TURBINES USED IN COMPRESSED AIR ENERGY STORAGE

Literature review

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Energy Technology, Bachelor's thesis

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Examiner(s): Associate professor, Aki Grönman

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ABSTRACT

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Keywords: Turbine types, storage size, compressed air energy storage(CAES) system.

Compressed air energy storage (CAES) systems play a critical part in the efficient storage and utilisation of renewable energy. This study provides insights into the application of different turbine types in three CAES sub-technologies (D-CAES, A-CAES and UW-CAES) and their relationship with storage size. A comprehensive literature review and analysis reveals the wide range of applications of axial turbine, radial turbine, and quasi-turbine in different CAES systems. The correlation between storage size and turbine selection is also explored, highlighting the preference for axial turbines in large systems and radial turbines in small scale and micro CAES systems. However, there are some limitations to this study, mainly in terms of the lack of in-depth analyses of turbine performance under real operating conditions, especially when dealing with varying loads and unsteady pressure conditions. In addition, due to the limited resources in the literature, the medium-sized CAES systems are not discussed. Future research should focus on addressing these limitations to enhance the application and optimisation of turbines in CAES systems. In conclusion, intensive research on CAES technology and its key components is essential to achieve a more sustainable and efficient energy system in the future.

ABBREVIATIONS

IEA	International Energy Agency
CAES	Compressed Air Energy Storage
D-CAES	Diabetic Compressed Air Energy Storage
A-CAES	Adiabatic Compressed Air Energy Storage
I-CAES	Isothermal Compressed Air Energy Storage
LTA-CAES	Low Temperature Adiabatic Compressed Air Energy Storage
UW-CAES	Underwater Compressed Air Energy Storage
CH-CAES	Combined Heat And Compressed Air Energy Storage
TES	Thermal Energy Storage
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
HPT	High Pressure Turbine
LPT	Low Pressure Turbine
GT	Gas Turbine
ST	Steam Turbine
LTT	Low Temperature Turbine
ORC	Organic Rankine Cycle
PHS	Pumped Hydro Storage
LS	Large-Scale
SS	Small-Scale
MS	Micro-Scale

BM	Battery Mode
LM	Low Pressure Expansion Mode
HM	High Pressure Expansion Mode
LHM	Dual Expander Mode

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1 Introduction

These years, electricity demand has been increasing and according to the International Energy Agency (IEA), total world final consumption of electricity reaches 22,848 TWh in 2019, growing by 1.7 % in 2018 (IEA, 2021). Rising prices of fossil fuels and increasing global warming trends are making conventional power generation lose its edge, while clean energy generation will have a bigger market. Utilization of renewable energy sources to the current market is increasing, and the share of variable renewables in renewable energy is not to be underestimated. IEA (2023) statistics shows that the proportion of electricity generated from renewables is estimated to increase by about 13% in the next 5 years.

Nevertheless, the built-in variability of intermittency in renewable energy sources can cause generator output fluctuations. Finding a solution to intermittency is crucial. Energy storage technology is a reliable solution for this issue. It is possible to store the excess power generated during the troughs of electricity consumption and release it during the peaks of electricity consumption to meet consumers demand. Additionally, energy storage, which enables intermittent energy sources to provide dispatchable services to the grid, could be an important feature of a decarbonized power sector.

Storage batteries are usually categorized as large-scale or small-scale, with large batteries being used primarily to balance power demand across the grid. However, the geographic requirements of pumped storage systems, as well as the high cost and/or low round-trip conversion efficiency of other alternative storage technologies (capacitors, flywheels, and magnetic fields) limit their use for utility-scale electricity storage (Denholm, Kulcinski, 2004). In contrast, the lower cost, high reliability, long lifetime and flexibility of CAES technology make it a focus of current and future energy research.

1.1 Objective of the thesis and research questions

Compressed air energy storage (CAES), an energy storage system, consists of three key components: compressor, storage space and expander. During charging phase, the motor drives the compressor to pressurise the air using electricity. During the exhaust phase, the pressurized air turns blades in expander that drives a co-axial generator to convert mechanical work into electricity. Since a CAES system is an "power-to-power" device, the energy converting efficiency is a key factor in measuring the performance of the system. The operating characteristics of the expander identify the power converting efficiency and the amount of power generated during the discharge period. Its performance greatly affects the round-trip conversion efficiency of the whole system. Expanders are categorised into volumetric types such as reciprocating expanders, screws and dynamic types for example axial and radial turbines (He, Wang, 2018). The objective of this thesis is to study the application of turbines in CAES.

Research questions:

- *What kind of turbines are used in different sub-technologies (A-CAES, UW-CAES, D-CAES…)?*
- *How much does the storage size affect turbine type?*

Despite the abundance of relevant literature, there are fewer studies on the relationship between different CAES systems, energy storage sizes and turbine types. This thesis provides a comprehensive overview of turbine types application in three CAES technologies and the relationship between turbine and energy storage sizing. And the aim is to fill this research gap and provide a comprehensive overview for future reference.

1.2 Research method and structure

This thesis is done in a literature review approach. When searching for literature that needs to be discussed, keywords firstly need to be extracted from the research question, such as turbine type, storage capacity, CAES technology, etc. Then the keywords is searched in Google scholar, LUT primo, websites and other databases to find the entries to read the literature. In the process of literature reading, it is possible to discover the application of turbines in different compressed air energy storage systems, research and future developments.

