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# Thermodynamic Analysis of an Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)

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***Abstract*** **–** The increase in population and industrialization in the world increases energy consumption and the need for energy production. The fact that most of the energy source is fossil-based causes negative situations such as air pollution and climate change. Therefore, many countries are turning to renewable energy sources such as solar and wind. However, the discontinuity in renewable energy sources prevents sustainability in this field. There is a need for the use of energy storage systems to eliminate fluctuations in renewable energy sources.

Among many energy storage systems, Compressed Air Energy Storage (CAES) method has attracted attention in recent years due to its ability to store energy mechanically and to provide high storage capacity. However, Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) systems have been proposed due to the fact that conventional CAES systems are fossil-based and have low efficiency. However, improvements are needed for these systems to become widespread and applicable.

In this study, an AA-CAES system is designed to supply energy from wind turbines. The thermodynamic analysis of proposed system is performed and the effect of the key parameters is investigated.

*Keywords – Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), Energy Analysis, Energy Storage Systems (ESS), Mathematical Modelling, Thermodynamic Analysis.*

## INTRODUCTION

The increasing need for energy with the development of technology leads to the search for various alternative energy sources. Studies on the integration of renewable energy sources are increasing day by day due to the decrease in fossil fuel reserves, which has the largest share among energy sources, and the damage it causes to the environment. However, the discontinuity in renewable energy sources restricts the use of electrical energy obtained from these sources. Energy storage technologies are therefore essential to ensure the continuity and stability of renewable energy while storing energy to keep energy supply and demand in balance.

There are generally two types of energy storage technologies available today for large-scale applications [1]. One of these is the Pumped Hydro Energy Storage (PHES) and the other is Compressed Air Energy Storage (CAES). Among many energy storage technologies, CAES systems attract the attention of researchers due to their high energy storage capacities and long discharge times [2].

There are two high capacity CAES plants in the world, one is the Huntorf Plant in Germany with an installed capacity of 290 MW and the other is the Mc Intosh Plant in the USA with an installed capacity of 110 MW [3]. Although a number of plants have been established around the world, these two are still the most well-known and large-capacity examples. Both of these plants are based on

Conventional CAES technology using fossil fuels. However, they proposed the AA-CAES method in order to design more efficient systems, since conventional CAES systems both use fuel and are more efficient. However, AA-CAES method has been proposed to overcome the negative effects of the fuel consumption of conventional CAES systems and to design more efficient systems [2]. With this method, systems that do not need a combustion chamber, meet the heat requirement by storing the heat of compression in the compressor with the help of Thermal Energy Storage (TES), and have higher efficiency are aimed.

RTE (Round Trip Efficiency) values of systems operating according to the conventional CAES are around 42% [3]. To overcome this challenge, researchers have studied the integration of CAES systems with various systems such as solar ([4], [5]) wind ([6]–[8]), trigeneration ([9]-[11]). In order to minimize energy-related problems in the future, systems that can both support the use of clean energy and benefit from long-term storage are needed, and the use of renewable energy sources gains importance at this point.

Thermodynamic analysis is the fundamental method used when designing a system. Many researchers have performed thermodynamic analysis of CAES based systems to study the parameters that affect the system performance. Grazzini and Milazzo [12] performed a thermodynamic analysis of the CAES/TES system for different combinations. They optimized the volume of the storage tank by examining the effect of the Thermal Energy Storage (TES) on the system. They also stated that the proposed system will be well compatible with wind energy. Grazzini and Milazzo [13] investigated the main design parameters for an A-CAES system and their impact on the system performance. Liu et al [14] investigated the impact of key parameters on system efficiency of multi-stage Regenerative Compressed Air Energy Storage. Luo et al [15] studied in detail the parameters affecting the efficiency of an A-CAES system. They concluded that the isentropic efficiencies of the turbine and compressor and the heat transfer rate of the heat exchanger are important parameters affecting the system efficiency. They also concluded that the multi-stage compression and expansion process up to a specific stage increases the system efficiency and that the charge-discharge time can affect the system efficiency. Szablowski et al [16] examined energy and exergy analyses for an A-CAES. The results was reported that heat recovery of compressed air increases system efficiency. Dividing compression and expansion processes into more stages and adding more heat exchangers also increases the system efficiency. Hartmann et al. [17] analyzed different A-CAES combinations. As a result, the application of inter and afterheating significantly increased the efficiency and showed that the two-stage system gave the best results.

