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Efficiency of Compressed Air Energy Storage

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Abstract:

The simplest type of a Compressed Air Energy Storage (CAES) facility would be an adiabatic process consisting only of a compressor, a storage and a turbine, compressing air into a container when storing and expanding when producing. This type of CAES would be adiabatic and would if the machines were reversible have a storage efficiency of 100%. However, due to the specific capacity of the storage and the construction materials the air is cooled during and after compression in practice, making the CAES process diabatic. The cooling involves exergy losses and thus lowers the efficiency of the storage significantly.

The efficiency of CAES as an electricity storage may be defined in several ways, we discuss these and find that the exergetic efficiency of compression, storage and production together determine the efficiency of CAES. In the paper we find that the efficiency of the practical CAES electricity storage is 25-45% and thus has a quite low efficiency, which is close to the efficiency of the simple diabatic CAES-process. Adiabatic CAES would reach significantly higher storage efficiency about 70-80%.

Keywords:

Compressed Air Energy Storage, Electricity storage, Exergy analysis

Nomenclature

| | |
|------------------------|------------------------------------|
| E_1 | Exergy to compressor inlet [MJ] |
| E_2 | Exergy to storage inlet [MJ] |
| E_3 | Exergy from storage outlet [MJ] |
| E_4 | Exergy from turbine outlet [MJ] |
| E_f | Exergy of inlet fuel [MJ] |
| Q_f | Fuel energy input [MJ] |
| W_c | Compressor work [MJ] |
| W_t | Turbine work [MJ] |
| η_s | Isentropic efficiency |
| η_{char} | Charging efficiency |
| η_{disc} | Discharging efficiency |
| η_{ee} | Energy efficiency |
| η_{pe} | Primary Energy efficiency |
| η_{sc} | Storage efficiency |
| η_{stor} | Cavern efficiency |
| η_{sys} | System electric efficiency |
| η_{th} | Thermal efficiency |
| $\eta_{x,c}$ | Exergetic efficiency of compressor |
| $\eta_{x,\text{stor}}$ | Exergetic efficiency of storage |
| $\eta_{x,t}$ | Exergetic efficiency of turbine |

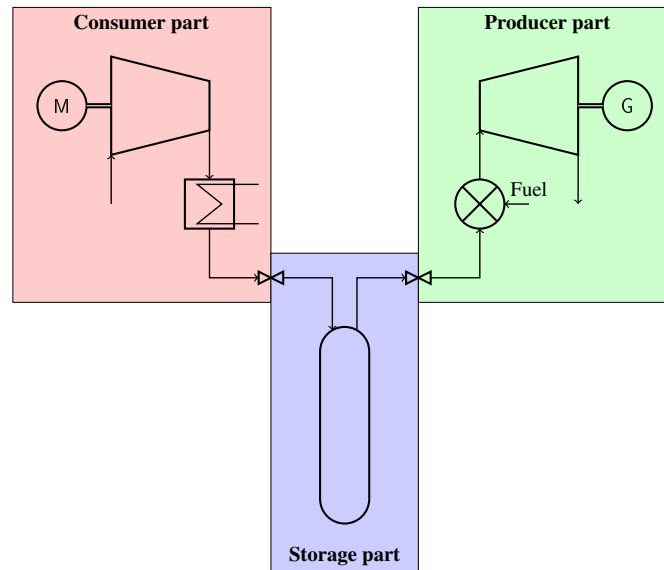


Figure 1: Diagram of the principle of a conventional, diabatic CAES plant

1. Introduction

Globally the introduction of intermittent sources of renewable energy in the energy system requires the operators of the electric grids to improve the system to be able to handle the variations of the power production in order to make demand and production correspond. This problem is seen as a major obstacle to installation of large shares of intermittent production if it is not handled in a feasible way.

Efficient electricity storage technology is one of the ways this problem may be handled. However, storage technology for large scale applications has not yet reached a breakthrough. Pumped hydro storage is in operation in some regions where geography makes it possible to store large volumes of water as potential energy.

