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Technical Conference Paper

Isothermal Compressed Air Energy Storage (I-CAES) in Solution Mined Salt Cavern

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Abstract

The increasing share of intermittent renewable energy in the electricity generation mix presents new challenges for grid operators and regulators. One such challenge is extended periods of significant underproduction. Pioneers of the energy transition in the North Sea region have experienced numerous under-supply events, a phenomenon dubbed “Dunkelflaute” in German. During 2024, Germany experienced three Dunkelflaute periods, including one lasting several weeks in November, which drove wholesale electricity prices to as high as 92 [Eurocents/kWh]. The impact of these phenomena is likely to increase along with rising demand for electricity (due to data centers and electrification of heat and transportation) and increased renewable deployment (aiming to reach 80% renewable share by 2030).

Policymakers around the globe currently face the challenge of ensuring long-duration backup power through conventional generation methods. Investment in new fossil fuel power plants is uneconomic in many geographies due to high fuel costs, low load factors, and carbon pricing. To maintain energy supply continuity, policy makers will need to incentivize construction of new fossil fuel power plants and/or long-duration energy storage (LDES) technologies.

Given the extended durations and limited annual cycles, LDES technologies require extremely low-cost storage reservoirs. Compressed air energy storage (CAES) can utilize solution-mined salt caverns as such cost-effective reservoirs. Traditional diabatic CAES (D-CAES) methods require additional storage elements such as natural gas reservoirs and large heat exchangers, while adiabatic CAES (A-CAES) methods require thermal energy storage dedicated to compensating for inherent temperature changes throughout the compression and expansion processes. These technologies can increase the storage cost and in the case of D-CAES also pollute the environment. Isothermal compression and expansion processes can be employed to maintain a constant air temperature, thereby eliminating the need for thermal compensation.

In this paper, we present the AirBattery™, a novel isothermal CAES (I-CAES) technology, developed and demonstrated by Augwind Ltd. This system employs a series of underground water pistons to compress and expand air, using solution-mined salt caverns as the storage medium. The air is kept near ground temperature because the controlled, slow underground process facilitates efficient heat exchange between the air, the water inside the piston, and the surrounding earth.

An installed 250 [kW] / 1 [MWh] AirBattery™ demonstration facility is reviewed, along with the technology’s scale-up potential, including a high-level techno-economic comparison to other technologies in terms of round-trip efficiency (RTE) and capital expenditures (CAPEX).

Based on a first technical assessment, caverns seem to be a promising option for storage of large volumes of compressed air under high pressures. Being quite comparable to gas storage in caverns, and with the existing experience of storage of compressed air in caverns in Germany and the US, the development of an AirBattery™ demonstration project including a (small) salt cavern seems highly feasible.

Key words: Isothermal Compressed Air Energy Storage (I-CAES); Caverns for Gas Storage; Storage Caverns; Long-Duration Energy Storage (LDES); Germany; United Kingdom; Denmark; Netherlands; Dunkelflaute.

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1. Introduction

The rapid growth of intermittent renewable energy sources (such as wind and solar) is introducing significant challenges in maintaining a stable and reliable power supply. Electric grids require a constant balance between supply and demand, yet renewables are non-dispatchable and can experience prolonged shortfalls in generation. For example, Germany recorded multiple Dunkelflaute events (extended periods of low wind and solar output) in 2024, including one lasting several weeks that drove electricity prices sharply higher. As renewable penetration rises (targeting 80% in Germany by 2030) and electricity demand grows (e.g. through electrification of heating and transport), such multi-day supply deficits are expected to become more frequent. This creates an urgent need for long-duration energy storage (LDES) solutions to ensure backup power over days or weeks. Traditional remedies like new fossil-fuel-peaking plants are often economically unviable or inconsistent with climate goals, which underscores the importance of advancing large-scale energy storage technologies as a key enabler of the energy transition.

Long-duration storage requirements differ fundamentally from short-duration needs. Most of today's grid storage is designed for short periods (seconds to hours) to provide ancillary services or daily load shifting, not for multi-day backup. Conventional battery systems (e.g. Lithium-ion) excel at short discharge durations but face limitations for extended storage. Despite recent cost improvements, Lithium-ion batteries have high energy-specific costs and degradation issues, making them economically unsuited for infrequent, multi-day cycles. Pumped hydro storage, the most established form of large-scale storage, can deliver longer durations but is highly site-dependent – it requires favorable topography and existing water reservoirs, which many regions lack. Other emerging LDES concepts (such as power-to-gas hydrogen or novel flow batteries) remain unproven at scale or suffer from low round-trip efficiency (RTE). This gap in practical long-duration storage options motivates the exploration of alternative technologies that can cost-effectively bridge multi-hour to multi-week supply-demand mismatches.

Compressed Air Energy Storage (CAES) has re-emerged as a promising solution for LDES, offering the ability to store very large energy quantities by compressing air into underground caverns. A key advantage of CAES is the use of solution-mined salt caverns as natural storage reservoirs, which provide abundant, airtight volume at low cost. Indeed, large salt caverns have been successfully used to store pressurized fluids (natural gas, hydrogen, etc.) and were employed for decades in the world's two legacy CAES plants (Huntorf in Germany and McIntosh in the USA). However, traditional CAES implementations have notable drawbacks. The legacy diabatic CAES (D-CAES) design requires burning fossil fuel (natural gas) during air expansion to reheat the air, which incurs additional cost and carbon emissions. More advanced adiabatic CAES (A-CAES) schemes aim to eliminate fuel by capturing the heat of compression in thermal energy stores, but this adds complexity and capital cost for large high-temperature heat exchangers and storage media. Both D-CAES and A-CAES thus involve efficiency penalties or additional subsystems to manage the thermal effects of compressing and expanding air. In contrast, an isothermal CAES (I-CAES) approach seeks to maintain a nearly constant air temperature throughout compression and expansion, thereby eliminating the need for external fuel or dedicated thermal storage. By carefully managing heat exchange during the process, I-CAES can significantly improve efficiency and safety: the compression/expansion cycle approaches the maximum theoretical efficiency (since less energy is lost to heating the air) and avoids the extreme temperatures that could otherwise stress equipment or cavern walls. These potential advantages make isothermal CAES especially attractive as a clean, efficient form of long-duration storage that leverages geological storage assets.

In this context, the present paper evaluates Augwind's AirBattery™ technology – an innovative implementation of I-CAES using solution-mined salt caverns as the storage vessel. Augwind Ltd. has developed a novel liquid piston method in which underground pressure chambers (acting as pistons) are used to slowly compress and expand air, achieving near-isothermal conditions. The AirBattery™ will store compressed air in salt caverns at pressures up to 200 bar (2,900 psi) while maintaining air temperature close to ambient ground temperature, thanks to effective heat exchange between the air, water, and surrounding earth. A 250 [kW] / 1 [MWh] pilot facility is already operational (in Kibbutz Yahel, Israel), demonstrating the AirBattery™ concept at a sub-commercial scale. This pilot facility achieved approximately 47% RTE and validated stable operation up to 40 bar (580 psi) of air pressure. The objective of this paper is to assess the feasibility and performance of deploying such an I-CAES system in a solution-mined salt cavern for grid-scale storage. The paper reviews the AirBattery™ design and pilot results, compares its expected performance metrics (e.g. RTE and capital cost) to other storage technologies, and discusses the scale-up potential of this I-CAES approach as a LDES solution. By analyzing both the engineering aspects and the geological considerations, the study aims to demonstrate how integrating Augwind's AirBattery™ technology into the CAES landscape could address the need for reliable, long-duration storage in an era of high renewable energy.

2. Three Major Categories of Energy Storage Needs (Under One Hour, Less Than One Day, More Than One Day)

Technological advancements and governmental policies have led to changes in the electricity generation mix. The share of intermittent energy sources (mainly photovoltaic solar and wind turbines) is rapidly growing, as shown in Fig. 1 [1].

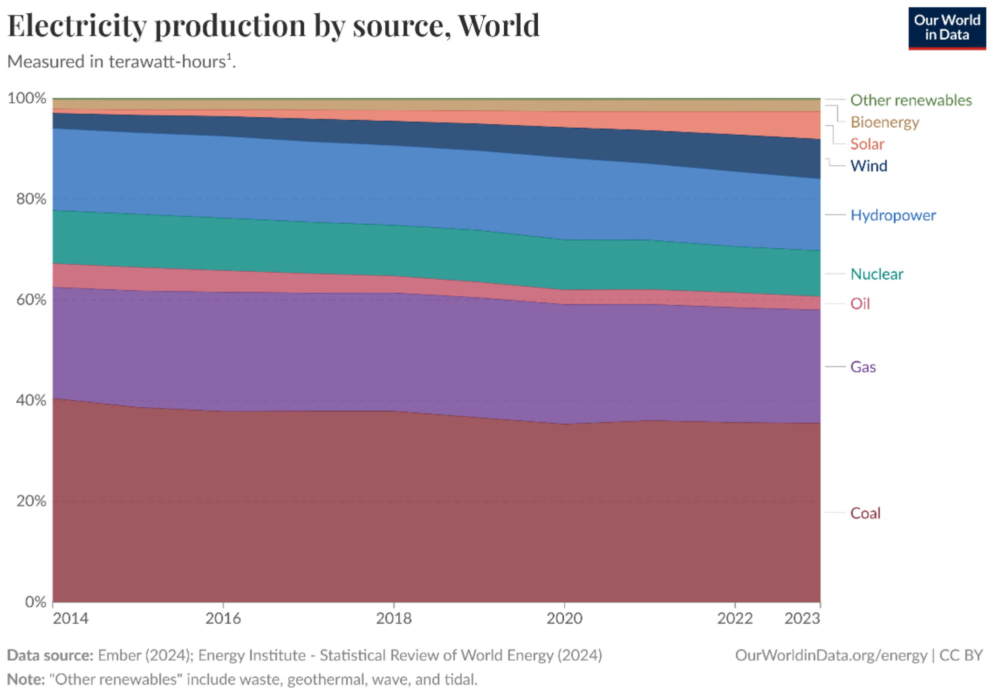


Figure 1. Intermittent renewables grew globally from 904 TWh in 2014 to 3,934 TWh in 2023, representing an 18% compound annual growth rate (CAGR). [1]

Electrical grid operations require constant balance between electric supply and demand. Intermittent renewables are not dispatchable upon demand, and do not have the rotating mass of thermal generators to provide stable frequency. Energy Storage Systems (ESS) can help grids balance supply and demand. Storage systems can be differentiated by several parameters such as technology, ramp-up times, power output, and RTE. One key differentiator is the discharge duration, defined as the maximum period during which the system can discharge at full capacity without charging. While definitions are relatively ambiguous in this paper, we will address 3 categories:

1. Short-duration-storage – for ancillary/frequency reserve (seconds to under one hour). Such storage is needed relatively early in the energy transition.
2. Intraday energy storage – for shifting renewables from daily peak production to daily peak demand periods, such as the well-known "duck curve."
3. Long duration energy storage (LDES) for inter-day durations – for shifting renewables from days/weeks/months with high renewables generation to days/weeks/month of low renewables generation. The need for such storage solutions is emboldened at a relatively late stage of the energy transition, e.g., Germany, which has a share of wind and solar generated electricity which has grown to nearly 50% in 2024, is susceptible to prolonged durations of underproduction, dubbed "Dunkelflaute". Fig. 2 [2] demonstrates a prolonged drop in the renewable share of generation in Germany during November 2024. Other countries surrounding the North Sea experienced similar patterns. According to The Royal Society of London for Improving Natural Knowledge (Royal

Society) [3], the UK alone will require approximately 88 [GW] of multi-day energy storage output capacity by 2050.

