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Introduction

Adiabatic Compressed Air Energy Storage (ACAES) is frequently suggested as a promising alternative for bulk electricity storage, alongside more established technologies such as Pumped Hydroelectric Storage and, more recently, high-capacity batteries, but as yet no viable ACAES plant exists. At first sight this appears surprising, given that technical literature consistently refers to its potential as a promising energy storage solution and the fact that two Diabatic Compressed Air Energy Storage (DCAES) plants exist at utility scale (Huntorf, Germany and Macintosh Alabama, USA), with over 80 years of combined operation.

In this article we discuss aspects of the main components that constitute a CAES system, the fundamental differences between how they operate in diabatic and adiabatic contexts and the design challenges that need to be overcome for ACAES to become a viable energy storage option in future. These challenges are grounded in thermodynamics and are consistent with evidence from pilot plants, where performance information has been made available. Finally, we suggest that adopting a whole systems design philosophy would maximise the chances of successful ACAES demonstration and discuss worthwhile areas of future research for both simulation and experimental studies.

Thermodynamics and design considerations

Any CAES system is charged using electricity to drive air compressors, resulting in compressed air and heat. In DCAES, the heat is extracted using heat exchangers (HEX) and dissipated (being of low grade and therefore low value), while the pressurised air is stored in a dedicated pressure vessel, referred to herein as the High Pressure (HP) store. Crucially, there is no heat transfer between the charging and discharging processes. To discharge the system, air is released from the HP store and heated by a combustion chamber using natural gas, and is finally expanded through turbines generating electricity. This process is illustrated in the lower section of Figure 1

The process for ACAES is conceptually similar to DCAES (Figure 1, upper section), however has different heat management. In ACAES the heat from the compression is stored and used to reheat the air

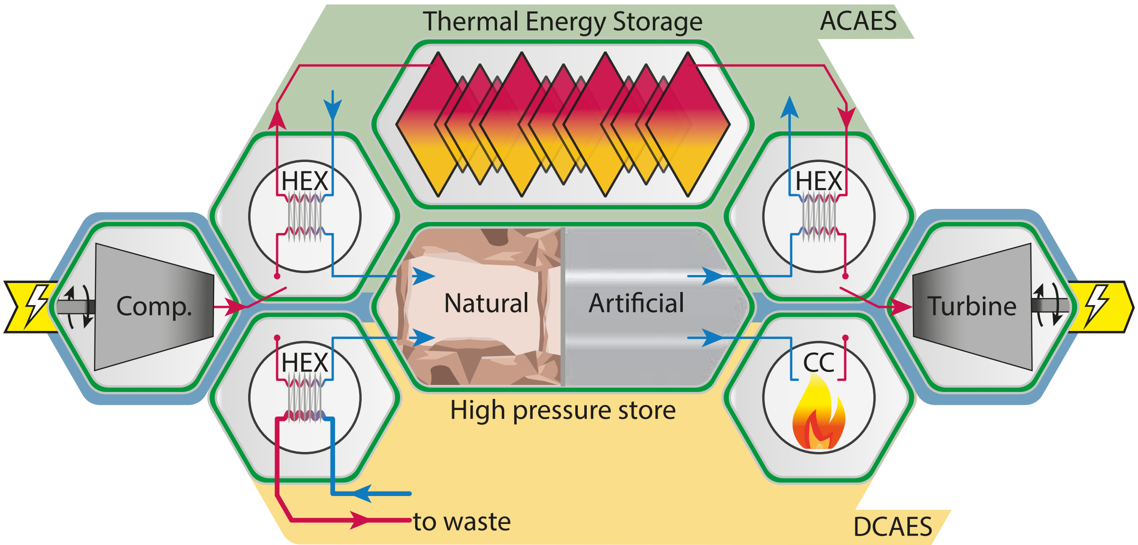


Figure 1: Operation of Compressed Air Energy Storage (CAES) concepts. The crucial difference between DCAES and ACAES is in the different heat management techniques. CC marks the combustion chamber and HEX flow imbalances are shown by differing line widths.

prior to expansion, removing the need for additional fuel but necessitating a Thermal Energy Store (TES). However, while DCAES and ACAES may be similar to some degree, the need to store the compression heat dramatically changes the design of nearly all of the common constituent components.

