 60 MW_e and 50 MW_e, respectively. Importantly, since these installations represent the diabatic CAES concept, the heat generated during the compression process is irretrievably lost to the environment. The compression waste heat can be recovered through the application of the A-CAES architecture.

In order to effectively recover the compression waste heat, a special approach for the design of the compression system needs to be adopted. One of the concepts refers to the so-called high-temperature A-CAES installations. In these systems, the air is heated up during the compression process to a temperature of about 600 °C [136]. The pressurized air at such a temperature is then directed to a single and specially designed TES buffer to dissipate the heat. Through this process, the air may heat up the TES material to temperatures of 600 °C or even higher. However, the air heating in the currently manufactured compressors is limited, and its temperature at the compressor discharge currently does not surpass 600 °C [158]. Hence, the compressor for the high-temperature A-CAES requires increased attention, and thorough research and development are needed to design a unit capable of withstanding the high pressure (>50 bar) and high temperature (>600 °C) of the flowing air.

The other concept for recovering the compression heat involves the use of several heat-receiving devices (heat exchangers or TES units), which are positioned between the individual compression stages [136]. This idea has been proposed for A-CAES configurations that operate with lower air temperatures. In such systems, the TES functions at a temperature that does not exceed 400 °C. In this matter, the literature draws a distinction between low- (<200 °C, see Figure 21) [164] and medium- (<400 °C, see Figure 22) [136] temperature A-CAES units. Owing to reduced temperature thresholds, the pressurized air that is used for heating the TES tanks can be maintained at temperatures below 400 °C. Such temperature levels are commonplace within the compression gas industry [158]. Therefore, leveraging the existing compressor technology presents a viable approach for designing compression units in low- and medium-temperature A-CAES systems. However, Wolf and Budt [136] highlight that maintaining even lower air temperatures (~100 °C) may require the inclusion of many (up to 10) interstage cooling units. Given the requirement of a substantial quantity of intercooling assemblies, the existing compression technologies, like multi-stage axial or multi-stage centrifugal (radial) compressors, may not offer the most suitable solution. As for the axial-flow units, their densely arranged configuration, comprising multiple stator and rotor wheel assemblies, precludes the insertion of an intercooler between the successive compression stages. Meanwhile, within off-the-shelf multi-stage radial compressors, the intercoolers are incorporated, but their number is usually limited to five units. Moreover, these elements are built into the compressor as pre-sized parts, making them difficult to access and potentially unsuitable for the required heat capacity. In place of these solutions, Wolf and Budt proposed the application of integrally geared radial turbocompressors [136].

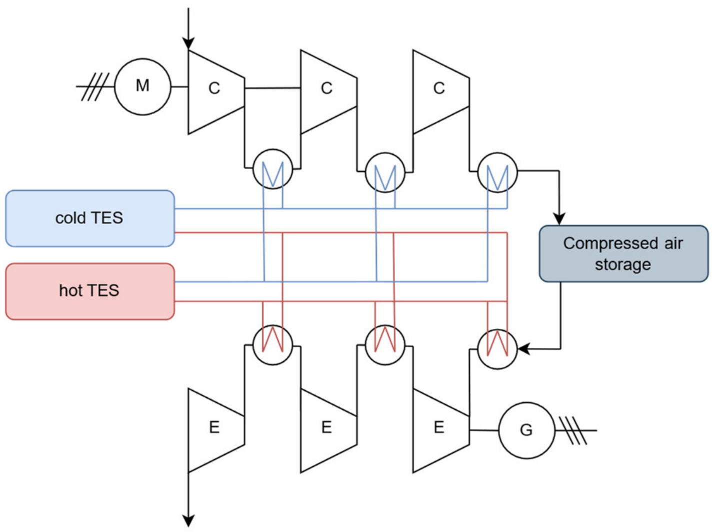

Figure 21. Compression heat recovery in a low-temperature (<200 °C) A-CAES system.

