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Journal of Thermal Engineering
https://jten.yildiz.edu.tr/
https://doi.org/10.47481/jten.0031

RESEARCH ARTICLE

Mathematical analysis of an adiabatic CAES system with integrated thermal energy storage

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Abstract

The share of renewable energy sources in the energy mix has become increasingly important for electricity generation in recent years. However, renewable energy sources have limitations; for example, they are not always available. An advanced adiabatic compressed air energy storage system is proposed to address this problem and maintain the balance between energy demand and production. When energy supply exceeds demand, it can be stored and released later when demand increases. This maintains a steady and uninterrupted electricity supply. The goal of this paper is to cut costs, improve energy efficiency, and speed up system response time. The findings indicate that increasing the compression ratio from 2 to 10 reduces the efficiency of an adiabatic compressed-air energy-storage system from 71% to 24%. In addition, using volcanic rocks as a storage material achieves high thermal storage efficiency, up to 85%.

Keywords: Adiabatic, compressed air, energy storage, thermal storage, heat recovery, levelized cost of energy

Cite this article as: Masaaf, Y., Ait El Kadi, Y., & Baghli, F. Z. (2026). Mathematical analysis of an adiabatic CAES system with integrated thermal energy storage. Journal of Thermal Engineering, 12(4), 1310–1323. https://doi.org/10.47481/jten.0031

1. Introduction

Compressed air storage, which can use underground caverns or above-ground reservoirs, is one of the most promising technologies for scale energy storage. Although this technology is still under development, several studies have been conducted to improve its overall performance. Using compressed air to store energy has been around since the 1940s [1].

Since then, numerous improvements have been made to CAES systems to enhance performance and reduce energy consumption. The goal is to make the system as efficient as possible.

During the charging phase, the compressor compresses atmospheric air using the excess energy generated by renewable energy sources. During the discharge phase, the stored compressed air will be released and injected into the turbine. Finally, the mechanical energy generated by the turbine is converted into electrical energy through a generator and then injected into the grid. In addition, during the storage process, compressed air is usually stored in underground locations such as salt caverns, aquifer (capable of supporting 2 to 8 MPa pressures) [2], abandoned mines, etc. Conventional (compressed air energy storage) is characterized by relatively low efficiency, about 50% [3]. The low efficiency of the system is explained by two primary energy deficits: heat loss during compression and the need to preheat compressed air before discharge. During the charging phase, compressed air generates significant heat, which is usually lost to the environment rather than being stored for reuse. Conversely, during discharge, expanded air is significantly colder, often requires preheating via fossil-fuel combustion to avoid thermal stress on turbine components and to maintain operating efficiency. It reduces the use of additional energy to supply usable heat during charging and to refill the air during discharge, thereby reducing round-trip efficiency of the system (ratio of energy produced to energy input). In addition, dependence on external fuel sources to re-increase operating costs and increases greenhouse gas emissions, reducing the environmental benefits of energy storage technology. [4]. To date, existing storage plants have been

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Submitted: 12 December 2024; **Accepted:** 10 July 2025

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University, İstanbul, Türkiye

on service and operational for over 20 years [5]; Hunter is the first, built in 1978 in Germany, with a storage capacity of 290 MW and an efficiency of about 46%. The McIntosh factory in the United States is the second, built in 1991, with a storage capacity of 110 MW and an efficiency of 54% [6].

Adiabatic compressed air energy storage addresses the limitations of traditional CAES by integrating thermal energy storage (TES) to recover heat that would otherwise be lost, usually in materials such as molten salts or solid media, rather than allowing it to dissipate into the environment. During discharge, this stored heat is recycled to preheat the extended air before it enters the turbine, thereby eliminating the requirement for fossil fuel combustion. By maintaining near-adiabatic conditions (reducing heat exchange with the environment), adiabatic compressed-air energy storage (A-CAES) achieves a system efficiency of 60–70%, a marked improvement over traditional CAES systems, which operate at 40–50% efficiency due to their dependence on external fuel. This closed-loop thermal management not only enhances energy recovery but also eradicates greenhouse gas emissions associated with the use of supporting fuel. [7]. In addition, by reproducing the stored heat used to warm compressed air before its expansion in turbines, the thermal energy storage system eliminates the need for fuel combustion. As a result, the A-CAES not only achieves high efficiency, but also functions as a zero-furnace process during discharge, strengthening its role in permanent energy storage solutions. [8-9]. Thus, the economic uncertainty of CAES is reduced [10].

Recent research, such as that conducted by Yang et al., shows that maintaining a constant expansion pressure while reducing the number of compression stages increases the system's output power. Conversely, increasing the number of expansion stages while maintaining a constant compression pressure improves the power output per unit mass of air. Advanced adiabatic compressed air energy storage (AA-CAES) systems with a constant overall pressure ratio are ideally configured with two compression stages and three expansion stages. The TES efficiency of the AA-CAES system is around 85% [11].

Zhao et al. [12-14] developed a dynamic model of an energy storage system combined with wind energy, where the storage system used is of the advanced adiabatic type. The simulation results showed that the output power was sufficient to satisfy the load demand.

Liu et al. [15] found that the exhaust temperature remained too high at the outlet of the low-pressure turbine of the AA-CAES, resulting in significant losses. They proposed improvements to increase the energy efficiency of AA-CAES systems. The analysis of the aboveground gas storage device for CAES yielded an overall efficiency of about 69.9%.

