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Review

A review on compressed air energy storage: Basic principles, past milestones and recent developments

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HIGHLIGHTS

- A review on the variety of CAES concepts and their historical background is given.
- An extensive classification and comparison of different CAES types is carried out.
- The concept of exergy is applied to enhance the fundamental understanding of CAES.
- The importance of accurate fluid property data for the design of CAES is examined.
- General aspects on CAES applications and upcoming R&D challenges are discussed.

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ABSTRACT

Over the past decades a variety of different approaches to realize Compressed Air Energy Storage (CAES) have been undertaken. This article gives an overview of present and past approaches by classifying and comparing CAES processes. This classification and comparison is substantiated by a broad historical background on how CAES has evolved over time from its very beginning until its most recent advancements. A broad review on the variety of CAES concepts and compressed air storage (CAS) options is given, evaluating their individual strengths and weaknesses. The concept of exergy is applied to CAES in order to enhance the fundamental understanding of CAES. Furthermore, the importance of accurate fluid property data for the calculation and design of CAES processes is discussed. In a final outlook upcoming R&D challenges are addressed.

Contents

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1. Introduction

Today the storage of electricity is of increased importance due to the rise of intermittent power feed-in by wind power and photovoltaics. Here, air can serve as a suitable storage medium by compressing it using an electrically driven compressor. At any later point in time the stored compressed air can be released and reconverted to electricity by means of a turbine generator – a very simple process already being applied for decades. There are various approaches to realize this seemingly simple process. Each process has its individual strengths and drawbacks, which have not been analyzed and compared thoroughly so far.

The present article attempts to give an overview on present and past approaches by classifying and comparing CAES processes. This classification and comparison is substantiated by a broad historical background on how compressed air energy storage (CAES) has evolved over time. The concept of exergy is applied to CAES in order to enhance the fundamental understanding of CAES. Furthermore, reasons are given why the usage of accurate fluid property data is especially important for the calculation and design of CAES processes. To summarize, the authors focus on both, theory and technology of CAES. Economic aspects are explicitly excluded because of their strong dependence on country-specific and short-term changing market conditions as well as on the political and regulatory framework. Due to that, an in-depth review of CAES economics would exceed the purpose of this article by far. Nevertheless, some general economic aspects of CAES applications are discussed wherever appropriate.

2. A brief history

In the manufacturing industry compressed air is broadly applied. Here, it is used either as an energy carrier for various processes like drilling or carving or it serves as a process fluid carrier e.g. for cleaning or varnishing. Either way, compressed air is generated almost exclusively on site by employing electrical energy. In Germany, for example, currently 16 TW h_{el} are consumed annually to provide compressed air for industrial purposes, which amounts to about 2.5% of the German overall electricity consumption [1].

Looking at utility scale energy supply, compressed air has never been established as an energy carrier. In comparison to electricity, gas and heat, its power density is lower and transportation losses are higher, which can be considered the main reason for this situation. Nevertheless, compressed air has been and still is applied as a storage medium for electrical energy at utility scale. Fig. 1 shows projects and R&D efforts over time, which will be described in detail later on.

2.1. How it all began

The fundamental idea to store electrical energy by means of compressed air dates back to the early 1940s [2]. By then the patent application "Means for Storing Fluids for Power Generation" was submitted by F.W. Gay to the US Patent Office [3]. However, until the late 1960s the development of compressed air energy storage (CAES) was pursued neither in science nor in industry. This can be ascribed to the lack of necessity for grid connected energy storage. It changed in the 1960s with the introduction of baseload generation in form of nuclear power and ever larger lignite coal fired power plants. Suddenly, there was an economic case to store inexpensive off-peak power from baseload generation capacities and transfer it to peak-load hours. Where possible this added value was taken advantage of by the installation of pumped hydro energy storage (PHES) plants. Nevertheless, PHES relies on suitable topological condi-tions, which limit its application to mountainous regions. In 1969, the need for storage capacity in northern Germany led to the decision to develop a CAES plant in this particular region. The decision was supported by suitable geological formations for storing large amounts of compressed gas in available underground salt domes. These salt domes were already used to build caverns reliably hosting large amounts of compressed natural gas. Furthermore, there was a need for black start capability for the northern German grid, which could be provided by CAES, too [4]. It is interesting to mention that the initial wording for the CAES technology by that time was still different. The utility Nordwestdeutsche Kraftwerke (NKW), which decided to build Huntorf, chose the acronym ASSET to label the new technology. ASSET stood for Air Storage System Energy Transfer plant indicating the utility's basic intention for the storage plant [5]. The technology supplier BBC Brown Boveri instead came up with the term "Gas Turbine Air Storage Peaking Plant" highlighting that CAES was basically derived from gas turbine technology serving as a peak-load capacity. None of the acronyms by that time is still in use today. The technical achievements connected to the development of the Huntorf plant still exist and will be described in greater detail in Section 4.1.

2.2. How the idea spread

Stimulated by the Huntorf project, the general interest in CAES technology began to rise by the mid-1970s [2,6]. Different from Europe, as the Huntorf plant was clearly industry driven, the US Department of Energy (DOE) initiated both an R&D and a predemonstration program for developing CAES, which was coordinated by the Pacific Northwest National Laboratory (PNNL) from the late 1970s to early 1980s [7,8]. The research and development (R&D) of the program focused on the following two major issues:

- Long-term reservoir stability criteria for CAES operating conditions.
- Feasibility of so-called second-generation CAES concepts including adiabatic CAES (A-CAES) aimed at minimizing the use of petroleum fuels for firing.

At the end of the research program diabatic CAES (D-CAES) was considered a technically feasible near-term technology. As a

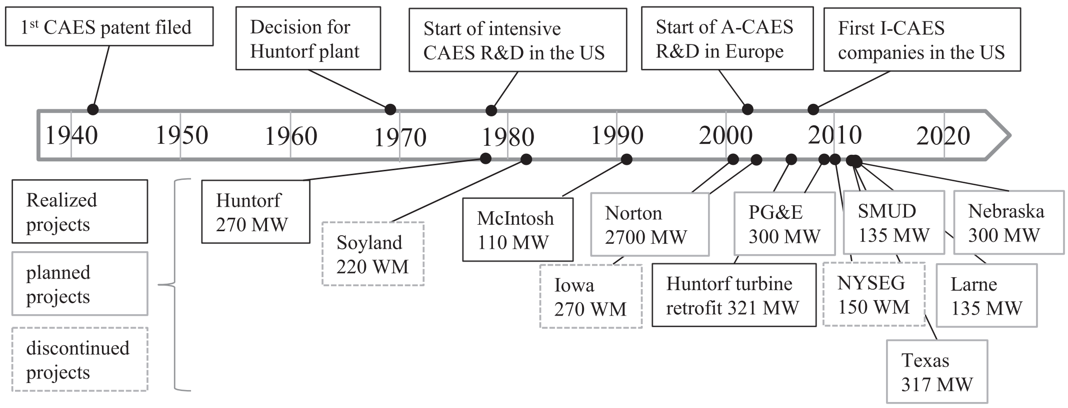

Fig. 1. Timeline of CAES R&D and industrial efforts; projects are not exhaustive and limited to the largest installations.

consequence, the responsibility for further R&D was transferred to the industry financed Electric Power Research Institute (EPRI). Development of second generation CAES like hybrid, adiabatic or isothermal CAES (I-CAES, compare Sections 6) was postponed and linked to a successful implementation of D-CAES in the USA. Among the different types of second generation CAES, PNNL considered A-CAES the most suitable and promising technology [9]. However, EPRI considered a hybrid CAES plant with a single-stage thermal energy storage (TES) and additional gas firing the most promising second generation solution based on the earlier extensive study by Glendenning et al. [7].

One outcome of the pre-demonstration program was a planned installation of a 220 MW_{el} D-CAES with heat recuperation[1] and a water-compensated underground cavern[2] at the Soyland Power Cooperative Inc. [10]. Contracts were already signed, but in 1982 the utility decided not to build the plant. The cancelation was officially justified by a more moderate growth in electricity demand than expected [11]. The first CAES plant in the USA was actually built in 1991 at the McIntosh site [12]. Operating utility was and still is the Alabama Electric Cooperative, while by the year 2008 the name changed to PowerSouth Electric Cooperative. The plant's technical achievements will be described in Section 4.2. The McIntosh plant led to interest in CAES technology by several US utilities like the Tennessee Valley Authority and the Hawaiian Electric Co. but none of them seriously attempted to set up a commercial facility [13]. In 2001, a CAES project was announced using a depleted limestone mine at Norton, Ohio [14]. The mine offers a total volume of approx. 9.6 million m^3. To make full use of this huge reservoir nine 300 MW_{el} turbines of the type Alstom ET11NM would have to be applied allowing for a continuous generating operation of 2 days [14,15]. However, the Norton project has not been realized so far. In December 2006 Alstom, as the main generating equipment provider, withdrew supply support citing insufficient internal resources. Dresser-Rand [16] joined the consortium as new equipment supplier. In November 2009, the rights to further develop the Norton CAES facility were purchased by the US utility FirstEnergy Generation Corp.[3] In 2013, FirstEnergy put the further development of the project on hold due to unfavorable electricity wholesale market prices. Beside this long term running project there are several companies that published plans for D-CAES plants in the USA more recently.

The first project of this group was the Seneca CAES project planned by NYSEG at the east coast of the USA, which was canceled in 2012 due to economic aspects [17]. In California PG&E is planning a 300 MW_{el} D-CAES with a reserve for 10 h of rated power stored in porous rock formations. The plant is intended to be in operation in 2020–2021 [18]. Sacramento Municipal Utility District carries out feasibility and conceptual engineering analyses for a wind farm coupled small D-CAES (15–50 MW_{el}) as well as for one or more 135 MW_{el} plants [19,20]. In Texas two plants have been announced by Apex CAES, at the Bethel Energy Center near Dallas and the Matagorda Energy Center near Houston [21]. New York Power Authority (NYPA) is planning a utility scale D-CAES and has recently completed the design, performance and thermodynamic studies on a small-scale D-CAES with about 10 MW_{el} of rated power and a storage capacity of 4.5 h by using steel pipes as aboveground CAS [22]. Further projects still on their way are an aboveground D-CAES on Hawaii [23] and a 100–300 MW_{el} plant by Nebraska Public Power District storing the air inside the Dakota porous sandstone formation, which is currently in test operation [24]. In Europe there are also plans for D-CAES plants. A 330 MW_{el} plant consisting of two 165 MW_{el} trains is to be built in Larne, Northern Ireland using an underground salt formation for storage. And further locations in UK, Germany, Denmark and the Netherlands have already been identified [25].

Despite the recent initiatives, both in industry and science, no more large scale CAES plants have been constructed after the McIntosh plant so far. Looking at the USA again, the development of second generation CAES is still not being pursued after all. The paradigm of EPRI to promote only CAES concepts to be built with no or just little development effort is being maintained. Only very slight attempts toward little or no fuel consuming CAES are made when EPRI announced to bring A-CAES back into focus [26]. However, at a smaller scale serious attempts are being undertaken in the USA toward near-isothermal CAES without fuel consumption. Several start-up companies are developing prototypes in the range of hundreds of kW installed power applying reciprocating piston engines to compress and expand air [27]. Air temperatures are kept low by directly injecting spray water or foam into the compression chamber. This concept is described in more detail in Section 6. To summarize, the main driver behind the increasing interest in CAES recently is totally different from the mentioned drivers leading to Huntorf and McIntosh. While at the time of Huntorf and McIntosh aspects such as black start capability and economic optimization by transferring cheaper baseload power toward peak hours were important, today the need for the balancing of intermittent renewable energy RES power feed-in can be considered the main driver toward CAES.

[1] Heat recuperation is a means of fuel saving by reusing the heat of the exhaust gases: compare Section 4.2.