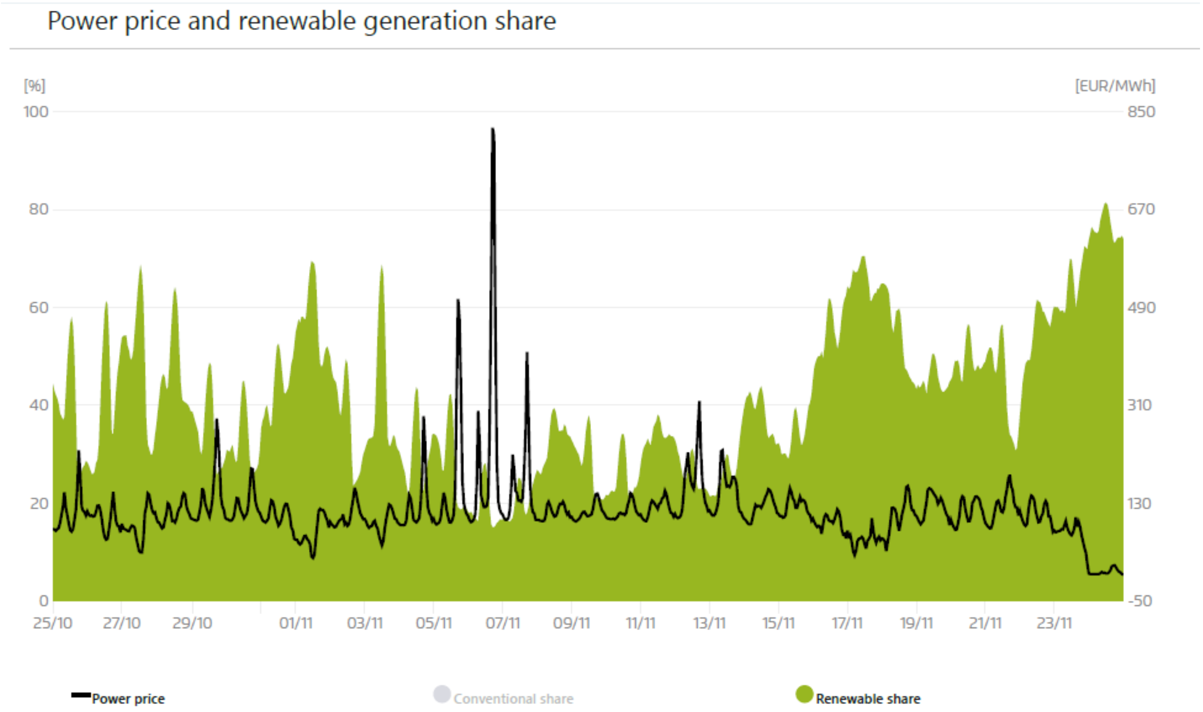


Figure 2. During the November 2024 Dunkelflaute in Germany, renewable share of generation dropped, and day-ahead price was around twice the yearly average [2].

Currently, the majority of global energy storage is based on fossil fuels, primarily stored in solution-mined salt caverns and oil and gas fields. However, in many renewable-oriented energy markets, several factors impede investment in new fossil-based generators, such as decreased load factors due to renewables integration, increased fuel costs due to geopolitical tensions, and governmental policies like carbon pricing. This creates opportunities for new technologies with favorable economic structures. These costs can be broadly divided into:

1. Capital expenditures (CAPEX) – the initial capital expenditure for asset deployment.
2. Operational expenditures (OPEX) – the ongoing expenditure required to charge the asset and maintain the asset operations.

CAPEX for ESS can be divided into two main categories:

1. Power component – affects the amount of energy the ESS can charge/discharge per hour (e.g., pumps and turbines in pumped hydro storage, cathode and anode in Lithium-ion batteries).
2. Energy component – affects the system's duration (e.g., reservoirs in pumped hydro facilities, Lithium cells in battery systems).

ESS CAPEX structures vary significantly by technology. For example, Lithium-ion batteries have a relatively low-cost power component (electrodes) but a relatively high-cost energy component (Lithium salt). Pumped hydro technology may require negligible energy component CAPEX if reservoirs naturally exist but incur significant power component costs (pumps and turbines).

In recent years, Lithium-ion technology CAPEX has decreased substantially, boosting its use for short-duration and intraday storage. However, commercial viability for Lithium-ion ESS depends heavily on the number of yearly charge-discharge cycles, since frequent cycles justify the high energy-component cost. Inter-day storage, however, requires few annual cycles, making Lithium-ion technology economically unsuitable for this use case despite expected cost improvements. Fig. 3 [4] provides a high-level categorization of storage technologies based on optimal power rating and duration.

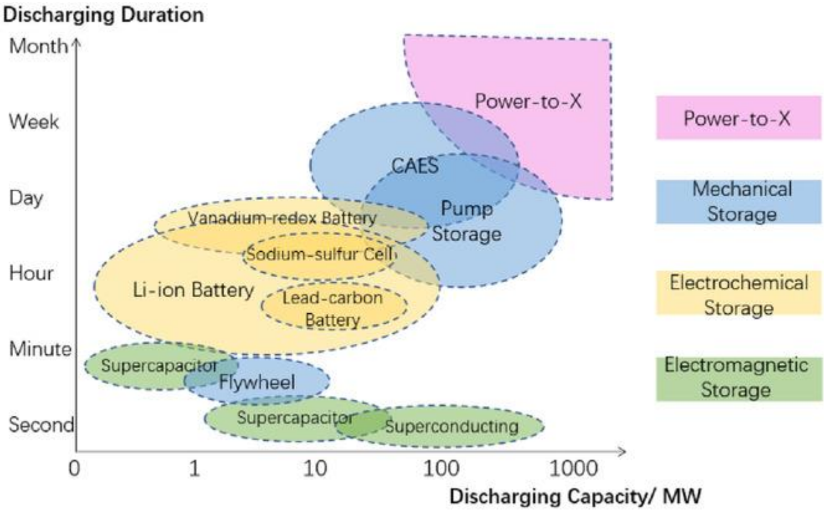


Figure 3. Energy storage technologies sorted by capacity and duration. [4]

While Lithium-ion battery technology's popularity has dramatically increased due to rapidly decreasing CAPEX (as well as improved lifespan, efficiency, and energy density), it remains primarily suitable for short-duration and intraday storage due to high energy-component costs. Inter-day storage's limited cycling makes Lithium-ion economically impractical.

Technologies such as hydrogen, CAES, pumped hydro storage, and iron-air rechargeable batteries, display lower RTE when compared to Lithium-ion. However, they are more suitable for inter-day durations due to potentially competitive CAPEX of their energy components. Hydrogen and iron-air technologies have yet to be proven commercially and are expected to display a RTE of up to ~40%. Pumped hydro storage and CAES viability is highly site dependent. While pumped hydro storage is relatively efficient (75-80% RTE), it requires specific topography and is most cost-effective where reservoirs already exist. Conversely, CAES requires suitable geological storage sites. Some research has investigated CAES viability in aquifers and abandoned mines, but thus far CAES has proven effective in solution-mined salt caverns in Germany, the USA, and China. While few sites in NW-European countries (Germany, the UK, Denmark, and the Netherlands) are suitable for pumped hydro, they do possess suitable salt formations for solution-mined salt caverns.

The Royal Society analyzed 37 years of historical weather data along with the CAPEX and efficiency assumptions for different technologies [3]. Their research suggested that the UK should deploy 55 [GW] of hydrogen-based multi-day storage and 23 [GW] / 3450 [GWh] of CAES. Despite the lower power rating, the research suggests that CAES would deliver more energy than hydrogen due to more frequent cycling and higher efficiency. Applying similar assumptions, Germany, the Netherland, and Denmark, would require over 55 [GW] of multi-day CAES.

Additionally, the Dutch research institute CE Delft and consultancy company Witteveen+Bos published a 2024 study outlining the electricity mix needed by 3035 for carbon-neutral electricity production [5]. This report highlighted significant multi-day energy storage potential, estimating an 8 [GW] capacity requirement. For NW-Europe, the total required storage capacity (including short-duration and intraday energy storage) is estimated to be between 55 and 110 [GW].

3. Isothermal and Adiabatic Compression/Expansion

Fig. 4 demonstrates a pressure-volume (p-V) diagram comparing isothermal (constant-temperature) and adiabatic (no-heat-transfer) compression/expansion processes. In thermodynamic terms, the work done by or on a gas corresponds to the area under the process curve on the p-V diagram. An isothermal expansion maintains a higher-pressure during expansion, since temperature stays constant and heat is absorbed from the surroundings, yielding a larger area (more work output) than an adiabatic expansion. By contrast, during compression the adiabatic curve is steeper (i.e. pressure rises faster for the same volume decrease) because no heat is removed, resulting in more work input area under the curve. In an isothermal process, the gas remains at constant temperature ($\Delta T = 0$), so its internal energy does not change. This means that during expansion, the gas absorbs heat to perform additional work, and during compression, it rejects heat, reducing the work required. In contrast, an adiabatic process (Q = 0) relies solely on changes in internal energy: compression raises the gas's temperature, demanding more work, while expansion cools the gas, resulting in less work output. Therefore, isothermal processes are more efficient – producing more power during expansion and consuming less power during compression – consistent with the larger p-V area for isothermal paths in Fig. 4.

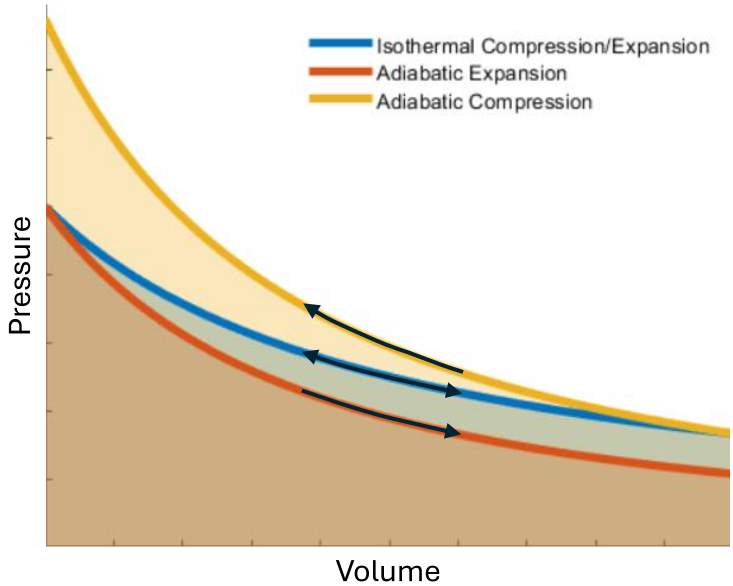


Figure 4. Pressure-Volume (p-V) diagram comparing isothermal (constant-temperature) and adiabatic (no-heat-transfer) compression/expansion processes.