Compressors and turbines

Equation 1 gives the isentropic work, ΔW, required to compress an air mass Δm from some inlet pressure and temperature, p_i and T_i respectively, to some outlet pressure p_o in a single adiabatic compression stage:

$$\frac{\Delta W}{\Delta m} = \begin{cases} h_o - h_i \\ c_p T_i \left[\left(\frac{p_o}{p_i} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] & \textit{perfect gas approximation.} \end{cases} \tag{1}$$

Here, $h_o - h_i$ denotes the change in enthalpy from the inlet to outlet air state, c_p is the specific heat capacity at constant pressure, $dh = c_p dT$ with the perfect gas approximation (simplifying the ideal gas model by assuming constant specific heats) and γ is the ratio of specific heats ($\gamma \approx 1.4$ for dry air at standard conditions). This process is isentropic and reversible, and accordingly Equation 1 also gives the work available from air expansion (available work has opposite sign).

Studying Equation 1, several aspects of CAES become apparent. Firstly, for both DCAES and ACAES, unless the pressure in the HP store is controlled to be constant, or there is significant over-compression, the final compression outlet pressure will be variable. This increasing outlet pressure during charging also leads to variable outlet temperatures and the effect is mirrored during discharging. Secondly, the compression and expansion processes are strictly coupled in ACAES, since without supplemental heat input the full compression work can only be recovered when the expansion inlet temperature is the same as the compression outlet temperature (*i.e.* $T_i^e = T_o^c = \left(\frac{p_o}{p_i}\right)^{\frac{\gamma-1}{\gamma}}$). Therefore, for maximum efficiency the expansion process must reverse the compression path and the TES should preserve the compression temperatures. This is not true in DCAES, as the external heat source can independently supply heat at a specified temperature, decoupling the charging and discharging processes. Thirdly, the work required to compress a given mass of air is minimised by staging the compression and cooling the air back to ambient temperature between stages (minimum work is attained with equal pressure ratio in all stages). In the limit of perfect inter-cooling and N stages Equation 1 becomes $\frac{\Delta W}{\Delta m} = \sum_{n=1}^{N} c_p T_i \left[\left(\frac{p_o}{p_i}\right)^{\frac{\gamma-1}{N\gamma}} - 1\right]$, which approaches the isothermal compression work $\frac{\Delta W}{\Delta m} = RT_i \log\left(\frac{p_o}{p_i}\right)$ as $N \rightarrow \infty$. These observations lead to crucial differences between the design of DCAES and ACAES systems, highlighting that the conceptual similarity of simply swapping the combustion chamber with a TES is highly misleading.

In reality, the switch between ACAES and DCAES means the turbo-machinery has to be completely re-engineered. As a result of the second and third observations, DCAES has a greater number of compression stages with inter-stage cooling and fewer expansion stages with high inlet temperatures. For example, the Huntorf DCAES plant has 20 axial compression stages (pressure ratio 1.05) and 6 radial compression stages (pressure ratio 1.8), whereas the expansion is accomplished in just two stages[6]. Conversely in ACAES, the charge-discharge coupling leads to a turn-around in operational principle: the turbine inlet temperature should be lowered while the compressor outlet temperatures should be increased. These requirements go against the general trends for compressors and turbines, since in compression losses tend to increase at higher temperatures and gas management becomes more challenging, while in gas turbines higher inlet temperatures yields higher power extraction (gas turbine inlet temperatures above 1200 K are now common). Furthermore, the sliding pressure is another limiting factor in ACAES, resulting in lower system efficiency even with idealised components[1]. While this is also an issue in DCAES, the system is less affected due to the larger number of compression stages, allowing for smaller individual pressure ratio variation, and fixed turbine inlet temperatures.