[2] A water compensated cavern allows for gas storage at almost constant pressure: compare Section 7.

[3] Source: Ohio Power Siting Board 99-1626-EL-BGN, http://www.opsb.ohio.gov/opsb/cases/case.cfm?id=4070.

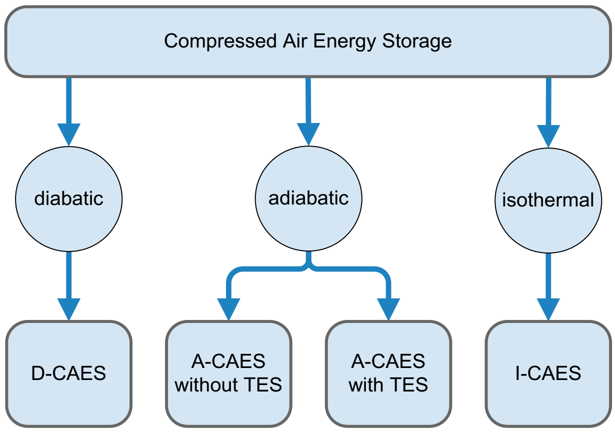

Fig. 2. Compressed air energy storage concepts classified by their idealized change of state: (D(diabatic)-, A(adiabatic)-, I(isothermal)-CAES).

Nevertheless, the ability of CAES to compensate for fluctuating renewable energies was already mentioned as early as 1976 by [6] and later on in 1981 in [28], although without being of major importance at that time. This has now changed dramatically with a significant penetration of intermittent renewable energies such as wind and photovoltaics in the electricity supply system in many countries around the world. CAES is perceived to be a key enabling technology for the integration of such intermittent renewable resources [29,30]. Bearing this new incentive for the future application of CAES in mind, a four year European research *AA-CAES*[4] project was initiated back in 2003 [31]. The aim of this project was to develop an A-CAES plant with 70% cycle efficiency overcoming the low cycle efficiency of D-CAES. Main outcome of the project was a conceptual plant layout for a 300 MW_{el} A-CAES plant. Despite the interest of several European utilities, this type of A-CAES has not been realized so far. The main obstacle seems to be the considerable development effort related to the adiabatic compressor and to the TES together with the very limited number of installations to be expected (compare Section 5).

The very beginning of the 21st century can be seen as the point in time when R&D on CAES technology has been resumed on a broader level. All different types of CAES plant concepts known today have their origin in this decade. A detailed description of these further developments is given in Sections 6. However, first a view on the general aspects of CAES is given in Section 3.

3. General concept of compressed air energy storage

The basic concept of CAES is rather simple. The storage is charged by the use of electrically driven compressors, which convert the electric energy into potential energy, or more precisely exergy, of pressurized air. The pressurized air is stored in CAS volumes of any kind (see Section 7) and can then be released upon demand to generate electricity again by expansion of the air through an air turbine.

Today, a huge variety of different CAES concepts exist at different levels of development, aiming at different applications and owning individual strengths and weaknesses. A general classification of the whole group of CAES concepts is shown in Fig. 2. Depending on the targeted idealized process, CAES technologies are differentiated into diabatic, adiabatic and isothermal concepts. The main criterion for categorization is the question how heat is handled during compression and prior to expansion of the air.

In D-CAES the heat resulting from air compression is wasted to the ambient by cooling down the compressed air; therefore an external heat source is needed for the discharging process to prevent condensation in and icing of the expansion machinery by preheating the compressed air upstream of the expander. In A-CAES the heat of compression is captured in additional TES devices and is utilized prior to expansion to prevent the need for other heat sources during the discharge phase. In contrast to D-CAES and A-CAES concepts, heat of compression is to be minimized or even prevented in I-CAES concepts. Technological implementations as well as further information on individual aspects and current projects for each of these subclasses are presented in Sections 4,5, and 6, respectively.

The different CAES concepts differ widely regarding quantitative parameters such as cycle efficiency, energy density and start-up time as well as regarding qualitative parameters like their status of development and fields of application. Table 1 gives an overview of these parameters of three classes of CAES.

3.1. Cycle efficiency of CAES

D-CAES is not a mere storage technology, but a hybrid electricity generation and storage technology. Consequently, a direct comparison of cycle efficiencies of D-CAES with those of mere storage technologies like PHES, batteries, flywheels, etc. including A-CAES and I-CAES is misleading. In order to discharge, D-CAES plants require additional heat which is usually provided by combustion of natural gas or light oil. This means two input energy streams exist – electrical energy for driving the compressors $E_{in,el}$ and thermal energy for heating-up the air before expansion $E_{in,th}$. Therefore, different approaches exist to calculate the cycle efficiency η_{cyc_eff} of D-CAES. A broad overview of these approaches is given in [34]. The most common approach is to consider both input energy streams as charging energy according to Eq. (1); another approach is to lower the value of the thermal energy contribution by a reference efficiency according to Eq. (2) [35].

$$\eta_{cyc\_eff\_1} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} \tag{1}$$

$$\eta_{cyc\_eff\_2} = \frac{E_{out,el} - E_{in,th} \cdot \eta_{reference}}{E_{in,el}} \tag{2}$$

Both approaches have their own strengths and weaknesses. $\eta_{cyc\_eff\_2}$ leads to a cycle efficiency which uses the efficiency of a virtual thermal power plant with the same source and amount of thermal input energy as a reference. In case of D-CAES using natural gas as additional energy input, suitable reference efficiency values would be those of other common gas firing conversion technologies such as open and combined cycle gas turbines or internal combustion engines. Taking into account this reference efficiency value, Eq. (2) results in a storage cycle efficiency comparable to those of mere storage technologies. Fig. 3 shows the dependency of $\eta_{cyc\_eff\_2}$ on the chosen $\eta_{reference}$. $\eta_{cyc\_eff\_1}$ on the other hand is just dependent on the measureable energy streams and is therefore useful to compare the efficiencies of different D-CAES plants among each other. Therefore, $\eta_{cyc\_eff\_1}$ will be used in the following paragraphs and in Section 3.

In Table 1, a cycle efficiency of $\eta_{cyc\_eff\_1}$ = 0.54 is given for a contemporary D-CAES plant. This value corresponds to the McIntosh plant (compare Section 4.2). In order to generate 1 kW h of electrical energy output $E_{out,el}$, the McIntosh plant requires 0.69 kW h of electrical energy $E_{in,el}$ to drive the compressor and 1.17 kW h of thermal energy $E_{in,th}$ to heat up the air before expansion [12]. Thus, it becomes clear that in the McIntosh D-CAES plant more electricity

[4] The acronym stands for Advanced Adiabatic Compressed Air Energy Storage. The project was carried out under the European Commission (FP5). http://cordis.europa.eu/search/index.cfm?fuseaction= proj.document&PJ_LANG=EN&PJ_RCN=6061072&pid=0&q=34A768288EFDC4A6169EF7E515783632&type=sim.

Table 1
Comparison of technical parameters for different CAES concepts according to [32] (enhanced by data from [33]).

	Diabatic		Adiabatic		Isothermal	
Cycle efficiency	Today	Goal	Today	Goal	Today	Goal
(AC to AC)	0.54	0.6	–	0.7	0.38	0.8
Energy density (per m^3 of CAS)	2–15 kW h/m^3		0.5–20 kW h/m^3		1–25 kW h/m^3	
Start-up time	10–15 min		5–15 min		<1 min	
Power range	5 MW–1 GW		1 MW–1 GW		5 kW–1 GW	
Development status	Application/Demonstration		Research/Demonstration		Research/Demonstration	

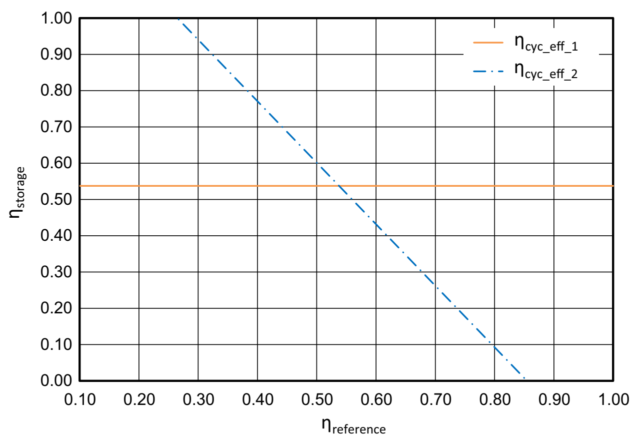

Fig. 3. Cycle efficiency of the D-CAES McIntosh calculated according to the discussed approaches.

can be discharged $E_{out,el}$ than is necessary for charging, $E_{in,el}$. This is a unique feature for any D-CAES plant demonstrating its hybrid status of being partially a peak generating technology and partially an electrical energy storage (EES) technology. In contrast, all remaining compressed air based EES technologies listed in Table 1 are mere EES technologies. For the non-diabatic CAES plant types, no additional thermal energy $E_{in,th}$ is involved in the process. Similar to any pure EES technology such as, e.g., electrochemical batteries, only electrical input and output energy is involved. Consequently, for non-diabatic CAES the amount of electricity to be discharged $E_{out,el}$ is smaller than that for the charging $E_{in,el}$ and the calculation of cycle efficiency η_{cyc_eff} can be simplified as follows:

$$\eta_{cyc\_eff} = \frac{E_{out,el}}{E_{in,el}} \tag{3}$$

Assuming a cycle efficiency of $\eta_{cyc\_eff} = 0.7$, as it is indicated in Table 1 as a future goal for A-CAES plants, an electrical charging energy of 1.43 kW h would be necessary in order to discharge 1 kW h.

3.2. A simple exergetic approach to CAES

To illustrate the fundamentals of CAES, it is advantageous to consider thermodynamic principles of a simplified system in quasi-stationary operation. In a thermodynamic study, an A-CAES plant can be simplified to the following system as shown in Fig. 4.

In charging mode, air is compressed from ambient temperature T_a and pressure p_a to temperature T and pressure p by an adiabatic compressor. The first law of thermodynamics yields

$$P_{el} = \dot{m} \cdot (h(T,p) - h(T_a,p_a)) \tag{4}$$

For the ideal reversible process, the electrical power P_{el} required to compress an air mass flow $\dot{m}$ is completely recovered when the compressed air is expanded again. The cycle efficiency of the reversible process is 100%. For practical reasons the air storage device is commonly operated at close to ambient temperature and heat is stored in a separate device as shown in Fig. 5. As long as the heat transfer in the ideal heat storage device is reversible (heat transfer with negligible temperature gradients), the separation of heat and air storage does not result in any difference.

Section 3.3 will highlight that it is important to consider real gas behavior of humid air for the design of CAES devices. However, to facilitate the fundamental understanding of the process, air is treated as dry ideal gas with the specific gas-constant $R_L = 0.287101$ kJ/(kg K) and a constant specific isobaric heat capacity of $c_p^o = 1.007$ kJ/(kg K) in this section. The resulting isentropic exponent is $\kappa^o = 1.3998$. With this assumption specific enthalpy h^0 and specific entropy s^0 differences between a state at T, p and ambient conditions become

$$h^o(T,p) - h^o(T_a,p_a) = c_p{}^o \cdot (T - T_a) \tag{5}$$

$$s^o(T,p) - s^o(T_a,p_a) = c_p^o \cdot \ln(T/T_a) - R_L \cdot \ln(p/p_a) \tag{6}$$

Under these conditions, the electrical energy required to run an ideal adiabatic compressor is equal to the exergy flow of the compressed air $\dot{E}_{air}$ and becomes

$$P_{el} = \dot{E}_{air}(T,p) = \dot{m} \cdot e_{air}(T,p)$$
$$= \dot{m} \cdot \left[\underbrace{T_a \cdot c_p{}^o \cdot \left(\frac{T}{T_a} - 1 - \ln\left(\frac{T}{T_a}\right)\right)}_{\text{temperature related contribution}} \underbrace{+ T_a \cdot R_L \cdot \ln\left(\frac{p}{p_a}\right)}_{\text{pressure related contribution}} \right] \tag{7}$$

Dividing the specific exergy e_{air} into temperature and pressure related contributions will be helpful for analyzing the CAES process later on.