Adiabatic operation in CAES poses significant thermal management challenges, especially in salt-mined caverns. During rapid adiabatic compression, the air temperature can soar to extreme levels, e.g. ~650 °C (1200 °F) when compressing air to ~70 bar (1000 psi) [6]. Injecting such extremely hot air directly into a salt cavern is dangerous – salt rock is typically limited to around 40–50 °C (104–122 °F), above which the cavern walls can deteriorate or crack due to thermal stress. Conversely, adiabatic expansion without external heat causes a sharp temperature drop. As the high-pressure air expands and cools – potentially to around -150 °C (-238 °F) – there is a risk of freezing moisture in the air and forming ice, which can block or damage turbine machinery and weaken materials. This extreme cold can also induce thermal shock in equipment and surrounding rock. Such temperature extremes during adiabatic cycles present operational safety hazards and threaten cavern integrity. Without mitigation, the cavern could experience freeze-thaw damage during expansion and heat-induced fracturing during compression. Therefore, purely adiabatic CAES requires careful control (e.g. intercoolers for compression and reheaters for expansion) to avoid freezing and overheating, ensuring safe operation and preserving the salt cavern structure.

Isothermal processes offer significant benefits for both energy performance and safety in CAES applications. By maintaining a constant temperature during expansion, an I-CAES system maximizes energy extraction. It achieves the highest possible efficiency of the cycle as the expanding air continuously absorbs heat to perform additional work. In practical terms, isothermal expansion allows the gas to deliver more power output for the same pressure drop compared to an adiabatic case, as evidenced by the larger work area under the isothermal p-V curve in Fig. 4. Equally important, isothermal operation avoids the extreme temperatures that cause problems in adiabatic systems. The air is kept near a safe, moderate temperature throughout, e.g. around 40 °C (104 °F) in some I-CAES designs, so there is no risk of outlet air dropping below freezing or spiking to damaging heat levels. This eliminates thermal stress on the cavern and equipment – no ice formation, no overheating of the salt walls – resulting in much gentler thermal cycling. By sidestepping the risks of thermal shock and material degradation, isothermal expansion ensures reliable long-term operation of the storage cavern.

4. Existing and Under-Construction CAES Plants

4.1 Diabatic CAES (D-CAES):

This technology has been successfully demonstrated at the 321 [MW] Huntorf plant in Germany and the 110 [MW] McIntosh plant in Alabama, USA (see Table 1). In these installations, the caverns are typically located at depths of appx. 400–700 [m] (1,300–2,300 [ft]), with operational pressures ranging from roughly 40 to 75 bar (580 to 1,090 psi). Notably, the Huntorf plant was commissioned in the 1970s and the McIntosh plant in the 1990s, reflecting early design practices that do not fully align with current subsurface storage industry standards, such as the double-barrier principle.

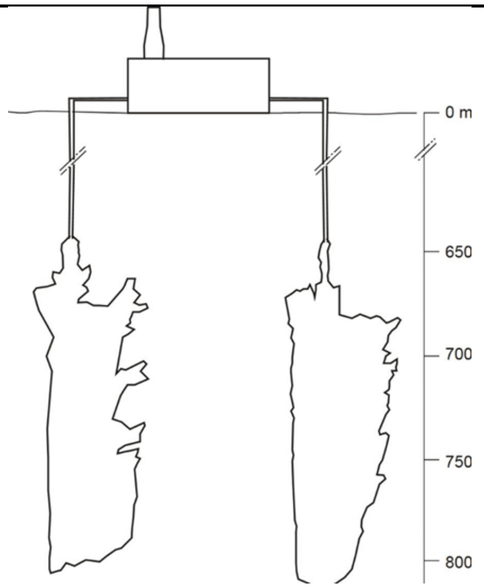
D-CAES utilizes multistage air compressors to compress air into high-pressure storage (such as a salt cavern), and a multi-stage turbo expander to harness the air's expansion energy. To counter the extreme temperature fluctuations inherent in adiabatic compression and expansion and to maintain optimal operational temperatures throughout the process, the air is cooled after each compression stage and pre-heated before each expansion stage. In existing D-CAES systems, pre-heating relies on external natural gas.

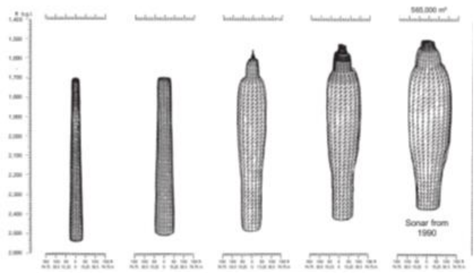
Despite these demonstrations, the RTE of these facilities remains relatively low, largely due to losses in turbomachinery and during the compression process. While hydrogen is being considered by companies such as Siemens and Corre Energy [7], it is not yet a viable alternative to natural gas, given its current cost and limited availability.

Several advances have been made over the years to promote new D-CAES projects. Among these are:

- The Larne CAES project, located on the east coast of Northern Ireland and developed by Gaelectric [8], which surveyed a potential 200-300 [MW] facility with a planned cavern depth of appx. 900 [m] (appx. 3,000 [ft]). However, the project was abandoned following the liquidation of Gaelectric in 2017.
- The SANECA project, designated for upstate New York by the New York State Energy Research and Development Authority (NYSERDA), targeted a 130-210 [MW] CAES facility but was discontinued at the end of the design phase due to economic constraints [9].
- More recently, Corre Energy has pursued several 320 [MW] projects in Germany, the Netherlands and Denmark [7], with hydrogen suggested as a heating fuel in some cases. However, none of these projects have yet materialized.

Table 1. Characteristics of the Huntorf and McIntosh CAES-plant and caverns.

Huntorf CAES-plant & caverns • Build date: mid 70's (nearly 50 years in operation) • Round-trip-efficiency: ~46% • Share of produced energy from compressed air: ~30% • Capacity: o Injection: 80 [MW] x 8 [hours] o Production capacity: 290-330 [MW] x 2-2½ [hours] • Number of caverns: 2 • Total cavern volume: ~ 310,000 [m³] (10,900,000 [ft³]) • Cavern depth: ~ 650-800 [m] (2,130-2,620 [ft]) • Pressure range: ~ 43-70 bar (624-1,015 psi) • Minimal permissible pressure: 1 bar (atmospheric) • Minimal exceptional operational pressure: 20 bar (290 psi) • Maximum pressure change rates: o 15 bar/hr (218 psi/hr) – theoretical o 5 bar/hr (73 psi/hr) – practical • Original purpose: back-up power for power plant • Present purpose: minute reserve, peak shaving, back-up load for reduced supply of renewables	

McIntosh CAES-plant & cavern • Build date: early 90’s (30 years in operation) • Round-trip-efficiency: appx. 54% • Share of produced energy from compressed air: ~40% • Capacity: o Production capacity: 110 [MW] x 26 [hours] • Number of caverns: 1 • Cavern volume: ~ 540,000 [m^3] (19,100,000 [ft^3]) • Cavern depth: ~ 460-760 [m] (1,510-2,490 [ft]) • Pressure range: ~ 46-75 bar (667-1,088 psi) • Advanced heat recuperator included, reducing the fuel consumption by approximately 25% • Original purpose: net balancing services	

4.2 Adiabatic CAES (A-CAES):

While similar to D-CAES, in an A-CAES process the heat produced during compression is used instead of natural gas to preheat the air during expansion. This results in increased efficiency and reduced OPEX (as no heating fuel is required). Several advances to deploy A-CAES systems have been made over the years.

The ADELE project located in Staβfurt, Germany, was intended to include 200 [MW] / 1 [GWh]. The project was pursued by German Aerospace Center (DLR), Ed. Züblin AG, Erdgasspeicher Kalle GmbH, GE Global Research, Ooms-Ittner-Hof GmbH and RWE Power AG. It was estimated to exhibit 70% RTE, but was placed on hold in 2016 citing uncertain business conditions and no further updates have been published [9].

In recent years, several new projects have been commissioned in caverns in China, following the commissioning of a 100 [MW] / 400 [MWh] demonstrator which utilizes artificial storage vessels in Zhangjiakou, Hebei. The project reported a 70.4% RTE [10].

In 2022, a CAES installation was commissioned in Changzhou, Jiangsu Province (East China), featuring a cavern depth of approximately 1,000 m (3,280 ft) and a capacity of 60 [MW] / 300 [MWh], utilizing a 1,200,000 [m^3] (42,000,000 [ft^3]) cavern. The expansion phase is currently under construction and expected to include 700 [MW] / 2.8 [GWh] of storage and a RTE of over 60% [11].

In May 2024, Zhongchu Guoneng Technology Co. commissioned a 300 [MW] / 1,800 [MWh] facility in Feicheng, Shandong province, China. According to an internet publication [12], the cavern wells reach a depth of 1,000 [m] (3280 [ft]) and the above ground footprint was 100,000 [m^2] (1,076,000 [ft^2]). The developer reported an RTE of 72% and a project cost of 208M USD (appx. 115 [USD/kWh]).

In January 2025, a 300 [MW] / 1,500 [MWh] facility, named “Energy Storage No, 1”, was commissioned in Jiangsu, China. This facility utilizes deep caverns with a volume of 700,000 [m^3] (24,700,000 [ft^3]) and is developed by China Energy Engineering Corp (CEEC) [13].

4.3 Isobaric A-CAES (IA-CAES):

Hydrostor Inc., a Canadian developer, is pursuing isobaric A-CAES (IA-CAES) in rock caverns by connecting a ground-level water reservoir to the cavern, whereby the water column maintains the cavern pressure. This technology was demonstrated in 2019 at a 1.75 [MW] / 10 [MWh] facility in Goderich, Ontario, and the company is planning two future facilities: one is a 500 [MW] facility in California and the other is a 200 [MW] facility in Australia. However, in 2021 the company estimated that the CAPEX for up to 12 hours of duration would range between 175 and 250 [USD/kWh] [14]. This high CAPEX relative to current Lithium-ion battery energy storage systems renders the technology less competitive at present.