The structure of this thesis can be briefly summarized as follows: the second part focuses on the working principle of the three different CAES technologies. The third part is divided into two sub-parts according to the research question. The first part is dedicated to an overview of the types of turbines used in the different compressed air sub-technologies. The second part explains the relationship between CAES storage size and turbine type. The fourth part summarizes the results of the two problems in the third part and discusses the shortcomings for this thesis. The fifth part is the conclusion, which summarizes the information in the whole thesis on the use of turbines in CAES systems and future developments.

2 The work principle for CAES system

Through literature review, the author found several mature technologies used in compressed air energy storage (CAES) and some CAES types currently being researched, as illustrated in Figure 1. They are diabatic CAES (D-CAES), adiabatic CAES (A-CAES), isothermal CAES (I-CAES), under water CAES (UW-CAES). For A-CAES, it can be divided into two categories: with and without thermal energy storage (TES) equipment. Meanwhile, Literature reading revealed that expanders need to be able to withstand moisture and two-phase flow during I-CAES expansion, where there is a potential blade corrosion problem. Therefore, turbines are not suitable for I-CAES systems (He, Wang, 2018). And it is out of the scope of this thesis. The purpose of this part is to introduce the working principle of D-CAES, A-CAES and UW-CAES compressed air energy storage power plants.

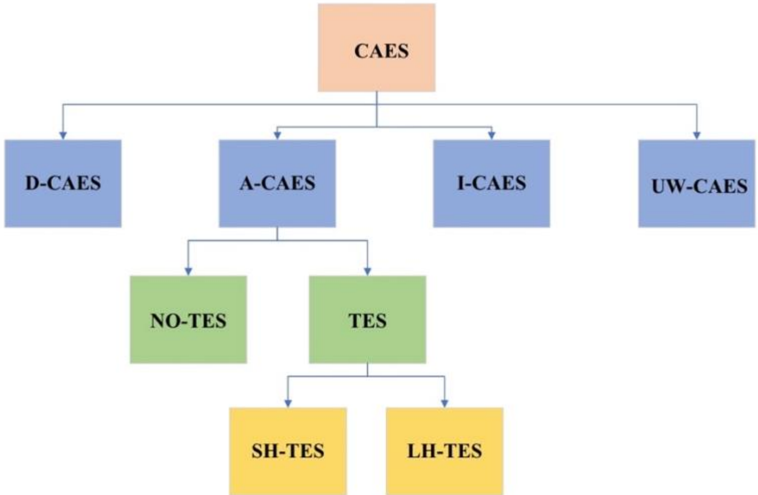


Figure 1. classification of compressed air energy storage configurations according to (Borri et al., 2022)

2.1 D-CAES

D-CAES is the concept underlying the original research into compressed air energy storage. There are two commercially available compressed air energy storage systems, Huntorf (310MW) in Germany and McIntosh (110MW) in the USA, which use D-CAES technology (Chen et al., 2020). The McIntosh plant works as shown in Figure 2. The compressor used in the system is multi-stage, and the intercooler in the compression process removes the heat generated during the compression of the air. This operation ensures that the temperature of the compressed air in the storage space does not become too high, thereby increasing the storage density. When discharged, the compressed air needs to reach the same temperature as before in the expansion process to ensure that the turbine operates properly, so additional fuel combustion is used to generate heat to compensate the heat lost in the intercooler.

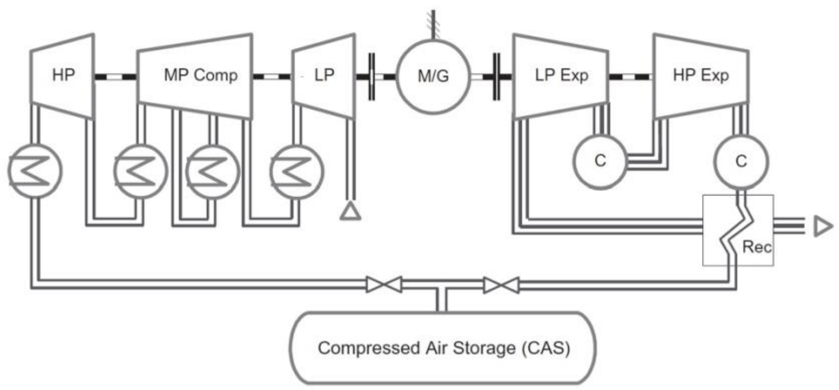
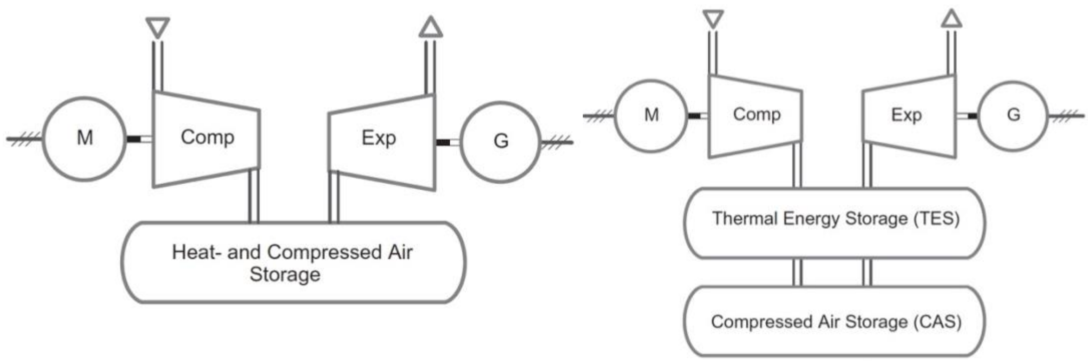


