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Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) Technologies—A Comparison Review of Technology Possibilities

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Abstract: This paper introduces, describes, and compares the energy storage technologies of Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES). Given the significant transformation the power industry has witnessed in the past decade, a noticeable lack of novel energy storage technologies spanning various power levels has emerged. To bridge this gap, CAES and LAES emerge as promising alternatives for diverse applications. The paper offers a succinct overview and synthesis of these two energy storage methods, outlining their core operational principles, practical implementations, crucial parameters, and potential system configurations. The article also highlights approaches to enhance the efficiency of these technologies and underscores the roles of thermal energy storage within their processes. Furthermore, it delves into the discussion of the significance of hybrid systems and polygeneration in the contexts of CAES and LAES technologies. Moreover, we briefly explore the potential integration of these technologies into other power systems.

Keywords: A-CAES; D-CAES; LAES; high-capacity energy storage; integrated thermal energy storage; energy storage trigeneration; energy storage polygeneration; thermal energy storage for CAES; thermal energy storage for LAES

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1. Introduction

The increasing share of renewable sources in power generation highlights the importance of energy storage technologies as integral components of power grids. Many renewable technologies are not able to consistently and reliably produce energy like conventional technologies, such as nuclear or coal power plants. Energy production from renewables is difficult to predict within a range of days or hours, particularly for wind and solar sources. Additionally, solar sources are unable to operate during night-time [1–3].

For these reasons, renewable sources are not suitable for base load production. At the beginning of this century, when the total power production from renewables was only a few percent, these disadvantages were not significant for power grid operation. However, the situation has changed in the present time. There is now a lack of adequate technologies for load-following grids with a high share of renewables. It is necessary to develop suitable, available, and reliable energy storage technologies to ensure the stable operation of power grids and to achieve the targets of a significant share of renewables in power generation [4].

These technologies should primarily possess a large capacity, high-rated power, and rapid response time, to fulfill their roles in energy grid stabilization. The optimal capacity for grid load following should fall within the range of 1 MWh to 48 GWh, while the optimal rated power should be between 1 and 2000 MW. Additionally, the response time should be lower than 15 min [4]. These requirements exceed the capabilities of many common energy storage solutions. Currently, only thermo-mechanical energy storage technologies are suitable for load following in the electrical grid. This category encompasses four technologies: Pumped Hydro Energy Storage (PHS), Pumped Thermal Energy Storage

(PTES), Compressed Air Energy Storage (CAES), and Liquid Air Energy Storage (LAES) [5]. The main parameters of these technologies are listed in the table.

Pumped Hydro Energy Storage (PHS) is a traditional technology that accounts for 94% of worldwide electric energy accumulation [6]. However, its further expansion is constrained by geographical conditions. PHS requires a large water reservoir located at higher elevations in rural areas for its operation. Presently, it is the only one among these four technologies that is widely utilized in industrial applications.

Pumped Thermal Energy Storage (PTES) is a collection of independent technologies and technological concepts that revolve around the idea of converting power into heat during the charging period and subsequently converting heat back into power during the discharge period [7]. These technologies, both LAES technologies, are sometimes referred to as "Carnot batteries" [8]. However, they suffer from relatively low efficiency, mainly due to the thermal cycle involved in the discharge process. Additionally, they require large-scale heat accumulators.

Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) are innovative technologies that utilize air for efficient energy storage. CAES stores energy by compressing air, whereas LAES technology stores energy in the form of liquid air. Both of these technologies employ a thermal cycle for energy discharge, which is derived from a highly modified Brayton cycle [6,7,9].

This article just focuses on CAES and LAES technologies, due to their same storage media and similar discharge cycle. The next chapters will describe both technologies, their particular modification for combined heat and power supply, their integration with other power systems, and finally, perspectives for that wide application will be discussed (Table 1).

Table 1. Technical parameters of large scale energy storage technologies [6,10–12].

Technology	Power Range [MW]	Capacity Range [MWh]	Energy Density [kWh/(m^3)]	Round Trip Efficiency [%]
CAES	1–320	≤1000	0.5–20	42–70
LAES	1–300	≤1000	50–200	45–70
PTES	10–150	≤1000	10–100	48–75
PHS	30–5000	100–2000	0.5–1.5	65–87
Technology	**Power CAPEX [$/kW]**	**Energy CAPEX [$/kWh]**	**Operation Lifetime [Years]**	**Site Constraints [-]**
CAES	400–1000	2–250	20–40	Yes
LAES	300–1000	1300–2200	20–40	No
PTES	-	-	20–40	No
PHS	2000–4000	5–100	30–60	Yes

2. Technology Basic Principle Overview

Both CAES and LAES technologies share the same storage medium and working cycle, which includes a charge period for energy storage and a discharge period for energy release. The entire technology is composed of three primary subsystems: the energy charge subsystem, the energy storage subsystem, and the energy discharge subsystem. In contrast, the characteristics of other technologies are entirely distinct.

Both CAES and LAES employ a thermal cycle for energy discharge, which is derived from a highly modified Brayton cycle. During energy discharge, the stored air is expanded through turbines, which drive generators to produce electricity. The integration of these technologies with renewable energy sources, such as wind and solar, can significantly enhance the overall efficiency and reliability of the power grid.

CAES stores energy in a mechanical form by compressing air to a highly pressurized gaseous phase, reaching several MPa in pressure, while maintaining a temperature near ambient levels. In contrast, LAES stores energy in a thermal form by utilizing liquid air at pressures near ambient and extremely low temperatures below the boiling point of air, which is below −195 °C. Due to these differences, the energy charge systems and energy storage systems for CAES and LAES are entirely distinct.

The energy discharge system of both technologies is founded on the same thermal cycle, known as the Brayton cycle. However, the working parameters and gas-preheating methods are entirely distinct. In the case of CAES, the air is preheated before expansion at high temperatures through natural gas combustion. Alternatively, in the case of AA-CAES, the air can be preheated using stored heat from compression through a recuperation heat exchanger.

In the case of LAES, the liquid air is initially compressed by a pump and then evaporated in the evaporator using ambient temperature. Additionally, it is possible to utilize process heat from air compression and process cold from air evaporation for storage, thereby enhancing the round-trip efficiency of the cycle.

For comparison of these energy storage technologies, we can use technical and economical indicators. The most important of them are listed in Table 2.