5. Isothermal (I-CAES) – A Review of Liquid Piston Technology

I-CAES, utilizing Liquid Piston technology, redefines large-scale CAES by shifting from air-based compressors and turbo-expanders to fluid-based pumps and hydraulic turbines. This transition from gaseous to liquid-phase turbomachinery significantly improves efficiency, since pumps and hydraulic turbines consistently outperform air compressors and gas turbines in energy conversion. Another advantage is the extended durability of fluid-based equipment, as pumps require less frequent maintenance than their air-compressing counterparts. Efficiency improvements are enhanced by integration of Variable Frequency Drives (VFDs) with the hydraulic turbomachines. The VFDs enable continuous adjustment of rotational speeds to preserve each pump and turbine's best efficiency point (BEP) while supplying real-time operational data for accurate control. Fig. 5 and Fig. 6 illustrate the fundamental concept of Liquid Piston technology. The system is comprised of two pressure chambers connected through a reversible hydraulic pump. Each chamber has valve-controlled air connections to the atmosphere and to the compressed air storage CAS.

5.1 Compression Process:

1. Chamber 1 is full of atmospheric pressure air and sealed from the atmosphere. Chamber 2 is full of water and open to the atmosphere.
2. Water is pumped from Chamber 2 into Chamber 1; as the water exits Chamber 2, atmospheric air spontaneously enters to fill the void. As the air in Chamber 1 compresses, air-to-water heat exchange occurs. This heat exchange is enhanced by recirculating water – drawing water from the bottom of the chamber and delivering it to the top, where it is sprayed to maximize contact with the compressed air.
3. Once the pressure in Chamber 1 exceeds the air pressure in the CAS, a valve connecting Chamber 1 and the CAS opens.
4. The water that continues to fill Chamber 1 forces the remaining air to transfer from Chamber 1 into the CAS. The added air increases the pressure in the CAS.
5. Once Chamber 1 is full of water, the valve connecting it to the air CAS closes, and the valve connecting it to the atmosphere opens, and the valve connecting Chamber 2 and the atmosphere closes, leaving Chamber 1 entirely filled with water and open to the atmosphere, while Chamber 2 is filled with air and sealed from the atmosphere.
6. The compression process can repeat with the roles of the chambers constantly interchanging, until all the air in the cavern reaches its maximum pressure.

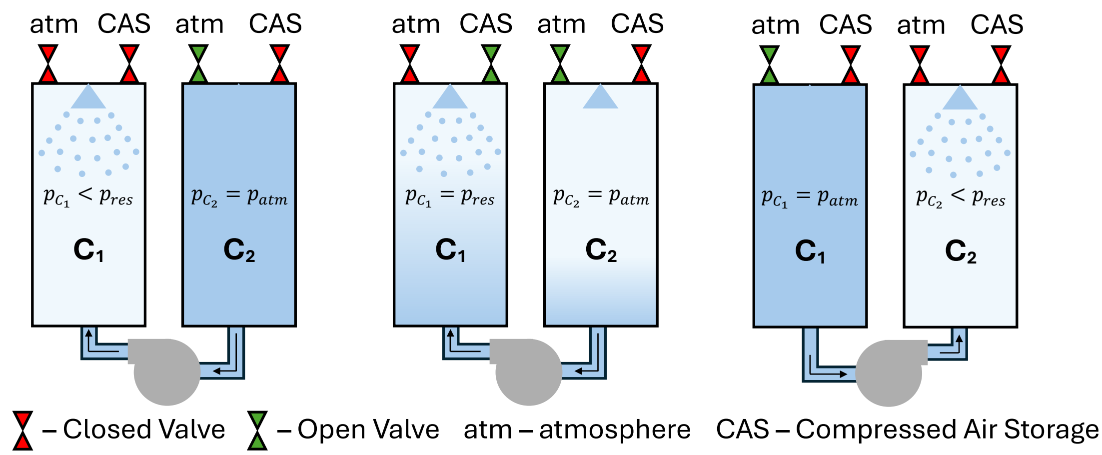


Figure 5. Fundamental concept of the Liquid Piston technology – Compression – Energy storage.

5.2 Expansion Process:

1. Chamber 1 is full of atmospheric pressure air and is open to the atmosphere. Cahmber 2 is full of water. During discharge, the reversible pump operates as a turbine (PAT – Pump As a Turbine) to generate electricity (a separate turbine can also be added).
2. The valve connecting Chamber 2 and the CAS opens, causing the pressure in Chamber 2 to rise to the pressure in the CAS.
3. Water is allowed to spontaneously flow from the pressurized Chamber 2 through the PAT towards Chamber 1, and electricity is generated.
4. Once an air mass equivalent to that contained in a chamber filled with atmospheric air has entered, the valve that connects Chamber 2 and the CAS closes.
5. Air continues to expand in Chamber 2 until all its water content has been transferred to Chamber 1, and the air in Chamber 2 has reached atmospheric pressure. As the air in Chamber 2 expands, water-to-air heat exchange occurs. The heat exchange can be expedited by spraying water taken from the bottom of the chamber and sprayed on the air located at the top of the chamber.
6. Once Chamber 1 is full of water, the valve connecting Chamber 1 to the atmosphere closes, the valve connecting Chamber 1 to the CAS opens, and the valve connecting Chamber 2 to the atmosphere opens.
7. The expansion process can repeat with the roles of the chambers constantly interchanging, until the air in the CAS has reached its minimum pressure.

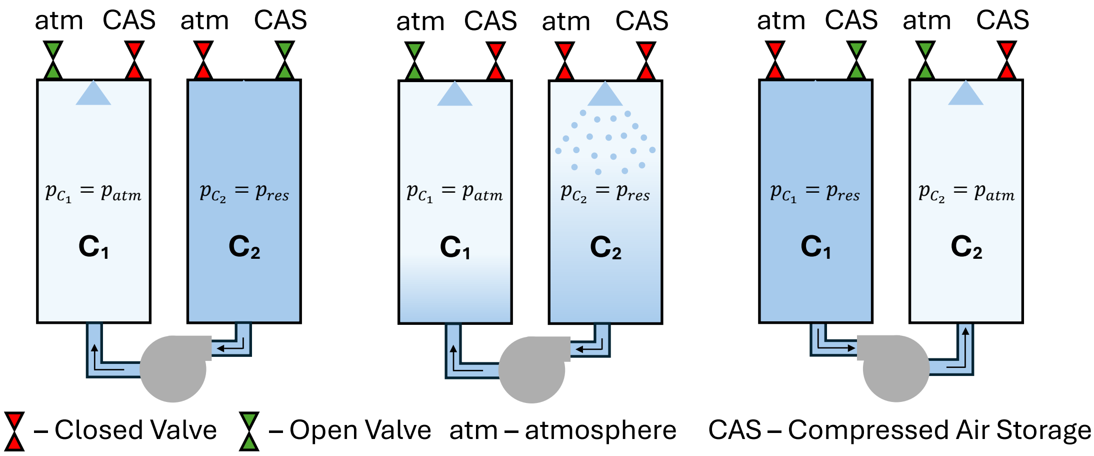


Figure 6. Fundamental concept of the Liquid Piston technology – Expansion – Energy release.

5.3 Recent Attempts in I-CAES

Multiple attempts were made to develop I-CAES systems above ground. At Oak Ridge National Laboratory, a small-scale prototype called Ground Level Integrated Diverse Energy Storage (GLIDES) was successfully demonstrated [15]. Several other companies have made commercial attempts to develop a commercial product. For instance, LightSail Energy (2008 - 2018) pursued an I-CAES model incorporating water injection for heat management. It claimed an astonishing 90% roundtrip efficiency [16], which exceeds the theoretical thermodynamic limit (therefore physically unattainable). Despite raising 70M USD, no pilot facility was built [16,17]. Similarly, SustainX (2008 - 2016) developed a 1.5 [MW] I-CAES system that employed a cool water spray for heat management, claiming 54% efficiency. However, despite a 30M USD investment, it failed to produce any successful pilot facility [16,18]. In contrast, CAES in solution-mined salt caverns have been technically proven for large-scale energy storage.

6. AirX™ – Novel Underground Pressure Chambers for Compression/Expansion

Augwind's AirX™ technology represents a breakthrough in I-CAES solutions by overcoming the limitations of conventional massive bulk steel tanks. Large high pressure steel tanks are expensive and have long lead times. The AirX™ is constructed onsite out of construction grade materials (steel rebar and cement) and a proprietary blend of polymers. The from bulk steel tanks to polymer-based structures is possible due to the low air temperature resulting from the isothermal compression. It enables a significant reduction in system costs, design flexibility, and supply chain simplification. As shown in Fig. 7, its unique design features a liner placed in a steel rebar cage cast with a cement mixture, allowing 70–90% of the system to be buried underground, thereby eliminating surface footprint and enabling dual land uses. The first-generation AirX™ (AirX™ 1.0) has been in commercial operation since 2016. Over 70 AirX™ chambers serve as compressed air buffer tanks across some of Israel's largest industries. The AirX™ has demonstrated more than 7 years of continuous daily operation. It is compliant with rigorous standards such as the Pressure Equipment Directive (PED), CE and ISO certifications (ISO 9001, ISO 45001, and ISO 14001). The AirX™ design enables larger, modular chambers operating at high pressures. It is installed in just a few days, offering a safe, durable, and maintenance-reducing solution that can be scaled to any size with zero operational degradation. This patented core technology forms the foundation of the AirBattery™ system as it hosts the compression and expansion processes.

Figure 7. AirX™ chambers installed on-site at Nesher Israel Cement Enterprises Ltd (March 2022).

7. AirBattery™ – The First Pilot Facility in Kibbutz Yahel, Israel

Augwind's AirBattery™ technology addresses a crucial gap in the energy transition by integrating the principles of compressed air and pumped hydro energy storage. The system is designed for multi-day and multi-week energy storage durations, at grid-scale.

Fig.8 (3D as-made model) and Fig. 9 (drone-captured aerial view) illustrate the pilot facility in Kibbutz Yahel. The pilot facility demonstrates the liquid piston, near-isothermal compression and expansion processes. Currently, it operates at a capacity of 250 [kW] / 1 [MWh], with an RTE of 47%.

The AirBattery™ system maintains near-isothermal compression and expansion due to three major mechanisms:

1. A large surface area between the water and the air – leveraging a thermal mass ratio exceeding 3500:1[1] – allows the water to absorb nearly all the generated heat from the compressed air with minimal temperature change.
2. The natural underground temperature, combined with the large surface area of the chambers and caverns, facilitate effective heat transfer between the water, air and the surrounding earth.

[1] *Calculated at 300 K. The thermal mass of a substance is given by the product of its bulk density, its specific heat capacity at constant pressure, and the volume it occupies. For water and air, each at a volume of 1 [m³]:* $\frac{C_{th,water}}{C_{th,air}} = \frac{\rho_{water} c_{p_{water}} \cdot 1[m^3]}{\rho_{air} c_{p_{air}} \cdot 1[m^3]} = \frac{1000 \cdot 4180}{\left(\frac{101325}{287 \cdot 300}\right) \cdot \left(\frac{7}{2} 287\right)} \cong 3536$

3. State-of-the-art control architecture cools the air by utilizing an optimal nozzle distribution array that spray water, swirling it from the bottom to the top of the chambers using highly efficient pumps.