This highlights the challenge that researchers face in designing compressors and turbines for ACAES. For compressors, highly adiabatic, high pressure-ratio compressors are required. The predicted long-duration, high-power role for ACAES perhaps favours axial machines, but aerodynamic limits make simultaneous high mass-flow and high pressure-ratio machines very challenging to design, typically requiring transonic flow to provide the necessary mass flow and compression. It can be noted that while some manufacturers do display compressor models able to reach high pressure ratios and flow rates, this does not mean that there is a "on-stock" model suitable for ACAES. Rather, it indicates a general design family that may be adapted, optimised and designed specifically to an application. For the expansion, ACAES research may be able to learn from the development of more efficient Lower Temperature Turbines (LTT) for other applications, particularly geothermal power production, Pumped Thermal

Energy Storage (PTES) and low grade heat-to-power and Organic Rankine Cycle (ORC) systems. As of the present time, LTT development specific to ACAES has been limited. Adapting steam turbines to ACAES applications is another possibility proposed in literature, as these generally operate at similar pressure level but significantly lower temperatures than their gas equivalent[5].

Heat exchangers

The compression-expansion coupling in ACAES also leads to major design challenges in the HEX. Equation 2 defines HEX effectiveness, ε — the ratio of actual heat transfer rate $\dot{Q}$ against the theoretical maximum $\dot{Q}^{MAX}$ — as a result of the generalised energy balance in a HEX (neglecting thermal losses to the environment).

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}^{MAX}} = \frac{C_h\left(T_{h,i}-T_{h,o}\right)}{C^{MIN}\left(T_{h,i}-T_{c,i}\right)} = \frac{C_c\left(T_{c,o}-T_{c,i}\right)}{C^{MIN}\left(T_{h,i}-T_{c,i}\right)} \tag{2}$$

Here, $C^{MIN} = \mathrm{MIN}[\dot{m}_c c_c, \dot{m}_h c_h]$ is the minimum heat capacity flowrate (the product of the fluid heat capacity and mass flow), $\dot{m}_c$ and $\dot{m}_h$ are the mass flow rates of the cold and hot fluids respectively and c_c and c_h are the respective heat capacities. $T_{c,i}$ and $T_{h,i}$ are the cold and hot fluid inlet temperatures while $T_{c,o}$ and $T_{h,o}$ are the outlet temperatures.

It is clear from Equation 2 that the TES can only achieve a temperature close to the compressor outlet temperature for a balanced HEX (*i.e.* $\dot{m}_c c_c = \dot{m}_h c_h$) with high effectiveness. However, in classical design methodologies high HEX effectiveness $\varepsilon > 0.9$ is achieved using severely unbalanced conditions ($C^{MIN}/C^{MAX} \ll 1$). For instance, a compressor aftercooler utilising water coolant may reach $\varepsilon = 0.9$ with moderate surface area, however normal coolant mass flow rates are around five times greater than the balanced condition, leading to a small coolant temperature change (20 K, in comparison to 100 K for the air). This imbalance allows for equipment compactness, with typical core volumes $\approx 0.5m^3$, reducing pumping losses and saving space. In contrast, if a 95% balanced flow condition is imposed, the HEX volume would increase by six-fold and it would still only be capable of reaching effectiveness 0.75—0.8. In this case, however, reversibility is significantly superior[7]. The first (unbalanced) HEX example is suitable for a DCAES plant whereas for ACAES the compression-expansion coupling requires the second approach. The primary design challenge for HEX in ACAES is finding the appropriate trade-off between effectiveness, reversibility and cost.