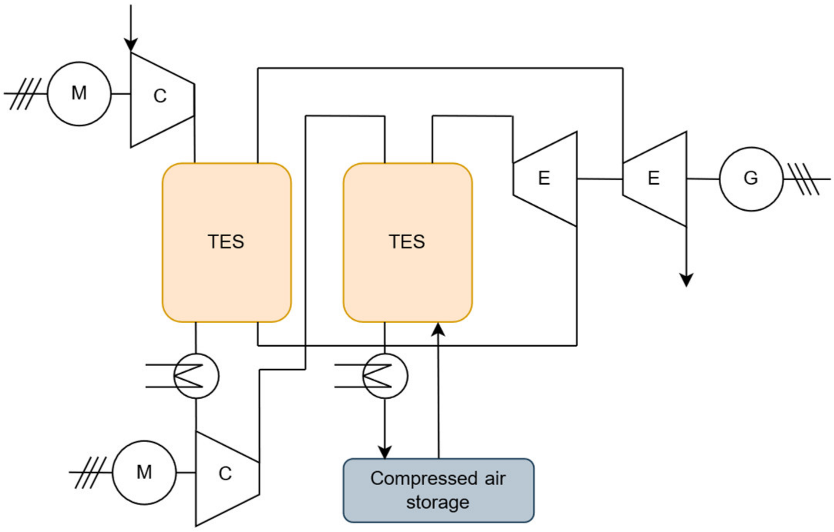

Figure 22. Compression heat recovery in a medium-temperature (<400 °C) A-CAES system.

A survey of investigated CAES architectures suggests that volumetric compressors, such as piston, screw, and scroll, also represent efficient and viable compression technologies, especially with regard to small- and micro-scale CAES installations. Liu et al. [165] showed that the scroll compressor can efficiently serve as the CAES compression unit, but detailed leakage analyses are needed to achieve an optimal design. Leszczyński et al. [166] utilized a screw compressor (Fini CUBE 10) to test the performance of a micro-scale CAES installation, indicating its potential use in the residential and industrial sectors.

Although rotary machines (scroll and screw) stand out as very efficient and promising CAES compressor technologies, many more studies and exemplary applications refer to reciprocating compression units. As an example, the TICC-500 CAES system developed in China integrates a five-stage reciprocating (piston) compression system to attain an air pressure of 112 bar [131]. Meanwhile, in up-to-date studies, much effort is made to enhance the efficiency of piston compressors by performing the compression process at near-isothermal conditions. However, maintaining a constant temperature during the air compression in the piston is very challenging. To address this problem, many techniques enhancing heat transfer conditions in the piston chamber were suggested. Heidari et al. [167] proposed the inclusion of metal annular fins inside the piston compression chamber. Owing to an increased heat transfer area, the authors reported an improved compression performance. The other approach for performing isothermal compression incorporates the already-mentioned liquid piston technology. This concept has been utilized in the development of real-world projects, including SustainX [107], GLIDES [168], REMORA [169], FLASC [170], and Enairys Powertech [171]. To further improve the heat transfer characteristics of liquid piston machines, some scholars have implemented methods that are known in the literature as liquid spray [172], aqueous foam [173], wire meshes [174], or porous material [175] methods. The experimental works demonstrate the viability of liquid piston technology, with the test rig presented in Figure 23 being one of the examples. Among other researched machines, the isothermal compressor–expander [176] unit, operating in both compression and expansion modes, also represents a promising choice for small-scale CAES installations.

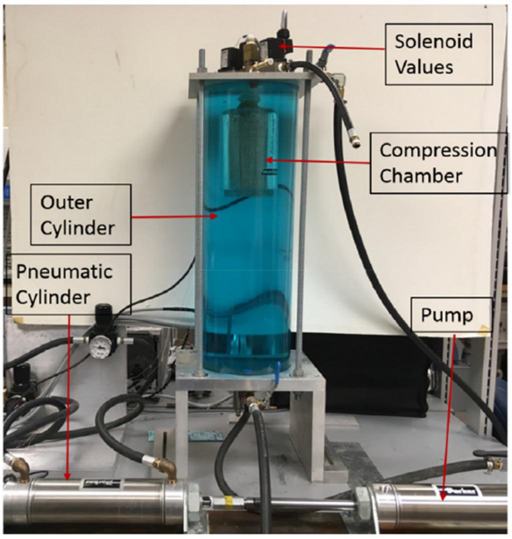

Figure 23. Liquid piston compressor setup [174].