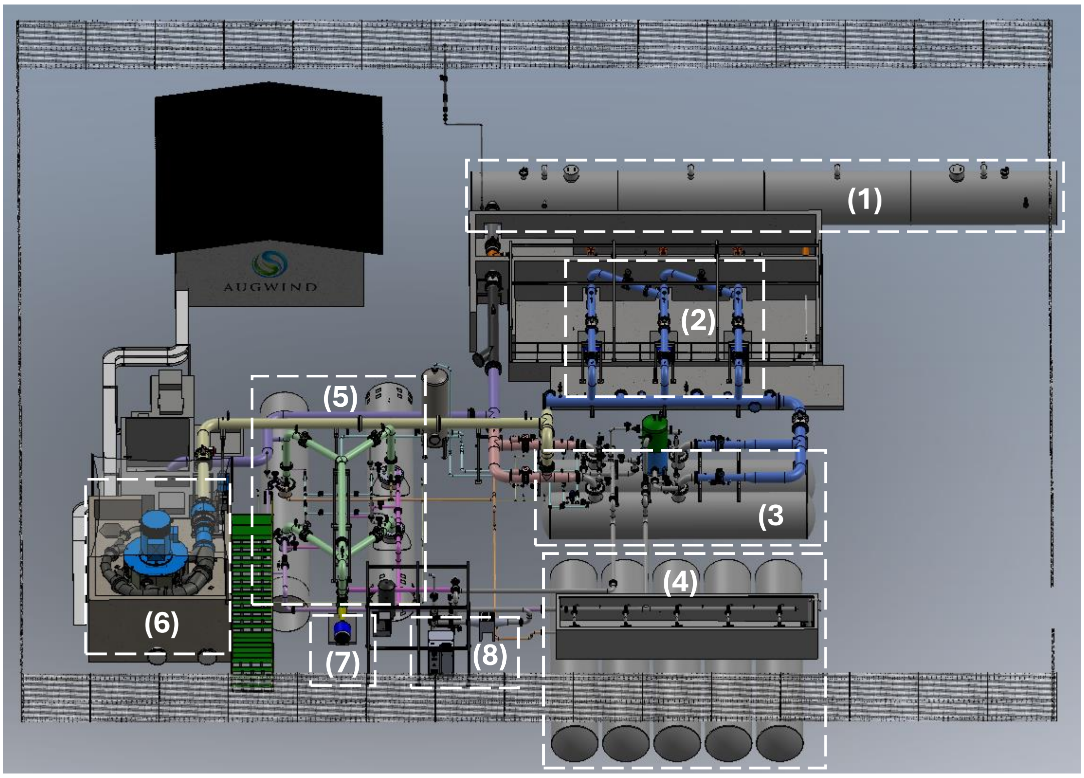


Figure 8. 3D as-made model of the Yahel pilot plan illustrating its main components: (1) water reservoir; (2) pump island with three PAT units (Torishima CPW250-501 pumps); (3) charging cycle compression chambers 1 and 2; (4) main reservoir of five chambers 3, 4, 5, 6, and 7; (5) discharge cycle compression chambers 8 and 9; (6) high-pressure Pelton turbine; (7) PAT unit for low-pressure energy recovery; and (8) blower unit for pre-pressurization before each compression cycle.

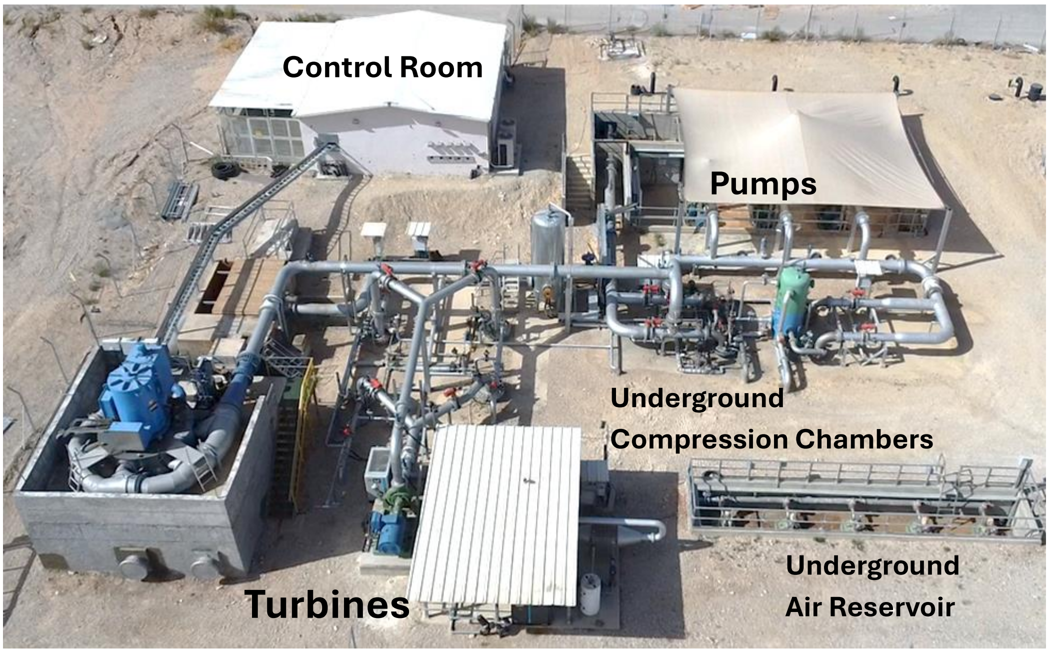


Figure 9. Aerial view of Augwind's state-of-the-art air battery demonstration facility in Yahel, Southern Israel.

The pilot facility comprises several key components, as illustrated in Fig. 8. These components include:

1) **Water Reservoir:** Stores water between operating cycles or during maintenance.
2) **Pump Island:** Consists of three PAT units functioning as pumps (Torishima CPW250-501 pumps) capable of delivering a maximum static head of 85 [m] (278 [ft]).
3) **Compression Chambers:** Two chambers utilized during the charge cycle for pre-pressurization and the compression of air via water transfer.
4) **Main Reservoir:** Constructed from five standard chambers that serve as the primary storage unit for compressed air.
5) **Expansion Chambers:** Two chambers operated during the discharge cycle.
6) **Pelton Turbine:** Designed for high-pressure operation and manufactured by Voith. The turbine net head ranges between 50 and 460 [m] (164 and 1510 [ft]). To minimize back-pressure, the turbine discharges into an above-ground reservoir that is open to the atmosphere. The turbine is mounted at an elevated position, ensuring optimal performance and efficient energy conversion.
7) **PAT Turbine:** A PAT unit functioning as a turbine designed for high efficiency over a wide range of operating conditions, especially for low-pressure energy recovery.
8) **Blower Unit:** Activated prior to each compression cycle for pre-pressurization, enhancing the initial air mass in each compression chamber.

Fichtner Consulting Engineers Ltd. performed an extensive validation and assessment of the demonstration facility, culminating in a comprehensive report available upon request [19,20]. Their rigorous analysis of complete charging and discharging cycles revealed that the system yielded a compression efficiency of approximately 62% – while the discharge phase via the Pelton turbine and PAT units, delivered a generation efficiency of about 74%. These findings, corroborated by precise pressure and temperature measurements confirming near-isothermal operation, substantiate the process assumptions. Furthermore, pump performance analysis indicated an average efficiency of 76%, with detailed power measurements revealing VFD idle consumption– highlighting potential areas for further optimization in component sizing and control strategies. The overall RTE of the system was calculated at approximately 46%. According to Fichtner assessment, an improved design and mechanical and electrical equipment could elevate the RTE to above 60%. Moreover, process efficiency can be improved by reducing hydraulic losses through shorter pipe runs, increased piping diameters, and optimized routing – as well as by enhancing the sprinkler system to decrease heat losses.

8. Commercial Scale Module & Commercial Scale Plant

A key advantage of the AirBattery™ stems from its modularity. Each AirBattery™ module would exhibit a power output capacity of 3-10 [MW]. A system could be comprised of multiple modules and multiple caverns, based on location and market needs. Building on the successful demonstration of the AirBattery™ system at Kibbutz Yahel and the comprehensive analysis conducted by Fichtner, which suggested that the AirBattery™ has the potential to yield an RTE exceeding 60%, a novel approach has been advanced to further enhance system costs and performance. The approach divides the process into distinct compression/expansion stages. Each stage is optimized to a specific pressure range. The different module's stages operate simultaneously, aligning each turbomachine with its optimal operating range. This reduces the installed power requirement for a given average power output (installed-to average power ratio. Fig. 10 and Fig. 11 illustrate a three-stage configuration for the charging and discharge processes. The chamber sizes are determined according to near-isothermal compression principles (i.e., $pV = constant$), ensuring that each chamber's volume is proportional to the pressure targeted at the end of its stage.

8.1 Charging Process:

Fig. 10 demonstrates the three-stage compression configuration used for charging a salt cavern. In this process, air is compressed along three distinct paths, each containing chambers of different sizes designed in accordance with the near-isothermal compression condition ($p_1V_1 = p_2V_2$). The detailed process is as follows:

1. In the LP path (depicted in green), three chambers of varying volumes are employed. Notably, the LP PAT transfers water only between the largest chambers, ensuring that all the air in the LP path – which spans large, medium, and small chambers – is ultimately compressed so that only the

medium and small chambers retain pressurized air at the end of the cycle (compressing from the blower pre-pressure to the LP level – i.e., $p_{blower}(V_L+V_M+V_S) = p_{LP}(V_M+V_S)$).

2. In the MP path (shown in orange), two chambers further compress the air from LP to MP levels, with the MP PAT transferring water exclusively between the medium sized chambers (i.e., $p_{LP}(V_M+V_S) = p_{MP}(V_S)$), thereby leaving the smallest chamber to complete the compression in the next cycle.
3. Finally, in the HP stage (represented in red), a single small chamber compresses the air from MP to HP levels. It should be noted that during the initial charging cycles, when the pressure in the HP chamber equilibrates with the cavern, a valve opens and the HP pump transfers water solely between the small chambers, displacing the remaining air bubbles into the cavern and incrementally increasing the cavern pressure; only in the final charging cycle does the cavern pressure reach the HP level.
4. Throughout all stages and only in the charging process, the blower maintains the water in the chambers that are connected to the intake of the pump at a pressure above atmospheric pressure to reduce the required compression ratio in each of the stages.