Air and heat storage

ACAES stores exergy both in *(i)* the compressed air in the HP store and (*ii*) thermal exergy in the TES. In the former, the pressure limits and volume define the energy storage capacity. The primary design criteria of thermo-mechanical integrity and air-tightness over the system lifetime are also shared with conventional DCAES. These are well documented in technical literature for both above-ground and underground storage. However in ACAES, the storage temperature behaviour must be properly integrated into the design process (*e.g.*,[11] reports the importance of the storage temperature in the system performance and in[1], losses associated with this temperature fluctuation are analytically addressed). Recent research has also conceptually outlined the thermodynamic benefits of isobaric air storage, however, the variable-volume HP air storage adds complexity and future research should explore this trade-off.

The TES is a critical part of the ACAES system and must be seamlessly integrated with the HEX. While in the two conventional DCAES plants currently in operation over half the energy generated is due to heat from combustion, in ACAES there is no external energy input. The TES must store and maintain the heat extracted after compression until it is reintroduced prior to expansion. Thermal storage is also used in a huge range of industrial and domestic applications and TES is a vast and parallel research field. Specific challenges to ACAES relate to the high temperatures (and potentially high pressures) involved and the long-duration and large capacity requirements, meaning the TES must be simultaneously mechanically strong, efficient and cheap. Moreover, the variable compressor discharge temperature (due to increasing pressure in isochoric storage) imposes the challenge of avoiding internal temperature mixing and the consequent losses. Aspects discussed in this sections are summarised in Fig. 2.

Current state of ACAES technology

Theoretical and numerical studies

Numerous examples of theoretical and simulation studies on ACAES can be found in technical literature, with predicted round-trip typically in the range 50—75%, *i.e.*[8,2]. Within these, the system individual subcomponents (*i.e.*, compressors, heat exchangers, turbines) are generally based on "black-box" thermodynamic models, generating performance indicators from a given number of inputs without considering the internal component detailing. While this approach is useful for conceptual studies and describing the general operating principles, it omits important equipment technical limitations and/or design challenges. This can result in unrealistic predictions of operating conditions and performance indicators. Papers which specify dynamic component performances also exist[9], however these are still based on generalised models rather than specific custom-designed components.

In a recent paper[1], we derive idealised performance limits for isochoric ACAES systems, providing both a reference for finding the limiting performance and also specifying the target component operation to achieve this. The highlighted component operation illustrates that typical assumptions regarding component performances used in many papers can be misleading, as they are based on examples from different applications with unique design requirements. While some recent work does consider individual components designed and optimised specifically for ACAES, there remains a lack of publications covering heavily-coupled components with consideration of internal design across the whole system. This is likely the reason for the disparity between simulated predictions and experimental measured performance at the current time.