## DESCRIPTION OF THE SYSTEM

The schematic diagram of the system proposed is given in Figure 1. The system consists of a two-stage CAES and a TES that utilizes the compression heat released during compression in the compressor. Wind energy provides the energy required for the operation of the system. Thus, a self-sufficient system is aimed. The operation of the system is based on two processes: charging and discharging. During loading, the compressor section operates and the air compressed by the compressor is stored in the compressed air tank at a certain pressure. When the energy demand increases, the discharge mode is activated and the air in the compressed air tank is passed through the turbine to generate electrical energy.

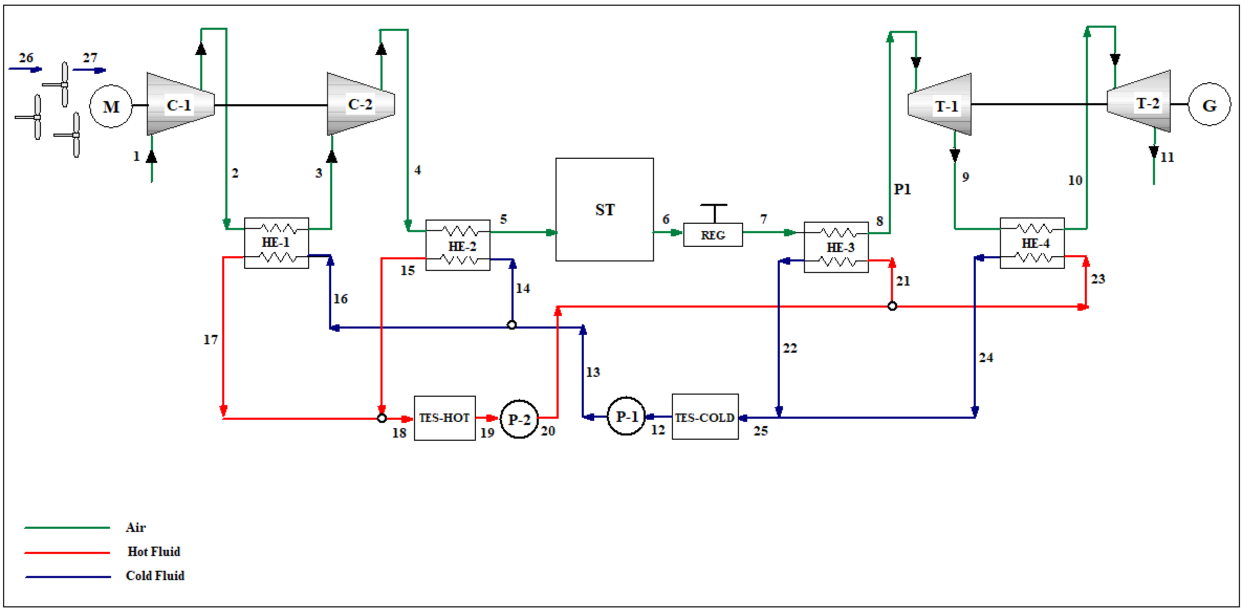
The system works as follows. The air taken from the environment (1) is compressed by the compressor-1 (C-1) and compressor 2 (C-2). The heat released during compression is stored in the Hot Thermal Energy Storage (TES-HOT) with the help of HE-1 and HE-2. The air coming out of the two-stage compressor enters the storage tank (ST). The air regulated with the help of a regulator (REG). Preheating is done by means of HE-3 and HE-4 and airflow is sent to turbine-1 (T-1) and turbine-2 (T-2) to produce electric power, respectively.

The choice of fluid to be used in thermal energy storage is one of the important factors affecting the heat storage performance [18]. Dowtherm-G, which is widely used in heat recovery systems and has a good heat transfer performance is preferred as TES working fluid [19], [20].

## METHODOLOGY AND MODELLING

In this section, the assumptions and governing equations related to the establishment of the mathematical model created for the thermodynamic analysis of the system are given.