Figure 2. Simplified process scheme of the McIntosh plant (Budt et al., 2016)

The McIntosh plant was built on the basis of the Huntorf plant. The major difference between the two plants is the utilization of waste heat from the exhaust gases. In McIntosh plant, waste heat after the low-pressure (LP) turbine is used in the recuperator to preheat the compressed air going into the high-pressure (HP) turbine. This strategy reduces the fuel consumption to some extent (about 25%). (Budt et al., 2016)

2.2 A-CAES

The obvious difference between A-CAES and D-CAES is the saving of the heat generated during the compression phase. The easiest way to utilize the temperature-dependent heat generated in compression is to store both the heat and the compressed air in a storage space (A-CAES without TES). This method allows higher temperatures to be reached at lower pressures. However, this also means that the technology will be limited to lower compression pressures because of the storage temperature, which will also result in lower energy density. (Budt et al., 2016) This technique is currently only realized in laboratory applications.



(a) A-CAES without TES (b) A-CAES with TES

Figure 3. Basic concepts of A-CAES. (Budt et al., 2016)

In contrast, A-CAES with TES can store heat and compressed air separately, and the cooled pressurized air can be stored in the storage space used in D-CAES, and the compressed air has an even higher pressure and greater energy density. (Budt et al., 2016) The heat stored in the TES can be fed back to the air through a heat exchanger before the turbine is operated, which supplies heat instead of fuel combustion. The system has a coupled charge/discharge due to the participation of TES, whereas in D-CAES these processes are optimized independently (Barbour & Pottie, 2021). In contrast to D-CAES, A-CAES is more environmentally friendly because it does not have to burn additional fuel.

2.3 UW-CAES

Although salt caverns and most pre-existing spaces meet the criteria for compressed air storage, capital costs and reasonable geological structures limit the widespread use of both of these CAES. At the same time, in order to be more useful for storing wind power, the use of storage space needs to be more flexible and cheaper. Researchers have found that UW-CAES can be more useful in storing wind power (Cheung, Carriveau & Ting, 2012). And land-based UW-CAES systems and UW-CAES systems located on offshore barges are two configurations that could be used. (Cheung, Carriveau & Ting, 2014).

The workflow diagram of UW-CAES is illustrated by Figure 4. It works similarly to A-CAES. But the principle of using storage space is different. A-CAES is stored using isovolumetric storage. The disadvantage of storing compressed air in this condition is that the electrical output of the turbine decreases as the compressed air pressure gets lower. This can be avoided with underwater storage, which allows the isobaric storage of compressed air by means of the hydrostatic properties of water, and maintains a state of constant pressure when the air is depleted. (Cacciali, Battisti & Occello, 2023).

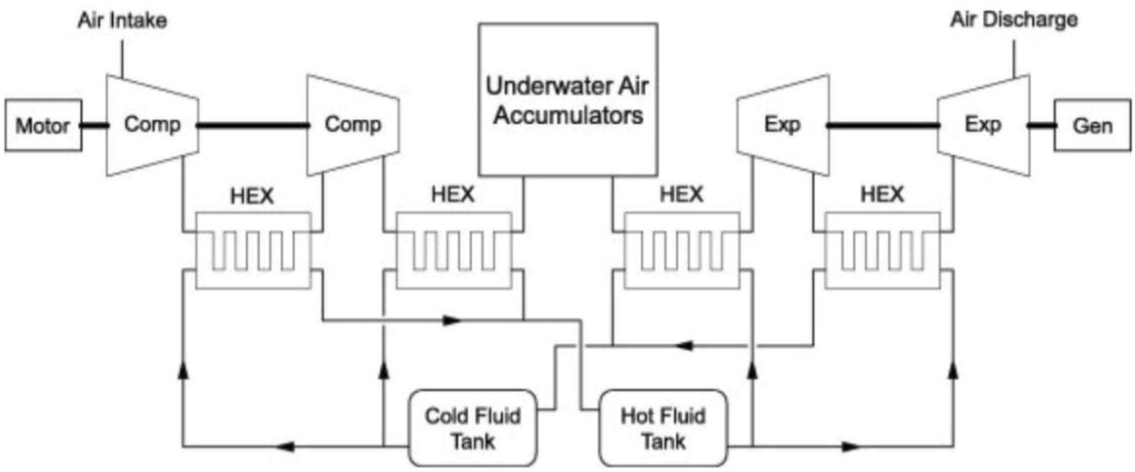


Figure 4. UW-CAES process diagram(Cheung, Carriveau & Ting, 2014)

3 Turbines used in CAES system

CAES technology has similarities with gas turbine (GT) technology as they both exploit the theoretical basis of the Brayton cycle. In a conventional gas turbine power station, 2/3 of the power output is supplied to the air compressor. With CAES, the output of the turbine is used exclusively for power generation. By comparison, since the compression and expansion processes in CAES are separate, the output efficiency of the whole system is increased (Dincer, Rosen, 2021). It can be seen that the turbine is a key element in the CAES and also is a crucial component in determining the rated power output and overall energy conversion efficiency.