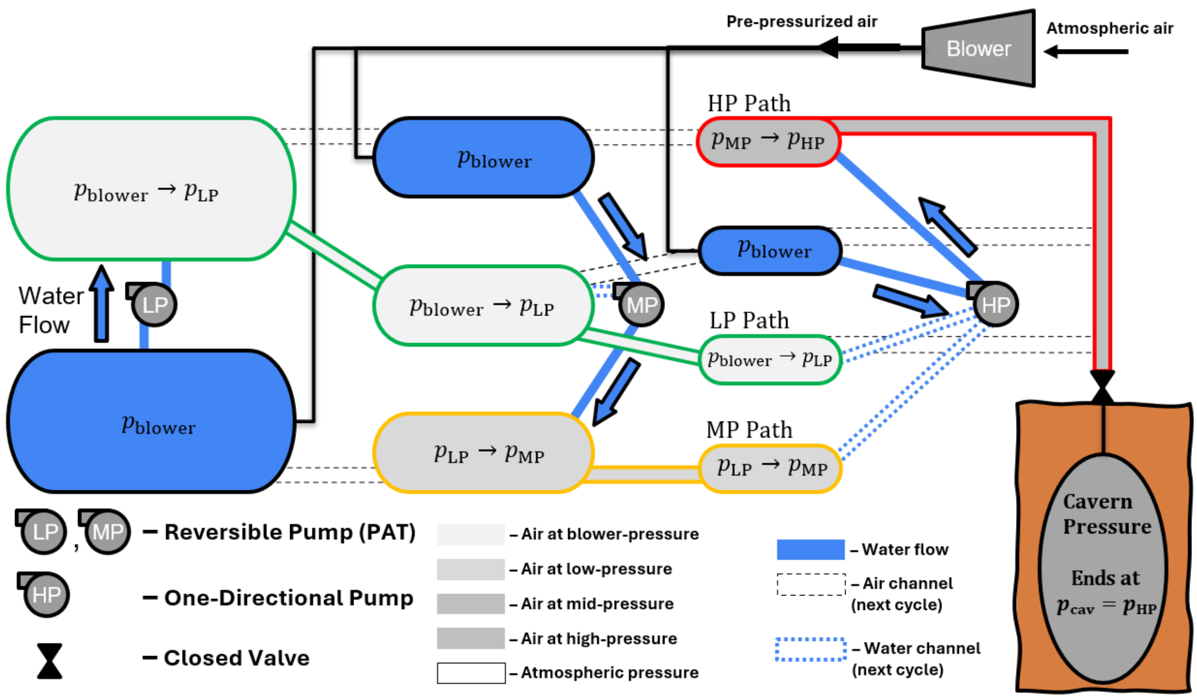


Figure 10. A three-stage compression configuration comprises three distinct compression paths corresponding to the low-, mid-, and high-pressure (LP, MP, and HP) stages.

8.2 Discharge Process:

Fig. 11 illustrates the expansion configuration utilized during the discharge process. The detailed process is as follows:

1. In this phase, the stored compressed air expands along the same three-stage path – spanning large, medium, and small chambers – to release energy.
2. While the air expands through all stages, the process mirrors the charging configuration in reverse.
3. It is important to note that during the discharge process, the cavern pressure is initially at the HP level; as each cycle progresses, the pressure gradually decreases until, in the final discharge cycle, the cavern reaches its minimum pressure level (which is higher than the MP but lower than the HP).
4. In this process, no blower is used, and the air expands against the atmosphere.
5. In the HP path, the HP pump is replaced with a Pelton turbine. This is due to efficiency limitations of PAT turbomachinery for such pressure range (HP to MP).
6. The optimized water transfer strategy is maintained throughout – where the LP PAT, MP PAT, and (now) the HP Pelton turbine operate on the largest, medium, and small chambers respectively – ensuring efficient energy release during the expansion process.

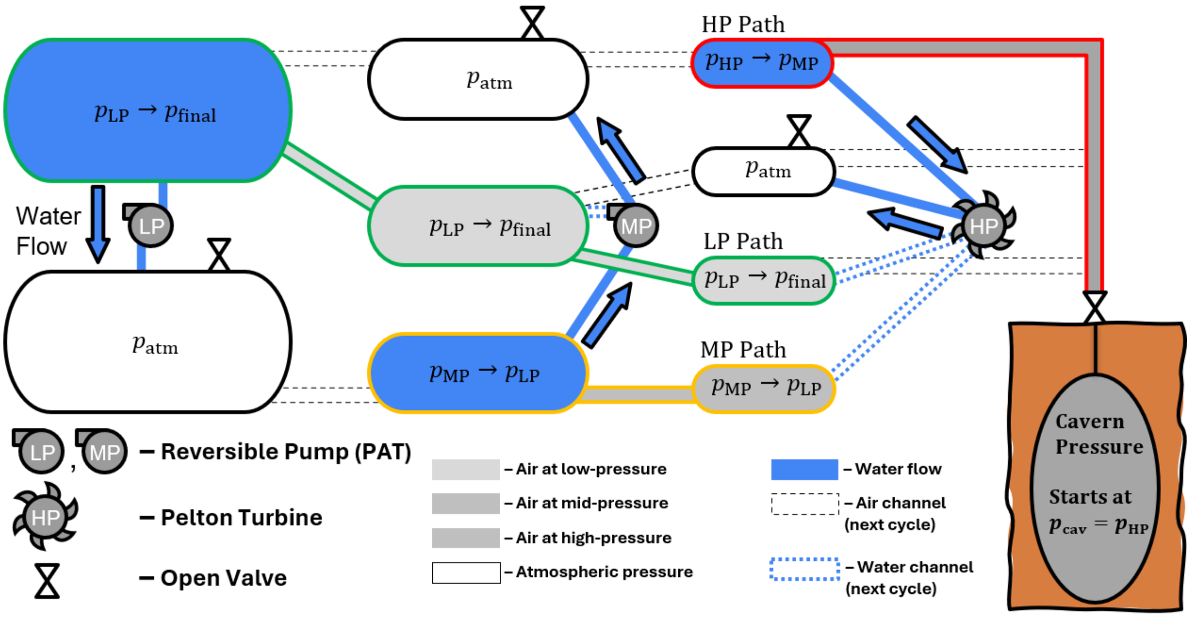


Figure 11. A three-stage expansion configuration comprises three distinct compression paths corresponding to the low-, mid-, and high-pressure (LP, MP, and HP) stages.

9. Competitive Cost Structure of I-CAES for Multi-Day/Multi-Week Durations Compared to Alternatives

Recent technological advancements in Lithium-ion battery technology have significantly raised the performance standards for mechanical storage systems. It is anticipated that the Lithium-ion energy component CAPEX will drop below 100 [USD/kWh] [21], while maintaining site-ability, RTE of nearly 90%, high energy density, and an extended lifespan.

Most mechanical systems exhibit a power component CAPEX well above 1,500 [USD/kWh] (compared to 100–200 [USD/kW] in Lithium-ion technology) and typically operate at lower efficiencies than Lithium-ion systems. To compete at the system CAPEX level, these systems must integrate a low-cost storage medium with extended duration capabilities. CAES in solution-mined salt caverns offers such potential. However, pre-heating during discharge presents challenges for both D-CAES and A-CAES systems. The heating fuel required for D-CAES increases OPEX and necessitates a wider arbitrage spread between charging and discharging, thereby reducing the facility's annual operating hours and overall return on investment.

In A-CAES systems, the thermal storage CAPEX is added to the energy component CAPEX, further increasing the overall cost. While thermal storage is effective for short-duration applications (using mediums such as water, thermal oil, or molten salts), preventing heat dissipation over multi-day durations is prohibitively expensive as it requires advanced insulation techniques such as vacuum technology. Although the Royal Society has referenced pit thermal energy storage (PTES) for its low cost, PTES requires extensive land, significant water resources, and multiple expansion stages due to its limited operating temperature range. Since I-CAES does not require pre-heating, it maintains low energy component related CAPEX and OPEX at any duration. This results in a constant marginal duration CAPEX (solely the cost of enlarging the cavern) and a very low average CAPEX for multi-week durations. Fig. 12 illustrates the CAPEX per kWh for various fuel-free energy storage technologies.

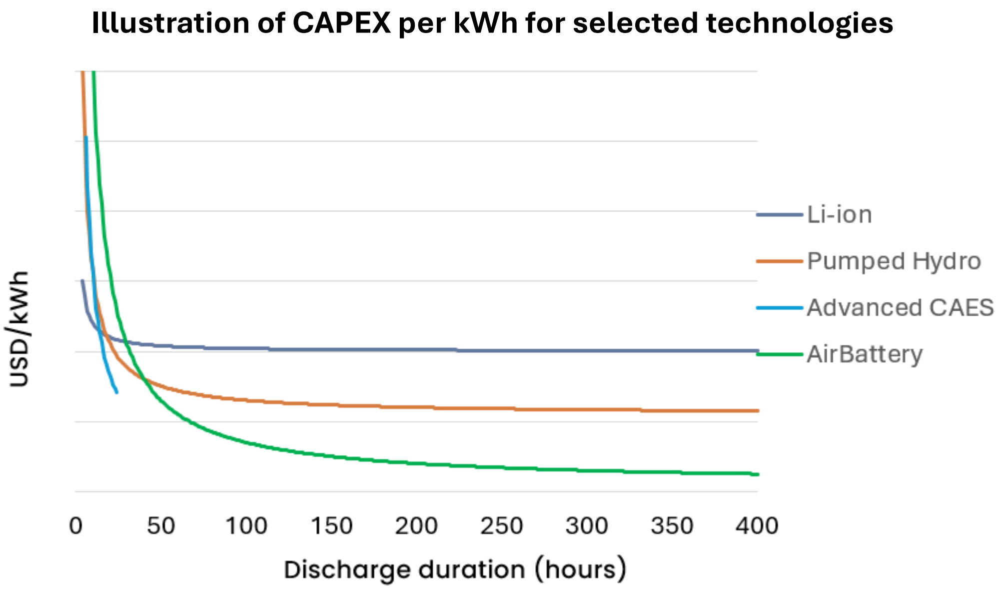


Figure 12. The CAPEX per kWh for various fuel-free energy storage technologies.

10. Caverns for Upscaling AirBattery™

Storage of natural gas and oil products in salt caverns is quite common worldwide. Table 2 summarizes cavern storage usage in selected European countries based on a 2017 SMRI study [22]. Since the study, additional caverns have been under development for storage of hydrogen gas.

Table 2. Summary of cavern storage usage in selected European countries.

Country	Gas Storage Caverns	Liquid Storage Caverns
Germany	284	>100
United Kingdom	113	7
France	40	35
Poland	13	10
Netherlands	7	0
Denmark	6	0

While the pilot facility in Kibbutz Yahel features a small and shallow air reservoir operating at a maximum pressure of 40 bar (580 psi), commercial projects will necessitate higher storage pressures and larger storage volumes. Solution-mined salt caverns provide an ideal storage space, with volumes generally ranging from 100,000 [m^3] (3,000,000 [ft^3]) to 1,000,000 [m^3] (35,000,000 [ft^3]) and located in the subsurface at depths ranges from appx. 400 [m] (1,300 [ft]) to over 1,500 [m] (5,000 [ft]), resulting in pressure ranges of appx. 30 to 300 bar (435 to 4350 psi). The cavern depth (i.e., the distance between the earth's surface to the top of the cavern) is directly related to the maximum pressure that the cavern can hold. The maximum pressure is typically determined by the strength of the so-called Last Cemented Casing Shoe (LCCS) of the well – the deepest point of the most deeply cemented casing in contact with the surrounding rock. Thus, it represents the transition from the man-made, drilled well to the cavern. When a gas (e.g., air) is injected into a salt cavern, the pressure increases, and conversely, it decreases when the gas is withdrawn. In other words, a salt cavern functions as an exceptionally large pressure vessel. Consequently, Augwind has investigated the feasibility of using salt caverns as large pressure vessels for storing compressed air for the AirBattery™. Typical characteristics of air storage in caverns are:

- A large storage volume of up to 1,000,000 [m^3] (35,000,000 [ft^3]) in an airtight material.
- A high volume of airflow that the cavern can deliver.
- Safe high-pressure storage for the surrounding environment, provided that general design and operational rules are followed.