4.3. Thermal Energy Storage

The theoretical efficiency of traditional CAES electrical storage systems, not equipped with a thermal energy storage unit, can only reach about 50%. This is caused by the fact that high-pressure gas needs an external heat source during expansion in order to be used in the gas turbine. In traditional systems, such heat was supplied by the combustion of fuel [177]. In order to increase the efficiency of the CAES systems, thermal energy storage is commonly used in order to collect part of the heat produced during the process of air compression and to use it during decompression.

There are three main methods of thermal energy storage for collecting heat, which can be utilized during the expansion of the high-pressure gas stored in the CAES system—based on sensible heat, latent heat, and thermochemical storage. The methods based on sensible heat storage are relatively mature compared to latent heat and thermochemical storage, which are considered promising technologies since their theoretical energy storage densities are at a much higher level. Gravimetric storage density varies from about 10–50 kWh/t in the case of sensible thermal storage to 50–150 kWh/t in the case of latent thermal storage up to even 250 kWh/t in the case of thermochemical storage [28]. The correct choice of heat storage method is crucial for the proper functioning of the installation at a specific scale. For this reason, examples of heat storage methods for CAES installations are described.

Most of the sensible thermal energy storage systems for CAES are based on a packed-bed heat storage with solids as a medium. Such a concept is based on an insulated structure filled with a solid medium such as sand, rocks, pebbles, etc. The storage is charged during the air compression process by hot air from the compressor and discharged with cold air from the cavern during the expansion. An example of such a system is presented by Geissbühler et al. [29]. The system presented in the paper consists of an AA-CAES system built in an unused tunnel with a diameter of 4.9 m and a length of 120 m. Thermal energy storage with a capacity of 12 MWh_{th} was placed inside the cavern and was based on a packed bed of various rock types with a mean diameter of about 2 cm. The plant was operated with air temperatures of up to 550 °C and achieved efficiency in a range between 78.7% and 90.9%. An example of a smaller-scale TES for the CAES system was described in Ref. [178]. In the paper, authors proposed a packed-bed unit with integrated heat exchangers, which can be charged directly by the system's stream of pressurized air with temperatures in a range between 214 °C and 550 °C. Silica sand was used as a storage medium due to its heat capacity and non-corrosivity. The authors achieved a round-trip thermal efficiency of the TES at the level of 86%. In order to predict the operation of CAES systems, Sciacovelli et al. [179] developed a numerical model of a A-CAES plant with integrated sensible thermal storage based on a packed bed containing gravel. The results indicate that it is possible to achieve a round-trip efficiency of the system exceeding 70% with only the efficiency of the TES being higher than 90%. The authors prove that, in order to properly simulate the dynamic performance of the CAES system, it is necessary to link the system performance with the dynamic performance of specific devices, because modern energy storage systems present a strong tendency towards transient operation. Another TES concept for CAES utilizing sensible heat is based on double-tank heat storage. Szablowski et al. [180] presented a numerical study, performed with the use of Aspen Hysys software, describing an A-CAES system with thermal energy storage in the form of synthetic oil stored in hot and cold tanks with volumes of 15,627.9 m^3 and 12,685.6 m^3, respectively. The system consisted of a 3.1×10^5 m^3 salt cavern, a two-stage compressor with the intercooler and two heat exchangers, a three-stage gas turbine with three heat exchangers, two oil coolers, and nine pumps. The pressure inside the cavern was in a range between 43 and 70 bar, while the temperatures of the oil were equal to 80 °C in the case of the cold oil and 300 °C in the case of the hot oil. The authors achieved an overall round-trip efficiency at the level of 50%. Ref. [47] describes a pilot CAES power plant with the TES based on water as a working medium. The volume of the analyzed air storage was equal to 100 m^3 with the pressure operation range between 25 and 95 bar. The water in the system was stored in two separate tanks with a volume of 12 m^3 for the cold and hot storage and was pressurized to 4 bar in order to avoid the water boiling. The authors managed to achieve an average round-trip efficiency equal to 23.1%, with 1375 kWh of energy consumed during the charging and 326 kWh produced during discharging. The authors conclude that the key parameter reducing the efficiency of the installation in the analyzed case was the size of the air storage, which caused unstable operational conditions. Overall, it is worth noting that CAES systems with TES based on sensible heat are intended for short-term operation and require additional space due to the relatively low volumetric density of the TES.