The operating principle of the turbine is based on the conversion of fluid kinetic energy to mechanical energy. In a CAES system, as high-pressure air passes through the turbine, the kinetic energy of the fluid forces the blades within the turbine to push or pull, causing the turbine shaft to rotate. This rotation is transferred through a mechanical transmission to a device attached to the turbine, converting the mechanical energy into the required work. As the fluid flows through, its kinetic energy decreases and is eventually discharged from the turbine's outlet, completing the energy conversion process.

With many types of compressed air energy storage, each technology has different gas operating conditions, so the selection of the appropriate turbine type needs to be customized to ensure that high performance of the system can be achieved (He, Wang, 2018). In the following, the turbine types in different compressed air energy storage technologies will be summarized to understand the current research results and the relationship between the selection of turbine type and energy storage capacity.

3.1 Turbine types used in different sub-technologies

Since the introduction of compressed air energy storage technology in the 19th century, turbines have been widely researched and applied as key components. The types of turbines can be classified by different classification ways including radial turbines, axial turbines (shown in Figure. 5, 6), and mixed-flow turbines. Radial turbines have blades centered on the center of a circle and the fluid passes in a radial direction. Axial turbines have blades parallel to the axis and the fluid passes in the direction of the axis. In contrast, the mixed-flow turbine combines both radial and axial characteristics at the rotor inlet. (He, Wang, 2018)

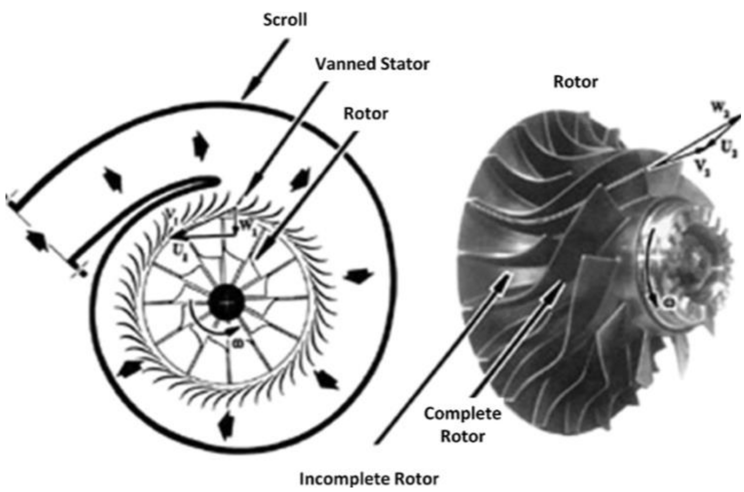


Figure 5. An illustrated radial turbine. (He, Wang, 2018)

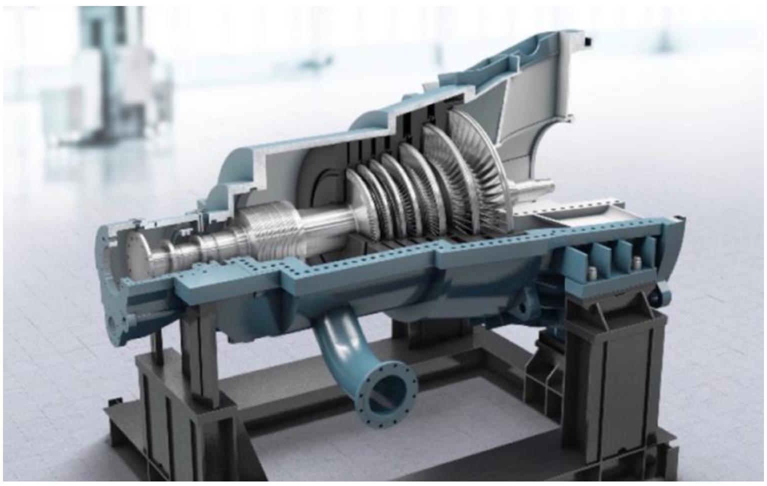


Figure 6. Axial steam turbine from Siemens. (He, Wang, 2018)

Apart from the turbines mentioned above used in CAES systems, turbines based on gas turbines are often used in such systems due to their high power density and fast response time. In CAES systems where air is the primary operating medium, turbines derived from steam turbines (ST) can be used in CAES systems to meet certain temperature and pressure requirements. Depending on the location and function of the turbine in the system, it can be further categorized into high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbines, which are responsible for handling air in different pressure ranges for energy conversion and power generation processes, respectively. The application of turbines in different types of CAES systems is discussed below.

3.1.1 D-CAES

The efficiency of traditional D-CAES is mainly affected by the Carnot efficiency of the heat engine, whose maximum operating temperature determines the efficiency level of the system (Rabi, Radulovic & Buick, 2023). Typically, the hotter the turbine inlet temperature, the more power is produced at the exhaust. (Salvini, Giovannelli & Farhat, 2022).

