A General Approach to Compare A-CAES by Exergetic Analysis Considering the Real Gas Behavior of Air

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ABSTRACT

Exergy analysis is a widespread tool for the detailed analysis of energy systems. The present paper gives an overview of exergetic analysis principles and methodologies in the scope of Adiabatic Compressed Air Energy Storage (A-CAES) plants. Furthermore, a modified exergy balance methodology for the investigation of A-CAES based on splitting the physical exergy of material streams into its pressure and temperature related part. This methodology is independent of the property data used and thus applicable both when considering ideal and real gas behavior. The exergetic balancing methodology presented in this paper enables the evaluation of the charging and discharging process decoupled from time-dependent losses occurring in the thermal energy storage and in the compressed air storage volume. Therefore, a more reliable exergetic analysis of the complex process of A-CAES systems can be performed, which supports the determination of the optimal design of all components.

1 INTRODUCTION

The first two compressed air energy storage (CAES) plants were already commercially commissioned in 1978 (Huntorf, Germany) and 1991 (McIntosh, USA) (Quast, 1981; Goodson, 1992). Since then, however, the CAES technology has hardly been in focus and no new plants have been built for decades. Nevertheless, in recent years several demonstration plants have been built all over the world (Hydrostor, 2015; Mei *et al.*, 2015; Wang *et al.*, 2017; Geissbühler *et al.*, 2018). The first A-CAES plant has been commercially commissioned in Goderich (Ontario, USA) in 2019 and further commercial A-CAES plants are under construction in China today (Hydrostor, 2021; Tong *et al.*, 2021).

During the last decades, a large number of studies have been published, especially on adiabatic CAES (A-CAES). As summarized in (Budt, 2016; Wang *et al.*, 2017; Yu *et al.*, 2019), these studies investigate different plant layouts regarding to thermodynamics by means of analytical methods and simulation. Main motivation is to investigate the complex thermodynamic processes of A-CAES systems and to identify potential for improvement.

An important tool for the thermodynamic investigation of energy technology processes is the exergetic analysis. In comparison to an energetic analysis, the exergetic approach – introduced by the second law of thermodynamic – reveals the real quality and quantity of energy. Thus, thermodynamic inefficiencies of the overall process can be precisely identified, which helps to find the optimum design of components to reduce exergy destruction. Exergy analysis is especially useful for investigating A-CAES systems since electrical energy supplied during charging is converted in two different forms of energy. On the one hand into potential energy in the form of compressed air and on the other hand into thermal energy in the form of heat. In order to determine the actually usable part of the stored energy and its distribution, an exergetic analysis is essential. Hence, the exergetic analysis of adiabatic CAES is a proven method to investigate different plant concepts and is widely used in literature. However, there is a wide range of used methodology and thermodynamic assumptions in the respective studies.

Model type: static vs. dynamic

Exergetic studies based on static models are mainly carried out in combination with parameter studies (e.g. (Liu and Wang, 2016; Guo *et al.*, 2017; Mazloum *et al.*, 2017a; Han *et al.*, 2018; Qing *et al.*, 2019; Xue, 2019; Mozayeni *et al.*, 2019; Ghorbani *et al.*, 2020)). In general, these studies aim to investigate essential process interactions, where the dynamic process behavior is of less importance. Moreover, depending on the level of detail, the computing times of static models are significantly lower than those of dynamic models. This can be a decisive criterion, especially for extensive parameter studies.

Nevertheless, for a realistic evaluation and for the development of control strategies for A-CAES, static calculations reach their limits. This conclusion was already stated in early studies on A-CAES systems (Kreid, 1976). Accordingly, a dynamic model is required to simulate the behavior of adiabatic CAES more realistically and to determine key performance indicators, e.g. the efficiency and part load ability for a complete storage cycle, as exemplary examined in (Buffa *et al.*, 2013; Budt *et al.*, 2016; He *et al.*, 2017b; Guo *et al.*, 2019b; Guo *et al.*, 2019a; Zhang *et al.*, 2020). Especially the consideration of the temporal behavior of the thermal energy storage (TES) and the compressed air storage volume (CAS) is essential for a detailed analysis and suitable design of all system components.

Property data: ideal gas vs. real gas

The majority of publications examining exergetic investigations on CAES are considering ideal gas behavior of the compressed air (Hadam, 2021). This is a sufficient assumption for the general investigation of new plant concepts or sensitivity analyses. However, in A-CAES systems, the ambient air is usually compressed to a pressure level between 30 and 200 bar, depending on the nature or design of the compressed air storage volume. In this range, significant deviations between the real and ideal gas behavior can occur. Therefore, treating air as real gas is recommended to ensure appropriate accuracy for thermodynamic investigations, especially for the detailed analysis of a specific plant (Wolf, 2011; Budt, 2016; Budt *et al.*, 2016).

Exergy distribution

The separation of the physical exergy of air into its pressure and temperature related contributions is generally carried out to accurately determine the amount of exergy stored in the CAS (pressure related exergy) and in the TES (temperature related exergy) during the charging process. The application of the exergy distribution to examine an A-CAES process is done, for example, by (Yang *et al.*, 2014a; Budt *et al.*, 2016; Arabkoohsar *et al.*, 2017; Cárdenas *et al.*, 2017; He *et al.*, 2017a; Mazloum *et al.*, 2017b; He *et al.*, 2018; Cárdenas *et al.*, 2019; Guo *et al.*, 2020; Cárdenas and Garvey, 2023).

(Budt, 2016) furthermore considers the exergy distribution for the exergetic balancing of individual components to precisely identify the type of exergetic losses occurring in each. An exergetic analysis of A-CAES based on a combination of dynamic calculations, real gas property data of air and distribution of exergy into pressure and temperature related contributions has only been carried out by (Budt, 2016) so far. This exergetic approach is substantially modified and presented in this study.

The present paper gives an overview of relevant fundamentals of exergy and its separation into pressure and temperature related contributions. Furthermore, an overview of the common balancing methods used for exergetic analysis of A-CAES is provided. Finally, a modified method for the detailed exergy balancing of A-CAES plants based on separating the physical exergy into its pressure and temperature related part is presented.