Table 2. List of technical and economical indicators

Technical Indicators	Economical Indicators
• Round-Trip Efficiency (RTE) • Exergy Efficiency • Response time • Duration of Storage • Volumetric density of energy storage (VDES) • Mass Density of Energy storage (MDES) • Scalability • Geographic Suitability • Enviromental impact	• Capital cost (CAPEX) • Operation and Maintenance cost (OPEX) • Levelized Cost of Energy Storage (LCOS)

Technical indicators are the most important for the technology comparison of RTE, VDES, and MDES. Round trip efficiency (RTE) is a key technical indicator of economic operation; this is the ratio of energy charged to electricity discharged; see Equation (1).

$$RTE = \frac{E_{discharge}}{E_{charge}} \tag{1}$$

Other important technical indicators are the volumetric density of energy storage (VDES) and mass density of energy storage (MDES). VDES is a ratio of discharged energy to volume of energy accumulator V_{acc}; see Equation (2). The VDES is a key technical indicator of the real size of technology.

$$VDES = \frac{E_{discharged}}{V_{acc}} \tag{2}$$

MDES is a ratio of discharged energy to mass of energy accumulator V_{acc}; see Equation (3).

$$MDES = \frac{E_{discharge}}{m_{acc}} \tag{3}$$

Economic comparison is the most important indicator of the Levelized Cost of Storage. This indicator is the ratio of total cost over the lifetime of energy storage facility $E_{discharge}$ and the sum of total discharged energy over the lifetime. The total cost over the lifetime usually consists of the sum of investment cost I_t, operation and maintenance cost M_t, and cost of fuel F_t. The r is the discount rate. LCOS is a key indicator of the real price of stored energy.

$$LCOS = \frac{sum\ of\ cost\ over\ lifetime}{sum\ net\ useful\ energy\ discharged\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{discharge\ t}}{(1+r)^t}} \quad (4)$$

2.1. CAES Basic Principle

Compressed air energy storage (CAES) is a technology that revolves around storing energy in the form of compressed ambient air. During the charging process, electric-powered compressors are used to compress the air. The power consumed by the compressor represents the actual charged power. To improve cycle efficiency and maintain air temperature within the material limits of the technology, air compression is divided into multiple stages with intercooling implemented [13,14]. An aftercooler is inserted after the final compression stage to ensure that the air temperature remains below the specified limits for storage [15]. The cooled and compressed air is then directed to the storage system. Due to the relatively low energy density of compressed air, the storage space required must be substantial. As a result, storage systems are typically formed in large underground spaces, such as salt caverns or old mines. Although ground pressure vessels are also an option, their overall capacity is relatively limited [16].

The discharging system, in its basic configuration, consists of a combustion chamber and a gas expansion turbine. The compressed air is first directed to the combustion chamber, where it is mixed with natural gas and combusted to generate heat in the form of an output flue gas mixture. Subsequently, the hot output flue gas expands through the gas turbine, producing electricity as it returns to the ambient atmosphere during the discharge period. Efficiency gains can be achieved by increasing the number of turbine stages and incorporating reheating. The basic cycle layout can be seen in Figure 1.

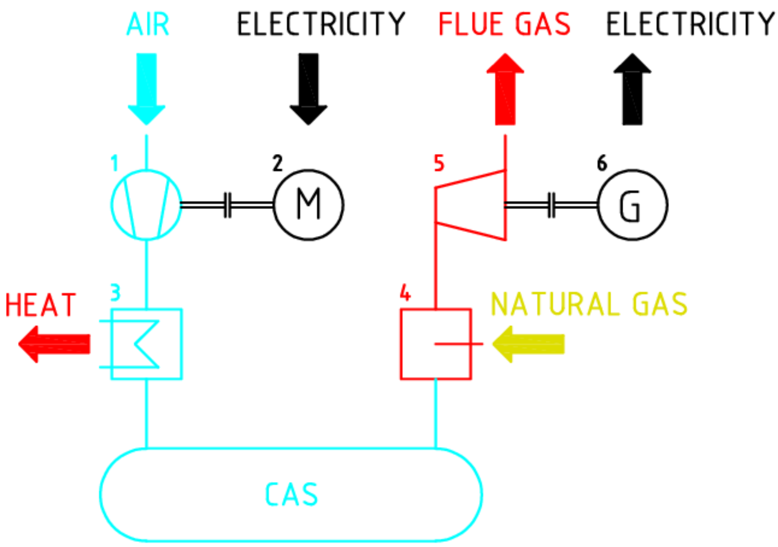

Figure 1. The D-CAES basic cycle layout. Legend: 1—compressor, 2—compressor electric motor, 3—after cooler, 4—combustion chamber, 5—gas expansion turbine, 6—electric generator, CAS—compressed air storage, 7—preheater/heater.

The aforementioned cycle represents the simplest configuration of CAES, which essentially operates as a Brayton thermal cycle divided into two stages: charging (air compression) and discharging (air heating and expansion). The energy that is charged corresponds to the energy used for air compression. However, a portion of the charged energy is extracted from the air through the intercooler and aftercooler before storage, resulting in a relatively low round-trip efficiency. The discharged energy exceeds the charged energy due to the additional heat generated by natural gas combustion. This necessity of natural gas combustion has led to the system being referred to as a hybrid energy storage system [7]. It is also known as Diabatic CAES (D-CAES), due to the energy loss during intercooling and aftercooling. The round-trip efficiency (RTE) of D-CAES is defined differently from the general RTE definition; see Equation (5), where $E_{gas\_discharge}$ is the same energy discharge of the gas power plant, which is about the same E_{charge} as D-CAES.

$$\eta_{RTE_{hybrid}} = \frac{E_{discharge} - E_{gas\_discharge}}{E_{charge}} \quad (5)$$

Advanced configurations that offer improved round-trip efficiency (RTE) in CAES systems include Adiabatic CAES (A-CAES), Advanced Adiabatic CAES (AA-CAES), and Isothermal CAES (I-CAES) [9,17,18]. Adiabatic CAES is a technology that enhances the utilization of extracted heat during air compression through intercooling and aftercooling. This heat is partially stored in a suitable thermal energy storage system and later utilized for air preheating during the discharge cycle. Although additional combustion of natural gas is still required for final air heating, the round-trip efficiency is superior to that of D-CAES. The basic cycle layout can be observed in Figure 2.

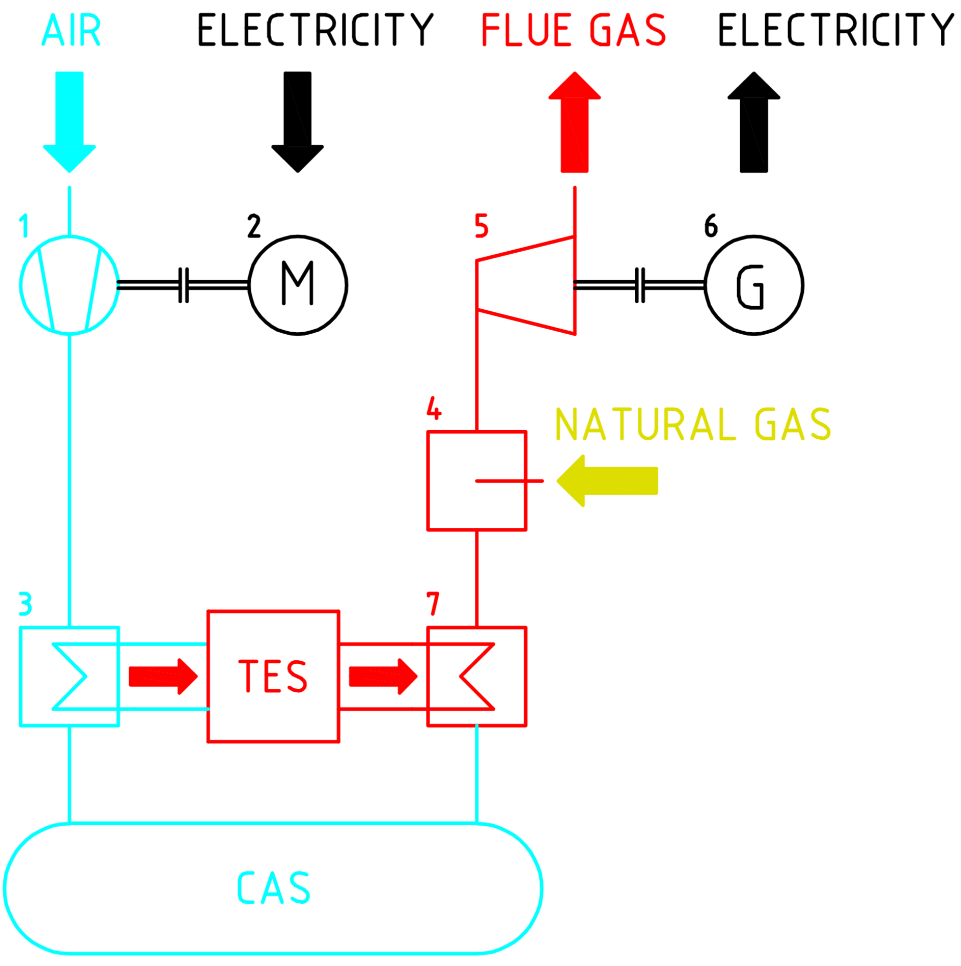

Figure 2. The A-CAES basic cycle layout. Legend: see Figure 1.