An electricity storage may in all cases be seen as a battery that is charged and uncharged according to the demands of the electric grid. When electricity production exceeds demand, the battery is charged, and oppositely when demand exceeds production.

1.1. Principle of Compressed Air Energy Storage

Another technology which is in actual operation is Compressed Air Energy Storage (CAES), which is in use two places in the world, Huntorf, Germany, and McIntosh, Alabama, USA. An increasing number of studies have been presented on the application of CAES in other places due to fluctuating production of electricity based on renewable sources.

A CAES plant consists of a large volume that can store air compressed to high pressure (the battery) and what is in principle a gas turbine which is divided into the compression part (charging battery/electricity consumer) and the expansion part (discharging battery/electricity producer). The two plants store the compressed air underground in caverns or rock formations.

The basic principle of the installed CAES plants is illustrated in figure 1. The consumer part consists of an air compressor and a cooler. The storage is an underground cavern. The production part contains a gas burner and a turbine. In the practical installation both compressor and turbine processes are divided into several stages with intercooling. The parts of the plant are separated by valves which control the operational state.

CAES is primarily seen as an electricity storage comparable to a battery, but it has other features which are also important. Due to the division of the gas turbine in its two parts, the power output from the turbine is not used for operating the compressor. Thus the full turbine power is supplied to the grid when producing electricity. This increases the power output from the plant by about a factor

of three.

1.2. Literature Survey

During the last decades CAES has received increasing interest, and several investigations on the subject have been presented in literature. In particular, the erection of the Huntorf plant initiated further studies for other locations.

In [1] CAES and an optimization procedure for weekly cycles is presented. The optimization is applied for selection of components for a given CAES case.

Schainker et al. [2] describe the status of CAES operation and economics in the mid eighties. [3] was also published shortly after the Huntorf plant was put in operation. The paper presents experiences from Huntorf and gives recommendations for design of plants. In the same proceedings Allen [4] present experiences from a closely related field, i.e., storage of gaseous fuel underground.

Nakhamkin et al. [5] investigate the possibility for opening a plant similar to McIntosh, Alabama in California. A similar study for a 280 MW CAES in Mississippi is presented in [6]. An important conclusion from this study is that a significant part of the investment presented in other studies may be saved. Stampler [7] presents activities on possible erection of CAES plants in the beginning of the 1990'ies. The work by Crotagino [8] gives an overview of operation experiences from Huntorf after 20 years operation. Not before this point in time it was found necessary to exchange parts of the plant due to wear.

Czinkóczy and Veér [9] summarize possible improvements of efficiency of CAES cycles, whereas Najjar and Zaamout present a CAES configuration for locations without access to cooling water[10]. During the last 10 years focus on the development of CAES has been increased significantly. In particular, Alstom has been active in this development, as described in e.g., [11]. Tuschy et al. [12] and [13] present the two existing plants in Huntorf and McIntosh. Moreover, the new Alstom CAES concept based on the ET11NM gas turbine is introduced. The process is developed such that the first turbine stage expands the air from the store without previous combustion. The combustion is done in two stages after each expansion. The air to the first turbine stage is heated regeneratively in by the second stage combustion. This design reduces NO_x -production by combustion at lower pressure.

Several suggestions for improvement of the usual CAES-process have been suggested. In particular focus has been on avoiding the loss of energy by cooling during compression. Instead the idea is to store the internal energy from the compression as well and use it regeneratively for heating air to the turbine. Grazzini [14] has studied such a configuration and finds an efficiency of 72%. Further studies of the configuration by exergy analysis are given in [15]. Recent activities are concerned with the AA-CAES-project, where AA is AA short for Advanced Adiabatic [16, 17, 18]. This project has resulted in the development of a concept for a practical solution of the storage of energy from compressor cooling and thus avoidance of requirement for fuel consumption. Studies of possible storage media are provided in the work.

Yoshimoto et al. [19] describe a CAES system in which the expansion part includes a combined cycle gas and steam turbine plant. The work presents an optimization of the operation of such a plant both in competition and cooperation with other production units. In [20] a CAES process including storage of compression heat in hot water is presented. The energy may be partially recovered during the expansion by humidifying air from the storage.