2 Relevant principles of exergy and exergy distribution

This section gives a brief overview of the exergy equations, which are relevant for the exergetic balancing methodology presented in Section 3.2. Detailed information about specifics of exergy can be found in the appropriate literature (e.g. (Kotas, 1985; Fratzscher *et al.*, 1986; Dincer and Rosen, 2013)).

In the case of overall plant simulations and global balancing of compressed air systems in general and A-CAES in particular, the chemical, kinetic and potential exergy components of the exergy of a material flow are negligible. Thus only the term of physical exergy remains for the determination of the exergy of the material flow. (Dincer and Rosen, 2013; Budt, 2016)

$$\dot{E}_{ph} = \dot{m} \cdot [(h - h_a) - T_a\,(s - s_a)] \tag{2.1}$$

Therefore, the physical exergy $\dot{E}_{ph}$ is a function of the thermodynamic state variables (enthalpy h, entropy s) of the considered material flow and is strictly related to the reference ambient conditions (h_a, s_a, T_a). For reasons of better readability, the index "ph" is omitted in the following.

In the case of adiabatic CAES, the supplied electrical energy during charging is converted into potential and thermal energy. In order to determine the quantity of both forms of energy, it is helpful to split the physical exergy into pressure and temperature related contributions ($\dot{E}_p$ and $\dot{E}_T$) according to Eq. (2.2). (Budt *et al.*, 2016)

$$\dot{E} = \dot{E}_p + \dot{E}_T \tag{2.2}$$

The pressure and temperature related exergy contribution of a real, moist gas is determined according to Eq. (2.3) and Eq. (2.4). To calculate the pressure related exergy $\dot{E}_{p,real}$, the state variables at ambient temperature (p, T_a, X_w) are related to the reference state (p_a, T_a, X_w), which in this case corresponds to the ambient condition. The temperature related exergy $\dot{E}_{t,real}$ is calculated by considering the final state (p, T, X_w) and the state (p, T_a, X_w). The extension of the equations by the mass fraction of water X_w allows to consider the water load of gases. (Budt, 2016)

$$\dot{E}_{p,real} = \dot{m} \cdot \left[\big(h(p, T_a, X_w) - h(p_a, T_a, X_w)\big) - T_a\,\big(s(p, T_a, X_w) - s(p_a, T_a, X_w)\big)\right] \tag{2.3}$$

$$\dot{E}_{T,real} = \dot{m} \cdot \left[\big(h(p, T, X_w) - h(p, T_a, X_w)\big) - T_a\,\big(s(p, T, X_w) - s(p, T_{a,} X_w)\big)\right] \tag{2.4}$$

It has to be noted that this distribution is not unique and therefore has no fundamental relevance. In contrast to the ideal resp. perfect gas approach, the enthalpy of real gases is pressure and temperature dependent. When calculating the pressure related exergy contribution using Eq. (2.3) the real gas effect of enthalpy and entropy at high temperatures is not considered. However, in the field of compressed air systems, this effect is marginal. For processes, where the ideal and real gas behavior deviate greatly from each other, e.g. in supercritical CO_2 systems, significant deviations can occur. Nevertheless, the given equations for splitting the physical exergy of a material stream into its pressure and temperature related contributions are widespread in literature (Marmolejo-Correa and Gundersen, 2012; Morosuk and Tsatsaronis, 2019).

3 Exergetic balancing methodologies for thermodynamic investigations of A-CAES

Fundamental for the exergetic analysis of energy conversion systems is the used balancing methodology and the definition of the system boundary. The present section gives an overview of commonly applied exergy balancing methodologies of A-CAES in respective studies (Section 3.1) followed by the introduction of a modified methodology based on exergy distribution (Section 3.2).

The definition of system boundaries is crucial for the exergetic analysis of technical processes. Depending on the definition of the system boundaries resp. the control volume, the exergetic evaluation of an overall system, subsystem and/or a component can be performed. In general, the exergy balance for a control volume undergoing a stationary flow process is given by Figure 1. The flow of exergy entering and leaving the control volume are associated with the inlet and outlet exergy of the material flow, $\dot{E}_{in/out}$, work, $\dot{E}_{wt}$, and/or heat transfer, $\dot{E}_Q$, as well as the exergy of destruction due to irreversibilities, $\dot{E}_D$, within the control volume. If the exergy of the material flow leaving the control volume, $\dot{E}_{out}$, is not used in a following process or component but is dissipated to the environment, it corresponds to exergy losses. The associated exergy balance is given by Eq. (3.1) (Kotas, 1985)

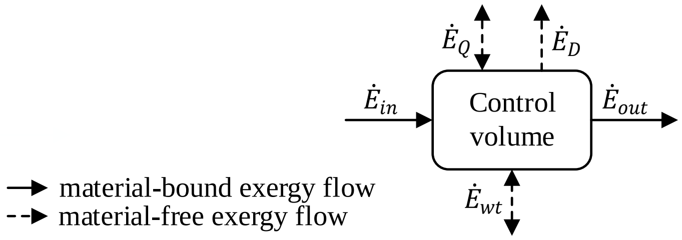

Figure 1: Exergy balance of control volume for a stationary flow process

$$0 = \dot{E}_{in} - \dot{E}_{out} \pm \dot{E}_{Wt} \pm \dot{E}_Q - \dot{E}_D \tag{3.1}$$

In transient flow processes in general and in adiabatic CAES in particular, exergy flows can vary during operation due to dynamic effects occurring during operation. In A-CAES systems, this is caused mainly due to the transient behavior of the Compressed Air Storage (CAS) and the Thermal Energy Storage (TES). In order to carry out a reliable analysis based on exergetic key figures, the quantity of exergy of a full storage cycle $E_i(t)$ have to be calculated. This is done by integrating the corresponding exergy flow $\dot{E}_i(t)$ over the period under consideration Eq. (3.2). The exergetic analysis presented in the following refers to the integrated exergy flows.