Due to the term $-\ln(T/T_a)$, which results from the temperature dependence of entropy, the temperature related contribution to the exergy of the compressed gas is smaller than the enthalpy increase, Eq. (5). This enthalpy increase is usually referred to as "heat of compression". Though this term is thermodynamically not correct, it will be used in order to be consistent to the commonly used denomination. The same applies to the term "heat storage". Actually energy is stored as internal energy or enthalpy of a storage material; thermodynamically the term heat only refers to the temperature gradient driven transport of energy from gas to storage material and vice versa.

For an adiabatic compressor, temperature and pressure after compression are related by

$$T = T_a \cdot \left(\frac{p}{p_a}\right)^{\frac{\kappa^o - 1}{\kappa^o}} \tag{8}$$

Fig. 6 shows the development of temperature and specific exergy of the compressed air throughout a compression starting at ambient conditions. Both curves increase continuously, but not linearly. At a pressure of 5 MPa the specific exergy of adiabatically compressed air already exceeds 50% of the specific exergy at 20 MPa.

Assuming that the air is cooled down to ambient temperature in the heat storage device and with $h^o(T,p) = h^o(T,p_a)$ for an ideal gas,

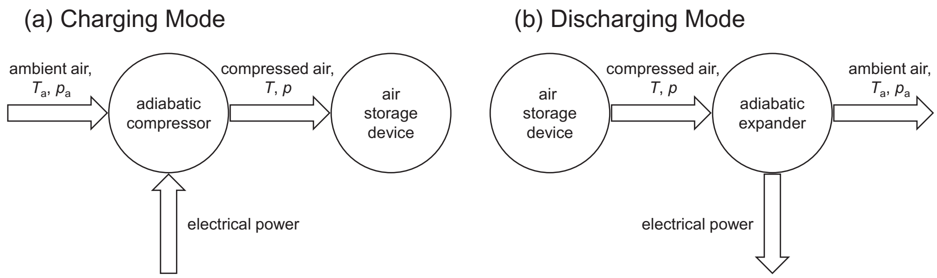

Fig. 4. Simplified system of charging (a) and discharging mode (b) of an A-CAES plant.

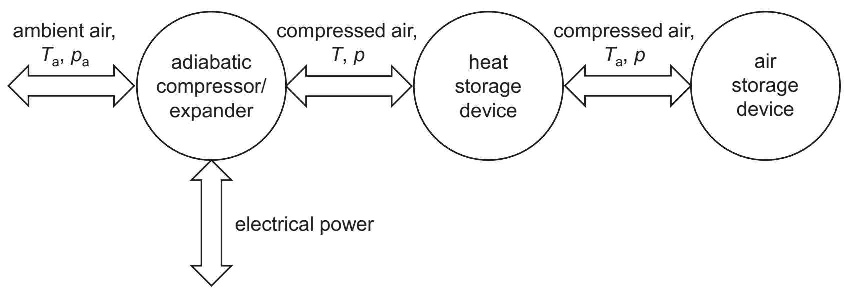

Fig. 5. Simplified system of an A-CAES plant with a separate heat storage device.

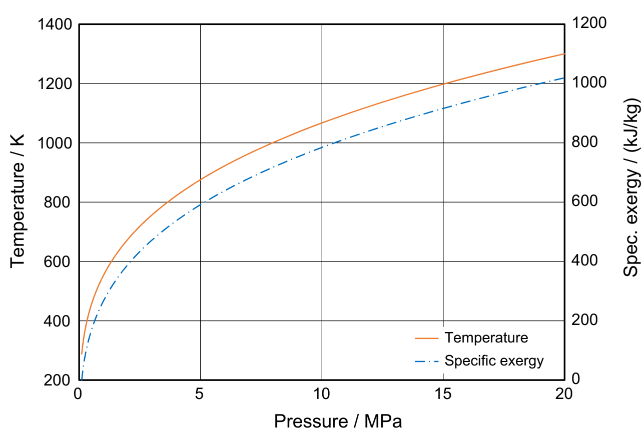

Fig. 6. Temperature and specific exergy of dry air adiabatically compressed from ambient conditions to the given pressure.

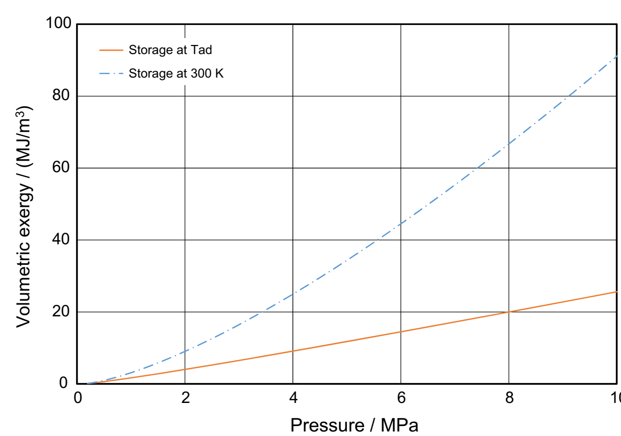

Fig. 8. Exergy stored in an ideal A-CAES process per volume of air supplied to the air storage device (differential calculation).

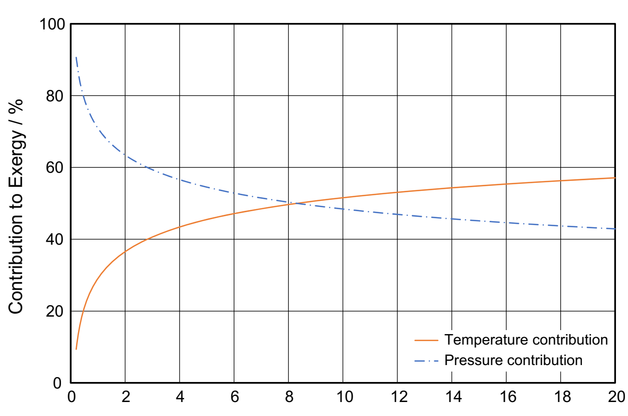

Fig. 7. Distribution of the exergy of adiabatically compressed air between the temperature and the pressure related contribution to exergy, see Eq. (6).

the heat flow $\dot{Q}_{\text{Storage}}$ stored becomes equal to the electrical power supplied to the compressor:

$$\dot{Q}_{\text{Storage}} = P_{el} = \dot{m} \cdot c_p^o \cdot (T - T_a) \tag{9}$$

The exergy flow related to any heat flow is related to the temperature at which heat is transferred. It is zero at ambient temperature and approaches the value of the heat flow at very high temperature; in thermal power plants, the average temperature of heat supply is chosen as high as possible to enable high efficiencies. However, the temperature at which heat is stored has no influence on the efficiency of ideal A-CAES plants, it only affects the relative size of the two terms in Eq. (7). Fig. 7 illustrates the distribution of exergy between the temperature related term and the pressure related contribution to exergy. At low storage temperature, which corresponds to a low pressure in A-CAES, the share of exergy stored in pressure is dominant. If the air is compressed to more than about 8.3 MPa in the ideal A-CAES process, the temperature related contribution to exergy becomes dominant. In any

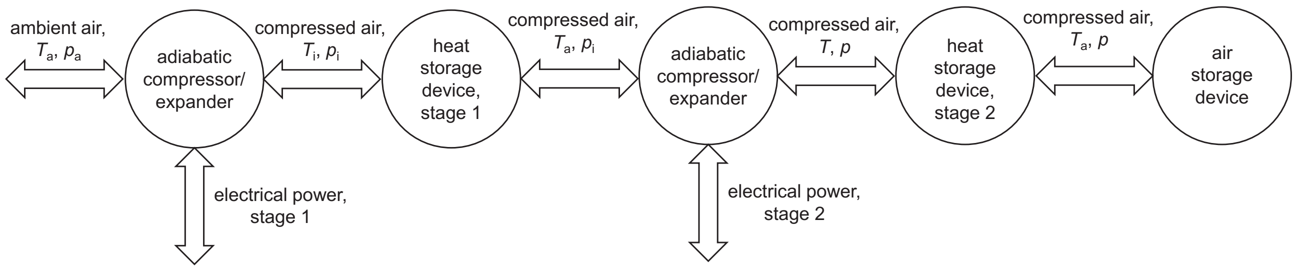

Fig. 9. Simplified system of an A-CAES plant with multiple stages.

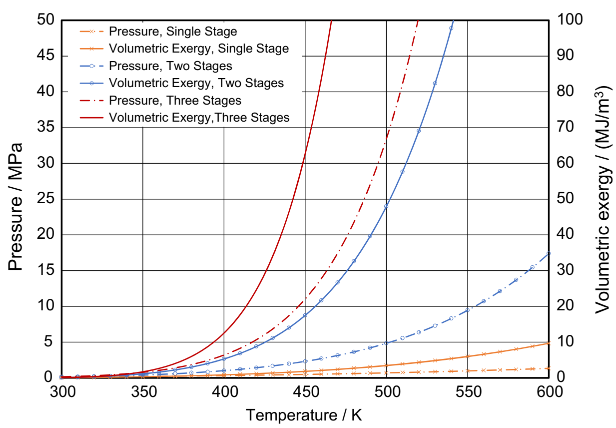

Fig. 10. Exergy stored per volume of air supplied to the air storage device (differential calculation, 300 K storage temperature) and storage pressure for ideal A-CAES processes with one to three stages, plotted over the compressor outlet temperature.

case, the complete exergy can be recovered during expansion – storage pressure and storage temperature have no influence on the cycle efficiency of an ideal A-CAES process.

However, even without considering irreversibility, low charging pressures have a negative effect on the size of the storage devices. Fig. 8 shows the exergy stored in one cubic meter of adiabatically compressed air at a certain pressure. Without a dedicated heat storage device, the volumetric exergy of compressed air (which is at adiabatic compression temperature in this case) increases almost linearly with pressure. If the air is cooled down to a temperature close to ambient in an ideal heat storage device after compression, the volumetric exergy increases disproportionately with pressure. In a single stage A-CAES process, high storage pressure and consequently a high compressor outlet/heat storage temperature is essential to limit the size of the air storage device. Similar considerations hold for the heat capacity, and thus the mass, required for the storage material in the heat storage device. With increasing temperature difference between charged and discharged status (T and T_a for the ideal storage device), less heat capacity is required to store a certain amount of energy.

In practical applications, adiabatic compression is limited to rather low pressures due to technical limitations regarding the temperature at the compressor outlet. To realize pressures attractive for air storage, intercooling has to be introduced. If the extracted heat is not utilized, exergy is wasted; the process becomes irreversible and the cycle efficiency falls below 100%. To avoid this limitation, processes with multiple stages can be introduced (Fig. 9).

With the idealized assumptions made in this section, the intermediate pressure level of a two-stage A-CAES process has to be chosen in a way that the pressure ratios of both stages are equal, $p_i/p_a = p/p_i$. After the first stage, the compressed air is ideally cooled back to ambient temperature in a first heat storage device. This way, the exit temperature of the second compression stage becomes equal to the exit temperature of the first compression stage, $T = T_i$. For a given compressor exit temperature, the electrical power stored per mass of air is equal to the number of stages multiplied by the power stored in the single stage process with the same compressor exit temperature. The total pressure ratio equals the pressure ratio of the single stage process with the same compressor exit temperature to the power of stages used. If the air is stored at a temperature close to ambient temperature again, the volumetric exergy increases dramatically due to the high storage pressure – the required storage volume becomes very attractive but now the high storage pressures limit the technical application. Fig. 10 shows the development of storage pressure and volumetric exergy plotted over the compressor outlet temperature for ideal A-CAES processes with one to three stages. The practical problems related to the large heat capacity required for thermal storage devices at low storage temperatures are not solved by processes with multiple stages, unless storage temperatures are chosen low enough to use water as a very cheap storage material.