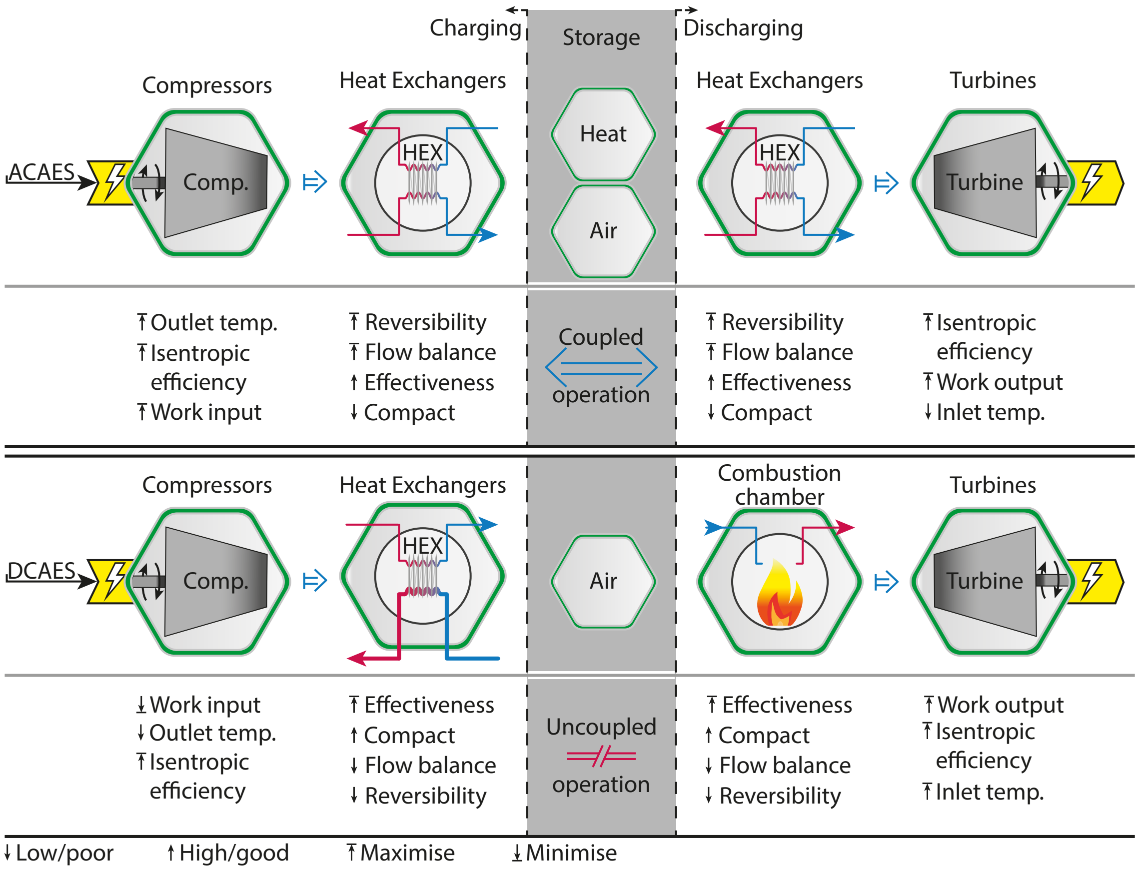


Figure 2: Illustrating the key differences between ACAES and DCAES, and the subsequent effects on the constituent components. Note the charging/discharging coupling in ACAES, whereas in DCAES these processes are optimised independently. Similarly to Fig. 1, DCAES heat exchanger flow imbalance is represented by different line thickness.

Experimental investigation

Most experimental studies are limited to studying ACAES components rather than conducting full plant analysis. The TICC-500 pilot plant is a rare example of a published, comprehensive experimental study. The plant achieved a measured Round-Trip Efficiency (RTE) of 22.6%, lower than its design efficiency of 41%[11]. This performance decrease was attributed to the transient HP store pressure on the turbomachinery and TES, as well as lower than anticipated HEX effectiveness. Nevertheless, the work provides a strong foundation for future full-system prototypes. In 2016, ALACAES published results for a pilot plant located in Switzerland, reporting an estimated round-trip efficiency between 63—74%[4]. However, this efficiency was estimated neglecting leakages, simulating an adiabatic compressor (with constant isentropic efficiency equal to 85%) and introducing a 90% efficient turbine, since the compressor used was unsuitable for ACAES and no turbine was included. Disregarding the efficiency estimate, the main aim was investigating the air-tightness of the cavern and the performance of a packed-bed rock-filled TES. Both of these components performed satisfactorily at the reduced operational pressures. The vast majority of other experimental academic studies have undertaken small-scale tests on single components, typically at reduced pressures yielding results that are difficult to scale up. Furthermore, misleading performance metrics are often presented, such as peak-instantaneous efficiency (defined as a ratio of specific discharging power to specific charging power within a very narrow pressure range) rather than measured RTE (the ratio of total generated to consumed energy).