$$E_i(t) = \int_{t1}^{t2} \dot{E}_i(t)dt \tag{3.2}$$

3.1 Conventional exergetic balancing methodologies of A-CAES

The exergetic balancing methods used in the literature to investigate A-CAES systems can be classified in three different categories:

- Balancing of the overall system to determine the overall plant efficiency
- Balancing of each component to determine the distribution of losses within the plant
- Balancing and evaluation of charging and discharging process

A low number of publications the exergetic analysis is only used to calculate the overall plant efficiency (Grazzini and Milazzo, 2008; Pickard *et al.*, 2009; Facci *et al.*, 2015). In most studies considered in this paper, the exergetic analysis of the overall plant is extended by a component-based balancing (Nielsen, 2013; Buffa *et al.*, 2013; Peng *et al.*, 2016; Ji *et al.*, 2017; Mazloum *et al.*, 2017a; Szablowski *et al.*, 2017; Han *et al.*, 2018; He *et al.*, 2018; Xue, 2019; Ebrahimi *et al.*, 2019; Dooner and Wang, 2019; Zhang *et al.*, 2020; Han *et al.*, 2020; Ghorbani *et al.*, 2020; Budt, 2016). This approach allows to allocate the exergy losses occurring in the overall system to individual components. Therefore, the component-based exergy analysis is well suited for determining the optimum design of components to reduce exergy destruction.

The calculation of the overall plant efficiency has a limited validity due to different thermodynamic assumptions and different system configurations between published studies. Thus, in several studies the exergetic balancing of adiabatic CAES is carried out by separating the overall system in charging and discharging process (Nielsen, 2013; Buffa *et al.*, 2013; Yang *et al.*, 2014a; Budt, 2016; Arabkoohsar *et al.*, 2017; Guo *et al.*, 2019a; Xue, 2019; Guo *et al.*, 2019b; Guo *et al.*, 2020). This allows the calculation of sub-process efficiencies and thus a more quantitatively comparison between different A-CAES plant layouts. Since the modified exergetic balancing methodology presented in this paper is based on this approach, it is described in more detail in the following.

The common methodology of splitting the overall system in charging and discharging process for exergetic analysis is illustrated using a simple A-CAES layout with a thermal energy storage in form of a 2-tank water system (Figure 2).

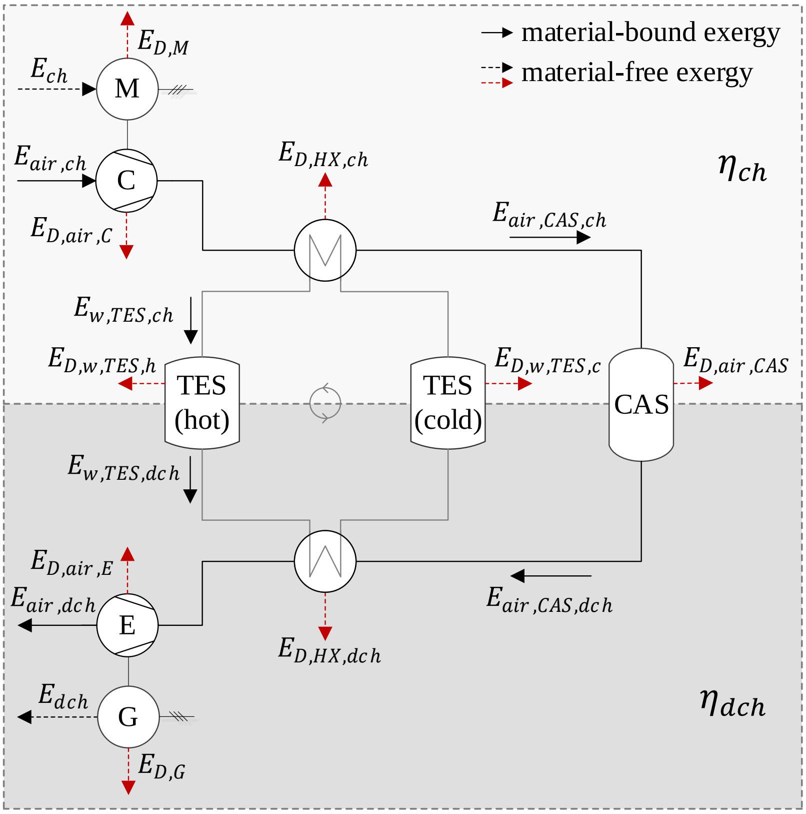

Figure 2: Relevant exergetic balance values to determine the charging and discharging efficiency $\boldsymbol{\eta_{ch/dch}}$ as well as exergy losses of the main components $\boldsymbol{E_{D,i}}$ of a simplified A-CAES

Exergy losses occurring in the main components due to irreversibility and dissipation of heat are represented by the term $E_{D,i}$ (Figure 2). In charging process, the supplied electrical exergy E_{ch} is used to drive a motor (M) driven compressor (C) which compresses ambient air to a given pressure. The heated compressed air is cooled down in a heat exchanger and stored in the CAS with the exergy $E_{air,CAS,ch}$. Most of the temperature related exergy of the compressed air is supplied to the heat storage medium (water) via the heat exchanger, which is then stored in the hot TES with the exergy $E_{w,TES,ch}$. During the discharging process, compressed air with the exergy $E_{air,CAS,dch}$ is released from the CAS. In the heat exchanger, temperature related exergy of the storage medium (water) $E_{w,TES,ch}$ is supplied to the exergy of compressed air. The heated compressed air is then expanded via an expander (E), which drives a generator to produce electricity during discharging E_{dch}.