A CAES plant will obviously not operate continuously, but compressor and turbine load and storage content will vary according to supply and demand. In [21] the compression part of a CAES plant is studied under the assumption that one-stage compression is applied. This will give serious challenges to the compressor operation due to risk for *surge*.

1.3. Scope of study

In the literature several statements of the efficiency of CAES and comparisons to other technologies are available, e.g., [22], [23], [24], [25], [26]. However, as CAES has two inputs of energy (electricity

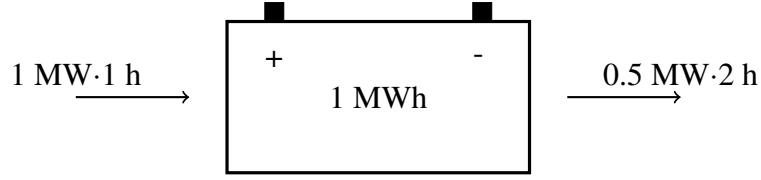


Figure 2: Reversible battery of 100% efficiency at different consumption and production power

to compressor and fuel to burner) that occur at different points in time, it is not obvious how to define the efficiency of storage and the actual definition used in the referenced studies is not clearly stated. Below we present an overview of ways to define CAES efficiency and how each definition should be applied. We provide values for the efficiency measures for the two CAES plants in operation and we conclude about the efficiency of CAES seen from the viewpoint of storage of intermittent electricity. Other measures may be used for comparison of storage technologies, e.g., energy or power density, but efficiency from input to output has highest priority.

2. Methods

For the use in energy systems with high shares of intermittent renewable sources of electricity, e.g., wind or solar power, storage technologies for bulk electricity will be required. In order to evaluate a technology the efficiency of the complete cycle from input to output electricity is crucial. Any type of storage is thus in principle a battery and they only differ based on the type of energy used for storage. For high efficiency low losses must be acquired for any type of storage. Figure 2 illustrates a reversible battery without losses and thus 100% efficiency. If the battery storage involves losses the efficiency of the energy storage will be defined as

$$\eta_{sc} = \eta_{char} \eta_{stor} \eta_{disc} \quad (1)$$

such that the losses in each of the three steps of the cycle together gives the efficiency of the storage cycle.

To find the efficiency of CAES we determine the state variables of the CAES process by carrying out a thermodynamic analysis with DNA[27] where the isentropic efficiency of the turbomachines and the pressures of the storage volume in empty and full condition are defined as parameters [28], [29]. Based on the results of the analysis we find the flows of fuels and electric power that are required to determine the efficiency.

2.1. Energy Analysis of CAES

Based on the energy flows two measures of efficiency of the cycle are defined: The gas turbine cycle efficiency and the efficiency from input to output.

2.1.1. Gas Turbine Cycle Thermal Efficiency

CAES is a gas turbine cycle. As such it is reasonable to define a thermal efficiency of the cycle:

$$\eta_{th} = \frac{W_t - W_c}{Q_f} \quad (2)$$

The value of the thermal efficiency cannot be used to express the efficiency of the electricity storage. It is a measure of the efficiency of the thermodynamic cycle of a heat engine, but the intention of a storage is not to convert heat power work, but to store work from one instance in time to another.

2.1.2. Plant Energy Efficiency

The output from a CAES plant is work. This may be compared to the input energy to the plant consisting of natural gas and compressor work:

$$\eta_{ee} = \frac{W_t}{Q_f + W_c} \quad (3)$$

This may be seen as an expression of the storage efficiency, but it may be questioned if this is a useful measure. It compares produced energy from the plant to the total energy input, which consists of two different types of energy that are consumed by different parts of the process and at different point in time, i.e., electricity for compressor operation when charging and fuel for turbine operation when discharging. The fuel cannot be seen as a part of the electricity storage but is only required due to the heating of the air to the turbine caused by compressor cooling.