In I-CAES processes, the temperature during compression is ideally kept equal to ambient temperature. Only the pressure related part of the exergy in Eq. (7) is transferred to the air. The power required to run the compressor is correspondingly lower. A heat flow equal to the power of the compressor has to be eliminated at ambient temperature. Since heat at ambient temperature has no exergy, this kind of continuous cooling does not result in exergy losses. During expansion, the same amount of heat has to be supplied continuously to the process at ambient temperature again, to ensure expansion at constant temperature. This way, the electrical power used to run the compressor during charging is completely recovered during discharging; the ideal cycle efficiency of I-CAES systems is 100%. However, common technical devices cannot realize compression and expansion processes at a constant temperature. Research on I-CAES processes focusses on the development of machinery that comes as close to an isothermal compression and expansion as possible [36].

In D-CAES processes, compressed air is stored at close to ambient temperature and heat is supplied by combustion of fuel during expansion (Fig. 11). During charging, the heat of compression is removed in a cooler and is completely wasted unless it is used otherwise, for example in combined heat and power concepts.

By cooling down the compressed air to ambient temperature, the temperature contribution to exergy as shown in Fig. 7 is lost; only the pressure related part of the exergy is utilized during expansion. From Fig. 7 it becomes obvious that high storage pressure is thermodynamically disadvantageous for D-CAES concepts. However, as shown before, low storage pressure is technically unattractive because it results in large air storage devices. Since gas turbines allow for higher turbine inlet temperatures than the highest compressor outlet temperatures that have technically been realized, the temperature of the air can be raised above the compressor outlet temperature in the combustion chamber. This way

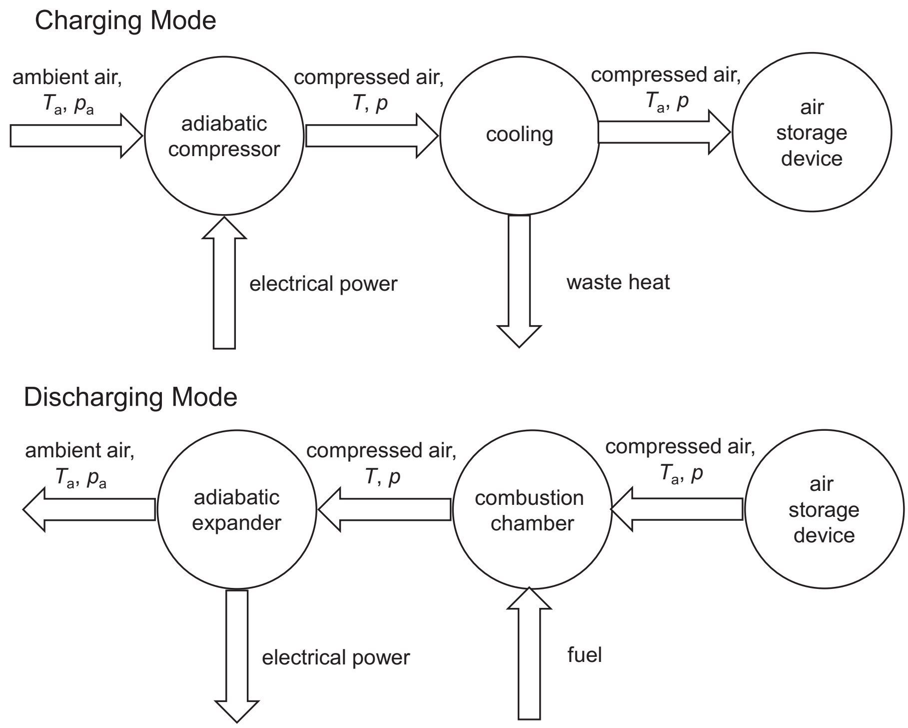

Fig. 11. Simplified system of a D-CAES plant.

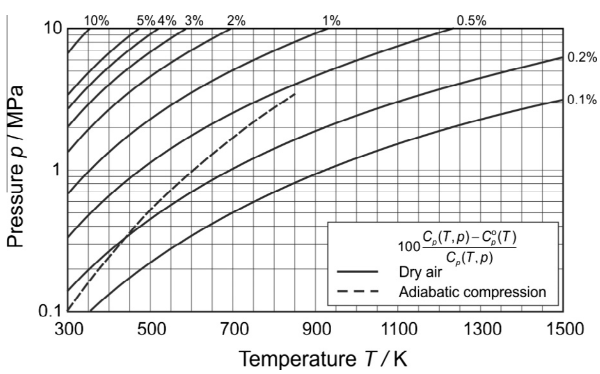

Fig. 12. Relative deviations between isobaric heat capacities of dry air, which were calculated using ideal gas [38] and real gas [40] property models, see also [37,39].

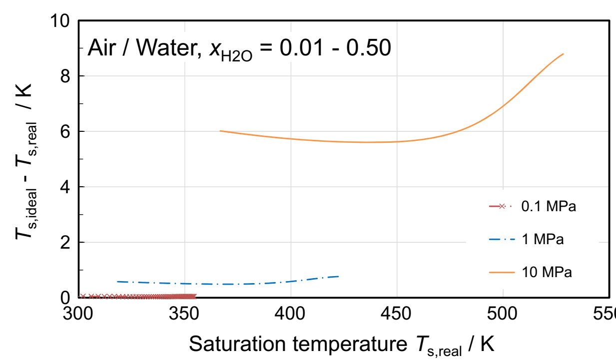

Fig. 13. Deviations between saturation temperatures calculated based on a simplified saturation model and based on a recent reference model [41].

more electrical power is gained during expansion, but at the expense of further increased losses. In this case, the air leaves the expander at a temperature above ambient temperature even under ideal conditions and exergy gets lost with the flue gas, unless this exergy is utilized in some kind of exhaust-heat recovery system.

Thermodynamically, D-CAES concepts become more attractive if the compression is carried out isothermally at ambient temperature or, as a technical approximation, with multiple intercoolers. This way the power required to drive the compressor is reduced, ideally to the pressure contribution to the exergy, see Eq. (7). During expansion, this power can be regained effectively. However, existing D-CAES plants work with adiabatic compression and expander exit temperature well above ambient temperature. Cycle efficiencies are correspondingly poor.

Real CAES processes deviate significantly from the results shown in this section. Irreversibilities in all sub-processes are by far not negligible and the relations given and used to generate the figures hold only for ideal gas with constant heat capacity – only Eq. (4) holds for real air, too. However, the general findings, such as the distinction of temperature and pressure related contribution to stored exergy, the process dependent relations between storage pressure and volumetric exergy of the stored air, and the fact that high cycle efficiencies do not require high storage temperatures can be translated into real processes and are helpful for the discussion in Sections 3–6.

3.3. Real gas properties of air

In most applications in energy technologies, air is treated as an ideal gas. Well established standards define how properties for air have to be calculated under this assumption [37–39]. Both the prevailing standards set by VDI (Verein Deutscher Ingenieure) [37] and by ASME (American Society of Mechanical Engineers) [39] use a plot like the one depicted in Fig. 12 to illustrate the limits of the ideal gas assumption. For dry air, Fig. 12 shows relative deviations between isobaric heat capacities calculated for dry air as ideal and as real gas; the isobaric heat capacity is used as an example for technically relevant thermodynamic properties. Deviations between ideal and real gas increase with increasing pressure and decrease with increasing temperature. For a typical adiabatic compression process starting at ambient temperature ideal gas models may be applied up to high pressure, because the air heats up during compression – deviations from the ideal gas assumption remain technically acceptable throughout the compression process. However, this assumption does not hold if the air is cooled down at high pressure, as is done in all kinds of CAES processes. In this case, deviations between ideal and real gas models become inacceptable and ideal gas models cannot be used for accurate technical calculations.

To consider real gas effects, the ASME standard [39] suggests that a model representing an ideal mixture of real gases should be used. For dry air, this model yields accurate results in the temperature and pressure range relevant for CAES. However, CAES uses humid air as working fluid. Water contained in the ambient air is condensed during inter- and final cooling of the compressed air. Optimized concepts with heat storage have to humidify the reheated air before expansion to increase the mass flow in the expansion devices and to utilize the stored heat efficiently. Thus, the saturation temperature of humid air at elevated pressure is an important parameter in designing a CAES process.

In simplified property models, the saturation temperature is commonly calculated using the ideal gas/pure liquid assumption, which implies that saturation is reached when the partial pressure of water in humid air is equal to the vapor pressure of water at the corresponding temperature. Fig. 13 shows deviations between saturation temperatures calculated according to this simplified assumption $T_{s,ideal}$ and saturation temperatures $T_{s.real}$ calculated using a recent reference model for thermodynamic properties of humid air and combustion gas like mixtures [41]. While deviations are technically acceptable up to pressures of about 1 MPa, deviations at higher pressure may lead to substantially suboptimal designs – an overestimation of saturation temperatures by several K is not acceptable for accurate process design. Appropriate real gas models have to be used to design high-pressure CAES processes.

A number of thermodynamic models have been published for the calculation of humid air properties. Goff and Gratch [42] and later Hyland and Wexler [43] developed virial models with second and third binary cross-virial coefficients fitted to experimental data. The virial equation of state by Rabinovich and Beketov [44] uses cross-virial coefficients calculated from theoretical models based on intermolecular interactions with the use of the Lennard-Jones potential. Ji and Yan [45] used a modified Redlich–Kwong cubic equation of state in combination with correlation equations for the enthalpy and entropy of the ideal gas for the description of humid air up to 20 MPa and 573 K. Lately, ab initio models for several water–gas mixtures (see e.g. [46] for the system water + nitrogen) were developed, from which second cross-virial coefficients are calculated. Detailed descriptions of different models and experimental data available for thermophysical properties of humid air are given in [47–49]. More recently, reference models treating humid air as mixture of the main air components and water were published [41,50]. Software solutions implementing these models are available. Due to their numerical complexity, the reference models may not be used directly in all applications. However, they provide a sound basis to check the accuracy of individual solutions for the calculation of thermodynamic properties of humid air.

4. Diabatic compressed air energy storage

The world's first CAES plant was put into operation in 1978 near the northern German village of Huntorf with an output power of 290 MW [5]. A second one with 110 MW output power was built in McIntosh/Alabama in the USA in 1991 [12]. Both plants are of the D-CAES type, use solution mined salt caverns as CAS, and have successfully been in operation up to now. Moreover, several smaller installations in the form of demonstration projects exist in Japan and Italy. Most of them are not in operation anymore. In the following, technical characteristics of the Huntorf and McIntosh plants will be presented.

4.1. Huntorf plant

In the Huntorf plant ambient air is compressed in an intercooled process by two separate turbo-compressor units to a maximum pressure of 72 bar. Before it is stored in the CAS, the air is recooled again (Fig. 14). The intercooled two-stage compression process limits exergy losses of the diabatic process design without heat storage device, but still more than 25% of the exergy supplied as electrical energy during compression is wasted due to cooling.