Advanced adiabatic CAES is an enhanced technology that operates without the need for additional natural gas combustion. In this system, the air is fully heated using only the stored heat from intercooling and aftercooling. On the other hand, isothermal CAES adopts a different approach to improve the round-trip efficiency of the basic D-CAES. It replaces the standard adiabatic compressor with an isothermal compressor, which prevents any temperature increase after compression. The basic cycle layout can be seen in Figure 3.

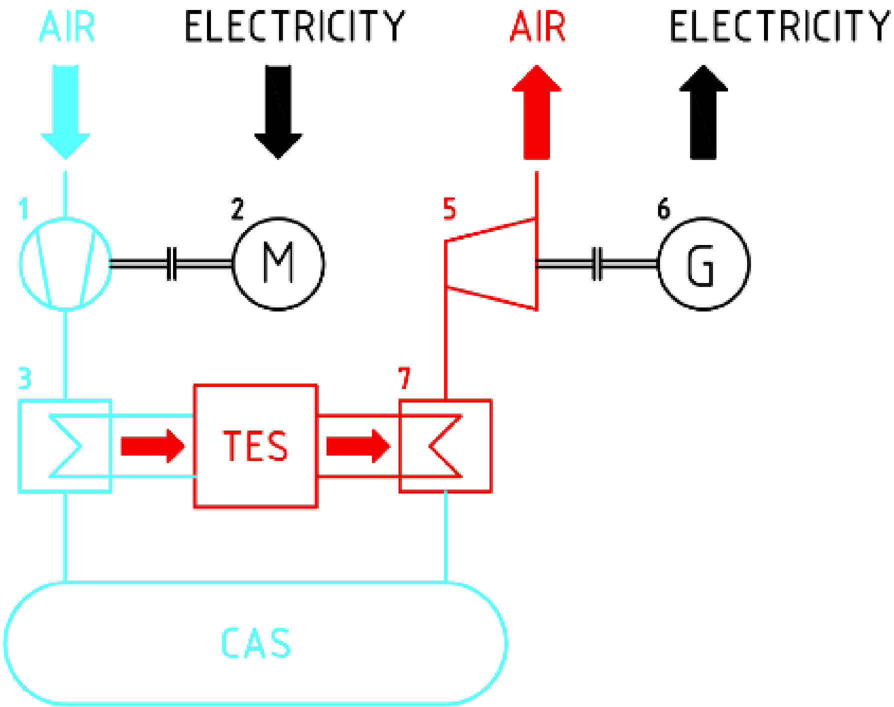

Figure 3. The AA-CAES basic cycle layout. Legend: see Figure 1.

2.2. LAES Basic Principle

Liquid air energy storage is a technology that involves the storage of energy in the form of liquefied air. During the charging phase, ambient air is liquefied using various liquefaction cycles. The power consumed during air compression for liquefaction represents the energy being stored. Several known cycles for liquefaction exist, each with different levels of efficiency [19,20].

The fundamental cycle used in liquid air energy storage is the Linde–Hampson cycle, where liquefaction occurs through air isoenthalpic expansion using the Joule–Thomson valve. The cycle layout can be seen in the Figure 4. The operation of the cycle is as follows: incoming air is filtered and compressed by a compressor, with the actual compression taking place in multiple stages with intercooling. After the final stage, an aftercooler is used to cool the compressed air to near ambient temperature. The final pressure must reach the critical pressure for successful liquefaction. The compressed air is then deeply cooled in a regeneration heat exchanger before expanding through the Joule–Thomas valve to ambient pressure. During the expansion, a portion of the air is liquefied and separated in the separator, which is then directed to the storage vessel. The gaseous residue from the expansion is utilized for precooling the compressed air entering the Joule–Thomas valve. The residue is heated in a regeneration heat exchanger and mixed with new air for the subsequent compression cycle.

One drawback of the Linde–Hampton cycle is the high operating pressure of the compressed air and the relatively low efficiency due to energy dissipation at the Joule–Thomas valve and the limited refrigeration capacity compared to the expander [19]. Other cycles incorporate a turboexpander for partial expansion of the air. The mechanical work produced by the turbine or expander is used to partially drive the compressor. Various cycle configurations exist, such as the Claude or Kapica cycles, which employ a turboexpander and offer improved efficiency, allowing for lower operating pressures.

During the storage phase, liquid air is stored in stainless steel tanks until it is ready for energy discharge. Heat from the compression process and cold from the evaporation process can be stored in a thermal energy storage system, employing concepts such as “two tanks”, “thermocline”, or “phase change”.

Energy discharge occurs through the expansion of heated air in an expansion turbine. The liquid air is first compressed by a pump, then evaporated in an evaporator using external heat. It can also be preheated by another external heat source before expansion. Finally, the air undergoes expansion in the expansion turbine, generating electricity from the stored heat energy.

Similar to CAES, there are numerous configurations for liquid air energy storage that allow for the utilization of heat from compression for air preheating and cold from evaporation for air precooling prior to liquefaction, see Figure 5. Additionally, LAES technology can be integrated into other energy systems, utilizing waste heat from external sources for air evaporation and preheating, or supplying heat and cold from technology operations for other purposes [8].