2.1.3. Primary Energy Efficiency

The plant energy efficiency (3) may be refined to be used as a measure of the utilization of primary energy used by the CAES plant:

$$\eta_{pe} = \frac{W_t}{\eta_{sys} Q_f + W_c} \quad (4)$$

The system efficiency η_{sys} is a measure of the efficiency of electricity production in the energy system. Its value will depend on which system the CAES plant is used in but would usually have a value between 30% and 50%. We use a value of 40% below, which is close to the average efficiency in the Danish energy system [30].

This measure is relevant for understanding how much energy is used in the system to produce the output of the CAES plant. It is, however, not a means for understanding how well the CAES plant operates as a storage.

2.2. Exergy Analysis applied to Electricity Storage

The above energy-based efficiency definitions all have shortcomings as measures of the storage efficiency of CAES. An electricity storage is a battery and as electricity is the equivalent of exergy, it is natural to calculate exergy losses and quantify exergetic efficiency to find the storage efficiency.

The definitions of equations (2)-(4) may be formulated based on exergy instead of energy, but their shortcomings still apply. The only difference from the energy-based definitions are that the fuel exergy is not exactly the same as the energy input. However, the difference between chemical exergy and heating value is small. Thus a more thorough exergy analysis should be done to calculate the efficiency the storage.

2.2.1. Storage Efficiency of CAES

By calculating exergetic efficiency of each part of the CAES cycle – consumption, storage and production – we define a measure of storage efficiency that is comparable to the efficiency of a battery in 1. By defining the exergetic efficiency of each part of the CAES process a useful storage efficiency can be defined. Thus the efficiency of the storage cycle of CAES is:

$$\eta_{sc} = \eta_{char} \eta_{stor} \eta_{disc} = \eta_{x,c} \eta_{x,stor} \eta_{x,t} \quad (5)$$

The exergetic efficiency of the three parts of the process are defined by:

$$\text{Compressor: } \eta_{x,c} = \frac{\Delta E_1}{W_c}. \text{ Storage: } \eta_{x,stor} = \frac{E_3}{E_2}. \text{ Turbine: } \eta_{x,t} = \frac{W_t}{\Delta E_{34} + E_f} = \frac{W_t}{E_3} \quad (6)$$

The definitions are based on [31]. For the turbine part the exergetic fuel is the chemical exergy of fuel and the exergy from the storage. The exergy of the outlet of the turbine is an exergy loss that is assigned to the turbine process.

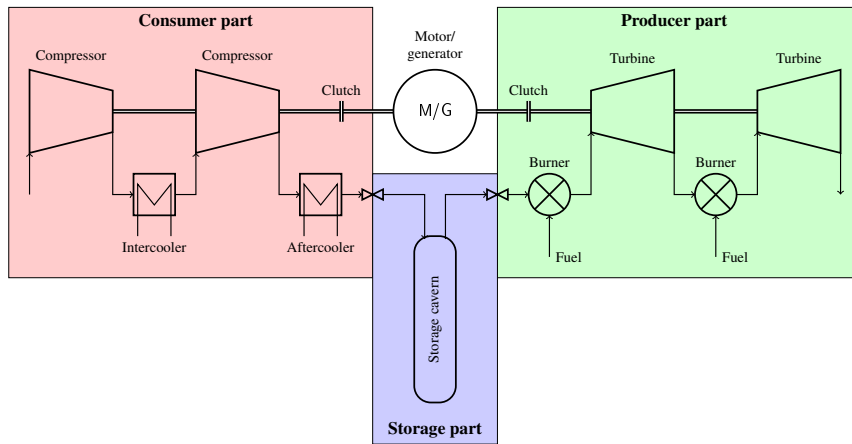


Figure 3: Huntorf CAES-process [28]