TES systems based on latent heat offer higher energy capacities and densities than ones based on sensible heat. The principle of such TES is based on the utilization of a specific phase change material (PCM) as the working medium. An example of such a system is presented in Ref. [181]. The authors of the study presented an analysis concerning the PCM selection procedure for a CAES system with a packed-bed TES. They concluded that, in order to maximize the round-trip efficiency of the CAES, the most important parameter of the TES PCM, determined by a TOPSIS analysis, is its density, followed by the melting temperature. Considering the air storage capacity, the most important factors were density and latent heat. Tassier et al. [182] studied the concept of a CAES system with a four-stage cascade of the PCM as a TES in terms of exergy. They concluded that the melting temperature and enthalpy of the PCM are parameters that could be considered in order to optimize such energy storage systems. The research conducted by Li et al. [183] concerned a dynamic model of a CAES system with separate tanks with a PCM (RT90 Paraffin) and water used as heat storage. The authors achieved a round-trip efficiency at a level exceeding 61%. In general, the literature lacks a paper describing the topic of heat storage systems utilizing latent heat for CAES purposes, which makes this topic worth exploring.

The highest gravimetric densities in terms of thermal energy storage are possible to obtain by utilizing thermochemical energy storage technologies. Such a concept is relatively innovative; thus, it does not offer many studies. However, it is considered one of the most promising. Lei et al. [184] presented a comprehensive numerical study describing the BaO_2/BaO couple as a promising candidate for a CAES TES material. The authors compared thermal storage systems based on a rock-filled packed bed with one based on a thermochemical system with barium oxides placed on top of the bed and rock at the bottom. The round-trip efficiency of the system with thermochemical storage exceeded the value of a sensible heat-based system by over 5%, reaching up to 59%. The study presented by Wu et al. [185] describes the thermodynamic analysis of a novel compressed air energy storage system powered by renewables. The thermal storage in this system is realized in the form of thermochemical storage, utilizing the process of the reduction of Co_3O_4 to

CoO. In order to charge the thermal storage, it is necessary to provide external heat to the reduction reactor with Co_3O_4, allowing the production of CoO. Cobalt oxides can be stored at ambient temperature for an extended period without insulation requirements, which makes the system a long-term energy storage solution. The authors managed to achieve a round-trip efficiency at the level of 56.4%, with an energy storage density at the level of 3.9 kWh/m^3 and an overall exergy efficiency of 75.6%.

5. Existing CAES Installations

The need to store energy related to the development of renewable energy sources causes the development of CAES electrical storage systems and the creation of further demonstrators of this technology. Table 1 shows the current state of development in this field.

Table 1. Literature review of existing CAES electrical storage units.

Facility	Discharge Time [h]	Deliverable Power	Pressure [Bar]	Round-Trip Efficiency [%]	Thermal Storage	Reference
Huntorf CAES	3	290 MW	43–70	29	No	[186]
McIntosh	26	110 MW	<76	36	No	[107]
Biasca, Switzerland	3	No turbine	7	63–74	Yes—packed bed with rocks	[29]
TICC-500	1	500 kW	100	41	Yes—based on sensible heat and water	[131]
TICC-500	1	430 kW	93	22.6	Yes—based on sensible heat and water	[47]
Changzhou CAES	5	60 MW	No data	>60	Yes	[51,187]
Zhangjiakou CAES	4	100 MW	No data	~70	Yes	[188, 189]
SustainX Project	0.67	1.5 MW	207	54	Yes—water	[190]
Hydrostor	4	1.75 MW	No data	No data	No data	[191]
GLIDES	1	1600 W	130	24	No	[168]

The conducted literature analysis proves that there are few completed projects in the field of CAES. Existing installations rarely include the possibility of heat recovery. If such a possibility occurs, it is usually accomplished through sensible heat storage in the form of water tanks or packed-bed storage. Theoretically, such an approach offers lower efficiencies, which justifies the further development of compressed air energy storage, especially with other forms of thermal storage included.