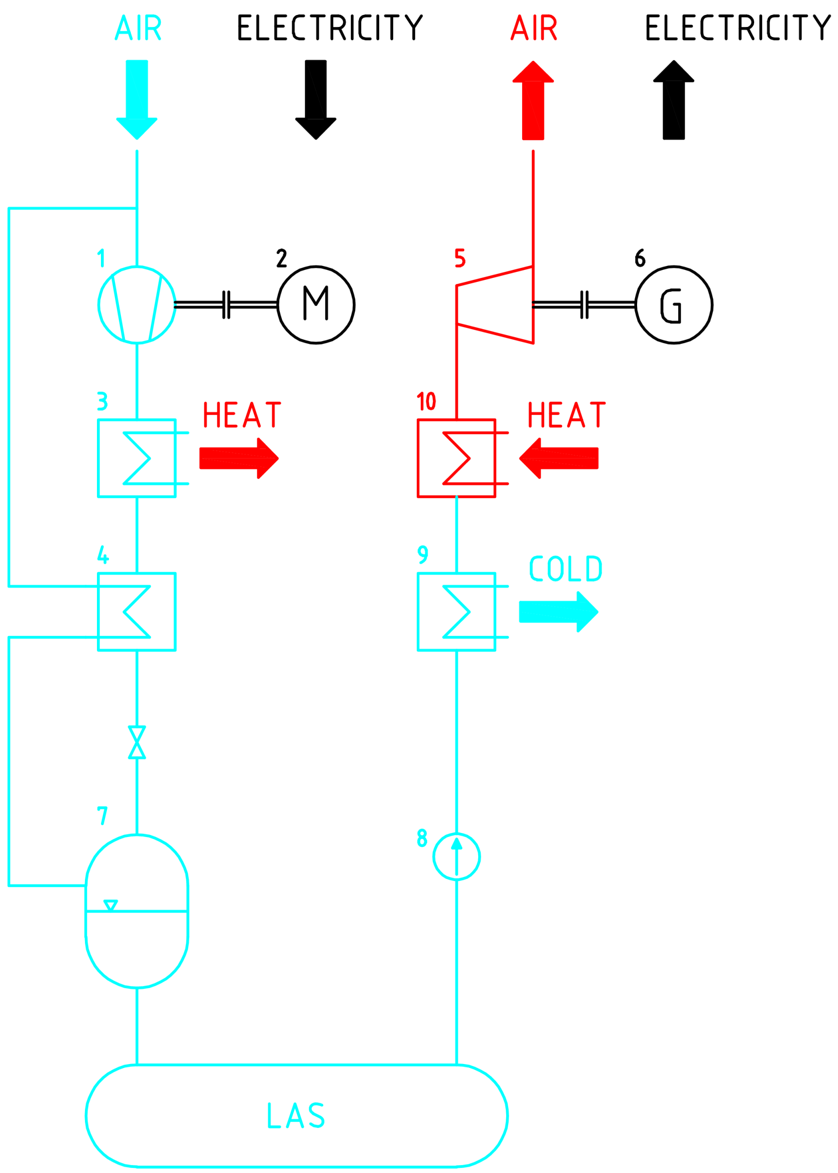

Figure 4. The LAES basic cycle layout (system without heat and cold storage and internal utilization). Legend: 1—compressor, the 2—compressor electric motor, 3—aftercooler, 4—regeneration heat exchanger, 5—gas expansion turbine, 6–electric generator, 7—liquid air separator, 8—liquid air feeding pump, 9—liquid air evaporator, 10—air superheater, LAS—liquid air storage, WTES—warm thermal energy storage, CTES—cold thermal energy storage.

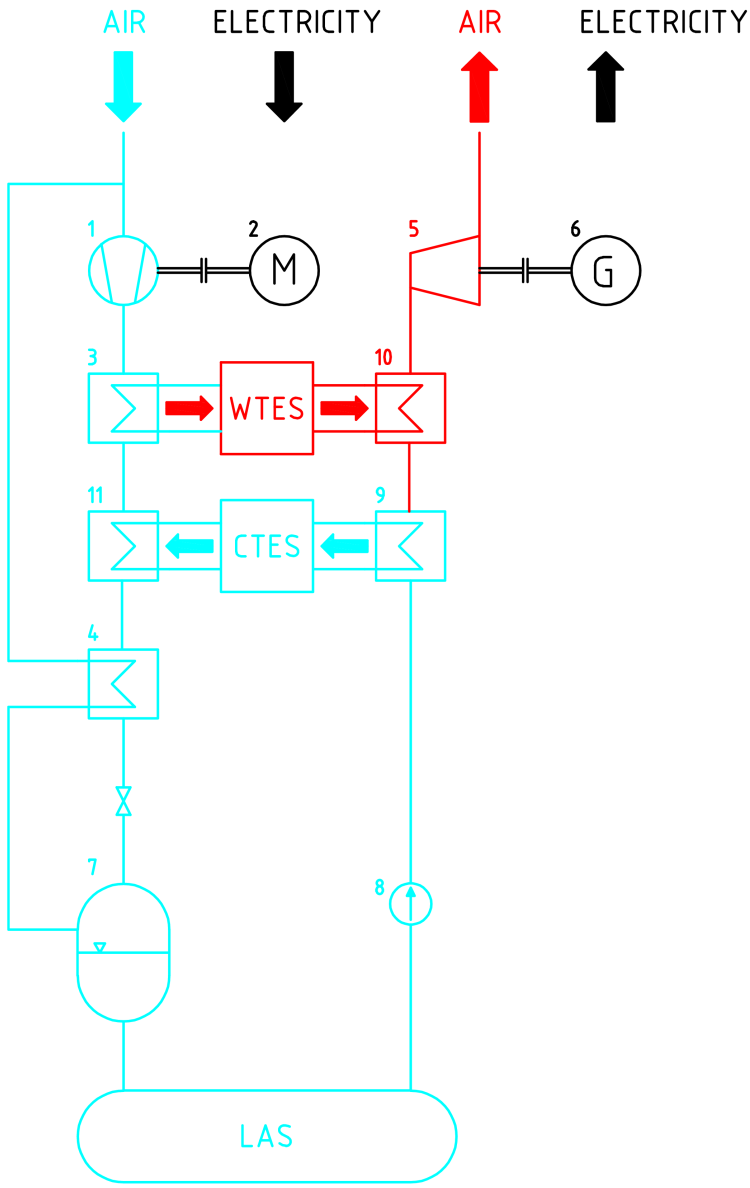

Figure 5. The LAES basic cycle layout (system with heat and cold storage and internal utilization). Legend—see Figure 4.

3. Design Options and Possibilities

The actual design of CAES and LAES technologies can vary due to several technological factors. They can divide the factors into internal design factors and external design factors. External design factors means factors that are related to interconnection and integration with other power or industrial facilities.

From an integration point of view, for these two technologies, there are two possible options. The independent energy storage system is connected only to the grid; these systems are called standalone. They are usually large-scale facilities. The second option is the integrated systems, which are integrated with other energy or industrial technology [6].

Integrated systems can be divided further into several subgroups based on the type of integration. One such subgroup is the hybrid system, which involves the integration of other power technologies, such as fossil [21], biomass, or nuclear power plants that solely produce electricity [22]. The advantage of this combination lies in the overall increase in efficiency achieved by integrating these two technologies, as opposed to operating them separately.

Energy storage technologies which are integrated with technology to combine heat, cold, and power are called polygeneration technologies. These energy storage technologies discharge stored energy in several forms (heat, cold, power) or are involved in the production of these energies. The advantage of this solution is higher round trip efficiency due to better stored energy use.

The energy storage technologies which are integrated to some industrial product production are called industrial integrated technologies. They are mostly represented by LAES technologies which are integrated to liquefaction or regasification LNG [23,24]. Also, there are known studies of LAES technologies which are integrated with oxygen production. Likewise, there are known studies on the integration of both technologies (LAES and CAES) with biofuel production in water desalination technologies [25,26].

The last group of integrated systems are microgrid technologies. These facilities are integrated with microgrids of communal industrial districts for power, and heat and cold supply. The energy storage is mostly used only for their own utilization without external grid power supply [10,12,27].

3.1. CAES Design

Currently, there are only two commercially operational CAES facilities: Huntorf in Germany and McIntosh in Alabama, USA. Both of these facilities belong to the first generation of D-CAES and utilize large underground caverns for storing compressed air.