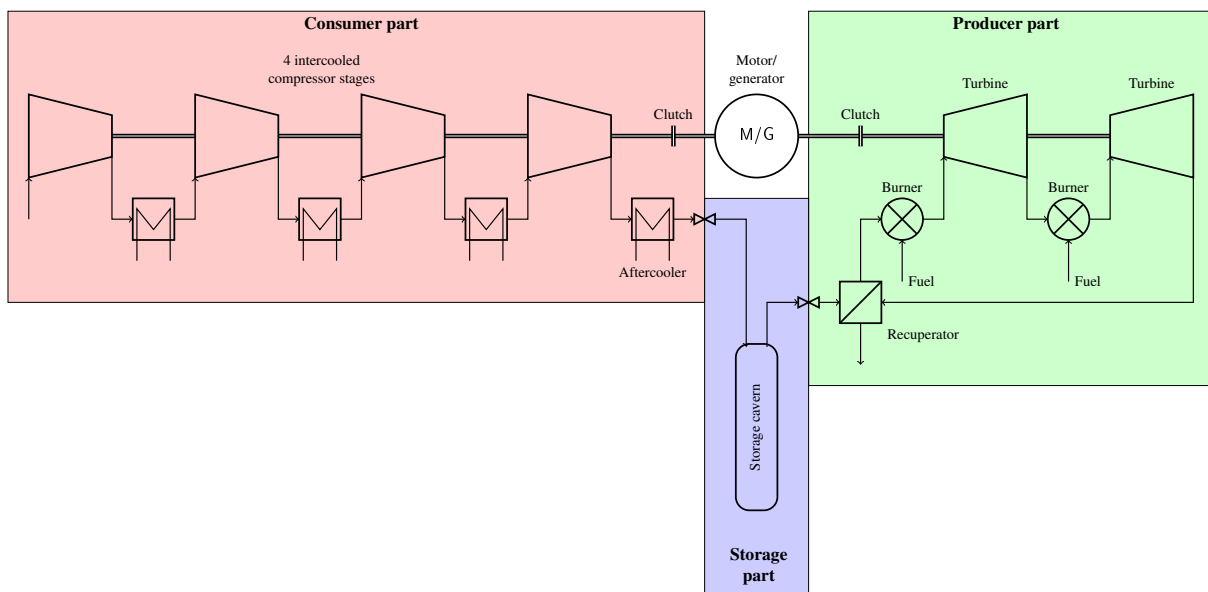


Figure 4: Alabama CAES-process [28]

This definition of efficiency is in accordance with the rationale of electricity storage. It also takes all three steps of the cycle into account and it makes it possible to distinguish between losses due to charging, storing and discharging and to account for the losses of the two inputs individually. We find that this definition is the correct one to use to calculate efficiency of CAES. The other definitions above are suited for other uses.

3. Results

3.1. Storage Efficiency of CAES

In figures 3-5 the process configuration of the the Huntorf plant, the McIntosh plant and a plant suggested for a Danish application[29], [28] based on the configuration suggested by Alstom[13] are presented. The two latter are improved compared to Huntorf, e.g., by recuperation.

Overall data and calculated performances of the three processes are presented in tables 1 to 3. It is obvious that the most recent cycles have better performance than the Huntorf plant. As discussed in section 2. it is the storage efficiency that is relevant to study the performance of CAES as an electricity storage. We find that it has a value of 29% for Huntorf and that 43% may be reached for the most recent design.

In order to understand the formation of the storage efficiency the exergy losses of the Alstom process