### A. *Matematical Model and Assumptions*




C-1: Compressor 1
C-2: Compressor 2
HE-1: Heat Exchanger 1
TES-HOT: Hot Thermal Energy Storage

HE-2: Heat Exchanger 2
HE-3: Heat Exchanger 3
HE-4: Heat Exchanger 4
TES-COLD: Cold Thermal Energy Storage

G: Generator
M: Motor
P-1: Pump 1
T-1: Turbine 1

P-2: Pump 2
REG: Regulator
ST: Storage Tank
T-2: Turbine 2

Fig. 1. Schematic diagram of the AA-CAES system [21].

The mathematical model developed for the thermodynamic analysis of the system is solved by using the Engineering Equation Solver (EES) software System components are considered as control volumes. Mass, energy, exergy and cost balances for the system components form the governing equations for the mathematical model. The design parameters of the mathematical model are presented in Table 1.

Following assumptions is made in the solution of the mathematical model:

- System components operate under steady-state conditions.
- Kinetic and potential energy changes in system components (except wind turbine) is neglected.
- The throttling process is assumed isenthalpic.
- The working fluid runs with the same mass flow rate between the charge and discharge processes.
- Pressure loss in pipes, storage tank and heat exchangers is neglected.
- Heat loss in compressors, turbines, pipes and heat exchanges is neglected.
- Motor and generator efficiencies are considered 100 %.
- Wind fluctuations are neglected.
- TES-HOT is isolated completely and flow processes are isothermal.

Table 1. Simulation conditions of the proposed system [21].

| Parameter | Symbol | Value |
|---|---|---|
| Ambient temperature | $T_0$ | 293.15 [K] |
| Ambient pressure | $P_0$ | 101.3[kPa] |
| Total input power of compressors | $\dot{W}_{C,total}$ | 8000 [kW] |
| Total output power of turbines | $\dot{W}_{T,total}$ | 10000[kW] |
| Blade diameter of wind turbine [22] | $d_{WT}$ | 34 [m] |
| Power coefficient of wind turbine [23] | $C_{p,wt}$ | 59 [%] |
| Inlet velocity of wind turbine | $V_{WT,in}$ | 8 [m/s] |
| Mass flow rate of TES fluid | $\dot{m}_{TES}$ | 10 [kg/s] |
| Max. pressure of storage tank | $P_{max}$ | 80 [x10$^5$Pa] |
| Min. pressure of storage tank | $P_{min}$ | 40 [x10$^5$Pa] |
| Charging time | $t_{ch}$ | 4 [h] |

### B. *Energy Analysis*

Energy analysis is an important and widely used tool for the thermodynamic understanding of a system and helps us to determine the fundamental parameters in the system. The general energy and mass conservation equations for the energy analysis of the proposed system are as follows:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad (1)$$

$$\dot{Q} - \dot{W} = \sum (\dot{m}h)_{out} - \sum (\dot{m}h)_{in} \quad (2)$$

The energy equations for the system components are given in Table 2.

The charge-discharge time ratio ($c_d$), which gives the relationship between charging and discharging times, is calculated as follows [15].

$$c_d = \frac{t_{ch}}{t_{dch}} \quad (3)$$

Table 2. Energy balance equations for system components [21].