A significant proportion of ACAES development has also occurred in commercial settings, often accompanied by optimistic, but opaque, performance claims. For example, the part-EU-funded project ADELE, originally intending to produce the world's first large-scale ACAES plant, claimed to have proven that 70% efficiency is technically feasible[12], however, no plant was ever built and design details were not published. The Canadian company Hydrostor operates two pilot plants and has recently announced it received substantive grants for R&D as well as two new plants. Performance metrics are not generally available, although information presented in[3] suggests that the first plant (which is a proof-of-concept) has very low-efficiency. Notably, Hydrostor employ an isobaric ACAES design to mitigate the variable pressure in the HP store. Other well-funded commercial ventures with previously optimistic performance claims, such as Lightsail and SustainX, have failed to produce any pilot plant and have since been discontinued. Two notable plants are also mentioned in the extensive review by Wang et al.[10], claiming round trip efficiencies of 55% and 60% for the 1.5 MW and 10 MW plants respectively, however the supporting references provided are defunct. Recent publications, major projects and technology milestones are summarised in Figure 3.

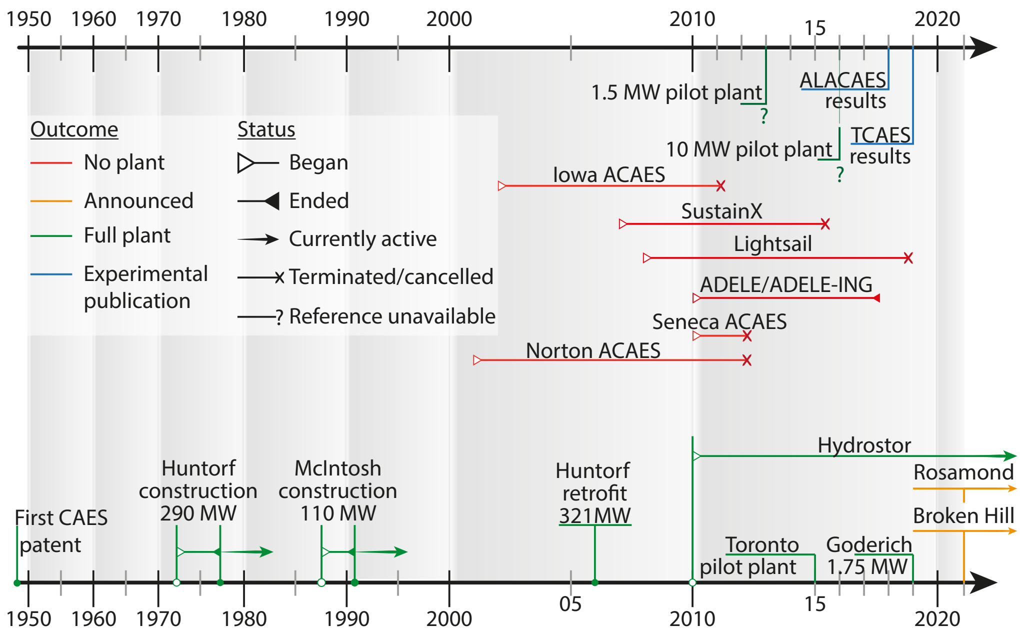
Technology Readiness Level

Despite the fact that the Technology Readiness Level (TRL) of DCAES is high, with two large-scale plants (we suggest TRL 8 due to lack of widespread adoption), the TRL of ACAES is low. At the current time, the TICC-500 experiment[11] is the sole example of a full prototype plant published in mainstream technical literature. Furthermore, several commercial ventures developing ACAES have failed despite very significant funding, leaving little in the way of documentation or lessons learned. Hence we suggest TRL 3-4 is appropriate. This puts ACAES at a similar TRL as Pumped Thermal Energy Storage (PTES), another unproven but promising energy storage option and arguably below Liquid Air Energy Storage (LAES), which has a demonstrator facility in the UK as well as a pilot plant at the University of Birmingham, UK. At first sight this may be surprising, since ACAES has a conceptually simpler layout than PTES and LAES and is conceptually similar to DCAES, however as discussed there are still major design challenges for a majority of components. As shown in Fig. 3a, recent Hydrostor announcements of two new plants could improve the TRL of ACAES, however this is dependent on their success or widespread dissemination of results and lessons learned. Figure 3b shows a comparison of the TRL across different technologies at the time of writing.