The Huntorf facility has been in operation since 1978 and has a round trip efficiency of 41.73% [28]. McIntosh, on the other hand, has been operational since 1991 and has a round trip efficiency of 54% [9]. Despite their operational differences, these facilities share similar parameters, which are detailed in Table 3.

Table 3. Technical parameters of existing CAES plant [7,28].

	Huntorf	McIntosh
Year of commissioning	1978	1991
Power of compression train [MW]	60	49
Duration of charging [hour]	8	41
Power provided during discharge [MW]	321	110
Duration of discharging at full power [hour]	2	26
Volume of cavern [(m^3)]	310,000	5,380,000
Pressure in cavern [bar]	43–70	46–75
Max. air mass flow [kg/s]	417	154
Electric energy required per kWh output [$kWh_{el,\ in}/kWh_{el,\ out}$]	0.8	0.82
Fossil energy required per kWh output [$kWh_{fossil,\ in}/kWh_{el,\ out}$]	1.6	1.21

From a technical perspective, the basic D-CAES system consists of three main subsystems: the charging subsystem, storage subsystem, and discharge subsystem. The charging subsystem comprises an electric-powered compressor, intercoolers, and aftercoolers. These components are standard industrial designs without any special features. For higher power capacities, turbo-compressors and shell and tube heat exchangers are suitable, while for lower powers (less than 1 MW), reciprocating compressors can be used as a cost-effective alternative. Various types of compressors, such as pistons, screws, and scrolls, have been studied for micro and small-scale A-CAES and I-CAES applications [29].

The key design consideration for this subsystem is the temperature of the air after compression. This temperature determines the compressor design, material requirements, and the number of stages. A higher temperature after compression results in a more expensive compressor but requires fewer stages and coolers. This feature involves optimization of the subsystem design. As a reference, the highest temperature in the Huntorf facility is 235 °C after the first stage, and the facility has four stages [16].

The performance of the air compression system significantly impacts the overall RTE (round trip efficiency). This is attributed to the fact that gas compression leads to an increase in gas temperature. There exist various approaches for enhancement. One approach involves improving the internal efficiency of the compressor and segmenting the compression process into stages with intercooling. Additionally, it is crucial to optimize the pressure distribution for optimal efficiency [13,14].

Another method to enhance the process involves the use of isothermal compression using either an isothermal compressor or a "water piston" compressor [30–33].

The compressed air storage subsystem is relatively straightforward and consists of a suitable volume for storing compressed air. Underground storage can be achieved in natural salt caverns or old mines, while ground solutions with pressure vessels can be used for smaller capacities.

In the case of underground storage, there is an additional system limitation. To ensure underground stability, the cavern's air temperature must be kept near ambient temperature, and the pressure at the end of the discharge phase should be slightly above atmospheric pressure. This measure helps to prevent the surrounding rock material from cracking during the lifespan of the CAES facility. Therefore, the air temperature must be cooled down after the final compression stage in D-CAES. In A-CAES and AA-CAES, heat from compression can be either removed from the cycle or stored in the thermal energy storage subsystem. Ground storage in vessels is also possible, but there are limits regarding vessel price and size. Furthermore, efficient insulation is required for ground storage vessels at higher temperatures. Ground storage is a suitable choice for micro and small-scale systems as it allows for independence from local geographical constraints.

A unique application of CAES is offshore CAES (OCAES), where compressed air energy storage is combined with wind power generation. In offshore cases, in addition to conventional air storage in caverns and saline aquifers, old oil or gas wells can be utilized [34,35].

Another unconventional storage solution is underwater energy storage (UWCAES), where air is stored in flexible reservoirs underwater. This approach utilizes the hydrostatic pressure of water to maintain a constant pressure in the reservoir, resulting in stable pressure during discharge [36,37].

The energy discharge subsystem typically follows a conventional design with a standard expansion turbine for large and medium-scale systems. For micro and small-scale systems, reciprocating expanders based on piston, screw, or scroll designs are preferable. The expansion process is usually split into two or three stages with superheating to improve efficiency, but more stages are not recommended due to the high cost of high-temperature heat exchangers [14].

In certain cases, systems can be designed as A-CAES or AA-CAES with the inclusion of thermal energy storage. In such instances, the standard CAES system layout must be enhanced with thermal energy storage tanks and suitable heat exchangers. Various storage methods are available, including sensible heat storage and latent heat storage. Sensible heat storage can be achieved through a "double tank" or thermocline setup using liquid storage media, as well as a "packed bed" configuration with solid storage materials. Latent heat storage, on the other hand, can be accomplished using a tank filled with an appropriate phase change material. The energy accumulation density is significantly higher when employing latent heat energy storage [9,38–43].

3.2. LAES Design

Currently, there is only one pilot-scale unit in operation, which is a collaborative project between the University of Leeds and Highview Power company. This unit has been operational since 2010 and has a capacity of approximately 350 kW and 2.5 MWh. Another pre-commercial scale unit developed by Highview Power was commissioned in 2018, with a capacity of about 2.5 MW and 15 MWh [6]. The specific parameters of all Highview units are detailed in Table 4.

Table 4. Technical parameters of existing LAES plant [44].

	Highview 1	Highview 2
Year of commissioning	2010	2018
Discharge power [MW]	0.35	2.5
Capacity [MWh]	5	15

Similar to CAES, LAES technology also consists of three main subsystems, with the option of adding a thermal energy storage subsystem. However, LAES operates within a wider temperature range and has the capability to utilize both warm and cold thermal energy, setting it apart from CAES. This characteristic opens up a broad range of potential applications for LAES, particularly when integrated with other technologies.

The charging subsystem in LAES is considerably more intricate compared to CAES, offering various configurations to choose from. It involves the utilization or production of both cold and heat. This subsystem relies on thermal cycles for gas liquefaction, as described in Section 2.2.

In terms of efficiency, cycles based on the Claude cycle demonstrate significantly better efficiency, thanks to energy savings at the turbo expander. These cycles are well-suited for high and mid-power installations. However, it is worth noting that the turbo expander is a more complex and expensive component compared to the J–T valve. Consequently, the simpler Linde–Hampton cycle is often considered as an alternative for low-power cycles [45]. A comparison of the main liquefaction cycles can be found in Table 5.

Table 5. Air liquefaction cycles parameters [19].

Cycle	Optimal Pressure [MPa]	Consumption [kW/kg]	Exergy Efficiency [%]
Linde–Hampton	25–26	2.5–2.6	2.47
Claude	3.8–4.5	0.72–0.73	12.16
Kapitza	3.8–4.5	0.71–0.72	12.1

The liquefaction cycle's performance significantly impacts the overall RTE (round trip efficiency). When considering this aspect, the Claude and Kapitza cycles emerge as superior options. However, the technological complexity of these cycles is heightened by the necessity of an expander. Interestingly, these cycles operate at a quarter of the operational pressure compared to the Linde cycle. This advantage contributes to a more cost-effective system. Current research is dedicated to enhancing the efficiency of these cycles. One avenue for improving liquefaction efficiency involves integrating ejector refrigeration after the final compression stage [20,46,47].

Another avenue for enhancing the cycle revolves around incorporating internal heat and cold storage [47–49].

The energy storage in LAES can involve various types of storage systems. The liquid air storage system is detailed in Section 2.2. Thermal energy storage systems are categorized based on storage temperature into heat storage and cold storage. Heat storage is employed for storing thermal energy above ambient temperature, while cold storage is used for storing thermal energy below ambient temperature. The generation of cold energy is one of the key distinctions between LAES and CAES.