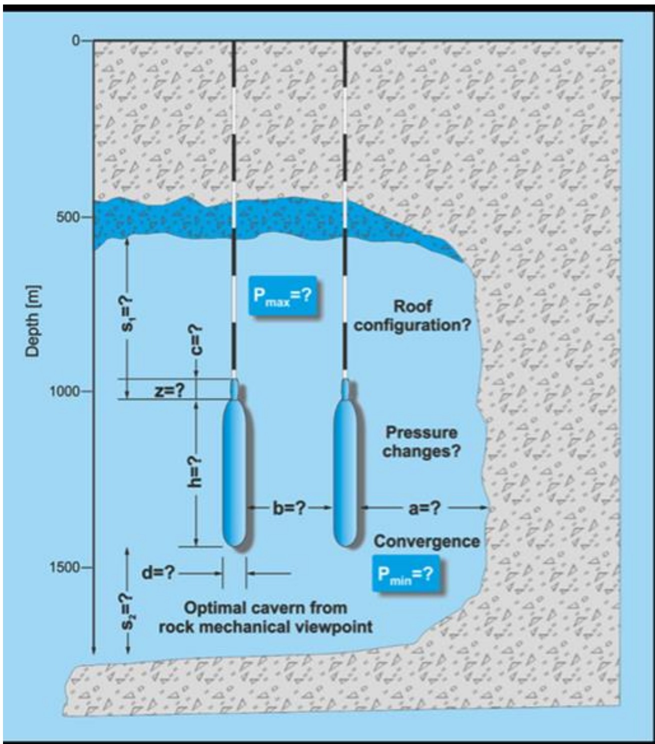
Storing compressed air (or other gases) in caverns introduces specific peculiarities compared to conventional pressure vessels. For example:

- The cavern is constructed within natural materials, which exhibit heterogeneities at both macroscopic and microscopic scales. Nevertheless, rock salt is assumed to be (nearly) impermeable to most gases (e.g., air).
- The material properties of the surrounding rock are predetermined and cannot be controlled, so they must be studied and accommodated.
- Once a cavern is created, its dimensions cannot be reduced or relocated; while expansion is possible, it entails significant (and costly) challenges.
- Subsurface activities, including the construction and maintenance of caverns and wells, inherently involve certain risks and uncertainties.

The safety level of high-pressure cavern storage depends on two critical factors:

- Appropriate design of the cavern.
- Adherence to proper operational use.

The design criteria encompass factors such as salt roof thickness, distance to neighboring caverns, cavern neck length, height, and diameter. Meanwhile, the operational guidelines address parameters including minimum and maximum pressures, the overall operational pressure range, allowable pressure and temperature change rates, and the necessity for frequent monitoring, among others. Fig. 13 presents the most critical design and operational parameters of storage caverns in graphical form [23].



Design Parameters	
s_1	thickness of the salt roof
s_2	thickness of the salt bottom
z	depth of cavern roof
c	distance casing shoe / cavern roof
h	cavern height
d	cavern diameter
b	minimum pillar width
a	minimum distance to the edge of the salt deposit

Operating Parameters	
p_{min}	minimum cavern pressure
p_{max}	maximum cavern pressure
dp/dt	maximum pressure rate

Figure 13. Important design and operating parameters of storage caverns in rock salt [22].

11. Depth Considerations for the AirBattery™ Cavern

As stated earlier, the pressure chambers of the pilot plant in Israel have a maximum air storage pressure of 40 bar (580 psi). Nevertheless, the AirBattery™ process is easily capable of delivering much higher pressures. The process can deliver up to 200 bar (2,900 psi) or even more, by adding compression and expansion stages and employing turbomachinery tailored for each stage. To limit the options, in Augwind's cavern study, four different cavern depths or pressure ranges have been assumed:

- A shallow cavern, with its top at a depth of 400 [m] (1,312 [ft]), a maximum pressure of 70 bar (1,000 psi) and a minimum (operational) pressure of 39 bar (565 psi).
- A shallow intermediate depth cavern, with its top at a depth of 550 [m] (1,804 [ft]), a maximum pressure of 100 bar (2,030 psi) and a minimum (operational) pressure of 55 bar (800 psi).

- A deep intermediate depth cavern, with its top at a depth of 720 [m] (2,362 [ft]), a maximum pressure of 130 bar (1,885 psi) and a minimum (operational) pressure of 72 bar (1,044 psi).
- A deep cavern, with its top at a depth of 890 [m] (2,920 [ft]), a maximum pressure of 160 bar (2,320 psi) and a minimum (operational) pressure of 88 bar (1,276 psi).

Deeper caverns may also be suitable for the AirBattery™, but are out of the scope of this paper.

12. Energy Capacity of the AirBattery™ Cavern

For a future demonstration project, Augwind has indicated a desired power generation capacity between 3 and 10 [MW]. The desired duration of power generation is between 200 and 400 hours, i.e. between 8 and nearly 17 days. Recent periods of limited renewable energy production over NW-Europe due to a lack of wind and sunshine, so-called 'Dunkelflaute' periods, in November 2024, have shown that these are realistic durations. The energy capacity of the cavern can be calculated as the product of the power generation capacity with duration, thus ranging between 600 [MWh] and 4 [GWh].

According to the Fichtner study [19,20], the discharge process of the pilot installation had an efficiency of appx. 74%. The report expects that this efficiency can be further enhanced in a larger-scale pilot plant, up to 82% for a 68 bar (986 psi) plant. For the cavern study, a conservative 80% efficiency is assumed. This means that the cavern should be able to deliver 125% of the required capacity, so the cavern should have a 'cavern energy storage capacity' between 750 [MWh] and 5 [GWh].

In general, a larger cavern energy storage capacity can be realized in two different ways (next to measures regarding reduction of friction losses, etc):

1. By raising the pressure range, i.e. by having a cavern at a larger depth. At a larger depth, the storage pressure will be higher, and the energy capacity of the air stored under this higher pressure will be larger.
2. By increasing the cavern volume, which can be achieved by increasing the cavern height or by increasing the cavern diameter.

For the above-mentioned required energy capacity, and given the possible cavern depth ranges, the required cavern volume has been statically calculated (so discarding any thermodynamical processes). It is taken into account that the energy is to be delivered by the working gas volume only and assumes several simplifications with regard to temperature changes (neglected) and frictional pressure loss over the well trajectory (set at a fixed value). Due to these simplifications, calculation results are assumed to have an error margin of +/- 10%.

These calculations show that the appropriate cavern volume for the required power generation capacities and durations ranges from appx. 65,000 [m^3] (210,000 [ft^3]) for the smallest cavern capacity with 750 [MWh] at the largest LCCS of 1,060 [m] (2,300,000 [ft^3]), to nearly 1,500,000 [m^3] (51,300,000 [ft^3]) for the largest cavern capacity with 5,000 [MWh] at the shallowest LCCS of 400 [m] (1,310 [ft]) – see Table 3.

Fig. 14 shows the cavern volume and pressure bandwidth for a 3 to 10 [MW] AirBattery™ with 300 hours of duration in graphical form. This clearly shows that due to the higher operating pressure of deeper caverns, less storage volume is required for the large energy storage capacity cases. While for the deepest caverns studied, with LCCS of appx. 1,060 [m] (3,480 [ft]) and volume of 326,000 [m^3] (11,500,000 [ft^3]) suffices for delivering air for a 10 [MW] AirBattery™ for 300 hours, at shallow depths (cavern roof at just over 400-meter depth) a cavern of over 1,000,000 [m^3] (over 35,300,000 [ft^3]) would be needed for the same duration and capacity.

Table 3. Overview of the required cavern volume (in 1000 m^3) for five different maximum cavern pressures (or depths of the LCCS) for the given cavern capacity (in MWh) for all studied cases.

Case	Generation Power [MW]	Duration [hours]	Available Energy Capacity [MWh]	Cavern Energy Storage Capacity [MWh]	Cavern Volume ×1e3 [m^3] (×1e6 [ft^3])	Cavern Volume ×1e3 [m3] (×1e6 [ft3])	Cavern Volume ×1e3 [m3] (×1e6 [ft3])	Cavern Volume ×1e3 [m3] (×1e6 [ft3])	Cavern Volume ×1e3 [m3] (×1e6 [ft3])
	Depth ranges of the LCCS [m] ([ft]) →				≅ 400 (≅ 1,310)	≅ 550 (≅ 1,800)	≅ 720 (≅ 2,360)	≅ 890 (≅ 2,920)	≅ 1,060 (≅ 3,480)
#1	3	200	600	750	218 (7.7)	141 (5.0)	102 (3.6)	80 (2.8)	65 (2.3)
#2	3	300	900	1,125	327 (11.5)	211 (7.5)	154 (5.4)	120 (4.2)	98 (3.5)
#3	3	400	1200	1,500	436 (15.4)	281 (9.9)	205 (7.2)	160 (5.7)	130 (4.6)
#4	5	200	1,000	1,250	363 (12.8)	234 (8.3)	171 (6.0)	133 (4.7)	109 (3.8)
#5	5	300	1,500	1,875	545 (19.2)	352 (12.4)	256 (9.0)	200 (7.1)	163 (5.8)
#6	5	400	2,000	2,500	727 (25.7)	469 (16.6)	342 (12.1)	266 (9.4)	217 (7.7)
#7	7	200	1,400	1,750	509 (18.0)	328 (11.6)	239 (8.4)	187 (6.6)	152 (5.4)
#8	7	300	2,100	2,625	763 (26.9)	492 (17.4)	359 (12.7)	280 (9.9)	228 (8.1)
#9	7	400	2,800	3,500	1,017 (35.9)	657 (23.2)	478 (16.9)	373 (13.2)	304 (10.7)
#10	10	200	2,000	2,500	727 (25.7)	469 (16.6)	342 (12.1)	266 (9.4)	217 (7.7)
#11	10	300	3,000	3,750	1,090 (38.5)	703 (24.8)	512 (18.1)	400 (14.1)	326 (11.5)
#12	10	400	4,000	5,000	1,453 (51.3)	938 (33.1)	683 (24.1)	533 (18.8)	435 (15.4)