The CAS consists of two solution mined salt caverns with a total storage volume of about 310,000 m^3. The CAS is made up of two caverns to guarantee high availability by facilitating plant operation even when one of the caverns is being maintained. During operation, the caverns never reach ambient pressure again, being cycled between approximately 46 and 72 bar. In emergency cases, the expansion train can be operated below 46 bar, too. Identical to the compression process (Comp), expansion (Exp) is carried out in two separate units in series. When the air leaves the cavern in expansion mode, it is first throttled down to a constant pressure of approx. 42 bar before entering the high pressure (HP) combustion chamber (point (1) in Fig. 14) [5]. Throttling of the air results in considerable exergy losses but allows for constant pressure operation of the HP combustion chamber and the HP turbine. Downstream of the HP combustion chamber (2) the air now heated up to 490 °C by the specific heat $q_{HP\text{-}C}$ is being expanded down to about 10 bar in the HP turbine (3), which is a derivate of a steam turbine. On this pressure level the air is heated up again to 945 °C in the low pressure (LP) combustion chamber by the specific heat $q_{LP\text{-}C}$ before entering the LP turbine. Both components are based on conventional gas turbine technology.

In 2006, after 28 years of operation, the whole expansion train was retrofitted. One retrofit measure was to lower the inlet temperature of the HP turbine (2) from 550 °C to now 490 °C, keeping the inlet pressure as before. In the LP combustion chamber, the process parameters were raised from 10 bar/825 °C to 13 bar/945 °C (4). As a consequence, the output power could be increased from 290 MW to 321 MW [51]. The exergy of the exhaust gas leaving the LP turbine at approximately 480 °C (5) is still not utilized in any way.

As can be seen in Fig. 15 as well as in the process scheme of Fig. 14, compression and expansion train are connected to each other by the electric machine. In this way, the electric machine acts as both, electric motor and- generator (M/G), and is coupled to the turbomachinery trains via a clutch on each side. Since the high pressure compressor works at elevated rotational speed, it is coupled by a gear box [52].

In recent years, the Huntorf plant has been operated as a reserve plant providing tertiary control reserve and for internal portfolio optimization. Moreover, the plant has black start capability and is able to provide reactive power, too. The provision of reactive power and frequency regulation can be performed even when the plant is neither charging nor discharging by opening both clutches. In this way, the synchronous machine can be operated idling in parallel to the grid. The described field of application leads to a small number of generator operational hours in the range of 200 h per year [51].

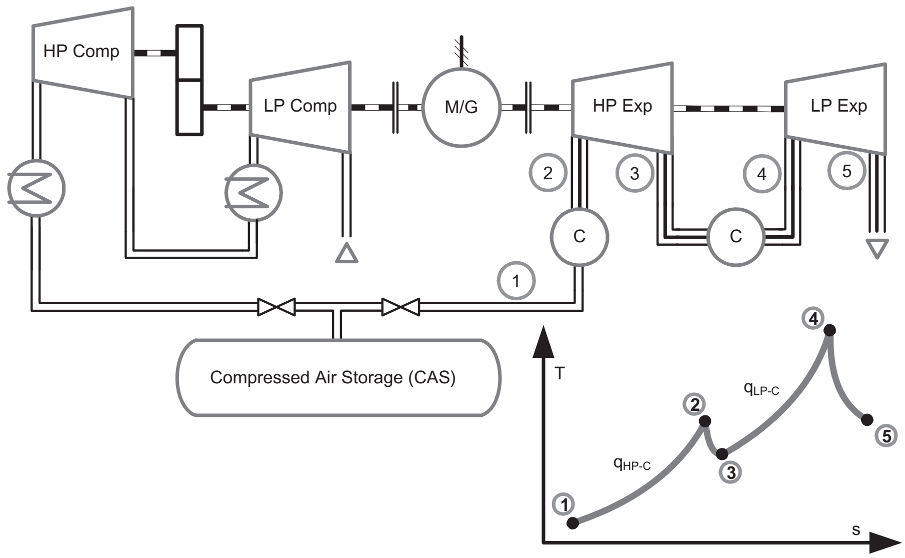

Fig. 14. Simplified process scheme and T,s-diagram of the expansion process of the Huntorf plant according to [32].

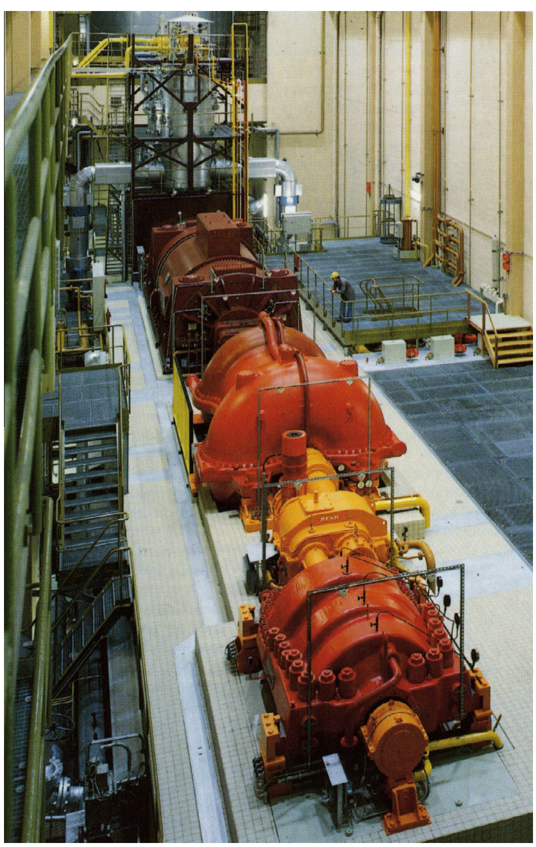

Fig. 15. View of the machine hall of the Huntorf CAES plant (Courtesy of E.ON Kraftwerke).

As a first-of-its-kind plant the Huntorf CAES plant came up with some unique features being implemented for the first time [51]:

- Compressed air storage in solution mined salt caverns.
- High pressure combustion chamber.
- High pressure expansion turbine and gas turbine with fast start-up capability.
- Power ratio motor/generator of one to five.

Despite this high density of innovations, a safe plant operation at high availability could be realized [51,53].

4.2. McIntosh plant

In 1991, 13 years after the installation of the Huntorf plant, a second large scale D-CAES plant was realized in McIntosh/Alabama [54]. The basic arrangement applying a motor generator in a single shaft design is essentially the same as in the Huntorf plant as depicted in Fig. 16. Even an underground mined salt cavern was chosen for the CAS. In contrast to the Huntorf plant, the CAS consists of only one large salt cavern with a total volume of 538,000 m^3 [55].

Similar to the Huntorf plant the McIntosh plant has no device for heat storage. However, multiple-stage intercooling reduces exergy losses during compression further. The usage of an exhaust-heat recuperator (Rec) poses the main difference and advancement compared to Huntorf. During expansion mode, the still hot exhaust gases of the LP expander (370 °C) are used to preheat the compressed air flowing out of the cavern. In this way the compressed air is heated to about 295 °C by the specific heat q_{rec} before entering the HP combustion chamber, where the specific heat $q_{HP\text{-}comb}$ is added too. After expansion in the HP expander the air is reheated in the LP combustion chamber by the specific heat $q_{LP\text{-}comb}$ to increase the power output of the LP expander. However, the exergy remaining in the exhaust gas is increased as well, because the pressure ratio of the LP expander is by far too small to cool down the exhaust gas to a temperature close to ambient temperature. The recuperator is applied as a simple form of exhaust-heat recovery to limit the exergy losses which would result from the hot exhaust gas otherwise. Fig. 17 gives a comparative overview using T,s-diagrams of the expansion process of the McIntosh plant (black line) and Huntorf plant (grey line). The left diagram compares the Huntorf and McIntosh expansion processes before the Huntorf retrofit in 2006. The diagram on the right hand side of Fig. 17 shows the same comparison after the Huntorf retrofit with modified turbine inlet parameters [12,51].

The dotted arrow in the left diagram in Fig. 17 indicates the transfer of heat of the exhaust gases q_{rec}. In doing so, the cold inlet air of the McIntosh plant is heated up from (1), (2). Consequently, only the remaining enthalpy difference from 295 °C to the HP-turbine inlet temperature of 538 °C has to be provided by

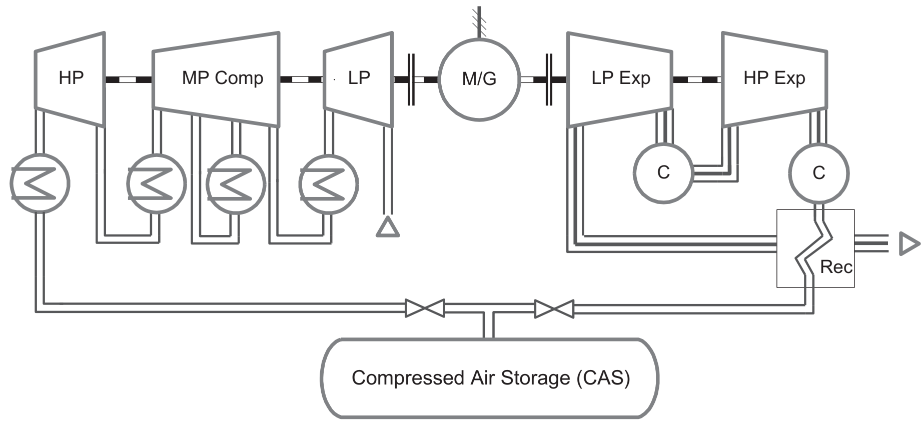

Fig. 16. Simplified process scheme of the McIntosh plant according to [32].

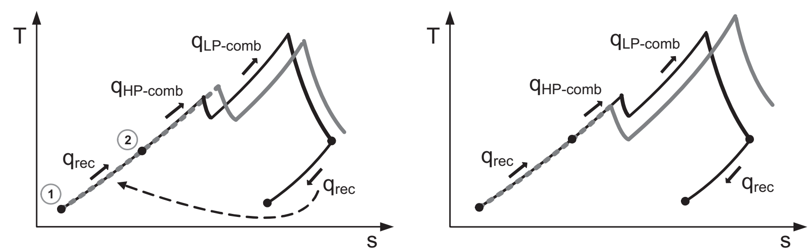

Fig. 17. T,s-diagrams of the expansion process of McIntosh (black line) and Huntorf (grey line) before (left diagram) and after (right diagram) the Huntorf retrofit according to [32]; absolute temperatures are indicated in Table 2.

combustion of natural gas, which in turn leads to fuel savings. The Huntorf expansion process (grey line) does not come up with any exhaust heat recuperation at all.

By comparing the two diagrams in Fig. 17 to each other, the impact of the retrofit in the Huntorf plant becomes visible. The HP turbine inlet temperature of the Huntorf plant (grey line) was lowered by the retrofit below that of the McIntosh plant (black line). On the other hand the LP turbine inlet temperature was significantly increased to about 70 °C above the McIntosh temperature, leading to a net rise in turbine power output. In Table 2 important plant parameters are displayed for both, the Huntorf and the McIntosh plant.

There are two striking aspects in the parameter comparison given in Table 2. First of all the McIntosh cycle efficiency is considerably higher than that of the Huntorf plant, reaching 54% instead of 42%. Technically, this can be explained mainly by the application of a recuperator which is completely omitted in the Huntorf plant. Only at second sight general technology advances in component efficiencies made during the 13 years between the two plant installations can be accounted. Nevertheless, the operational regime of the McIntosh plant requires the cycle efficiency to be as high as possible. When taking a look at the charging and discharging period in Table 2, it becomes clear that McIntosh was designed to perform load shifting on a weekly basis [12]. The Huntorf plant on the other hand with its short charging and discharging period was primarily designed to provide reserve power and blackstart capability where high efficiency is of minor importance [52].

5. Adiabatic compressed air energy storage

As already stated in Section 3, A-CAES store the heat of compression and reuse it during the discharging process. As shown in Fig. 18, this can theoretically be done in two ways.