Cold storage can be achieved using liquid refrigerants or packed beds. Liquid propane, methanol, or quartzite rock are commonly used as storage media. Hot storage can be accomplished using liquids such as molten salts with low freezing temperatures (e.g., Hitec, Hitec XL) and thermal oil (e.g., Therminol VP1). Various well-known specific heat storage technologies, such as the "two-tank" system and "thermocline" concept for liquid storage, or packed bed systems for solid materials, can be employed [47,50].

Power generation in LAES can be achieved through four different methods: direct expansion of liquid air, Rankine cycle, Brayton cycle, or a combination of these approaches.

In the direct expansion cycle, the stored air serves as the working fluid. The liquid air is compressed by a cryo pump, evaporated, and preheated before expanding in a gas expansion turbine. Special cryogenic equipment is required for the low-temperature side of the system [51–53].

Another promising approach is the integration of an Organic Rankine Cycle (ORC) with LAES to enhance energy production. The specific parameters of the organic working fluid allow for the utilization of waste cold and heat within the cycle [54]. Additionally, the integration of an Absorption Refrigeration Cycle (ARC) into the ORC cycle can further increase the ORC efficiency by reducing the condensation temperature [19,55].

4. Technology Perspectives and Differences

Both of these analyzed technologies hold substantial potential for widespread future applications, exhibiting both similarities and differences. Notably, the most significant contrast lies in the fundamental nature of their primary energy storage mechanisms.

LAES, or Liquid Air Energy Storage, functions by storing energy in the form of thermal energy within highly cooled liquid air. On the other hand, CAES, or Compressed Air Energy Storage, stores energy as mechanical energy within compressed air. This fundamental distinction underscores the key characteristics of each system. Notably, LAES boasts a significantly higher energy storage density, ranging from 50 to 200 Wh/L, in comparison to CAES, which ranges from 5 to 20 Wh/L [6]. However, CAES necessitates a substantial compressed air reservoir for storage, which often requires large underground caverns for higher power capacities, due to the considerable spatial demands. This geographical limitation presents a notable drawback of the CAES technology.

Conversely, the advantage of CAES lies in its cost-effectiveness as an energy storage solution in regions without the aforementioned geographical constraints. Within such areas, CAES emerges as a promising and potentially superior choice over LAES. A comprehensive description of underground gas storage can be found in references such as [56–61].

Furthermore, CAES demonstrates promise in coastal and offshore applications, particularly through the utilization of the underwater compressed air concept (UCAES) and its associated benefits. In these scenarios, the typical geographical limitations inherent to land applications are alleviated. Notably, the synergy between UCAES and wind power presents a particularly advantageous application of CAES [36,62–65]. Additionally, CAES exhibits significant potential when combined with desalination technologies for freshwater production from seawater. Of note in UCAES research is the importance of investigating airbags for compressed air underwater storage, as highlighted in references such as [34,66–68].

So, we can say that LAES technology is better from the point of view of geographical constraints, which are none. Due to an order of magnitude, the larger energy storage density in the LAES facility will be always smaller. In areas with appropriate underground spaces or appropriate sea conditions, the CAES will be a better choice, due to a better economy [6,10–12,19].

In general, both technologies can be designed in various configurations based on process heat utilization. Several possible plant configurations include:

- Standalone configuration: This design represents a single-purpose facility solely focused on the storage of electric energy. Typically, these facilities have large capacities, often reaching hundreds of MWh.
- Hybrid configuration: This configuration integrates the energy storage technology with another energy source, such as biomass, nuclear power plants [69], or geothermal power stations [70]. It can also be integrated with industrial operations like LNG liquefaction and regasification [24,71,72].
- Polygeneration configuration: This configuration includes technologies capable of supplying electrical energy, heat, and cold simultaneously [73,74].
- Microgrid configuration: This configuration involves systems with smaller energy supply capacities that are connected in close proximity to the end user.

One of the main advantages of both technologies is their high potential for integration with existing or planned power generation technologies that utilize heat. Prominent candidates for integration include biomass power plants [75], nuclear power stations [69], combined heat and power generation technologies, and various industrial processes [71].

In this context, integration refers to the seamless interconnection of either CAES or LAES with the thermal cycle of a plant. Specifically, the waste heat generated by CAES or LAES is harnessed to enhance the efficiency of the plant's thermal cycle through the utilization of regenerative heat exchangers [22,76,77].

The current problem for microgrid application is low RTE, compared to standard batteries, like lead-acid or Li-On. In the case of microscale CAES and LAES, RTE can be from 15 to 30%, which is too low [9,78,79]. That can make a simple microgrid application of CAES and LAES unfeasible. Also, the size of these CAES or LAES microsystems is bigger in comparison to the same power battery storage [80].

Incorporating CAES and LAES into polygeneration and microgrids offers the distinct advantage of achieving elevated efficiency in scenarios involving the simultaneous generation of both heat and power (cogeneration), or alternatively, heat, cold, and power (trigeneration). The pivotal factor lies in effectively managing the consumption of these diverse energy forms. To address variations in the production and consumption of heat and cold, polygeneration systems must be outfitted with suitable thermal energy storage systems for both heat and cold, as highlighted in Reference [9].

The second key barrier for wide extension of CAES and LAES systems is availability of small scale compressor and expansion machines [39].

The key benefit of this integration is the improved utilization of the heat generated by both processes. Ultimately, the overall round-trip efficiency is expected to be even better in polygeneration configurations compared to simple standalone units.

5. Technology SWOT Analysis

This chapter has summarized the advantages and disadvantages of both technologies. For each technology was made a SWAT matrix, see Table 6 which is for CAES, and Table 7 which is for LAES. These matrixes were made based on the study of the referred literature.

5.1. CAES Technology

Table 6. The CAES SWOT matrix. [6,11,12,14,29,39,41,81].

Strengths	Weaknesses
• Simplicity: simple technology with available components—compressor, expansion turbines, heat exchanger. • Proven technology: CAES has been commercially demonstrated with successful projects in operation, showcasing its reliability and feasibility. • Scalability: CAES has the potential for large-scale energy storage due to its ability to store and release large volumes of compressed air. • Long duration of storage: CAES system can store energy for extended periods.	• Geographical constraints: CAES requires suitable geological formations or underground caverns for air storage, limiting its deployment to specific locations. • Need a natural gas for operation (only in case of D-CAES). • Environmental impact: due to natural gas combustion (only in case of D-CAES) CAES can emit greenhouse nad polutants. • Energy efficiency: CAES systems experience energy losses during the compression and expansion processes, resulting in lower overall efficiency compared to some other energy storage technologies.
Opportunities	**Threats**
• Renewable integration: CAES can facilitate the integration of intermittent renewable energy sources by storing excess electricity and providing a more stable and dispatchable power supply. • Utilization: CAES can be used for secondary production of heat and cold. • Enhanced efficiency: Research and development efforts aim to improve the energy efficiency of CAES systems, which could enhance their overall performance and competitiveness.	• Lack of natural gas (only in case of D-CAES). • Emerging technologies: the rapid advancement of other energy storage technologies, such as lithium-ion batteries and flow batteries, could pose a threat to the widespread adoption of CAES. • Policy and regulatory challenges: inconsistent or inadequate policies and regulations related to energy storage deployment and revenue mechanisms may impede the growth and integration of CAES systems.