6. Summary on CAES Technologies and Comparison with Other Systems

6.1. General Characteristics of the Overviewed Compressed Air Storage Technologies

Table 2 gives an overview of the features of the previously described CAES systems and their individual components.

Table 2. Comparison of CAES systems and their elements.

CAES Technology/Component	Benefits	Drawbacks	Initial Expense	Technical Maturity	Reference
CAES technologies					
D-CAES	well-known, relatively old technology; easy handling and installation; possible use of gas turbine separately when storage is empty	required use of fossil fuels during operation, large heat losses while charging	✓	✓✓✓	[6,29]
A-CAES	lower required energy, low storage temperature	limitations in available system components that require time to reach full efficiency	✓✓✓	✓	[25,41,42]
I-CAES	lower required energy, low working temperature	components in development, lower power systems	✓✓	✓	[56,57]
compressed air cars	low-cost, easy operation; environmentally friendly alternative to ICEs	low-energy density, short range of operation	✓	✓✓	[70]
W-CAES	better performance than traditional wave energy converter systems	large initial costs	✓✓✓	✓	[89]
CAES components					
underground storage chambers	the possibility of operation with a pressure of up to 200 bars and storage of very high volumes of gas	the installation of the underground storage of compressed air requires a favorable location and favorable geology conditions	✓✓	✓✓✓	[98]
underwater containers	high possible usability for floating wind farms and flexible underwater vessels, low manufacturing price	high dependence of energy density on the depth of the location with high difficulty of connection with wind turbines anchored to seabed and wind and PV farms onshore	✓	✓	[27,113,116]
aboveground vessels	scalability, technology maturity, different applications	short-term installation, more space requirements, high variability of operating pressure, high investment cost	✓✓✓	✓✓✓	[2,128]
dynamic expander–compressor	great scalability (1 kW_e–500 MW_e), high efficiency (~90%), flexible design (multi-stage or multi-unit (train) arrangement)	high investment cost, not adapted for isothermal or two-phase expansion–compression	✓✓✓	✓✓✓	[132–135,159,160]

Table 2. *Cont.*

CAES Technology/Component	Benefits	Drawbacks	Initial Expense	Technical Maturity	Reference
volumetric expander–compressor	adapted for isothermal or two-phase expansion–compression (I-CAES), a single unit can be operated in both expansion and compression modes, relatively low investment cost	application limited to micro- and small-scale (<1 MW_e) CAES systems, lower efficiency than that of dynamic units	adiabatic expansion–compression units—✓ isothermal or two-phase expansion–compression units—✓✓	adiabatic expansion–compression units—✓✓✓ isothermal or two-phase expansion–compression units—✓	[131,145,146,155,165–167,172–175]
thermal energy storage	increased round-trip efficiency, reduced CO_2 emissions	high initial costs, additional space requirements, technical immaturity of systems based on latent heat and thermochemical energy	✓✓✓	✓	[177]

Note: check marks refer qualitatively to the scale of the initial investment or technical maturity of the CAES technology/element, where ✓represents the smallest, ✓✓represents the medium, and ✓✓✓represents the greatest value in the scale.

6.2. Performance and Expenditure Comparison of the CAES Electrical Storage Installations and Other EES Systems

Given that a significant part of this review was devoted to the CAES concepts that operate as EES systems, they are summarized in this section along with other EES technologies. In particular, Table 3 provides an overview of various types of EES systems categorized by the storage type, energy efficiency, lifetime, storage period, capital expenditure (CAPEX), and operational expenditure (OPEX). Since one of the CAES concepts takes advantage of thermal energy storage (TES), the list of the potential TES technologies is also included.

Table 3. Overview of the CAES electrical storage systems and other EES technologies. As part of A-CAES installations, TES technologies are also included [28,192].