A-CAES without thermal energy storage (TES)

The simplest way to reuse the temperature related part of the exergy of the compressed air is to store the hot air itself inside a combined thermal energy and compressed air storage volume (Fig. 18a). Due to the high temperatures already reached at rather low pressure ratios these concepts require highly temperature resistant storage volumes. Adiabatically compressed ambient air for example heats up to about 277 °C if reversibly compressed just to a moderate pressure of 10 bar. Most of the CAS discussed so far are not able to withstand these temperatures (more details in Section 7). Therefore, A-CAES without TES are restricted to rather low storage pressures and consequently to low energy densities as well [56,57].

This type of A-CAES has only been realized at laboratory scale so far [58] and a commercial application cannot be expected in the near future due to considerable material requirements for the CAS device which have to be met to provide a safe and secure plant operation. Furthermore, as a consequence of the relatively low density of hot compressed air, a huge surface has to be protected against heat losses. Both issues imply high initial cost [32].

A-CAES with thermal energy storage (TES)

The limitations of A-CAES without TES described above lead to the use of a dedicated TES device in most of the A-CAES concepts (Fig. 18b). By removing the temperature related part of the exergy from the air stream, the cooled pressurized air can be stored in a CAS of any kind (see Section 7). Additionally, much higher final pressures can be addressed and higher energy densities can be reached. Typical final pressures of A-CAES are at least 60 bar. This value is taken as the basis for the following statements.

The most important parameter of A-CAES is the chosen storage temperature. It has a direct influence on the system engineering as well as on the operating behavior of the whole storage plant. In contrast, cycle efficiency is hardly dependent on the absolute storage temperature (Fig. 19). The slight decrease in cycle efficiency

Table 2
Comparison of technical parameters of operating D-CAES plants (data source: [12,15,51,55]).

	Huntorf	McIntosh
Plant		
Operating utility	E.ON Kraftwerke	PowerSouth
Cycle efficiency[a]	0.42	0.54
Energy input for 1 kW h_{el} energy output	0.8 kW h_{el}/ 1.6 kW h_{gas}	0.69 kW h_{el}/ 1.17 kW h_{gas}
Energy content (related to power output)	642 MW h	2640 MW h
Planning – construction – commissioning	1969–1978	1988–1991
Compression		
Compressor manufacturer	Sulzer (today MAN Turbo)	Dresser-Rand
Max. el. input power	60 MW	50 MW
Max. air mass flow rate	108 kg/s	Approx. 90 kg/s
Compressor units	2	4
Charging time (at full load)	Approx. 8 h	Approx. 38 h
Storage		
Cavern construction company	KBB	PB-KBB
Cavern pressure range	46–72 bar	46–75 bar
Cavern volume	310,000 m^3	538,000 m^3
Expansion		
Turbine manufacturer	BBC (today Alstom)	Dresser-Rand
Max. el. output power	321 MW	110 MW
Control range (output)	100–321 MW	10–110 MW
Discharging time (at full load)	Approx. 2 h	Approx. 24 h
Start-up time (normal/ emergency)	14/8 min	12/7 min
Max. mass flow rate	455 kg/s	154 kg/s
HP turbine inlet	41.3 bar/490 °C	42 bar/538 °C
ND turbine inlet	12.8 bar/945 °C	15 bar/871 °C
Exhaust gas temperature	480 °C	370 °C (before recuperator)

[a] In the case of D-CAES plants cycle efficiency is not identical to AC/AC cycle efficiency as given for the other pure EES technologies, since additional firing is required for discharge (compare Section 3).

with lower storage temperatures is a result of exergy losses occurring from additional heat exchange processes (Section 3.2) [59].

Corresponding to the considerable differences in terms of system engineering, TES technology and the resulting operating behavior, three process types can be distinguished. As shown in Fig. 19, this can be done in the following way:

- High-temperature processes with storage temperatures above 400 °C.
- Medium-temperature processes with storage temperatures between 200 °C und 400 °C.
- Low-temperature processes with storage temperatures below 200 °C.

5.1. High-temperature processes

The concept of high-temperature A-CAES with single-stage TES (Fig. 20) was already discussed during the development of the first diabatic processes [7,63]. At that time, D-CAES were rated as technically and economically advantageous and no further development was carried out. The concepts were picked up again in 2003 by a European research project which resulted in the high-temperature concept called *AA-CAES* [31,47,64–67].

In the *AA-CAES* concept (Fig. 20) ambient air is compressed to a moderate pressure of 2.4 bar and is then recooled. To this point, the temperature related part of the exergy of the compressed air is wasted to the ambient. This happens for two reasons. On the one hand, the inlet temperature of the second compression stage can be adjusted and this directly affects the storage temperature and further decouples the following process from ambient conditions. On the other hand, this recooling minimizes the compression work needed to reach the final pressure and actually increases the cycle efficiency. Without recooling, the outlet temperature of the air after expansion would be considerably above ambient temperature due to irreversibilities of the applied turbomachinery. Thus, an exergy loss is unavoidable, and dumping the temperature related part of the exergy after the first compression stage is the most favorable way to deal with this unavoidable exergy loss. The following compression up to the final pressure of 65 bar is carried out without any additional cooling. This leads to an outlet temperature of around 580 °C. The pressurized air flows through a packed bed TES (see Section 7). Here, the temperature related part of the exergy of the air is transferred to the solid thermal storage media. Afterwards the air is conditioned by an additional cooler and enters the CAS with defined temperature and pressure. During the discharging process the air flows through the same TES device in reverse direction and is thereby heated up to a temperature of approximately 570 °C. Afterwards the hot pressurized air is expanded to ambient pressure in a generator-coupled turbine (Fig. 21).

Since 2010, the former *AA-CAES* concept has been developed further in the research projects 'ADELE' (2010–2013) and 'ADELE-ING' (2013-present) [60,68]. The major strength of these concepts is their high cycle efficiency of up to 70% [69,70]. However, to actually build such storage plants two major challenges have to be overcome. On the one hand, a high-temperature TES withstanding the combination of thermal and mechanical stress requires special materials as well as complex system engineering [71,72]. On the

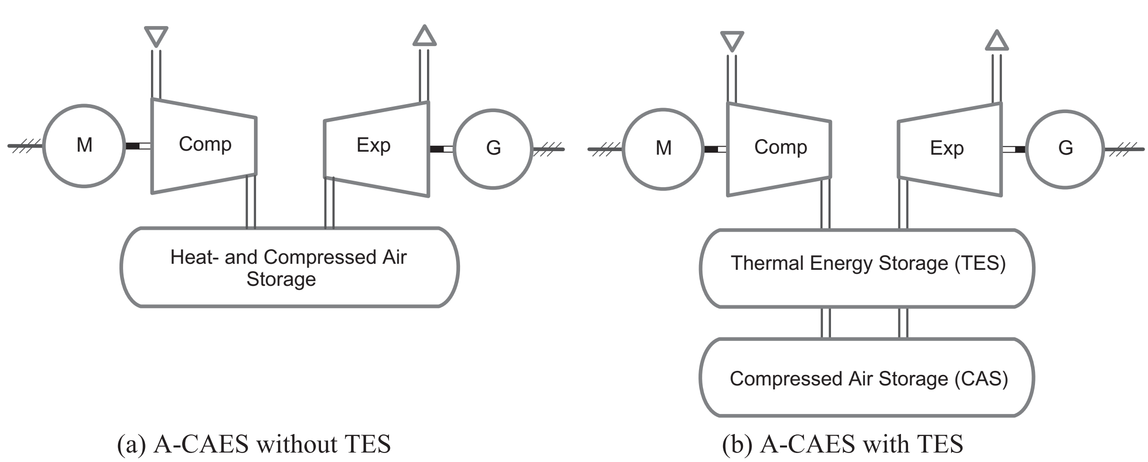

Fig. 18. Basic concepts of A-CAES according to [32].

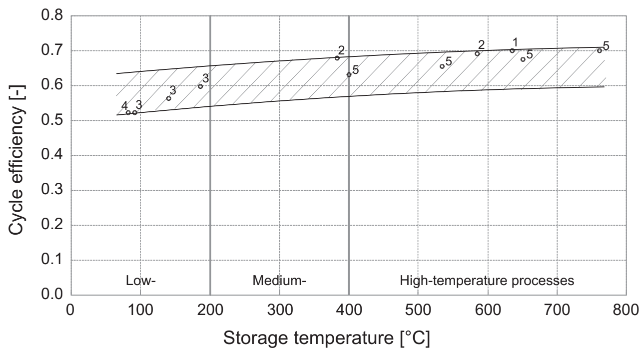

Fig. 19. Predicted cycle efficiencies of A-CAES depending on storage temperature (1 = [60], 2 = [32], 3 = [33], 4 = [61], 5 = [62]) based on [59].

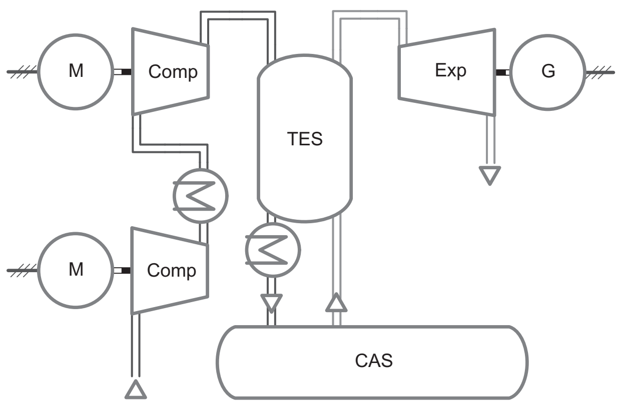

Fig. 20. Block diagram of a high-temperature A-CAES [32] as it was designed in the *AA-CAES* project.

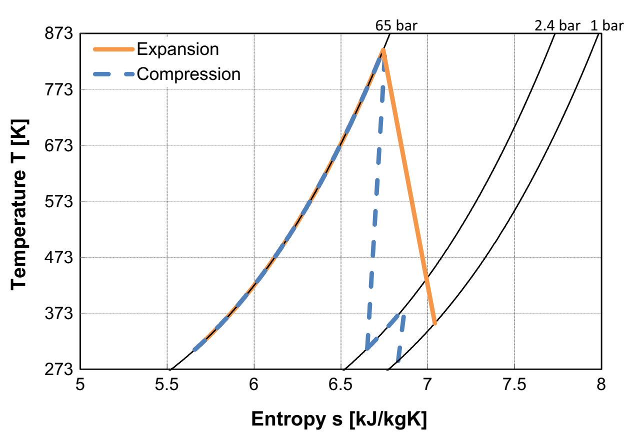

Fig. 21. T,s-diagram of a high-temperature A-CAES in *AA-CAES* layout (data source: [32]).

other hand, there is no electrically driven compressor available off-the-shelf that operates at the high-outlet temperature planned in *AA-CAES*. In general such machinery is technically feasible but a considerable engineering effort is needed to apply knowledge from gas turbine technology to an electrically driven compressor.

As in all other A-CAES concepts, humidity in the air will condense in the TES and/or in heat exchangers. Depending on ambient conditions and process layout, the related enthalpy of condensation may have a considerable and frequently neglected impact on heat balances. To avoid mismatches in the energy balance of charging and discharging, and to optimize the power output of the system, condensed water should be reinjected into the process during discharge in a suitable way; see Section 3.3 for a brief discussion on suitable property models.

With regard to energy economics the reaction time of a storage technology is a major parameter since storage devices with shorter reaction times are able to participate in additional, lucrative markets [73]. Talking about CAES, the dominating reaction time is the start-up time of the system from cold conditions. Due to thermal stress, high-temperature A-CAES plants need 10–15 min for a start-up process if the tolerable thermal gradients are respected [32]. In terms of start-up times, high-temperature A-CAES are as flexible as gas turbines, but rather slow compared to PHES, which are able to start-up within two minutes [74].