| **Comp.** | **Energy Balance Equations** | |
|---|---|---|
| **C-1** | $\dot{W}_{C-1} = \dot{m}_c.(h_2 - h_1)$ | $\eta_{C-1} = \frac{h_{2s} - h_1}{h_2 - h_1}$ |
| **HE-1** | $\dot{Q}_{HE-1} = \dot{m}_c.(h_2 - h_3)$ | $\varepsilon_{HE-1} = \frac{h_2 - h_3}{h_2 - h_{3(T_{16})}}$ |
| **C-2** | $\dot{W}_{C-2} = \dot{m}_c.(h_4 - h_3)$ | $\eta_{C-2} = \frac{h_{4s} - h_3}{h_4 - h_3}$ |
| **HE-2** | $\dot{Q}_{HE-2} = \dot{m}_c.(h_4 - h_5)$ | $\varepsilon_{HE-2} = \frac{h_4 - h_5}{h_4 - h_{5(T_{14})}}$ |
| **HE-3** | $\dot{Q}_{HE-3} = \dot{m}_e.(h_8 - h_7)$ | $\varepsilon_{HE-3} = \frac{h_8 - h_7}{h_{8(T_{21})} - h_7}$ |
| **T-1** | $\dot{W}_{T-1} = \dot{m}_e.(h_9 - h_8)$ | $\eta_{T-1} = \frac{h_8 - h_9}{h_8 - h_{9s}}$ |
| **HE-4** | $\dot{Q}_{HE-4} = \dot{m}_e.(h_{10} - h_9)$ | $\varepsilon_{HE-4} = \frac{h_{10} - h_9}{h_{10(T_{23})} - h_9}$ |
| **T-2** | $\dot{W}_{T-1} = \dot{m}_e.(h_{11} - h_{10})$ | $\eta_{T-2} = \frac{h_{10} - h_{11}}{h_{10} - h_{11s}}$ |
| **P-1** | $\dot{W}_{P-1} = \dot{m}_{tes,ch}.(h_{13} - h_{12})$ | $\eta_{P-1} = \frac{h_{13s} - h_{12}}{h_{13} - h_{12}}$ |
| **P-2** | $\dot{W}_{P-2} = \dot{m}_{tes,dch}.(h_{20} - h_{19})$ | $\eta_{P-2} = \frac{h_{20s} - h_{19}}{h_{20} - h_{19}}$ |
| **WT** | $\dot{W}_{WT} = \frac{1}{2}\eta_m.\rho.A_{wt}.C_{p,wt}.V_{\mathrm{wt,in}}^3.\eta_{wt}$ | |

## PERFORMANCE CRITERIA

Round Trip Efficiency ($\eta_{RTE}$) and Energy Storage Density (ESD) were used as performance criteria to evaluate the energy analysis.

$\eta_{RTE}$, is an important indicator of system performance in energy storage systems. It provides information about the loss that occurs during the transfer of energy. It is defined as the ratio between discharge energy and storage energy of the system for one cycle of operation [24].

$$\eta_{RTE} = \frac{\dot{W}_{T_{total}}.t_{dch}}{\dot{W}_{C_{total}}.t_{ch}}.100 \quad (4)$$

*ESD* can be defined as the ratio of the power generated by the turbines to the volume of the storage tank [25].

$$ESD = \frac{\dot{W}_{T_{total}}.t_{dch}}{V_{st}}.100 \quad (5)$$

## RESULTS AND DISCUSSION

The mathematical model of the system was developed with the Engineering Equation Solver (EES) program. While developing the mathematical model, total powers for turbine and compressor of the proposed system are assumed to be constant. In this section, the thermodynamic analysis results for the proposed system are discussed in detail. Ranges for the key parameters are presented in Table 3.

Table 3. Ranges for the key parameters.

| **Key Parameters** | **Range** |
|---|---|
| Minimum ST pressure $P_{min}$ | 20-60$x10^5\ Pa$ |
| Maximum ST pressure $P_{max}$ | 70-105$x10^5\ Pa$ |
| Isentropic efficiency of compressors $\eta_C$ | 80-92 % |
| Isentropic efficiency of turbines $\eta_T$ | 70-92 % |

Figure 2 shows the effect of increasing $P_{min}$ on $\eta_{RTE}$ and *ESD*. As $P_{min}$ increases between $20 - 60(x10^5\ Pa)$:

- The pressure of the air passing through the turbines increases and the mass flow rate of the air passing through the turbines decreases. Accordingly, the charging-discharge time ratio ($c_d$) decreases and discharge time ($t_{dch}$) increases. As can be seen from Equation (4), the increase in the unloading time causes a 26.7% increase in $\eta_{RTE}$ value.

- There is an increase in the mass flow rate of the air passing through the compressor. The increase in mass flow rate during loading leads to an increase in the volume of air stored in the air tank ($V_{st}$). However, since the increase in discharge time ($t_{dch}$) is more dominant than the increase in $V_{st}$, this causes the *ESD* value to increase by 16.9%.
- The highest values are reached at $P_{min} = 60x10^5$ Pa with $\eta_{RTE}$ %51.13 and *ESD* 16.36 $MJ/m^3$.