By separating the overall process in charging and discharging process, both processes can be evaluated independently. According to the exergy balancing illustrated in Figure 2, the efficiency of the charging process η_{ch} is the ratio between the charged exergy in the CAS, $E_{air,CAS,ch}$ and TES $E_{w,TES,ch}$ to the exergy supplied to the process E_{ch} (Eq. 3.3). The discharging efficiency η_{dch} indicates how efficiently the temporarily stored exergy in the CAS and TES is converted into electricity E_{dch} again (Eq. 3.4).

$$\eta_{ch} = \frac{E_{air,CAS,ch} + E_{w,TES,ch}}{E_{ch}} \qquad (3.3)$$

$$\eta_{dch} = \frac{E_{dch}}{E_{air,CAS,dch} + E_{w,TES,dch}} \qquad (3.4)$$

To determine the sub process efficiencies, additional exergy consumption, e.g. due to the operation of circulation pumps, must also be considered. However, the separation into charging and discharging process is not consistent in respective studies. Particularly in dynamic process simulations and when considering transient thermal exergy losses in the CAS and TES, the respective charged and discharged exergy differs. The exergy losses occurring in the CAS and TES are generally allocated to the charging efficiency (like illustrated in Figure 2). When performing a steady-state calculation resp. when neglecting these losses, the stored and released exergy of the storage units are identical ($E_{air,CAS,ch}$ = $E_{air,CAS,dch}$ and $E_{w,TES,ch}$ = $E_{w,TES,dch}$) and are usually denoted as E_{CAS} and E_{TES}. The multiplication of both sub-process efficiencies yields to the overall system efficiency η_{CAES} (Eq. 3.5).

$$\eta_{CAES} = \eta_{ch} \cdot \eta_{dch} \tag{3.5}$$

3.2 Modified exergetic balancing methodology

Further development and modification of the commonly used exergetic balancing methodology for A-CAES is presented in the following. Basis of the approach is the distribution of the physical exergy into its temperature and pressure related parts (Chapter 2). For a more detailed allocation of occurring exergetic losses, the overall system is split up into three parts: charging, storage and discharging process (Figure 3).

Efficiency of the charging and discharging process

The evaluation of the energy conversion process during the charging process is carried out by considering the sub-system consisting of motor (M), compressor (C), air-side part of the heat exchanger, pipes as well as other air-carrying components like condensers with the corresponding exergy losses $E_{D,M}$, $E_{D,C}$ and $E_{D,air,HX,ch}$ (Figure 3). Thus, in contrast to conventional balancing, only the working fluid air is considered to calculate the charging efficiency. As a result, the exergetic charging efficiency η_{ch} is calculated by the exergy supplied to the CAS $E_{air,CAS,ch}$ and TES $E_{T,air,TES,ch}$, by compressed air and the electricity E_{ch} required to drive the compressors (Eq. 3.6). The term $E_{T,air,TES,ch}$ corresponds to the integrated temperature related exergy (see Eq. 2.4) derived from the compressed air and transferred to the storage medium.

$$\eta_{ch} = \frac{E_{air,CAS,ch} + E_{T,air,TES,ch}}{E_{ch}} \tag{3.6}$$

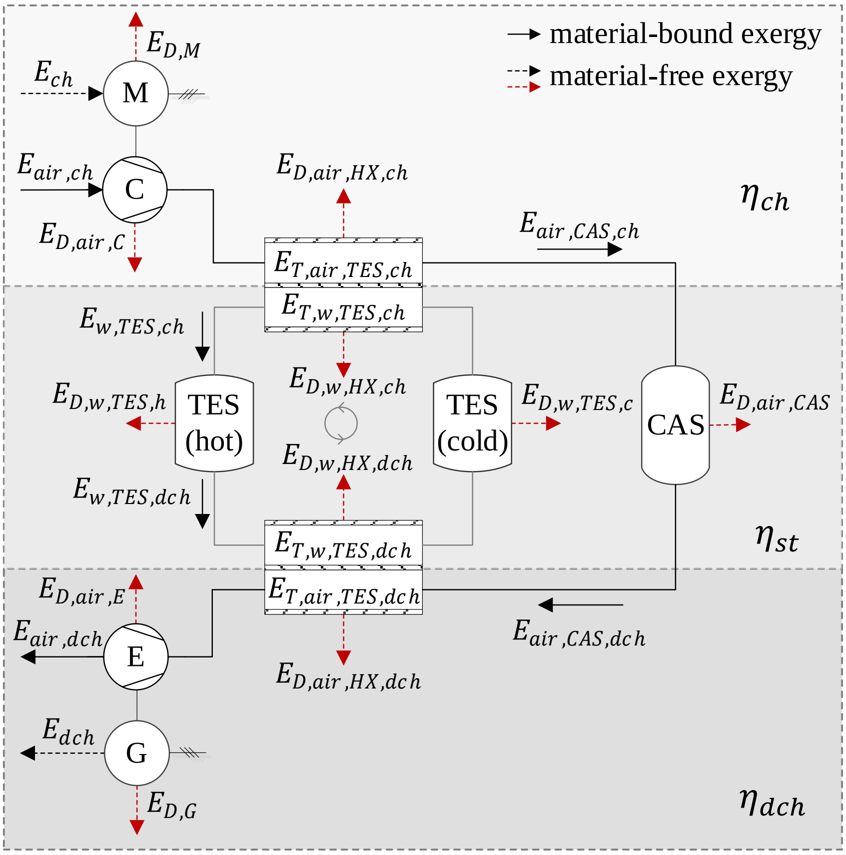

Figure 3: Relevant exergetic balance values to determine the charging, storage and discharging efficiency $\boldsymbol{\eta_{ch/st/dch}}$ as well as exergy losses of the main components $\boldsymbol{E_{D,i}}$ of a simplified A-CAES

The exact division between charging and storage process is illustrated by the detailed exergetic balancing of the heat exchanger in Figure 4. The exergetic quantities of the air and water side are strictly separated, leading to an exergy balance according to Eqs. (3.7) and (3.8). Additionally, the exergy of air and water at the inlet and outlet of the heat exchanger $E_{air,HX,in/out}$ and $E_{w,HX,in/out}$ is spitted in its pressure and temperature related contribution $E_{p/T,i}$. Air-sided exergy losses in the heat exchanger due to pressure losses $E_{D,air,dp}$ and heat losses to the environment $E_{D,air,Q}$ are allocated to the charging process (Eq. 3.7). Water-sided exergy destruction due to heat and pressure losses $E_{D,w,Q}$ and $E_{D,w,dp}$ as well as due to the temperature difference required for heat transfer $E_{D,w,dt}$ are allocated to the storage process (Eq. 3.8). The temperature related exergy supplied to the water during charging $E_{T,w,TES,ch}$ is equal to the temperature related exergy provided by compressed air minus exergy losses caused by the temperature difference $E_{D,w,dt}$ (Eq. 3.9).