5.2. Medium-temperature processes

A-CAES concepts with two-stage TES and therefore lower temperatures have also been discussed since the beginning of CAES development [7,75,76]. In order to avoid the need for extensive research and development efforts, the process temperature is lowered below 400 °C by transferring the temperature dependent part of the exergy of the compressed air to TES devices twice (Fig. 22).

The slightly lower cycle efficiency (compare Fig. 19) is compensated by the applicability of the off-the-shelf compressor-technology and TES media like molten salt or thermal oil which are already used in similar applications [77]. Thermal storage in conventional or PCM-filled packed bed TES is possible as well [69,78,79]. Due to these advantages, medium-temperature processes are also in the focus of current research [32,68,80]. Beside these technical advantages, the economically relevant start-up time is still in the range of 10–15 min due to high thermal stress [32].

In the medium-temperature A-CAES shown in Fig. 22, ambient air is compressed to 2.4 bar in a first stage and is further compressed to 19 bar in a second stage after intermediate recooling (see also Fig. 23). The air leaves the second stage at about 380 °C and is cooled down again by flowing through a first TES device and an aftercooler. Afterwards the air is compressed to the final pressure and thus heated up to about 380 °C again, followed by heat exchange in a second TES device and storage in the CAS. The discharge process involves two expansion stages with preheating by the two TES devices [32].

5.3. Low-temperature processes

Basically, the idea to use storage temperatures below 200 °C is not new [7], but detailed concepts are results of current research [33,59,61,81–84]. The major advantages of low-temperature A-CAES are the applicability of liquid TES media, which can be pumped and which enable the use of common heat exchangers, and the applicability of off-the-shelf compression and expansion devices. To reach low storage temperatures in combination with still acceptable energy density, heat transfer after every single stage is used (Fig. 24). As a further advantage, storage plants of this kind would be able to start-up within 5 min, which allows the participation in additional energy markets [33].

A basic concept of a low-temperature A-CAES plant with liquid TES media and two tank TES is shown in Fig. 24. Depending on the state of charge, the liquid is stored inside the hot tank in case of charged storage or inside the cold storage tank otherwise. During the charging and the discharging process, the liquid is pumped through the heat exchangers to cool or preheat the air, respectively. Such an active TES system requires more advanced control compared to passive TES systems, but enables enhanced process control as well.

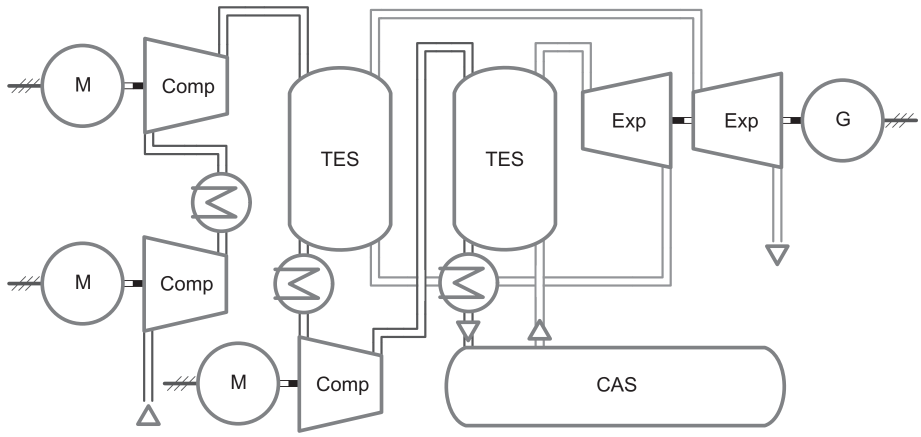

Fig. 22. Block diagram of a medium-temperature A-CAES (Ref. [32]).

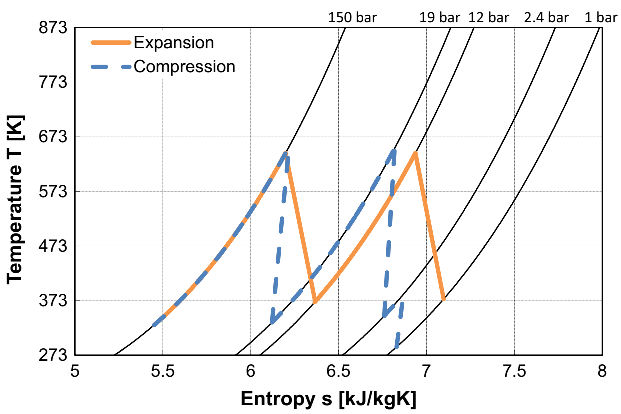

Fig. 23. T,s-diagram of a medium-temperature A-CAES (data source: [32]).

The concept shown in Fig. 24 is designed to work with five compressor and expander stages and heat exchange between each of these. The pressure ratio of each stage is identical and storage temperature is limited to about 132 °C at a final pressure of 200 bar (Fig. 25) [82].

6. Isothermal compressed air energy storage

I-CAES try to prevent temperature increase in the compressors during charging and temperature drop during discharging in the expansion devices. All I-CAES concepts known so far are based on piston machinery since these machines can perform a comparably slow compression or expansion process which leaves enough time for heat exchange processes inside the machinery itself. For example, the heat exchange can be carried out using additional heat exchange surfaces and a liquid piston [85]. Another way is to spray liquids into the plug room of a common piston machine or the compression of a pre-mixed foam [86].

The concept of I-CAES was implemented in so called hydro-pneumatic energy storage first. In these devices a liquid is used to compress the gas. In the case of closed cycle hydro-pneumatic energy storage (C-HyPES) this is achieved by pumping a liquid, for example hydraulic oil, into the storage tank, where the gas volume is reduced, which in turn causes a rise in gas pressure (Fig. 26). When electricity is needed, the gas pressure is released

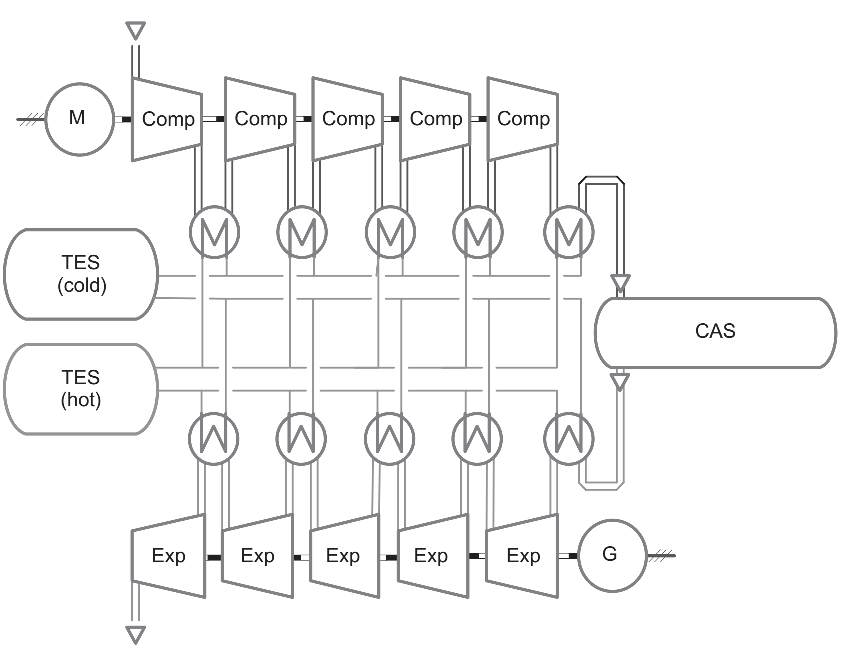

Fig. 24. Block diagram of a low-temperature A-CAES [82].

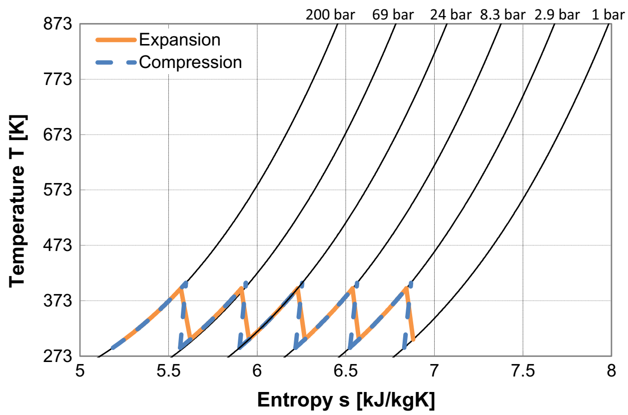

Fig. 25. T,s-diagram of a low-temperature A-CAES (data source: [82]).

by letting the liquid flow in reverse direction through the pump turbine (P/T), which now acts as a turbine driving the generator [32]. The major drawback of C-HyPES is their low energy density. For this reason these systems have not been built commercially, yet, but are subject to investigation at laboratory scale [85,87].

To overcome the drawbacks of C-HyPES, an open cycle concept (O-HyPES) combines the higher energy densities of air–air systems with the advantages of applying a liquid as working medium. In an O-HyPES system, air is compressed by a liquid piston before entering the CAS at high pressure (Fig. 26). This concept requires at least two alternating cylinders, where a liquid can be pumped into and out of, and a system of valves allowing a cyclic air supply and release [32].

In contrast to the closed cycle system, O-HyPES has been realized not only at laboratory scale [88] but has been further developed to a utility scale storage unit. A first pilot plant with a rated power of 2 MW was built in Texas and has been in test operation since 2012 [89].

In both concepts charging and discharging power is limited by the heat exchange surface formed by the liquid surface in contact with the gas. At high power, temperature gradients increase and the efficiency of the no longer isothermal process decreases. This limitation can be overcome by spraying water into the compression chamber, which results in a huge water surface in contact with the gas [27]. This way an efficient heat transfer is reached and the use of common piston technology becomes possible. Of course, corresponding piston compressors/expanders have to be modified to withstand the water content inside. Latest result of this research is the compression of a pre-mixed foam to further increase the heat transfer [86]. A first full-scale prototype storing air and water together inside an aboveground steel pipe CAS (compare Section 7) has been in test operation since the end of 2013.

In particular in open cycle concepts (O-HyPES) effects related to the humidity of ambient air and to the saturation water content of air at operating conditions have to be taken into account carefully. Condensate may affect the properties of the used hydraulic oil and the cooling capacity of sprayed water is closely related to evaporation which may be followed by condensation once a higher pressure-level is reached.

7. Compressed air storage

Compressed air can be stored either at constant volume (isochoric) or at constant pressure (isobaric). In case of constant volume storage, the pressure varies and thus indicates the state of charge. The most common example of isochoric storage is a steel pressure vessel or, at large scale, a salt cavern. Constant pressure storage requires a varying volume to maintain pressure at a constant level while charging and discharging. In this case, the volume indicates the state of charge. Constant pressure storage can technically be realized using, e.g., a hydraulically compensated reservoir where pressure is kept approximately constant by a second reservoir of liquid at elevated geodetic height as depicted in the center of Fig. 27 [32].

The major drawback of isochoric CAS is their effect on the compression and expansion machinery. These machines have to follow the changing pressure and are therefore not operating in their design pressure ratio, which leads to lower efficiencies. In case of D-CAES using an isochoric CAS, like the plants in Huntorf and McIntosh, the cavern pressure above the tolerable pressure of the combustion chamber even has to be throttled (Section 4.1). Latest D-CAES concepts overcome the exergy loss due to throttling by the implementation of flexible expander stages between CAS and the first combustion chamber [25]. Isobaric storage volumes do not affect the machinery in that way, but are more complex and not widespread.

In principle, isochoric and isobaric CAS are both applicable above- and underground. Aboveground CAS can be built of steel or sandwich material tanks or pipes. Even concrete storage volumes are possible when thinking of lower final pressures. The major characteristics of aboveground CAS are:

- installable widely location-independent,
- high pressure difference resulting in high energy densities realizable,
- high specific investment costs,
- high land consumption even at moderate storage sizes,
- need for regular pressure and security tests.