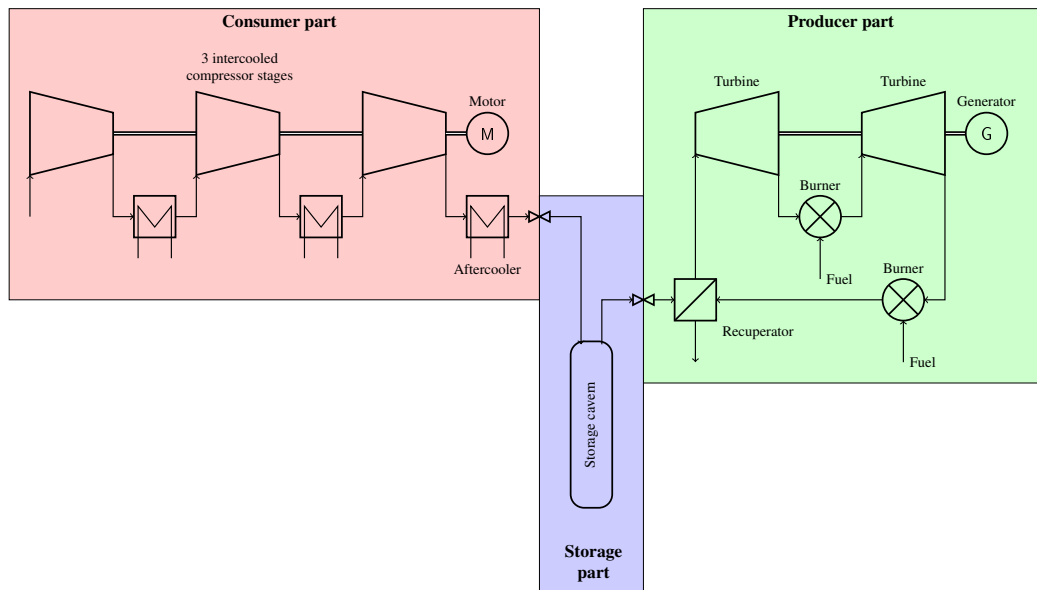


Figure 5: Alstom suggested CAES-process [28]

| | Min. storage pressure | Max. storage pressure |
|--------------------------------------|-----------------------|-----------------------|
| Storage Pressure [bar] | 48 | 70 |
| Compressor Power [MW] | 57 | 65 |
| Charging time [h] | 8 | |
| Charging Exergetic Efficiency [%] | 73 | 59 |
| Fuel consumption rate [MW] | 491 | 491 |
| Combustion Temperature [°C] | 853 | 853 |
| Turbine Power [MW] | 294 | 294 |
| Discharging time [h] | 2 | |
| Discharging Exergetic Efficiency [%] | 45 | 44 |
| Gas turbine efficiency [%] | 10 | |
| Plant energy efficiency [%] | 40 | |
| Primary energy efficiency [%] | 20 | |
| Storage Efficiency [%] | 29 | |

Table 1: Huntorf process data

| | Min. storage pressure | Max. storage pressure |
|--------------------------------------|-----------------------|-----------------------|
| Storage Pressure [bar] | 50 | 78 |
| Compressor Power [MW] | 45 | 50 |
| Charging time [h] | 42 | |
| Charging Exergetic Efficiency [%] | 72 | 72 |
| Fuel consumption rate [MW] | 132 | 132 |
| Combustion Temperature [°C] | 853 | 853 |
| Turbine Power [MW] | 116 | 116 |
| Discharging time [h] | 26 | |
| Discharging Exergetic Efficiency [%] | 51 | 49 |
| Gas turbine efficiency [%] | 30 | |
| Plant energy efficiency [%] | 56 | |
| Primary energy efficiency [%] | 29 | |
| Storage Efficiency [%] | 36 | |

Table 2: Alabama process data

| | Min. storage pressure | Max. storage pressure |
|--------------------------------------|-----------------------|-----------------------|
| Storage Pressure [bar] | 60 | 80 |
| Charging time [h] | 10 | |
| Compressor Power [MW] | 205 | 222 |
| Charging Exergetic Efficiency [%] | 69 | 68 |
| Fuel consumption rate [MW] | 417 | 417 |
| Combustion Temperature [°C] | 1030 | 1030 |
| Turbine Power [MW] | 362 | 362 |
| Discharging time [h] | 10 | |
| Discharging Exergetic Efficiency [%] | 63 | 62 |
| Gas turbine efficiency [%] | 36 | |
| Plant energy efficiency [%] | 57 | |
| Primary energy efficiency [%] | 29 | |
| Storage Efficiency [%] | 43 | |