$$E_{air,HX,out} = E_{air,HX,in} - E_{T,air,TES,ch} - E_{D,air,dp} - E_{D,air,Q} \qquad (3.7)$$

$$E_{w,HX,out} = E_{w,HX,in} + E_{T,air,TES,ch} - E_{D,w,dp} - E_{D,w,Q} - E_{D,w,dt} \qquad (3.8)$$

$$E_{T,w,TES,ch} = E_{T,w,TES,ch} - E_{D,w,dt} \qquad (3.9)$$

The exergy of the material flow of air leaving the heat exchanger $E_{air,HX,out}$ correspond to the exergy supplied to the CAS $E_{air,CAS,ch}$ (Figure 3), if no additional pressure or thermal losses in pipes or other components as well as condensing water are considered. In typical system layouts of adiabatic CAES, the heated compressed air after compression is cooled down near to ambient temperature via heat exchanger before it is supplied to the CAS. Therefore, the temperature related exergy of air is almost completely supplied to the TES. Consequently, the physical exergy of the compressed air at the outlet of the heat exchanger $E_{air,HX,out}$ consists almost exclusively of the pressure related part $E_{p.air,HX,out}$.

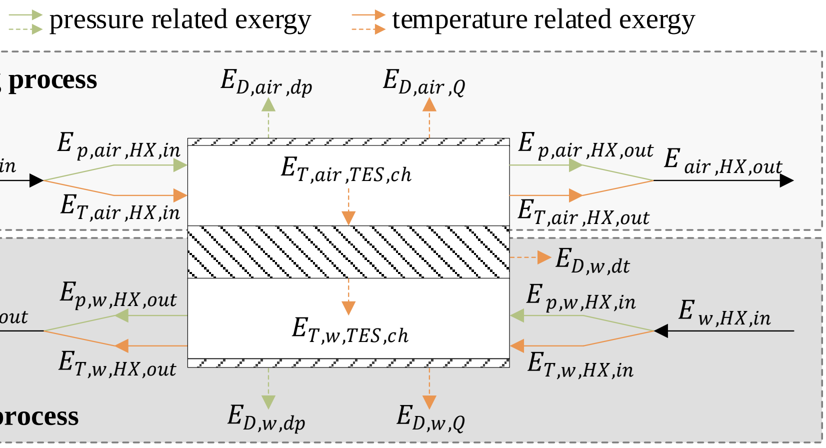

Figure 4: Exergy balance of the heat exchanger and separation of charging and storage process by determine the pressure and temperature related exergy of material streams

The separation of the balance variables of working and heat storage medium enables the evaluation of the charging process independently of exergetic losses occurring in both storage systems (CAS and TES) and water-sided losses during heat transfer. By applying the balancing method presented, the exergetic charging efficiency (Eq. 3.6) represent the efficiency of the primary working cycle (air sided components). In most studies performing exergetic analysis of A-CAES, the effectivity of the CAS and TES is included when calculating the efficiency of the charging process (see Figure 2).

The discharging process is not discussed in detail in the present work since the methodology of the exergy balance is analogous to the charging process. The efficiency of the discharging process η_{dch} is determined by Eq. (3.10). This subprocess efficiency indicates how efficiently the exergy released from the CAS $E_{air,CAS,dch}$ and temperature related exergy supplied by the TES $E_{T,air,TES,dch}$ is converted into electricity E_{dch}.

$$\eta_{dch} = \frac{E_{dch}}{E_{air,CAS,dch} + E_{T,air,TES,dch}} \tag{3.10}$$

Efficiency of the storage process

The exergetic balancing of the storage process includes the temporally storing of exergy in CAS and TES as well as the water-sided part of the heat transfer processes during charging and discharging (Figure 3). Consequently, time-dependent losses - primarily caused by thermal losses in the CAS and TES - as well as losses during heat transfer due to the necessary temperature gradient and mixing of material flows are considered when calculating the storage efficiency. Required auxiliary energy for electrical consumers are also taken into account. As a result, the efficiency of the storage process η_{st} is calculating by the efficiency of CAS η_{CAS} and TES η_{TES} (Eq. 3.11). The storage efficiencies are weighted by the terms $x_{air,CAS,ch}$ and $x_{air,TES,ch}$, which correspond to the respective share of exergy provided by the compressed air in to the storage systems during the charging process ($E_{air,CAS,ch}$ and TES $E_{T,air,TES,ch}$ in Figure 3) according to Eq. (3.12).

The distribution of the supplied exergy into CAS and TES is significantly determined by the A-CAES plant layout and the resulting process temperatures as well as the implemented heat management.

$$\eta_{st} = x_{air,CAS,ch} \cdot \eta_{CAS} + x_{air,TES,ch} \cdot \eta_{TES} \tag{3.11}$$

$$x_{air,CAS,ch} = \frac{E_{air,CAS,ch}}{E_{air,CAS,ch} + E_{T,air,TES,ch}} \qquad x_{air,TES,ch} = \frac{E_{T,air,TES,ch}}{E_{air,CAS,ch} + E_{T,air,TES,ch}} \tag{3.12}$$

The efficiency of the TES η_{TES} is defined by the temperature related exergy supplied to the TES by the compressed air during charging $E_{T,air,TES,ch}$ and the temperature related exergy released during discharging $E_{T,air,TES,dch}$ (Eq. 3.13).

$$\eta_{TES} = \frac{E_{T,air,TES,dch}}{E_{T,air,TES,ch}} \tag{3.13}$$

The efficiency of the CAS η_{CAS} is analogously calculated by the exergy of compressed air supplied to the CAS $E_{air,CAS,ch}$ and released from the CAS $E_{air,CAS,dch}$ (3.14).