In the Huntorf plant, the expansion process of the turbine work is carried out in two stages, high and low pressure. The inlet temperatures and pressures of the HP turbine and LT turbine are normally kept at around 550 °C, 42 bar and 825 °C, 11 bar respectively (Rabi, Radulovic & Buick, 2023). GT technology allows for high turbine inlet temperatures and relatively low inlet pressures, while ST technology is the opposite. The range of pressure values at the inlet of the HP turbine (45-76 bar) is comparable to those of an industrial steam turbine, and therefore Huntorf's high pressure turbine is built on the basis of a small medium-sized steam turbine model (Giovannelli, Tamasi & Salvini, 2020). The range of typical gas turbine is about 11 bar, then the typical turbine derived from gas turbine is used as a LP turbine in this system. (Compressed Air Energy Storage, 2024).

Zhao et al. (2016) designed a model for the application of axial flow turbine in D-CAES system and discussed the round trip cycle of the whole system. Two axial turbines arranged in series are used in the experiments are high pressure and low pressure axial turbines respectively. Work was carried out in two emission modes (constant turbine inlet pressure pattern and variable turbine inlet pressure pattern). They finally discovered that the round trip efficiency of the system was high in the case of variable turbine inlet pressure type.

Gambelli et al. (2019) used a quasi-turbine in evaluating the performance of a residential small-size D-CAES, which is a Model QT.6LSC Steam. and it is a volumetric unidirectional-flow. The internal structure of the turbine is presented in Figure 7, where the rotor is driven by pressure, and it has a four-bladed structure with continuously variable torque. In the space between the rotor blades and the stator shell, the compression and expansion processes take place sequentially. With each revolution, these four blades complete two stages of compression. When used as a turbine, eight expansion stages are generated per revolution.

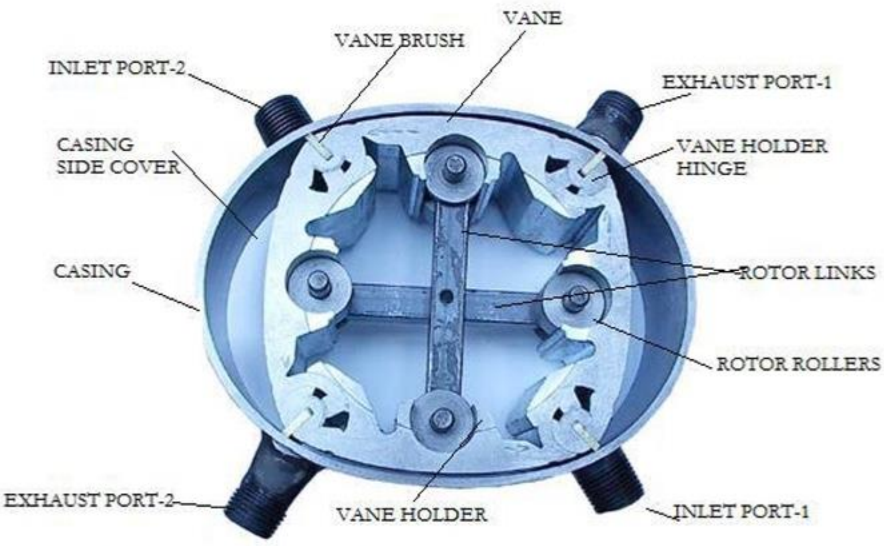


Figure 7. Schematic of the quasi-turbine. (Gambelli et al.,2019)

3.1.2 A-CAES

A typical final pressure for A-CAES is at least 60 bar (Budt et al., 2016). By comparing the typical pressure values with those of D-CAES systems, it can be seen that the energy density of the storage space of A-CAES systems is higher. By economic considerations, researchers are more interested in A-CAES.

Tola et al. (2017) modelled a 100 MW output power CAES system and a turbine air mass flow rate of about 170 kg/s. In this system, they designed to use an expansion train of HP radial turbine and LP axial turbine for emission generation. Due to the advantages of high expansion pressure ratio, high reliability, low cost, and small size of a single-stage radial turbine, it was chosen as the high-pressure turbine (HPT) in this experiment. For the LP part, an axial flow turbine was selected because it has an expansion pressure ratio that greatly exceeds that of the HPT (slightly less than 30), which allows for better stage coupling, although the stage pressure is lower.

A multi-stage radial turbine, comprising several single-stage radial turbines installed in separate shells connected in series, is employed. Moreover, heat exchangers are integrated between the stages to preheat the compressed air. (Tong, Cheng & Tong, 2019). The design can effectively utilise kinetic energy and improve the energy conversion efficiency. Besides, the flexible and stable characteristics of the turbines are also preferred by the researchers.

The 500 kW A-CAES pilot plant "TICC-500," developed by the Key Laboratory of Cryogenics, TIPC, CAS and Tsinghua University, employs a three-stage radial turbine for air expansion. This choice is appropriate considering the small scale of the electricity plant and the high flow rate through the turbine. Likewise, the 1.5 MW pilot plant utilizes a four-stage radial turbine to power a simultaneous generator (Li et al., 2020).