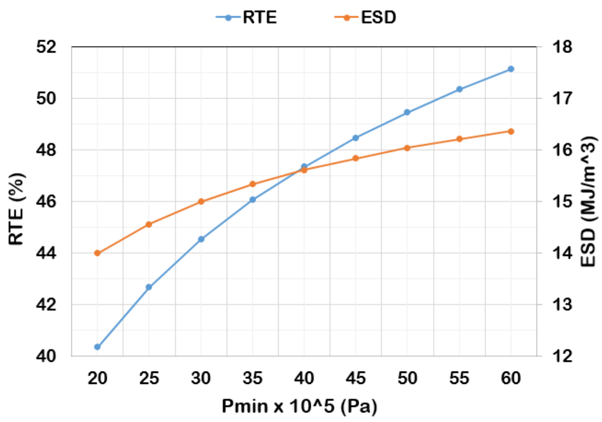



**Figure 2.** Influence of $P_{min}$ on $\eta_{RTE}$ and ESD.

Figure 3 shows the effect of increasing $P_{max}$ on $\eta_{RTE}$ and *ESD*. As $P_{max}$ increases between $70-105(*\,10^5\ kPa)$:

- The pressure of the air passing through the compressors increased and the mass flow rate of the air passing through the compressors decreased. The thermal oil stored at higher temperatures reduced the mass flow rate of air through the turbines. However, the decrease in the mass flow rate of the air during charge process dominates the decrease in the mass flow rate of the air during discharge process, leading to an increase in the value of $c_d$. This has an effect on shortening the discharge time ratio ($t_{dch}$) of the system. As can be seen in Equation (4), the $\eta_{RTE}$value decreases by 11.08% as a result of the decrease in the discharge time ($t_{dch}$).
- The decrease in mass flow rate during charging process causes a decrease in the volume of air stored in the air tank ($V_{st}$). The decrease in $V_{st}$ causes an 80% increase in *ESD* value to dominate the decrease in $t_{dch}$value.
- The highest values are reached by $\eta_{RTE}$with 49.28% when $P_{max} = 70x10^5$ Pa and *ESD* with 23.04 $MJ/m^3$ when $P_{max} =$ 105x10$^5$Pa.

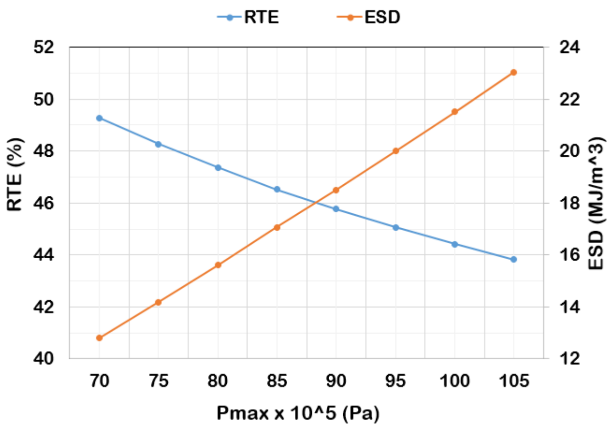



**Figure 3.** Influence of $P_{max}$ on $\eta_{RTE}$ and ESD.

Figure 4 shows the effect of changing the isentropic efficiency of the compressors on $\eta_{RTE}$ and *ESD* value. As the isentropic efficiency of the compressors increases between 80-92%:

- There is an increase in the mass flow rate of air passing through the turbines. This leads to a decrease in $c_d$ and therefore an increase in $t_{dch}$. As can be seen in Equation (4), the $\eta_{RTE}$ value increases by 14.12% as a result of the increase in discharge time ($t_{dch}$).
- The mass flow rate of the air passing through the compressor increases. This causes the volume of the air tank ($V_{st}$) to increase. Equation 5 shows that the discharge time and the tank volume both increase. However, since the increase in $V_{st}$ is greater than the increase in $t_{dch}$, the *ESD* value decreases by 18.79%.
- The highest values are reached by $\eta_{RTE}$ with 51.07% when $\eta_C = 92\%$and *ESD* with 17.03 $MJ/m^3$when $\eta_C = 80\%$.