$$\eta_{CAS} = \frac{E_{air,CAS,dch}}{E_{air,CAS,ch}} \tag{3.14}$$

The efficiency of the TES is usually in the range of 50-90 °C depending on the storage temperature, used technology, design, insulation and downtime. In contrast, an efficiency of over 95 % are usually achieved when storing compressed air in CAS. Due to the lower losses in the CAS and the higher value of potential energy compared to thermal energy, electrical energy supplied into the A-CAES should be primarily converted into pressure related exergy to achieve high overall plant efficiencies. Due to thermodynamic laws, however, this is only possible to a limited extent. A typical range of the share of exergy stored in the TES $x_{air,TES,ch}$ in A-CAES plants is between 10 % and 40 %. The share of exergy stored in the TES is strongly dependent on the overall pressure ratio, efficiency and number of compression stages as well as the heat management. However, the lower share of stored exergy in the TES reduces the influence of its high losses on the overall efficiency (see Eq. 3.11).

In contrast to exergy losses in the TES, losses in the CAS have a direct influence on the overall efficiency of an A-CAES. Nevertheless, in most thermodynamic studies regarding A-CAES (e.g. (Wolf, 2011; Zhang *et al.*, 2013; Yang *et al.*, 2014b; Budt, 2016; Szablowski *et al.*, 2017; Ghorbani *et al.*, 2020; Ji *et al.*, 2017; Arabkoohsar *et al.*, 2017)) the CAS is modeled simplified by assuming an isothermal or adiabatic behavior. Both assumptions resulting to a CAS efficiency of 100 %, whereas an adiabatically charging and discharging of compressed air additionally leads to temperature fluctuations in the storage volume reducing the amount of exergy that can be stored. However, for a more realistic calculation of the efficiency of the CAS and thus evaluation of the overall plant process, the consideration of a diabatic CAS model is essential. This is especially the case for decentralized A-CAES concepts with smaller storage volumes. (Hadam, 2021)

Efficiency of the overall system

The evaluation of the overall A-CAES plant is determined by the efficiency of the overall system η_{CAES}, which is calculated by multiplying the efficiencies of the three sub-processes charging, storage and discharging according to Eq (3.15).

$$\eta_{CAES} = \eta_{ch} \cdot \eta_{st} \cdot \eta_{dch} \tag{3.15}$$

The separation of the overall plant process into three sub-processes enables a more detailed exergetic analysis of A-CAES systems. This is achieved by decoupling the charging and discharging process from time-dependent exergy losses occurring in the CAS and TES as well as of exergy losses of the heat transfer medium. Thus, losses due to temperature gradients, thermal losses in heat exchangers and especially time-dependent thermal losses in the storage reservoirs are not considered when calculating the efficiency of charging and discharging process.

The aforementioned advantages of separating the overall system of an A-CAES and to determine sub-process efficiencies are also partly presented in recent publications of the Chinese research group [Guo et al. 2020]. A significant difference compared to the methodology used in this work is the consideration of losses occurring during heat transfer - e.g. in the form of mixing, pressure losses in the heat storage medium and temperature differences - for the determination of the charging and discharging efficiency. In contrast, the balancing method presented in this paper includes these exergy losses to calculate the efficiency of the TES. This allows an improved comparison of different thermal energy storage concepts (e.g. passive or active, direct or indirect) used in published A-CAES plant layouts. Furthermore, the exergetic balancing carried out by [Guo et al. 2020] is based on ideal gas behavior and only considers pressure related exergy supplied to and removed from the CAS during charging resp. discharging. However, in real A-CAES processes the compressed air supplied to the CAS always contains a certain amount of temperature related exergy, which must be taken into account when evaluating the storage efficiency. This applies in particular to A-CAES considering smaller CAS volumes, where the charged compressed air is heated up significantly. On the one hand, this leads to a lower usable storage volume due to lower density of the compressed air and to considerable thermal losses during operation.

4 CONCLUSIONS

The present paper is focusing on basic principles as well as the application of exergetic analyses on A-CAES considering real gas properties of humid air. Exergetic analysis is a well-proven tool to investigate the complex thermodynamic processes and interrelationships in A-CAES.

Many studies performing exergetic investigations on A-CAES are available in literature. However, the considered thermodynamic assumptions as well as the methodical approach are different. The models used for the exergetic analyses are a mixture of static and dynamic ones, mostly treating air as ideal gas. The splitting of the physical exergy into its pressure and temperature related contributions is only done in few studies.

According to the author's knowledge, there are no exergetic studies of A-CAES in which the A-CAES system is divided into the three sections of charging, storage and discharging process according to the method presented in this paper. Furthermore, an exergetic analysis of A-CAES based on a combination of dynamic calculations, real gas property data of humid air and exergy distribution has only been carried out by (Budt, 2016) so far. In the scope of the present work, a modified exergetic balancing methodology for the evaluation of A-CAES addressing both aforementioned aspects is presented.

The modified exergetic balancing methodology for A-CAES enables a more detailed allocation of occurring losses to specific process sections of the system. By using the modified method, charging and discharging process is decoupled from the storage process and thus from time-dependent losses occurring in CAS and TES. Doing so, the influence of various input parameters on sub-process efficiencies can be calculated and evaluated more detailed. Doing so, the understanding of the complex dynamic processes occurring in a storage cycle of an A-CAES can be improved, which can help to determine more reliable optimal designs of all components. Additionally, an improved comparability of different published A-CAES plant layouts is achieved when the three sub process efficiencies presented in this paper are calculated. The introduced exergy approach can also be applied to different industrial processes, especially when multiple forms of energy and heat storages are involved.

REFERENCES

Arabkoohsar, A., Dremark-Larsen, M., Lorentzen, R. and Andresen, G.B. (2017), “Subcooled compressed air energy storage system for coproduction of heat, cooling and electricity”, *Applied Energy*, Vol. 205, pp. 602–614.