Storage Type	Energy Efficiency [%]	Lifetime [Year or Cycle]	Storage Period [Time]	CAPEX [€/kW]	OPEX [€/kWh]
Mechanical energy storage					
Gaseous media (D-CAES)	40–55	20–40	days	340–1145	0.01–0.26
Gaseous media (A-CAES)	60–68	20–40	days	600–800	n/a
Gaseous media (I-CAES)	95	20–40	days	n/a	n/a
Solid media (flywheel)	85–90	10,000–100,000	hours	125–275	1
Liquid media (PHES)	65–87	-	days/months	n/a	n/a
Electrical energy storage					
Supercapacitors	90–95	1 million	seconds/minutes	125–300	n/a
Superconducting magnets	90–95	>1 million	minutes/hours	300–915	n/a
Electrochemical energy storage					
Lead-acid batteries	74–95	203–1500	days/months	200–490	0.16–0.76
Lithium batteries	90–97	3500–20,000	days/months	100–200	0.13–0.76
Nickel batteries	71	350–2000	days	385–1100	n/a
Sodium–sulfur batteries	75–85	2500–8250	days/months	285–1075	0.07–0.76
Redox flow batteries	60–80	700–15,000	days/months	710–1790	n/a
Thermal energy storage					
Sensible TES	45–75	5000	days/months	80–130	0.1
Latent TES	75–90	5000	hours/months	80–160	0.1–0.5
Thermochemical	80–100	5000	hours/days	n/a	n/a

"n/a"—not applicable.

The parameter that is marked in Table 3 as CAPEX refers to the initial investment costs associated with the construction and commencement of operations of a storage system. These costs are only incurred once and include expenses related to the infrastructure establishment and system startup. Meanwhile, OPEX encompasses the ongoing costs associated with the operation of a storage system, such as electricity procurement, maintenance, and insurance expenses. These costs are typically calculated based on the energy converted and can be further categorized into fixed operating costs (e.g., personnel, maintenance, and insurance) and variable operating costs (e.g., electricity or fuel procurement and replacement parts).

Table 4 is complementary to the CAES technologies listed in Table 3, because it outlines various types of potential air storage chambers, detailing their influence on the total unit cost (€/kW) of the CAES electrical storage plant.

Table 4. Influence of various types of air storage chambers on the total cost of the CAES electrical storage plant [128].

Type of Material/Element for the Air Storage Chamber	Size of the Electrical Storage CAES System [MW]	Cost for the Energy Storage Components [€/kWh]	Typical Storage Time [h]	Total Cost of the CAES Electrical Storage System [€/kW]
salt	200	1	10	340
porous media	200	0.1	10	330
hard rock	200	29	10	610
surface piping	20	29	3	415

7. Potential Perspectives for the CAES Technology

In today's fast-paced world, the search for new, more efficient, and sustainable energy sources is not only a priority but an imperative. In the context of an increasing energy demand and the need to reduce greenhouse gas emissions, innovative technologies are becoming a key element in the transformation of the energy sector.

One promising solution in the field of energy storage and energy production is the CAES electrical storage technology. In comparison to pumped storage power plants, CAES systems can be brought into operation 2–3 times faster, which increases the reliability of the electricity system [40].

The use of excess energy from renewable energy sources (RESs) in CAES systems is a promising solution for the efficient storage of electricity. RESs, such as mostly solar and wind power, are characterized by intermittent energy production, depending on the weather conditions and time of day. It is, therefore, necessary to find efficient ways of storing excess energy generated during the periods of high production in order to use it during the periods of lower demand or when there is no on-site production from RESs. In addition, the possibility of using aboveground vessels for short-term storage and the associated increase in the efficiency of such systems to balance the production of renewable energy with the energy needs of users is explored. In [193], numerical and experimental work is described for polytropic charging and discharging processes, the changes in the time of the temperature, the flow parameters of the inlet and outlet valves under choked and subsonic conditions, and the characteristics of the air motor.

Developments towards the use of CO_2-free CAES systems are expected in the near future, including combined renewable sources, e.g., PV systems for electricity generation, and the use of H_2-CAES as CO_2-free diabatic CAES systems. Such a system has been proposed and analyzed in [194]. It can effectively meet user requirements in terms of the annual availability and electricity production. One possible direction of development is the use of hydrogen as a combustible fuel [195]. In this case, it may be possible to additionally implement an electrolyzer into the system, which could produce hydrogen using excess electricity from renewable energy sources. This solution is relatively novel and requires further research. Such a system has been proposed and analyzed in [196]. The authors showed that, provided the right conditions are met, such a system can be cost-effective. However, it should be borne in mind that this and similar studies are purely theoretical at present and may differ to some extent from a potential real system.