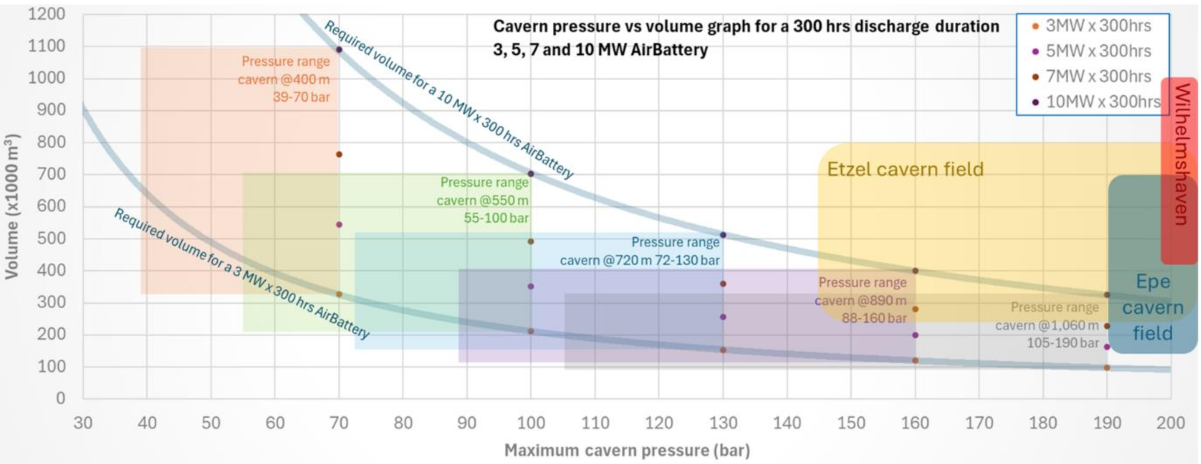


Figure 14. Graphical overview of the required cavern volume (in 1000 m^3) for five different maximum cavern pressures (or depths of the LCCS) for a 300 hours duration AirBattery™ of 3, 5, 7 and 10 [MW]. Largest German cavern fields are indicated based on known volumes and depths.

Of course, not all these volumes are realistic, e.g., very large caverns hardly exist at shallow depths, and most deep caverns have volumes of more than 400,000 [m^3] (14,100,000 [ft^3]). But the results give a good first idea of the minimum required cavern depth and the volume for a single AirBattery™ module.

And due to the highly flexible generation capacity, which can simply be reduced or enlarged by removing or adding AirBattery™ units, and the flexible duration, the range of suitable caverns is even broader than shown here. The majority of the volumes fall in the 100,000-800,000 [m^3] (3,500,000-28,000,000 [ft^3]) range, which happens to be the most common volume of most storage caverns.

The positive outcome of the study is promising for acquiring a possible cavern for the AirBattery™ first-of-a-kind project and for development of the AirBattery™ throughout NW Europe and other locations. Especially the smaller and shallower caverns in existing cavern fields, like the Epe and Etzel cavern fields (see Fig. 14), seem promising options. One thing to emphasize is that smaller depth caverns, which are less suitable for storage of gases (like natural gas and hydrogen in the future) can be suitable as well. These may include former oil storage caverns, which are expected to become available in the upcoming decade due to the reduced demand for oil products which will lead to a significant decrease of the strategic oil reserves countries will be obliged to have. Especially when only partially debrined, to prevent high salt creep at the bottom in case of large height caverns, these caverns may be suitable.

13. Additional Subsurface Considerations for the AirBattery™

Several key factors must be addressed when storing compressed air from the AirBattery™ in salt caverns. The most critical of these factors are briefly described below.

Pressure change rate:

For the studied AirBattery™ cases, all pressure change rates remain significantly below the legally prescribed limit of 10 bar/day (145 psi/day), although the scientific basis of this limit remains insufficiently substantiated. The highest anticipated average pressure change rate occurs at the maximum depth considered, with an operating pressure ranging from 190 to 105 bar (2,755 to 1,523 psi) over the shortest operational duration (200 hours). Under these conditions, the calculated rate slightly exceeds 10 bar/day (149 psi/day). However, this estimation is static; in reality, pressure change rates are not linear and may vary due to thermodynamic interactions occurring within the cavern.

Cavern height:

The AirBattery™ is expected to operate as an LDES technology, handling small daily cycles as well as longer, nearly continuous production periods lasting from multiple days up to several weeks. Periods of low pressure may thus occur, potentially delaying cavern recharging immediately after a prolonged production phase. Therefore, similar to seasonal gas storage, a cavern with limited height is preferred, as excessive creep closure could otherwise cause cavern shrinkage, leading to increased surface subsidence. Alternatively, a cavern with greater height but only partially debrined could be considered. From an abandonment perspective, lower-height caverns are favored over narrower, taller caverns.

Temperature changes:

Especially in cases with relatively high depletion rates, temperature changes occurring in the cavern have to be considered, as these may negatively impact the cavern integrity due to rock-mechanical developments like dilation. Based on the expected operating profile of small daily cycles combined with a limited number of longer during continuous production, and the relatively limited pressure change rates, this aspect is expected to be well manageable.

Storage wells:

For the moment, it can be assumed that a standard double-barrier gas storage completion, so with a packer and tubing, should be applicable. Nevertheless, the fact that air is being transported in a salty environment requires extra measures regarding corrosivity protection. This is comparable to ‘normal’ CAES [7]. A subsurface safety valve is assumed not to be necessary as other measures should be able to provide the same level of blow-out prevention.

Regarding the wellhead and storage tree, extra measures to prevent corrosion are expected to be required as well.

Assuming a standard gas storage well size, with a 13-3/8” LCC and a 9-5/8” production tubing, air flow in the well is expected to remain at an acceptable level and well below the generally assumed threshold of 30 [m/sec] (100 [ft/sec]). This means that, in contrary to ' normal’ CAES, the demonstration project can do with one single, normal sized well.

Humidity and salt particles in the produced air:

Several aspects of air quality, mainly during the production (discharge) phase, may play a crucial role during CAES. These mainly concern the humidity of the produced air as well as the concentration of salt particles in the produced air.

Humidity is an issue both in air storage and in natural gas storage, mainly due to the temperature drop during the production phase. At many of the UGS locations there is the possibility of drying the gas after production from the cavern. Due to the expected limited pressure change rates, temperature drop is expected to be limited as well, as is consecutive condensation. Furthermore, and in contrary to 'normal' CAES, the air from the cavern is not directly driving the turbine, the displaced water is. This means that cavern air will not come into contact with sensitive parts of the electricity generation equipment (expander and turbine). Furthermore, the expansion chambers are already water filled, so a little bit of extra moisture there is not expected to cause any harm.

Theoretically, salt particles present in the air stream may pose an issue. However, decades of operational experience (from the CAES-plants in Huntorf, Germany, and McIntosh, Alabama), have resulted in no known issues related to such salt particles. As the air flow in general seems lower than in normal CAES, the risk of salt particles seems even smaller, especially as the air does not have to go through a vulnerable expander and turbine but only must fill an expansion chamber. Salt particles will probably be collected in the water of the expansion chamber, so only the slowly increasing salinity of this water might be an issue to consider.

Monitoring and maintenance:

The main subsurface monitoring and maintenance activities concern periodical cavern shape monitoring and regular well integrity monitoring, which follow from legal requirements and are very similar to activities at UGS caverns and normal CAES caverns. Regarding cavern shape measurements it is assumed that a future AirBattery™ cavern, after being brought to its minimum pressure – 105 bar (1,523 psi) for the deepest cavern configuration studied – can be measured using existing tools, such as Socon's laser tool. For well integrity monitoring, the corrosivity of the stored medium requires extra monitoring of corrosion of the well completion. As workovers for replacement of the completion are always challenging, corrosion protection should be of a high level and monitoring should be done on a regular basis. In case completion replacement would be required, this should either be done at atmospheric pressure (if allowed for by the cavern depth), or the completions should be designed such that this replacement can be safely done with the cavern under pressure (like a downhole, double barrier plugging option).

14. Conclusions and Further Directions

The study finds that isothermal compressed air energy storage (I-CAES) in solution-mined salt caverns is a technically feasible and promising option for long-duration energy storage (LDES). A first technical assessment and the initial pilot demonstration indicate that salt caverns can safely accommodate the large volumes of high-pressure air required for multi-hour to multi-week storage. Drawing on decades of industry experience in underground gas storage and the successful operation of legacy compressed air energy storage (CAES) plants, the deployment of Augwind's AirBattery™ system in salt caverns is deemed highly achievable with current engineering know-how. In other words, the integration of the AirBattery™ I-CAES technology into the energy infrastructure could provide a viable solution to support grids during extended renewable energy lulls. This novel approach effectively bridges the gap in the storage spectrum by offering a multi-week storage resource that can be sited in flat regions (where pumped hydro is not possible) and dispatch grid-scale power on demand. The successful evaluation of a 1 MWh pilot and the favorable comparison with alternative technologies reinforce the conclusion that I-CAES in salt caverns can play a meaningful role as long-duration storage becomes increasingly essential.

Several key advantages of the proposed I-CAES solution were highlighted in the analysis. First, the use of solution mined salt caverns provides a superior cost structure for long duration when compared to electrochemical batteries. This inherent cost-effectiveness makes very long discharge durations (many hours to days) economically practical. Second, the AirBattery™ system operates without any fossil fuel input, unlike diabatic CAES, and thus produces no direct emissions during operation. Aside from minor ancillary electricity usage, the process simply transfers energy in and out via compressed air and water, giving it a minimal environmental footprint and a clear advantage in sustainability over gas-fired peaking plants or generators. Third, the isothermal operation enables a respectable round-trip efficiency (RTE) and as Fichtner projections suggest that larger-scale (multi-MW) installations could attain an efficiency of above 60%. While this efficiency is lower than that of Lithium batteries, the AirBattery™ suffers no capacity fade or cycle-life degradation, meaning its performance remains stable over a very long lifetime. Furthermore, the near-constant temperature reduces thermal stress on the cavern and equipment, contributing to operational safety and durability. These advantages – cost-effective scaling of storage duration, competitive efficiency with zero fuel use, and strong longevity and environmental benefits – position I-CAES as an attractive energy storage method for grid resilience.

Future research and development should build on these findings to fully realize the potential of cavern-based I-CAES. One important direction is the optimization of the isothermal compression/expansion process – for instance, improving heat exchange methods (e.g. water spray configurations, multi-stage compression) and accelerating the process. In parallel, cost reductions research should continue, including on aspects such as mass production and advanced materials for turbomachinery. Operational efficiency improvements, such as enhancing turbomachinery performance and reducing auxiliary energy consumption, will also increase the system's economic viability. By addressing these aspects through further research, engineers and developers can expedite the transition to grid-scale deployment of I-CAES.

In conclusion, the integration of Augwind's AirBattery™ I-CAES technology into solution-mined salt caverns offers a compelling pathway for achieving reliable, LDES. Continued progress along the outlined directions will help unlock its full capabilities, enabling this innovative storage solution to contribute substantially to future low-carbon power grids.

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