Budt, M. (2016), *Thermodynamische Analyse adiabater Druckluftenergiespeicher unter Berücksichtigung feuchter Luft und Wassereinspritzung mittels dynamischer Simulation*, Dissertation, *UMSICHT-Schriftenreihe*, Band 81, Karl Maria Laufen, Oberhausen.

Budt, M., Wolf, D., Span, R. and Yan, J. (2016), “A Review on Compressed Air Energy Storage. Basic principles, past milestones and recent developments”, *Applied Energy*, Vol. 170, pp. 250–268.

Buffa, F., Kemble, S., Manfrida, G. and Milazzo, A. (2013), “Exergy and Exergoeconomic Model of a Ground-Based CAES Plant for Peak-Load Energy Production”, *Energies*, Vol. 6 No. 3, pp. 1050–1067.

Cárdenas, B. and Garvey, S. (2023), “A directly charged thermal store for compressed air energy storage systems”, *Journal of Energy Storage*, Vol. 71, p. 108183.

Cárdenas, B., Hoskin, A., Rouse, J. and Garvey, S.D. (2019), “Wire-wound pressure vessels for small scale CAES”, *Journal of Energy Storage*, Vol. 26, p. 100909.

Cárdenas, B., Pimm, A.J., Kantharaj, B., Simpson, M.C., Garvey, J.A. and Garvey, S.D. (2017), “Lowering the cost of large-scale energy storage: High temperature adiabatic compressed air energy storage”, *Propulsion and Power Research*, Vol. 6 No. 2, pp. 126–133.

Dincer, I. and Rosen, M.A. (2013), *Exergy: Energy, environment and sustainable development,* 2nd ed, Elsevier Science, Oxford.

Dooner, M. and Wang, J. (2019), “Potential Exergy Storage Capacity of Salt Caverns in the Cheshire Basin Using Adiabatic Compressed Air Energy Storage”, *Entropy*, Vol. 21 No. 11, p. 1065.

Ebrahimi, M., Carriveau, R., Ting, D.S.-K. and McGillis, A. (2019), “Conventional and advanced exergy analysis of a grid connected underwater compressed air energy storage facility”, *Applied Energy*, Vol. 242, pp. 1198–1208.

Facci, A.L., Sánchez, D., Jannelli, E. and Ubertini, S. (2015), “Trigenerative micro compressed air energy storage. Concept and thermodynamic assessment”, *Applied Energy*, Vol. 158, pp. 243–254.

Fratzscher, W., Brodjanskij, V.M. and Michalek, K. (1986), *Exergie: Theorie u. Anwendung,* 1. Aufl, Deutscher Verlag für Grundstoffindustrie, Leipzig.

Geissbühler, L., Becattini, V., Zanganeh, G., Zavattoni, S., Barbato, M., Haselbacher, A. and Steinfeld, A. (2018), “Pilot-scale demonstration of advanced adiabatic compressed air energy storage, Part 1: Plant description and tests with sensible thermal-energy storage”, *Journal of Energy Storage*, Vol. 17, pp. 129–139.

Ghorbani, B., Mehrpooya, M. and Ardehali, A. (2020), “Energy and exergy analysis of wind farm integrated with compressed air energy storage using multi-stage phase change material”, *Journal of Cleaner Production*, Vol. 259, p. 120906.

Goodson, J. (1992), *History of first U.S. Compressed Air Energy Storage (CAES) Plant (110-MW-26h): Volume 1: Early CAES Development*, Final Report.

Grazzini, G. and Milazzo, A. (2008), “EXERGY ANALYSIS OF A CAES WITH THERMAL ENERGY STORAGE”, 18.-22. Mai, Eindhoven.

Guo, C., Xu, Y., Guo, H., Zhang, X., Lin, X., Wang, L., Zhang, Y. and Chen, H. (2019a), “Comprehensive exergy analysis of the dynamic process of compressed air energy storage system with low-temperature thermal energy storage”, *Applied Thermal Engineering*, Vol. 147, pp. 684–693.

Guo, H., Xu, Y., Chen, H., Guo, C. and Qin, W. (2017), “Thermodynamic analytical solution and exergy analysis for supercritical compressed air energy storage system”, *Applied Energy*, Vol. 199, pp. 96–106.

Guo, H., Xu, Y., Guo, C., Zhang, Y., Hou, H. and Chen, H. (2019b), “Off-design performance of CAES systems with low-temperature thermal storage under optimized operation strategy”, *Journal of Energy Storage*, Vol. 24, p. 100787.

Guo, H., Xu, Y., Zhang, X., Zhou, X. and Chen, H. (2020), “Transmission characteristics of exergy for novel compressed air energy storage systems-from compression and expansion sections to the whole system”, *Energy*, Vol. 193, p. 116798.

Hadam, M. (2021), “Thermodynamische Analyse eines modularen A-CAES mit umkehrbar betreibbaren Turbo- und Kolbenmaschinen”, Dissertation, Ruhr-Universität Bochum, Fakultät für Maschinenbau, Bochum, 2021.

Han, Z., Guo, S., Wang, S. and Li, W. (2018), “Thermodynamic analyses and multi-objective optimization of operation mode of advanced adiabatic compressed air energy storage system”, *Energy Conversion and Management*, Vol. 174, pp. 45–53.

Han, Z., Sun, Y. and Li, P. (2020), “Thermo-economic analysis and optimization of a combined cooling, heating and power system based on advanced adiabatic compressed air energy storage”, *Energy Conversion and Management*, Vol. 212, p. 112811.

He, W., Luo, X., Evans, D., Busby, J., Garvey, S., Parkes, D. and Wang, J. (2017a), “Exergy storage of compressed air in cavern and cavern volume estimation of the large-scale compressed air energy storage system”, *Applied Energy*, Vol. 208, pp. 745–757.

He, W., Wang, J., Wang, Y., Ding, Y., Chen, H., Wu, Y. and Garvey, S. (2017b), “Study of cycle-to-cycle dynamic characteristics of adiabatic Compressed Air Energy Storage using packed bed Thermal Energy Storage”, *Energy*, Vol. 141, pp. 2120–2134.