Table 3: Alstom process data

| | Exergy loss [MW] | Relative exergy loss [%] |
|---------------|------------------|--------------------------|
| Compressor 1 | 6764 | 2% |
| Intercooler 1 | 14283 | 5% |
| Compressor 2 | 6765 | 2% |
| Intercooler 2 | 15443 | 6% |
| Compressor 3 | 7606 | 3% |
| Aftercooler | 20907 | 8% |
| Throttling | 12209 | 4% |
| Recuperator | 22902 | 8% |
| Air turbine | 5823 | 2% |
| Combustion 1 | 124722 | 45% |
| Turbine | 14537 | 5% |
| Combustion 2 | 25398 | 9% |

Table 4: Exergy losses of Alstom process

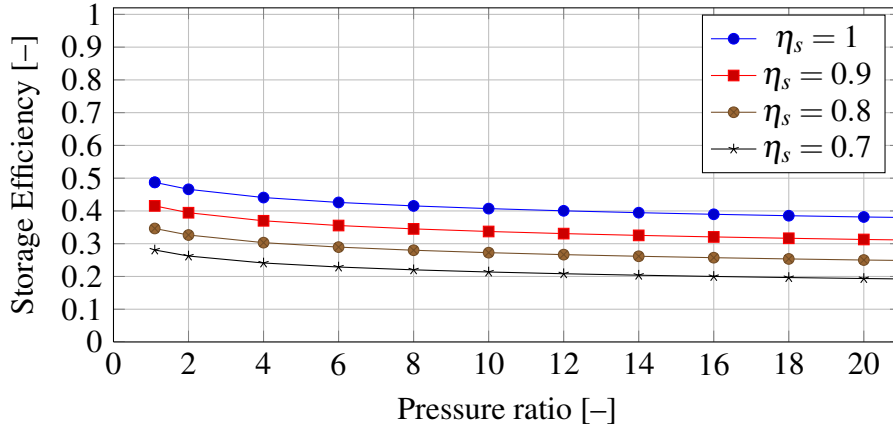


Figure 6: Storage Efficiency of Diabatic CAES

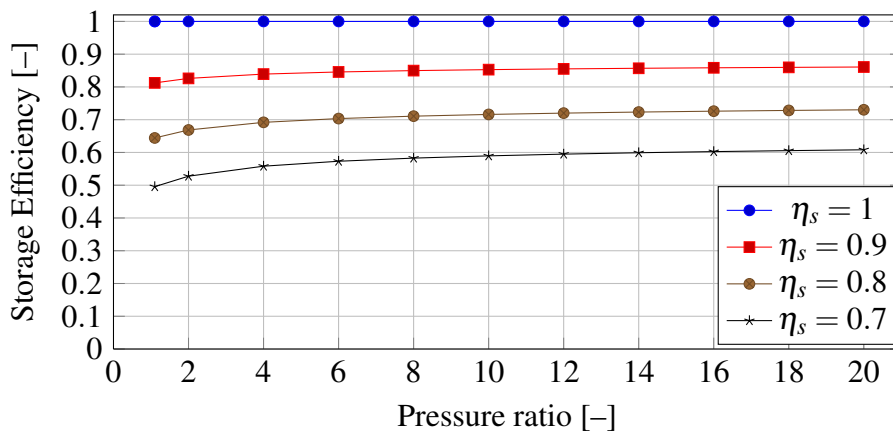


Figure 7: Storage Efficiency of Adiabatic CAES

in table 4 may be used. We find that significant losses occur due to cooling during compression (6% of input exergy) and in particular due to combustion and heat transfer from combustion products during discharging (27%). Returning to the battery analogy we may see the CAES processes as batteries where significant loss occur during charging and a significant amount of electricity (exergy) is added during discharging, while even larger losses occur.

The other efficiency parameters illustrate that the CAES cycle has efficiency comparable to gas turbines except for the extra compressor cooling and that a CAES utilizes about 30% of the primary energy consumed.