It is also possible to develop systems based not only on air but also on other gases such as CO_2. The use of CO_2 in energy storage systems has been analyzed in [197]. Such systems are environmentally friendly, highly efficient, and economically accessible, and can also achieve higher efficiencies due to easier compression and expansion processes.

It is possible to combine CAES systems not only directly with RESs (in series, parallel, or series–parallel) [198] but also with high-temperature solid oxide cells (SOFCs). In [199], hybrid systems combining gas turbines, SOFCs, and CAES are understood as an appropriate approach to the development of CAES systems. The results of work on such systems show that it is possible to increase the efficiency and to provide flexible operating modes. Energy storage in the form of compressed air—CAES systems—allows the flexible release of energy in the form of electricity at a later time. In addition, SOFCs, RESs, and CAES can be hybridized through thermal integration to maximize the power output during production, to store energy when demand is low, and to reduce energy prices through renewable generation [200]. Scalability is a key factor in the success and future development of energy storage systems, particularly CAES [201]. These systems have the potential to be easily scalable, as described in the sections above. Consequently, the scalability of CAES systems is a key element of their attractiveness as an energy storage solution, as it allows them to flexibly adapt to different conditions and requirements (of capacity or power), both locally and globally.

CAES technology can be applied in different geographical areas, depending on local needs, climatic conditions, and the availability of energy resources [202]. Significant location independence stems from the possibility of using not only underground but also underwater or aboveground storage systems. Its flexibility and scalability make it a promising solution for future global energy needs.

Improving the energy efficiency of CAES technology is a key objective for the further development and commercialization of this solution. With continued technological advances and the optimization of operational processes, CAES systems have the potential to become increasingly efficient and competitive solutions for electricity storage [194]. There are several technical aspects that should be analyzed in the near future in order to increase the efficiency of the technology:

- Compression efficiency: This has a significant impact on the overall system efficiency. Modern compressor technologies, such as screw or turboprop compressors, offer a higher efficiency compared to traditional reciprocating compressors. Additional advancements can be achieved through isothermal compression technology.
- Expansion efficiency: This substantially affects the overall system efficiency. Modern expanders (both volumetric and dynamic) can achieve high levels of efficiency, contributing to a high CAES round-trip performance.
- Improved thermal insulation: Heat loss can be reduced during energy storage by using insulation materials with a high thermal efficiency.
- Development of heat recovery systems: High-efficiency heat exchangers can be used to recover heat released during the air compression and expansion.
- Optimization of adiabatic processes: Adiabatic processes that minimize heat energy loss by rapidly compressing and expanding air with minimal heat exchange with the environment can be used.
- Use of control and monitoring systems: Advanced control and monitoring systems that enable real-time optimization of the CAES system can be implemented.
- Integration with other technologies: Integrating the CAES system with other energy storage technologies and grid infrastructure can help increase its overall efficiency. For example, waste heat from the technological processes can be used to increase the temperature of the air during the expansion process.

The integration of CAES technology into existing power grids is a key element of its practical application. It requires cooperation between the distribution and transmission system operators, as well as appropriate energy management regulations and standards. However, through effective integration, CAES systems can contribute to the more sustainable, flexible, and reliable operation of energy networks [203]. The main benefits in this respect are as follows: balancing supply and demand, stabilizing electricity grids, and supporting the development of renewable energy.

The prospects for the development of CAES technology also include further innovation in the use of advanced materials and storage technologies, as well as the development of intelligent management and control systems. With advances in technology and increasing interest from the energy sector, further development and deployment of CAES systems can be expected worldwide.

As awareness grows of the need to move towards more sustainable energy sources and the need to store excess electricity, CAES technology is becoming an increasingly attractive and competitive option. From the perspective of the future transformation of the energy sector, CAES appears to be a key element in building more flexible, resilient, and sustainable energy systems around the world.