He, Y., Chen, H., Xu, Y. and Deng, J. (2018), “Compression performance optimization considering variable charge pressure in an adiabatic compressed air energy storage system”, *Energy*.

Hydrostor (2015), *Hydrostor Activates World's First Utility-Scale Underwater Compressed Air Energy Storage System*, Press Release.

Hydrostor (2021), *Projects*.

Ji, W., Zhou, Y., Sun, Y., Zhang, W., An, B. and Wang, J. (2017), “Thermodynamic analysis of a novel hybrid wind-solar-compressed air energy storage system”, *Energy Conversion and Management*, Vol. 142, pp. 176–187.

Kotas, T.J. (1985), *The exergy method of thermal plant analysis*, Butterworths, London, Boston.

Kreid, D.K. (1976), *Technical and Economic Feasibility Analysis of the No-Fuel Compressed Air Energy Storage Concept*, Richland, WA.

Liu, J.-L. and Wang, J.-H. (2016), "A comparative research of two adiabatic compressed air energy storage systems", *Energy Conversion and Management*, Vol. 108, pp. 566–578.

Marmolejo-Correa, D. and Gundersen, T. (2012), "A comparison of exergy efficiency definitions with focus on low temperature processes", *Energy*, Vol. 44 No. 1, pp. 477–489.

Mazloum, Y., Sayah, H. and Nemer, M. (2017a), "Exergy analysis and exergoeconomic optimization of a constant-pressure adiabatic compressed air energy storage system", Vol. 14, pp. 192–202.

Mazloum, Y., Sayah, H. and Nemer, M. (2017b), "Exergy analysis and exergoeconomic optimization of a constant-pressure adiabatic compressed air energy storage system", *Journal of Energy Storage*, Vol. 14, pp. 192–202.

Mei, S., Wang, J., Tian, F., Chen, L., XUE, X., LU, Q., Zhou, Y. and Zhou, X. (2015), "Design and engineering implementation of non-supplementary fired compressed air energy storage system: TICC-500", *Science China Technological Sciences*, Vol. 58 No. 4, pp. 600–611.

Morosuk, T. and Tsatsaronis, G. (2019), "Splitting physical exergy: Theory and application", *Energy*, Vol. 167, pp. 698–707.

Mozayeni, H., Wang, X. and Negnevitsky, M. (2019), "Exergy analysis of a one-stage adiabatic compressed air energy storage system", *Energy Procedia*, Vol. 160, pp. 260–267.

Nielsen, L. (2013), *GuD-Druckluftspeicherkraftwerk mit Wärmespeicher*, Vol. 14, Cuvillier Verlag, Göttingen.

Peng, H., Yang, Y., Li, R. and Ling, X. (2016), "Thermodynamic analysis of an improved adiabatic compressed air energy storage system", *Applied Energy*, Vol. 183, pp. 1361–1373.

Pickard, W.F., Hansing, N.J. and Shen, A.Q. (2009), "Can large-scale advanced-adiabatic compressed air energy storage be justified economically in an age of sustainable energy?", *Journal of Renewable and Sustainable Energy*, Vol. 1 No. 3, pp. 1–10.

Qing, H., Lijian, W., Qian, Z., Chang, L., Du Dongmei and Wenyi, L. (2019), "Thermodynamic analysis and optimiziation of liquefied air energy storage system", *Energy*.

Quast, P. (1981), "The Huntorf Plant: Over 3 Years operating experience with compressed air caverns", paper presented at International Conference on Seazonal Energy Storage and Compressed Air Energy Storage, 19.-21.10.1981, Seattle, Washington.

Szablowski, L., Krawczyk, P., Badyda, K., Karellas, S., Kakaras, E. and Bujalski, W. (2017), "Energy and exergy analysis of adiabatic compressed air energy storage system", *Energy*, Vol. 138, pp. 12–18.

Tong, Z., Cheng, Z. and Tong, S. (2021), "A review on the development of compressed air energy storage in China: Technical and economic challenges to commercialization", *Renewable and Sustainable Energy Reviews*, Vol. 135, p. 110178.

Wang, J., Lu, K., Ma, L., Wang, J., Dooner, M., Miao, S., Li, J. and Wang, D. (2017), "Overview of Compressed Air Energy Storage and Technology Development", *Energies*, Vol. 10 No. 7, p. 991.

Wolf, D. (2011), *Methods for design and application of adiabatic compressed air energy: Storage based on dynamic modeling*, Dissertation, Karl Maria Laufen, Oberhausen.

Xue, H. (2019), "A comparative analysis and optimisation of thermo-mechanical energy storage technologies", Apollo - University of Cambridge Repository, 2019.

Yang, K., Zhang, Y., Li, X. and Xu, J. (2014a), "Theoretical evaluation on the impact of heat exchanger in Advanced Adiabatic Compressed Air Energy Storage system", *Energy Conversion and Management*, Vol. 86, pp. 1031–1044.

Yang, Z., Wang, Z., Ran, P., Li, Z. and Ni, W. (2014b), "Thermodynamic analysis of a hybrid thermal-compressed air energy storage system for the integration of wind power", *Applied Thermal Engineering*, Vol. 66 1-2, pp. 519–527.

Yu, Q., Wang, Q., Tan, X., Fang, G. and Meng, J. (2019), "A review of compressed-air energy storage", *Journal of Renewable and Sustainable Energy*, Vol. 11 No. 4, p. 42702.

Zhang, W., XUE, X., Liu, F. and Mei, S. (2020), "Modelling and experimental validation of advanced adiabatic compressed air energy storage with off-design heat exchanger", *IET Renewable Power Generation*, Vol. 14 No. 3, pp. 389–398.

Zhang, Y., Yang, K., Li, X. and Xu, J. (2013), "The thermodynamic effect of air storage chamber model on Advanced Adiabatic Compressed Air Energy Storage System", *Renewable Energy*, Vol. 57, pp. 469–478.