Additionally, high temperature and pressure environments are possible in A-CAES system, and handling compressed air in such environments can lead to material tolerance issues, increased heat loss, reduced system efficiency, and increased safety risks. These issues could result in system instability, reduced energy efficiency, and safety hazards. To avoid these challenges, Wolf and Budt (2014) introduced a low-temperature A-CAES (LTA-CAES) technology using a multi-stage radial compressor and turbine (where the thermal TES is at 95-200 °C), with singles stage rotating at different speeds in order to intermediate cool and reheat the air stream. Also in the study by Luo et al. (2016), the A-CAES system with low-temperature TES uses turbines derived from gas turbine and these turbines are grouped into a turbine unit with series connection (1 high pressure turbine and 3 low pressure turbines).

Besides the typical A-CAES system, Zhao et al (2023) developed a combined heat and compressed air energy storage (CH-CAES). In the subsystem of this system there are two parts, the A-CAES part and the electric heater. The high pressure turbine (HPT) and low pressure turbine (LPT) employed in the expansion train used in A-CAES are of axial turbine type.

It is evident from the examples above that there are lessons to be learnt from the use of low-temperature turbines (LTTs) in other areas for application to A-CAES systems, such as geothermal power generation, pumped hydro storage (PHS), and low-grade combined heat and power Organic Rankine Cycle (ORC) systems. Progress has been made in these areas in terms of the reliability of LTT use. But up to now, LTT development specifically for ACAES has been limited (Barbour, Pottie, 2021). This suggests that more research and development are still required to overcome these limitations in order to further optimize and develop ACAES systems.

3.1.3 UW-CAES

The UW-CAES system is shown in Figure 8, in which an offshore wind turbine produces electricity to drive a motor that turns a compressor to compress air and then the compressed air is stored underwater. The compressed air is transferred through a pipeline to an onshore facility where the compressed air is expanded through an axial flow turbine to release energy to turn a generator to produce electricity.

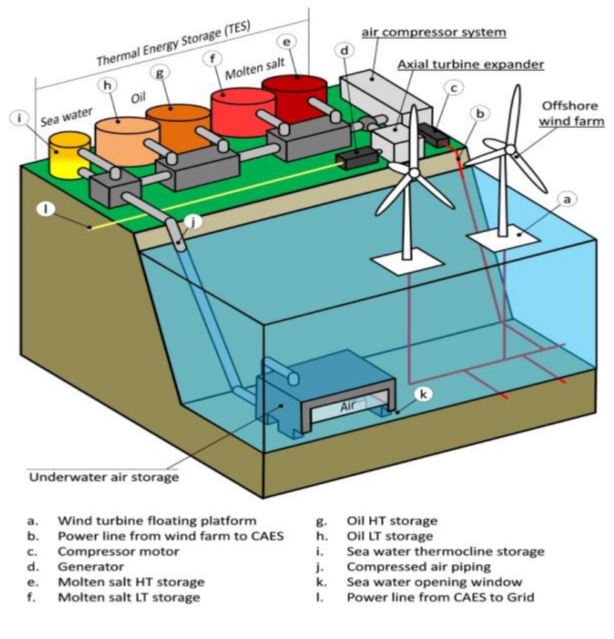


Figure 8. Conceptual view of the UW-CAES system (HIRN, BELLOLI, 2017)

Witanowski, Klonowicz and Lampart (2016) performed optimisation calculations for a radial turbine (270 kW) used in the UW-CAES system using Matlab and the NIST Refprop library. The optimised turbine as shown in Figure 9 has 20 stator vanes and 11 rotor blades with a rotor wheel diameter of 194 mm.

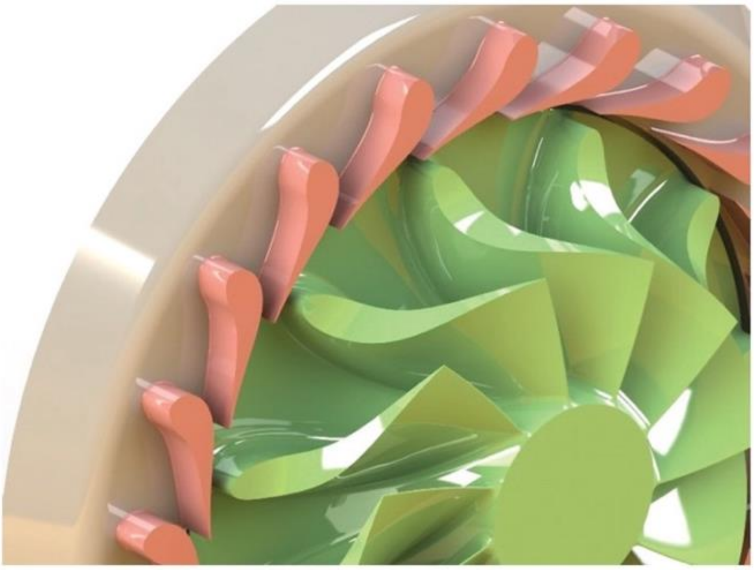


Figure 9. 3D model of optimized turbine using in UWCAES system (Witanowski, Klonowicz and Lampart 2016)

Wang et al. (2016) examined a 2-stage UW-CAES system so that to enhance the efficiency of UW-CAES. In this system there are two groups of accumulators, low pressure and high pressure, and there are two groups of turbines, LPT and HPT.