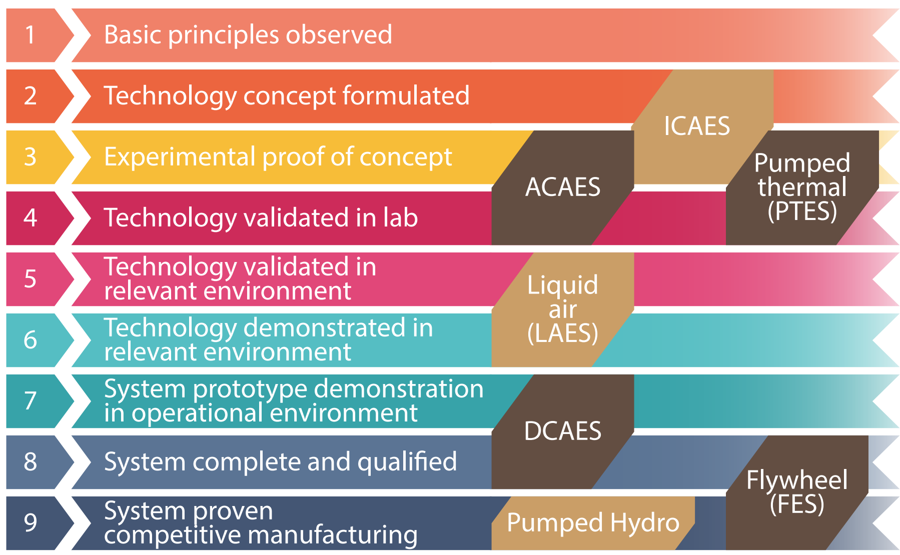
Future development

Although conceptually well-established, ACAES remains unproven at a viable performance level. However, there are a number of promising avenues for future research to explore. In particular, the adoption of a whole-system design approach, relating component performances to feasible designs (i.e. without black box or generic component models) across the system, would be hugely valuable. These studies may then accurately reflect the achievable performance in pilot projects, which could subsequently be optimised for both performance and viability. In terms of component development, simultaneous development of higher outlet temperature compressors and lower inlet temperature turbines is vital. This includes theoretical description, analytical performance prediction, CFD and actual tests at different scales. Isobaric storage is also an interesting avenue to explore due to the potential to mitigate challenges associated with the transient pressure. Experimental research should focus on the design and control of the constituent components under real operational conditions. Full-plant prototypes in academic settings would hugely advance the state of knowledge surrounding ACAES. This research would be symbiotic with the development of other promising thermo-mechanical energy storage concepts, such as PTES, where the development and control of highly-reversible turbo-machinery is also a major challenge.

Overall, given its potential as a clean and cost-effective electricity storage method for the future, we strongly recommend that funding bodies support further research in ACAES. While the private sector is arguably better at raising significant capital, the short time horizons for which investors want return-on-investment combined with low TRL makes ACAES a difficult option. Furthermore, recent failures in the commercial sector have thus far yielded little in the way of lessons learned and contributed to uncertainty in the technology. Therefore, large-scale research in academic settings with a commitment to transparent documentation would be most worthwhile and unverifiable performance claims should not influence funding awards. Finally, future academic articles should not blindly repeat performance claims without due scrutiny. If ACAES is to finally fulfil a protagonist role in the future energy market, research must first tackle key outstanding challenges which have been, so far, mainly overlooked.



(a) Timeline of recent and relevant CAES projects, publications and operating facilities. Adapted from[1].



(b) Technology Readiness Level (TRL) score of thermo-mechanical energy storage systems.

Figure 3: Composite figure depicting **(a)** a timeline with relevant CAES projects and **(b)** TRL comparison of different thermo-mechanical storage technologies.

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Declaration of Interests

The authors declare no competing interests.