5.2. LAES Technology

Table 7. The LAES SWOT matrix. [10,19,46,47,49,76,82,83].

Strengths	Weaknesses
• Scalability: LAES has the potential for large-scale energy storage due to its ability to store and release liquid air. • Long duration of storage: LAES system can store energy for extended periods. • Independency: no additional energy need for LAES operation. • High energy capacity: LAES systems can store significant amounts of energy, allowing for the provision of sustained power output over extended periods. • Wide range of temperatures of heat production—a wide range can possibly be integrated into CHP facilities. • Fast and flexible operation . • Energy efficiency: LAES can achieve high round-trip efficiency by utilizing waste heat during the expansion phase, improving overall energy utilization.	• Technological maturity: LAES is still in the development and demonstration phase, and there may be challenges in scaling up the technology for widespread commercial deployment. Need special design of system components—pumps, expanders, valves. Need tanks for liquid oxygen storage
Opportunities	**Threats**
• Independency on location: due to no geological constraints, it is possible to use a wide range of locations for units. • Renewable integration: CAES can facilitate the integration of intermittent renewable energy sources by storing excess electricity and providing a more stable and dispatchable power supply. • Technological advancements: ongoing research and development efforts can lead to improvements in LAES efficiency, performance, and cost-effectiveness, making it more competitive in the energy storage market.	• No verified technology—the unit is not built at full industrial scale yet. • A high integration level into the CHP cycle is very complicated. • In the case of high round trip efficiency cycle, it is very complicated. • Policy and regulatory challenges: inconsistent or inadequate policies and regulations related to energy storage deployment and revenue mechanisms may impede the growth and integration of LAES systems. • Emerging technologies: the rapid advancement of other energy storage technologies, such as lithium-ion batteries and flow batteries, could pose a threat to the widespread adoption of CAES.

6. Design Indicators

The main performance indicators in these storage technologies are round trip efficiency (RTE), exergy efficiency, energy storage capacity, and energy storage power. From these indicators, the most important quality parameters are round trip efficiency and system capacity. The most interesting designs are referred to in Table 8.

Table 8. Cycle parameters comparison

Cycle Description	Round Trip Efficiency [%]	Exergy Efficiency [%]	Operation Temperature Range [°C]	Power Range [MW]
Original LAES system [84]	58–61	51–61	−194–237	0.009–0.011
Original LAES system [48]	45	67	−194–5	0.982
LAES system coupled with solar heliostats [84]	75–90	36–51	−194–350	0.014–0.15
LAES system with isothermal compression, coupled with solar heliostats [84]	115–124	53–55	−194–350	0.014–0.15
LAES system integrated into steam power plant [77]	49- 94	-	−194–181	27–80

Table 8. *Cont.*

Cycle Description	Round Trip Efficiency [%]	Exergy Efficiency [%]	Operation Temperature Range [°C]	Power Range [MW]
LAES system with gas thermal cycle [85]	77	65	−194–1270	1
LAES system, coupled with nuclear power plant [69]	71	-	−194–280	77
Standard D-CAES system (Huntorf) [12]	42	-	20–945	321
Standard AA-CAES system [86]	71–77	-	25–600	100

7. Economic Indicator

A useful indicator for comparing both technologies is the Levelized Cost of Storage (LCOS). This parameter serves as the most suitable basis for a fair comparison. Through a thorough analysis of the literature [6,9,11,22,87,88], we have obtained two charts, namely Figures 6 and 7, which compare the Levelized Cost of Energy (LCOE) of various CAES and LAES technologies.

From these charts, it becomes evident that CAES technology appears to be more cost-effective. This can be attributed to the fact that CAES relies on technologically simpler and more affordable components, benefiting from a better temperature range. On the contrary, LAES is designed to work with liquid air at temperatures below approximately 200 °C, which necessitates specialized steel for extreme temperatures, a dedicated cryo pump, and a vessel. The incorporation of such expensive equipment results in LAES being a more costly technology.

Moreover, the comparison highlights differences between the types of technology. Standalone systems exhibit higher LCOS, leading to a lower round trip efficiency (RTE) due to their independent operation. Conversely, hybrid and polygeneration technologies demonstrate lower LCOS, primarily attributed to their enhanced thermal utilization, resulting in a better RTE.

The last one is microgrid technologies. We can see that this technology looks more expensive than standalone. That is a result of small-scale technology, which has the worst economy due to lower RTE.

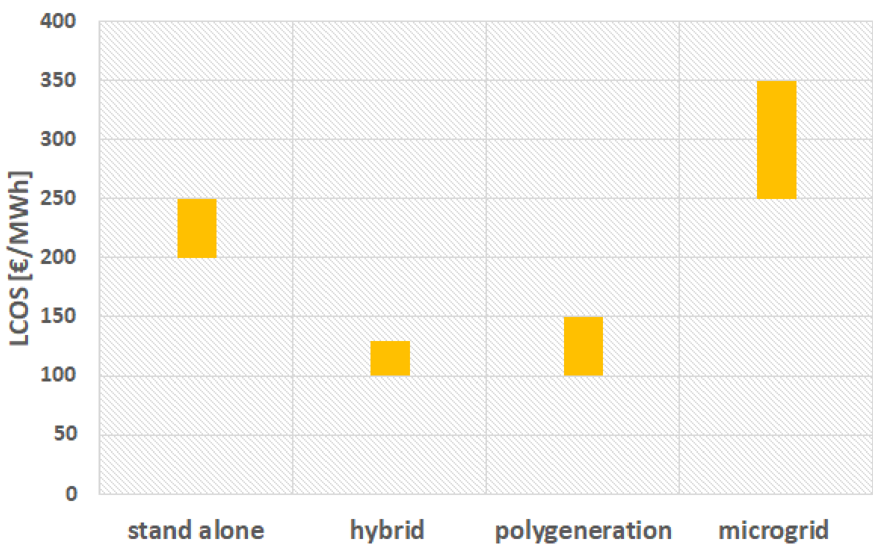

Figure 6. Comparison of Levelized Cost of Storage for several types of CAES technologies [6,9,11,22,87,88].

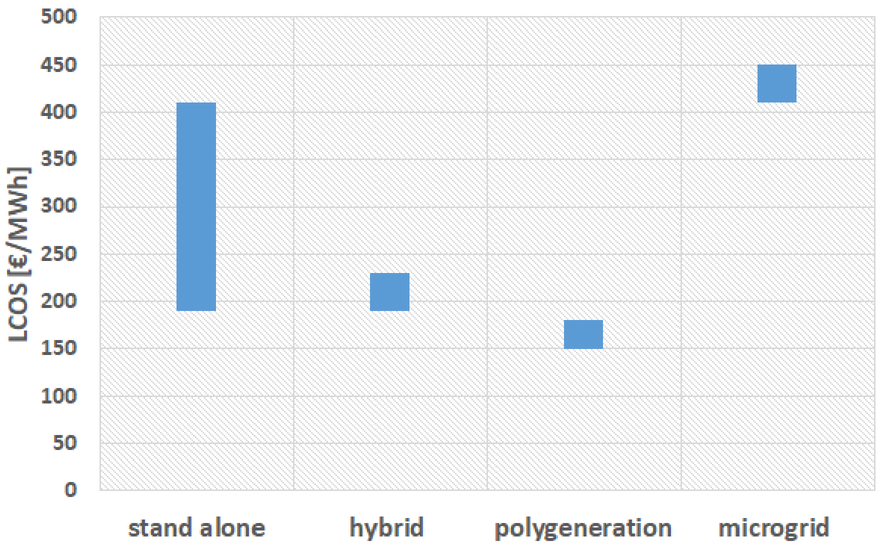

Figure 7. Comparison of Levelized Cost of Storage for several types of LAES technologies [6,9,11,22,87,88].