During discharge, the CAES system operates in four modes: Battery Mode (BM), Low Pressure Expansion Mode (LM), High Pressure Expansion Mode (HM), and Dual Expander Mode (LHM). In BM, the system relies solely on the battery when demand is below the low-pressure turbine's rated power. When demand is between the low and high-pressure turbine's ratings, LM activates, utilizing the low-pressure turbine at its rated power while supplementing with battery power. HM engages when demand falls between the high-pressure turbine's rating and the sum of both turbines' ratings, with the high-pressure turbine operating at its rated power and extra power sourced from the battery. Finally, in LHM, both turbines operate simultaneously if demand exceeds the sum of their ratings, with additional battery power. (Wang et al., 2016)

3.2 The relationship between CAES storage size and turbine types

CAES storage sizes can be categorised by storage capacity. These are large CAES with power greater than 100 MW, micro CAES with tens of kilowatts, and small CAES that are situated in between (He, Wang, 2018). Large CAES systems are more suitable for large grids to meet long-period energy storage requirements and play a role in balancing the load on the grid, thereby reducing reliance on conventional power plants and improving grid reliability and stability. In contrast, small, and micro-scale systems have the advantages of low self-discharge, long lifetime and low maintenance costs (He, Wang, 2018). In particular, 1-10 MW CAES systems have demonstrated their potential to be efficient and economical for off-grid and self-consumption applications (Giovannelli, Tamasi & Salvini, 2020). Different storage sizes have different power outputs and different turbines are used. Turbine types are discussed below in terms of large-scale, small-scale and micro-scale .

3.2.1 Large-scale CAES system (LS-CAES)

Large-scale CAES systems are now in commercial use and are more mature than small or micro CAES technologies. In general, high-pressure and low-pressure turbine units and turbines derived from gas turbines and steam turbines can be used in LS-CAES system.

Similarly, large-scale A-CAES systems with HP radial turbine and LP axial turbine expansion units can also improve the energy conversion rate. The researchers concluded that axial flow turbine is the preferred type for power plants with power greater than or equal to 10 MW. It is known for its high speed of operation. Although axial turbines have lower pressure ratios than single-stage radial devices, its capacity is quite large (He, Wang, 2018). By evaluating the actual operation of a MW-scale CAES system, the researchers also analyzed the aero-dynamic performance and flow characteristics of an axial turbine operating in a CAES (Guan et al., 2023). Typically, either axial-type or axial/radial-type assemblies can deliver the massive capacity needed to develop grid-scale CAES facilities. However, further research is needed for systems with bulk CAES for axial-type components to ensure their effectiveness and reliability for large-scale capacity development (Zhao et al., 2016).

3.2.2 Small-scale CAES system (SS-CAES)

Although large CAES systems play an important role in meeting the energy storage requirements of large grids, small CAES systems are gaining attention as an alternative as the energy sector transforms and there is a continuous demand for flexible, distributed energy solutions. (Khaljani et al., 2021) The appearance of distributed generation technologies and systems has provided a new scope for small CAES systems.

The radial turbine has great potential in small CAES systems. It is typically designed for higher pressure ratios and lower flow rates than axial turbines commonly used in large CAES, with power outputs ranging from a few kilowatts to several megawatts. (He, Wang, 2018).The distributed generation small compressed air radial turbine studied by Rahbar et al. (2017) can overcome centralised power generation. He applied 3D CFD modelling and optimised the turbine blade profiles of stator and rotor for minimum losses and maximum power output in his experiments. In addition to this, Castellani et al (2018) developed photovoltaic integrated small compressed air energy storage system in addressing building constraints. The device can be installed in the unused basement of a building without occupying public space. The expansion stage in this system uses quasi-turbine.

Moreover, in real-world scenarios, significant variations in air pressure, temperature, and mass flow rate occur during the discharge phase, leading to relatively low turbine efficiency (18-52%). Ennil developed a dynamic model for a small CAES system using MATLAB/Simulink. And a small axial-flow air turbine (1kW) was developed through CFD modeling in order to improve the operating efficiency. (Bahr Ennil, 2017).

3.2.3 Micro-scale CAES system (MS-CAES)

When researches are being done on small and micro CAES systems, turbines derived from conventional gas turbines are no longer suitable. Special small or micro turbines need to be developed. However, there are few specific evaluations of microturbine sizes in the literature, and micro CAES systems defined as slightly less than 1 MW or 15 kW are possible.

There is a size 500 kW CAES system which has the highest microturbine pressure input from an axial flow microturbine developed by Deprag (Cheayb et al., 2022). On the other hand, Backman and Kaikko referred to the technical data of many microturbine manufacturers such as Capstone and Siemens to get the power range of radial microturbines starting from 30 kW (Cheayb et al., 2022). Radial turbines, however, are usually less efficient during off-design operation. Therefore it becomes particularly important to evaluate the performance of radial turbines for off-design operation and the conversion of CAES systems with radial turbines (He, Wang and Ding, 2017).

4 Discussion

This thesis is based on a literature review exploring the application of different types of turbines in different CAES sub-technologies and their use in different storage sizes, and the author has organised the types of turbines discussed in the paper to be shown in Tables 1, 2 respectively.