3.2. Storage Efficiency Limits of Basic CAES

The exergy losses occurring in the CAES processes suggest that the storage efficiency may be improved by avoiding the heat transfer and combustion, thus making the process adiabatic. CAES processes may be classified as:

- Diabatic CAES (cooled compressor, storage, combustion, turbine and recuperator)
- Adiabatic CAES process (compressor, storage, turbine)
- Advanced adiabatic CAES (cooled compressor, air storage, thermal energy storage and turbine)

The plants in operation are of the diabatic type. Figure 6 displays the storage efficiency that may be reached by a diabatic CAES process under the condition that the outlet from the turbine has no

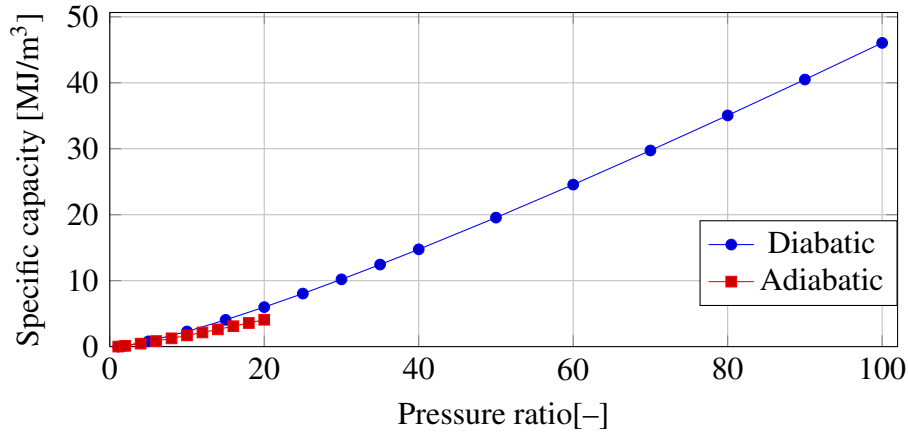


Figure 8: Storage capacity

physical exergy content, thus temperature and pressure are at the reference conditions. We see that a higher pressure in the storage results in lower efficiency and that the efficiency converges to a constant value for a given isentropic efficiency of the turbomachinery for storage pressure above 20 bar. The efficiency is similar to the values found in the plants in operation.

The results for the Adiabatic CAES in figure 7 are contrary to this. We see that the storage efficiency of a reversible adiabatic process is unity as would be expected intuitively. The efficiency of the turbomachinery has a significant influence on the storage efficiency. The efficiency of the adiabatic CAES shows that the potential of this process is far better than the conventional type. The results show that CAES may reach 70-80% efficiency for a practical plant.

4. Discussion

Figure 8 shows that the specific storage capacity based on turbine output of diabatic CAES is much higher than the adiabatic process. The reason is mainly that the pressure in the storage may be higher because the temperature of the compressed air is lowered during compression. Advanced Adiabatic CAES including thermal energy storage may to some extent remedy this because the storage temperature is low as heat is stored in a separate volume. However, the heat transfer between compressed air and heat storage and between thermal energy storage and expansion air will involve irreversibilities due to finite temperature differences and varying temperature of the thermal energy storage.

The storage efficiency of plants in operation is low, and does not seem to justify the application of CAES as an electricity storage in a future energy system with minimal consumption of fossil fuels. Exergy losses in the storage will require significant increases of the required land area to produce the electricity consumed by society and thus high-efficiency storage is needed. The high consumption of fuel of a diabatic CAES is another hurdle for the use of this process for leveling out intermittent production in an economically feasible way.

5. Conclusion

The CAES plants in operation, Huntorf and McIntosh, as well as other process suggestions for diabatic CAES has been investigated in detail by exergy analysis. We find that the storage efficiency is less than 45%, which is lower than values presented in literature previously. This is in accordance with results found for a basic diabatic CAES which does not exceed 50% storage efficiency either. As the process consumes a large share of fuel, diabatic CAES will be of limited value in future energy systems where electricity storage will be required increasingly.

Adiabatic CAES on the other hand may for a reversible process reach a storage efficiency of unity, and more than 70% for practical applications. Further research on these plants is required to utilize storage capacity in the best possible way.

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