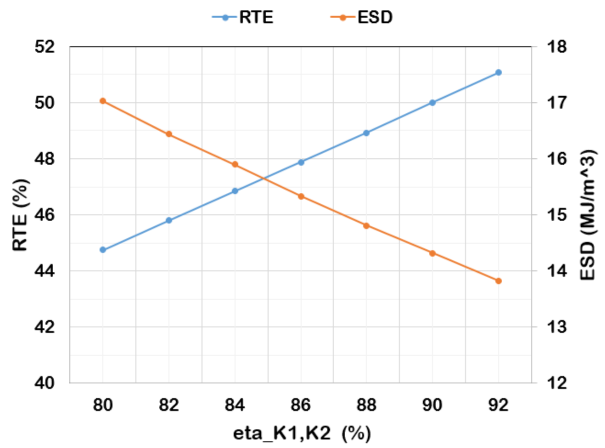



**Figure 4.** Influence of isentropic efficiency of compressors on $\eta_{RTE}$ and ESD.

Figure 5 shows the effect of changing the isentropic efficiency of the turbines on $\eta_{RTE}$and *ESD* value. As the isentropic efficiency of the turbines increases in the range of 70-92%:

- As the mass flow rate of the air passing through the turbine decreases, the $c_d$ value decreases. This causes an increase in the discharge time ($t_{dch}$). The increase in discharge time ($t_{dch}$) leads to a 30.37% increase in $\eta_{RTE}$ value as seen in Equation (4).
- There is an increase in the mass flow rate of air passing through the compressor. The increase in mass flow rate during charging process causes an increase in the volume of air stored in the air tank ($V_{st}$). However, since the increase in discharge time ($t_{dch}$) is greater than the increase in $V_{st}$, this causes an increase of 19.33% in the *ESD* value.
- The highest values are reached by $\eta_{RTE}$ with 51.13% when $\eta_T = 92\%$and *ESD* with 16.36 $MJ/m^3$when $\eta_C = 92\%$.

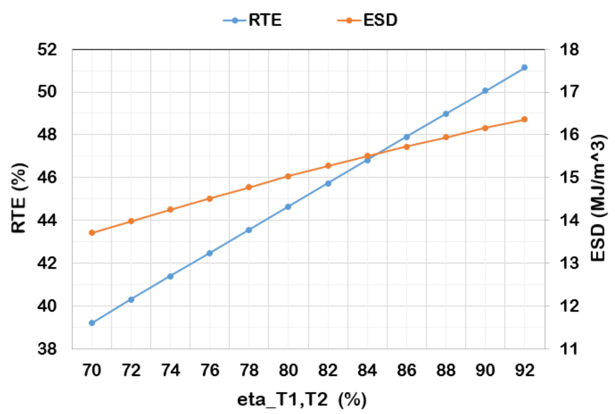



Figure 5.Influence of isentropic efficiency of turbines on $\eta_{RTE}$ and ESD.

## Conclusion

In this study, a self-sufficient AA-CAES system with wind turbine as energy source is proposed and thermodynamic analysis is performed. As a result of the study:

- It is observed that changing the minimum pressure of the air tank ($P_{min}$) causes an increase in both *ESD* and $\eta_{RTE}$.
- It is observed that increasing the $P_{max}$ value decreases the $\eta_{RTE}$ value while increasing the *ESD*. Increasing the maximum pressure of the air tank increases the pressure and temperature of the air going to the turbines and increases the storage temperature.
- It is observed that the increase in the isentropic efficiency of the compressors decreases the *ESD* value, while causing an increase in the $\eta_{RTE}$.
- The increase in the isentropic efficiency of the turbines leads to an increase in both $\eta_{RTE}$and *ESD* of the system.

Based on obtained data, it is seen that the effect of the isentropic efficiency of the turbines on the system is significant and therefore the turbines have the biggest role in AA-CAES systems. However, after the isentropic efficiency of the turbines, the minimum pressure of the air tank is of second importance since it causes an increase in both $\eta_{RTE}$ and *ESD*.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