Table 1 demonstrates the application of different types of turbines in different CAES sub-technologies. As shown in Table 1, the types of turbines used in the D-CAES system are more diverse, with almost all types of turbines shown in table 1 applied, except for radial turbines. This indicates that the D-CAES system has high flexibility and adaptability for various turbine types. In contrast, relatively few types of turbines are used in A-CAES and UW-CAES technologies which are radial turbine, axial turbine and high-pressure and low-pressure turbine units. Among the different CAES sub-technologies, researchers are more interested in axial turbine and turbine units of high pressure and low pressure.

Table 1. Turbine types used in CAES sub-technologies.

Turbine Types	CAES Sub-technology
Radial Turbine	A-CAES, UW-CAES
Axial Turbine	D-CAES, A-CAES, UW-CAES
HP Turbine + LP Turbine	D-CAES, A-CAES, UW-CAES
Turbine derived from gas Turbine	D-CAES, A-CAES
Turbine derived from steam Turbine	D-CAES
Quasi-turbine	D-CAES

The correspondence between turbine types and CAES storage sizes is demonstrated in Table 2. It shows radial and axial turbines are widely used in different sizes of CAES, whilst Quasi-turbines are only used in small-scale (SS-CAES) systems. From the storage sizing comparisons, it can be concluded that the study of turbine type applications in large-scale CAES systems is more extensive. In addition to the application of high-pressure and low-pressure turbine units, LS-CAES systems also employ turbines from gas turbine and steam turbine.

Table 2. Turbine types in different CAES storage size.

Turbine Types	CAES Storage Size
Radial Turbine	LS-CAES, SS-CAES, MS-CAES
Axial Turbine	LS-CAES, SS-CAES, MS-CAES
HP Turbine + LP Turbine	LS-CAES
Turbine derived from gas Turbine	LS-CAES
Turbine derived from steam Turbine	LS-CAES
Quasi-turbine	SS-CAES

By reviewing and summarizing the published literature, axial turbines are generally highly adaptable and suitable for a wide range of CAES system scales, especially in large scale systems. They are designed to effectively cope with high pressure and temperature conditions. Radial turbines, although are also used in a variety of applications, are more suited to smaller CAES systems. Because of the more compact design, they are able to adapt better to space constraints, and perform well under partial load conditions. In contrast to the above two types of turbines, the quasi-turbines are a turbine designed for specific situations. It offers the benefits of high efficiency and compactness at the same time.

Storage size, as mentioned above, also plays a key role in determining the appropriate type of turbine. Large-scale CAES systems usually require more efficient energy conversion and more processing power, and therefore axial turbines are often chosen to fulfil these needs. Whereas, in micro CAES systems, due to space and cost constraints, radial turbines may be more suitable as they usually have a smaller size and simpler design. Therefore, storage size holds a key position in determining the appropriate type of turbine.

However, this study still has some limitations. Although the author have summarised the different types of turbines and their applications in CAES, the paper is unable to provide an in-depth analysis of the turbine's performance under real operating conditions due to the constraints of the literature resources. In addition, the lack of performance assessment of turbines in handling variable loads and unstable pressure conditions restricts an accurate comparison of the reliability and efficiency of turbines in real CAES systems. In terms of energy storage size, intermediate CAES systems are not considered in the discussion of the effect of energy storage size on turbine type, as there are few studies of intermediate CAES systems in the existing literature and not enough information could be found to cover intermediate systems.

5 Conclusion

This thesis comprehensively examines the application of turbines in different CAES sub-technologies and their relationship with storage size. Through literature review and analysis, this study reveals the wide range of applications of axial turbines, radial turbines, hybrid turbines, and quasi-turbines in different CAES systems. It is found that there are more types of turbines used in D-CAES technology and the researches are more mature. In addition researchers are more proficient in the use of axial flow turbines and high pressure and low pressure turbine sets. Whereas the types of turbines used in A-CAES and UW-CAES techniques are yet to be explored in the future.

The choice of turbine is closely related to the storage size. The results of this study show that large-scale CAES systems tend to use axial turbines or combined axial/radial turbines to meet their high energy conversion needs and efficiency requirements. In contrast, small-scale and micro CAES systems may be more suited to radial turbines or specially designed microturbines to cope with their specific performance and space constraints.

In summary, although this study provides a more comprehensive discussion of the application of turbines in CAES systems, there are some shortcomings. Due to limited literature resources, this paper has not been able to analyse in depth the performance of the turbine under real operating conditions, especially in terms of managing varying loads and unsteady pressure conditions. In addition, this paper lacks information on medium-sized CAES systems as there is less available literature on this and the information is not sufficient for adequate coverage. Therefore, future researches need to focus on analysing the performance of the turbine under real operating conditions with more validation experiments and simulations to optimise its application in CAES systems. At the same time, the impact of the latest technological advances and innovative designs on turbine selection should be considered to improve system performance and economic efficiency. With the increasing demand for renewable energy use and energy storage, the optimisation of CAES technologies and their key components will have a critical impact in achieving a more sustainable and efficient energy system. Continued technological innovation, including the development of new turbine designs and materials, can enhance the performance and economics of CAES systems and advance their future development.

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