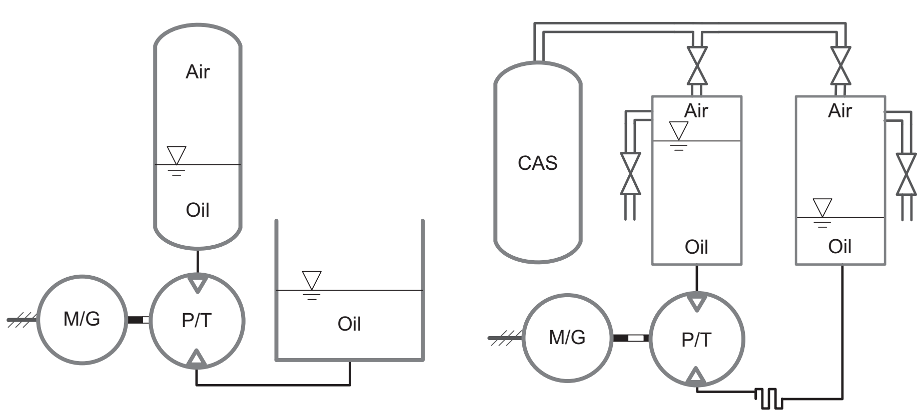

Fig. 26. Simplified process scheme of a C-HyPES (left) and an O-HyPES (right) [32].

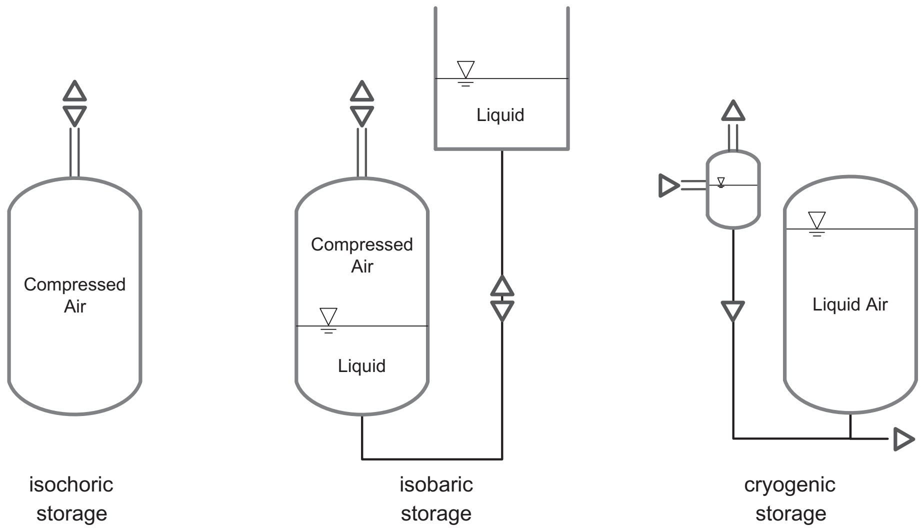

Fig. 27. Different types of air storage devices according to [32].

For the application of underground CAS a variety of choices exists. In general, each underground cavity, which is able to withstand the needed pressure and which is air tight, can be used. Solution mined salt caverns, gas fields or mine shafts are just some possibilities. Major characteristics of all these CAS are:

- low aboveground land consumption,
- low specific investment costs,
- depending on usable geology,
- limited pressure difference due to rock mechanic stability.

For large scale CAS systems, salt caverns are the dominating technology as they are the only choice implemented for compressed air energy storage in commercial application so far; the behavior of pressurized salt caverns has been known from the storage of natural gas for decades. Both existing D-CAES plants use solution mined salt caverns as isochoric CAS [12,53]. Construction of salt caverns is a state of the art procedure. The salt formations they are built in are air tight by nature as long as the temperature of the stored air stays below the site specific and depth dependent maximum allowed temperature. To keep the cavern stable, there is also a demand for a minimum operation pressure to withstand the outer forces from the surrounding rock [90]. The air in the cavern can generally be considered saturated with water at cavern pressure and temperature. Condensation and evaporation of water in the cavern can be highly relevant for the stability of the cavern.

An isobaric salt cavern was planned for a D-CAES is the USA, but has never been constructed, just as the plant itself [10]. Based on experience with the use of isobaric salt caverns for the storage of hydrogen (Teesside, UK), there are still CAES concepts encompassing the use of isobaric salt caverns with brine shuttle ponds [91,92].

The use of other geological underground formations has so far just been tested but has never been used commercially for air storage. Aquifer storage tests were carried out especially in the USA in the early 1980s. A good overview on results of a field test at the Pittsfield aquifer is given in [93,94]. Air injection and withdrawal generally was found to be feasible at Pittsfield, but various wells would have been needed to reach the air flow required, which would have led to increased drilling costs. In Europe, Italy showed some interest in aquifers for CAES purposes as well. In 1986, a test installation was put into operation at Sesta using an aquifer in a geothermal region at an underground temperature of 110 °C [95]. To summarize, it can be stated that compressed air storage in aquifers is generally feasible, but was not employed so far on a commercial basis, essentially due to the high risks of not being successful in drilling and in the site selection process. In the USA new interest in aquifers for CAES arose at the Dallas Center Iowa aquifer structure. Careful site examination by acoustic geophysical logs and model based analysis was undertaken [96]. Nevertheless the project was canceled because test results with the first well show much lower volume flow than planned [97].

Since geologic salt formations do not exist in Japan, the Japanese focus is on using exploited mines as compressed air reservoir. One site is reported at Kamioka in the Gifu prefecture using a former zinc mine at 1000 m depth for testing purposes [98]. A closed volume of 200 m^3 was created by sealing a part of the mine by a concrete plug. The cavern is filled to a maximum pressure of 7 bar, but air tightness could not be achieved since no measures for sealing the interior of the cavern were undertaken. Another Japanese testing cavern uses a former coal mine at Sunagawa in the Hokkaido prefecture [99]. The Sunagawa cavern is located at a depth of 450 m with a volume of 1600 m^3. Unlike the Kamioka cavern, the walls are equipped with concrete segments and back-filling concrete. Air tightness is successfully kept by an inner rubber sheet allowing for air pressures up to 80 bar [100]. Furthermore, [101] reports on a successful test of a CAES tank at 20 bar in an urban environment. The tank is made of reinforced concrete lowered into a shaft to a depth of 200 m. In Germany a project consortium examined the feasibility of exploited mines for CAES purposes [102]. A current project in Switzerland investigates the use of unused tunnels [103]. Beside these, the use of lined rock caverns (LRC) is another option for storing gas underground [104,105]. This concept is being examined for CAES purposes as well [106].

Another possibility to construct isobaric CAS is placing the storage volume not just below ground but under water. These so called subsea CAS use the geodetic height of the seawater above to realize a volume changing storage system at constant pressure. This can be done by direct contact of water and air in a solid structure constructed at the sea ground or by the use of flexible balloons fixed to the ground. These separate air and water physically and change their volume depending on the amount of air inside them [107]. Recently, an underwater CAES reference facility has been applied in Toronto using an underwater air storage in Lake Ontario [108].

Beside the isochoric and isobaric storage of compressed air, there is also the possibility to store the air as a liquid at cryogenic temperatures (Fig. 27). This technology has the following major characteristics:

- installable location-independent,
- low specific investment costs,
- low land consumption due to high energy density,
- need for liquefaction of the air.

The use of cryogenic storage requires a change in energy conversion technology as well. This so called liquid air energy storage (LAES) technology is not only related to CAES but also to air separation facilities. LAES layouts can be subdivided in diabatic, adiabatic and isothermal processes, just like CAES layouts. As the focus of this paper is on CAES technology, LAES is mentioned just for the sake of completeness. Detailed information can be found in the work of the Centre for Low Carbon Futures [109] and further literature [110–114].

8. Conclusions and outlook

In contrast to frequently published and cited expectations, CAES has not become a widespread storage technology competitive to PHES in the past decades. A variety of both technical and economic reasons for the limited success of CAES can be identified. Some of these reasons are general by nature, some are specific for certain national power grids and markets. The following list indicates some frequently cited reasons without being exhaustive.

Economic aspects:

- The changing conventional mix of power plants, together with the rise of large quantities of grid connected photovoltaics decreases the peak/off-peak price spread, which negatively affects the profitability of grid connected storage, especially those in energy shifting applications like CAES.
- With combined cycle gas turbines (CCGT) and fast starting hard coal plants more economical flexibility options in comparison the D-CAES have arisen over the decades.
- CAES show lower cycle efficiencies than PHES or batteries.
- A variety of measures like grid extension, more transparent ancillary services market and integration of decentralized generation by forming virtual power plants lead to comparably cheap short term flexibility reducing the need for grid connected storage short to mid-term.

Technical aspects:

- There is still no off-the-shelf machinery available that is suitable for highly efficient CAES plants, especially not for high-temperature adiabatic ones.
- Geological restrictions and uncertainties arose in exploring suitable sites for underground CAS.

Despite the current unfavorable framework conditions CAES is a comparably cheap storage technology for a typical discharge period of several hours to days. Such discharge periods today lack an economic case in various countries and markets due to the aspects indicated above. Nevertheless, CAES might become very attractive once there is an actual technical need and business case for such discharge periods in the power markets of the next decades.

Facing the technical and economic limitations mentioned above, several challenging issues for R&D of CAES can be identified:

- Flexibility in terms of short start-up times as well as fast ramping is needed to participate in ancillary services market.
- Site independent and low cost air reservoirs are needed.
- Decentralized CAES plants could be implemented at off-grid locations and might help to solve the challenges of renewable energy feed-in on the low voltage grid level.
- Heat storage devices with high power and energy densities are needed for the realization of A-CAES.
- (Turbo) machinery capable of being used as compressor and turbine (comparable to pump-turbines of PHES plants) could reduce the CAPEX of CAES.
- Motor-generators for direct driven turbo machinery at elevated rotational speed could increase the efficiency of compression and expansion processes.
- Tools for detailed simulations including, e.g., the performance of heat storage devices, effects related to humidity, part-load and dynamic operation of machinery, and finally of course the economic performance for realistic annual charge/discharge profiles need to be developed to enable fast and profound decisions when a storage technology has to be chosen for a certain application in a certain market scenario.

Beside these more technical issues the further development of renewable energy feed-in will be crucial for the implementation of CAES plants. From a higher point of view, the implementation of a broad mix of storage technologies will be necessary with increasing amounts of renewable energies. Herein, CAES, as a technology that is able to shift energy in the timeframe of some hours up to several days, fills the gap between short-term battery and long-term conversion storage technologies like Power-to-Gas (PtG).

However, the implementation and operation of storage technologies has to be economic. E.g. short-term battery storage devices are in economic operation in some applications already today. They are used in off-grid and self-consumption applications as well as for the provision of ancillary services on the lower grid levels. Mid-term technologies, like CAES, with typical energy shifting timelines from several hours to days might be used for similar business cases in the near future and for energy shifting later on. Energy conversion storage technologies (e.g. PtG) will be needed for long-term storage in the long run, if we assume that further development of intermittent renewable energies will result in significant amounts of excess energy not only over some hours during PV peak production but over several days as is the case for on- and especially offshore wind.

Nevertheless, newly built and economically operated CAES plants will probably be smaller than the existing ones. Huge plants like in Norton or still R&D-intensive high-temperature A-CAES process types will follow later on. This can already be observed in the field of I-CAES plants. Here, modular and decentralized pilot plants in the one-digit megawatt scale are in operation today. Other types of CAES which focus on huge plants have not set up operation yet. At small to medium scale, it is easier to overcome economic barriers for technology development – development costs are smaller and larger markets are expected in terms of deployed units. The ability to provide ancillary services, multifunctional market participation and off-grid solutions will be needed to set up business cases for CAES in the next years.

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