8. Conclusions

This work was aimed at giving a review of the past and current advancements in compressed air energy storage (CAES) technology. Based on the published literature and available data, a detailed overview was provided, covering the CAES electrical storage installations (diabatic, adiabatic, and isothermal), as well as other prospective technologies that make use of pressurized air (compressed air cars and wave-driven CAES). Moreover, future perspectives and possible challenges were also underlined. On the basis of the information collected, the following conclusions have been drawn:

- Turbines, along with centrifugal and axial compressors, represent mature and well-adapted technologies for medium- to large-scale CAES architectures (1 MW_e–500 MW_e).
- Positive displacement machines, including piston, screw, and scroll expanders–compressors, are well adapted to small- (<1 MW_e) and micro-scale (<100 kW_e) CAES applications.
- To achieve a low temperature (<200 °C) in the thermal storage tank in adiabatic CAES (A-CAES) systems, many interstage cooling units must be placed between the compression units, and a dedicated design of compressors is required.
- Achieving a very high air temperature (>600 °C) in an A-CAES system necessitates specialized compressor designs capable of withstanding high air temperatures and pressures.
- The cycle efficiency of A-CAES systems is largely affected by incorporated TES technology. The development and applicability of these systems depends on technological advancements in both fields.
- Compression–expansion under near-isothermal conditions can be achieved in piston-derived constructions with the use of such techniques as (1) liquid piston technology, (2) the injection of liquid or foam into the piston cylinder, and (3) structural modifications of the piston that take advantage of wire meshes or porous materials.
- The utilization of thermal storage is necessary to achieve a satisfactory level of round-trip efficiency.
- For large-scale electrical storage CAES systems, it is necessary to improve the capability of the element of thermal storage, especially by utilizing latent heat and thermochemical storage.
- The literature lacks studies describing the operation of CAES systems with latent heat and thermochemical heat storage, which justifies further projects.
- A number of underground structures and techniques can be employed for the storage of compressed air, including the following four types: rock salt caves, abandoned mines, artificially excavated hard rock caverns, and aquifers. As a mature technology, salt caverns have been widely used. It has certain merits, such as a large capacity, higher storage pressure, and lower construction cost, compared to other storage technologies.
- The capital cost of electrical storage CAES installations using salt caverns is at least 10 times lower than that of aboveground installations.
- To increase the scalability and availability of the electrical storage CAES plants, it is possible to use aboveground compressed air vessels, making such systems more accessible to local power systems.
- Different innovative solutions based, for example, on the usage of hydrogen and solar energy vehicles using energy stored in compressed air produced by a compressor have also been suggested, being perceived as environmentally friendly and prospective vehicles.
- Research into efficiency improvements is needed to make CAES competitive with PHES for further development and deployment.

- Due to the increasing capacity of RESs, it is necessary to balance the system by absorbing surplus energy and supplementing the system in times of RES shortage. The large-scale use of CAES will make it possible to balance the electricity grid and avoid overloading it.

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Abbreviations

AA-CAES	advanced adiabatic compressed air energy storage
ADELE	Adiabater Druckluftspeicher für die Elektrizitätsversorgung
AOE	accumulated ocean energy
A-CAES	adiabatic compressed air energy storage
ASME	The American Society of Mechanical Engineers
C	compressor
CAES	compressed air energy storage
DOE	Department of Energy
D-CAES	diabatic compressed air energy storage
E	expander
EB	electrochemical battery
EES	electrical energy storage
G	generator
GT	gas turbine
IRENA	International Renewable Energy Agency
I-CAES	isothermal compressed air energy storage
LRC	lined rock cavern
M	motor
ORC	organic Rankine cycle
PCMs	phase change materials
PED	Pressure Equipment Directive
PHES	pumped hydroelectric energy storage
PV	photovoltaic panel
RESs	renewable energy sources
SF-CAES	supplementary-fueled compressed air energy storage
SRC	salt rock cavern
TES	thermal energy storage
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TUV	Technischer Überwachungsverein (Technical Inspection Association)
UWCAES	underwater compressed air-based energy storage
WT	wind turbine
W-CAES	wave-driven compressed air energy storage

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