8. Conclusions

CAES and LAES represent highly promising technologies with immense potential to emerge as leading solutions for large-scale energy storage. They can function either independently or as hybrid facilities. A notable advantage of LAES lies in its ability to overcome geographical constraints, offering a high energy density in the form of liquid air. Conversely, CAES thrives in areas with favorable geographical conditions, boasting simplicity and widespread availability compared to LAES. Consequently, CAES may be the preferred choice in various scenarios.

The integration of hybrid facilities, combining CAES and LAES, into conventional power systems, such as coal and nuclear plants, demonstrates their adaptability. As standalone facilities, they effectively contribute to grid stabilization by collaborating with renewable energy sources like wind or solar power.

These groundbreaking technologies are not restricted solely to large-scale applications; they also hold relevance in small and medium-scale integrated systems. In community and industrial settings, polygeneration systems, and microgrid contexts, CAES and LAES can be used for combined heat and power generation. CAES, with its simplistic design, suits combined heat and power production and effectively utilizes thermal energy storage for surplus energy from renewable sources. It proves versatile across a wide range of power levels. On the other hand, LAES excels in polygeneration applications, facilitating simultaneous generation of low and high-grade heat. This characteristic makes it ideal for combined heating and cooling purposes in various industrial processes, including integration into the LNG industry for liquefaction and regasification processes.

The integration of CAES and LAES faces challenges regarding efficiency and relatively high investment requirements at this power scale. When compared to battery storage, standalone electric energy storage systems are not as competitive. However, for lower power scales, a more viable perspective emerges through the adoption of combined storage systems that encompass heat and cold production, known as polygeneration.

While both CAES and LAES exhibit tremendous potential for expansion, certain factors currently limit their further development. Continued research and development efforts are essential to enhance efficiency and reduce costs. Supportive policies and regulations are crucial in incentivizing adoption, and scaling up the technologies to meet the demands of the rapidly evolving energy storage market presents a significant challenge.

The issue of efficiency stands as one of the most substantial barriers to the widespread adoption and expansion of both LAES and CAES technologies. Despite their promising energy storage solutions, their overall efficiency rates remain relatively lower than other storage technologies.

The relatively low round trip efficiency (RTE) can be attributed to the nature of the stored energy itself. In the case of CAES, the stored energy is mechanical in the form of compressed air, while LAES stores thermal energy as liquid air. Both technologies incur substantial energy losses in the form of heat during the charging process. Although these thermal energy losses can be mitigated to some extent through methods like internal thermal energy storage (such as AA-CAES) and its subsequent utilization during discharge, these approaches have inherent limitations.

For achieving improved RTE, a promising avenue lies in the adoption of hybrid systems on a larger power scale and embracing polygeneration concepts for mid, small, and micro power levels. These strategies offer potential pathways to enhance overall energy efficiency and address the challenges posed by the specific characteristics of CAES and LAES technologies.

In comparison to lithium-ion batteries, CAES and LAES have the worst energy storage density, RTE, response time, and capital cost. That is a very significant disadvantage.

Their primary advantage lies in their extended lifespan, thanks to the employed technologies, coupled with a more affordable storage cost. Additional benefits include a considerably more environmentally friendly manufacturing process that does not rely on specialized materials like lithium. Moreover, decommissioning expenses can be reduced due to the absence of chemical-related challenges. Another noteworthy advantage is the potential for hybrid or polygeneration applications.

This characteristic renders Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES) more preferable options for sizable energy storage systems. Conversely, for smaller-scale applications where secondary thermal energy is not a requirement, batteries prove to be a superior choice.

For LAES, the energy-intensive process of liquefying and later regasifying air accounts for a major efficiency limitation. The cryogenic cooling required for this conversion consumes a significant amount of energy, leading to energy losses during the storage and retrieval process. Improving the efficiency of the liquefaction and regasification stages is vital to enhance the economic viability and competitiveness of LAES systems.

Similarly, CAES faces efficiency challenges, particularly during the compression and expansion stages. The compression process demands substantial energy inputs, and the subsequent expansion of compressed air to generate electricity can be associated with lower overall efficiency compared to other energy storage technologies. Optimizing these processes and increasing round-trip efficiency are critical areas for improvement in CAES.

Enhancing efficiency is paramount for both LAES and CAES to boost economic viability, reduce operating costs, and effectively compete with other energy storage technologies like lithium-ion batteries. The ongoing research and development endeavors aim to develop innovative solutions and technologies to address these efficiency challenges and optimize the overall performance of LAES and CAES systems.

The most significant topics which restrain the next extension of both technologies are these:

- Development of thermal energy storage technologies which will be cheaper, with fast charging and discharging.
- Development technologies for high-grade cold storage (LAES).
- Searching new locations with suitable geological conditions (CAES).
- Development of effective technologies for heat exchange between heat storage and other parts of the storage system.
- Development of new integrated technologies with involved CAES or LAES.
- Development of new operation models of CAES and LEAE operation in grits with renewables.
- Intensification of operational parameters of systems components (compressors, heat exchangers and atd.) of round trip efficiency improvement.

9. Literature Review

Table 9 displayed a literature review of the most useful and significant literature used to create this article. Articles are assorted by their focus on technology typical problems.

Table 9. Literature rewiev.

Type of Technology	Article Focus	Reference
CAES	Topic and technology overall review	[11,12,29]
	Technology components review and study	[13,14,68,89]
	Thermal energy storage and CAES technology	[9]
	Compressed air storage and caverns	[25,56–61]
	Thermodynamic analysis, thermal cycles and optimization	[36,39,41,86,90,91]
	Polygeneration	[23,78–82]
	Underwater energy storage	[34,36,62–68]
LAES	Topic and technology overall review	[6,10,19,76]
	Technology components review and study	[20,47,49,92]
	Thermal energy storage and LAES technology	[93,94]
	Techno-economic analysis of LAES system	[46,72,75,77,83]
	Thermodynamic analysis, thermal cycles and optimization	[24,45,51,65,84,95–99]
	Technology integration with nuclear power plants	[22,69]
	Technology integration with renewable power sources	[70,75,84]
	Polygeneration	[82]
	Industrial integration and LNG regesification	[71,72,74]

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Abbreviations

ARC	Absorption Refrigeration Cycle
CAES	Compressed Air Energy an Storage
AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
A-CAES	Adiabatic Compressed Air Energy Storage
D-CAES	Diabatic Compressed Air Energy Storage
CAS	Compressed Air Storage
CHP	Combined Heat and Power
CTES	Cold Thermal Energy Storage
LAES	Liquid Air Energy Storage
LAS	Liquid Air Storage
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
LNG	Liquefied Natural Gas
RTE	Round Trip Efficiency
TES	Thermal Energy Storage
ORC	Organic Rankine Cycle
UCAES	Underwater Compressed Air Energy Storage
WTES	Warm Thermal Energy Storage

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