Lu [16] developed an experimental model combining CAES with solar and wind energy. The study examined different parameters under various conditions and using different fluids, and proposed guidelines for an ideal storage system based on an analysis of system efficiency.

Du et al. [17] developed a mathematical model of the storage efficiency of the system based on the first law of thermodynamics. The results demonstrated an average system storage efficiency of 76.9%, and a volumetric energy density of 309.48 kJ/m³, which was double that of traditional rigid gas storage tanks.

Mou, H. et al. [18] provide an overview of different CAES derivatives, especially the adiabatic system. The overview covers the theoretical developments and current trends in CAES systems. It concludes that the efficiency of an Adiabatic CAES can reach 70 %, whereas the diabatic or traditional CAES system cannot exceed 50 %, and requires fossil fuels. Moreover, the study discusses the importance of integrating Thermal Energy Storage (TES), explaining how TES can help maintain efficiency and provide potential economic benefits, particularly when combined with renewable energy sources.

Chen et al. [19] performed a feasibility study of large-scale CAES systems, focusing on the technical difficulties of creating effective heat storage systems. To improve overall system performance, you need to reduce heat loss during the compression and expansion processes. The study indicates that enhancements to the TES system would increase the efficiency of the A-CAES system, potentially raising it to 65%–75%.

Li et al. [20] conducted an analysis of the thermodynamic efficiency of A-CAES systems under various conditions. This analysis also looks at how well thermal storage systems work based on the materials used to store them. The research indicates that a well-constructed adiabatic CAES system can achieve an overall efficiency of up to 70%, contingent on the materials used.

Boudries et al. [21] investigated how temperature and pressure in underground cavern storage affect how well Adiabatic CAES systems work overall. The study finds that using advanced insulation techniques to maintain stable cavern conditions can improve system efficiency by up to 10%. It emphasizes that future systems require real-time monitoring and advanced thermal control to operate optimally.

Liu et al. [22] examined the impact of diverse factors, including geological attributes and aquifer permeability, on the efficacy of A-CAES systems. It was found that if the aquifer is highly permeable, thermal energy can escape, which reduces the overall efficiency of the Adiabatic CAES system. However, these effects can be mitigated by using improved thermal insulation and selecting optimal storage locations for items. This keeps the system operating at approximately 70% efficiency.

Bushehri, M. et al. [23] provides an in-depth examination of the scalability and technical difficulties associated with large-scale Adiabatic CAES systems. The study shows that when thermal energy recovery is at its best, there is a lot of room for high efficiency. However, it also makes clear that high capital costs and complex engineering, especially in heat exchanger design, remain significant challenges.

Sarmast, S. Et al. looked for ways to improve the performance of a near-adiabatic CAES system. They sought to determine the design and size of this system. The study found that if you balance the heat and air compression right you can store energy more efficiently and make the whole system work better [24].

Ultimately, the performance of a compressed air energy storage system depends on the temperature and pressure of the air when it is discharged from the well. These two factors affect system efficiency. The people conducting the study also found that the amount of air injected into the system is an important factor. It affects the temperature and pressure, in the cavern, which's a key part of the Compressed Air Energy Storage system [25].

The work on compressed air energy storage, or A-CAES, has been substantially improved by addressing key issues concerning the materials used, system performance, and overall system optimization. The other studies only looked at materials that can store heat, such as molten salts or solids that do not change phase. We examined more than 20 materials, including volcanic rocks, metals, and fluids that undergo phase changes. We sought materials for thermal energy storage so that we could achieve efficiencies of up to 85 percent.

We also developed a method to the A-CAES system's response to changes, which other studies have paid little attention to. By examining the system's thermal performance and cost, we can design energy storage systems that are cost-effective and integrate effectively with renewable energy.

All of these findings that we identified are important for enabling the global deployment of A-CAES technology. The A-CAES technology can be scaled up. The goal is to use it in real life. The A-CAES systems can be made to work and to be more efficient, which is what we need to do.

This paper begins with an introduction to the subject, followed by a comprehensive literature review. In the methodology section, the mathematical analysis of the model is described in detail to provide a clear understanding of the system's operational principles. Finally, the results are presented in three phases: the system without Thermal Energy Storage (TES), the system with TES, and the proposed improvements aimed at enhancing the overall system efficiency.

2. Material and method

Our adiabatic CAES system incorporates a thermal storage unit to recover energy degraded during charging. This degraded energy will later be reused to heat the air at the turbine inlet during the discharge process.

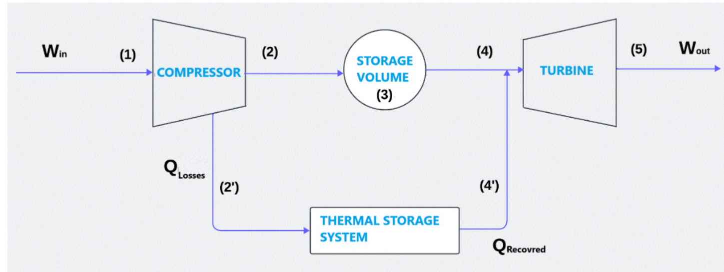

Figure 1. Studied system

We present the main equations used to analyze this system at each point shown in Figure 1.

2.1. Air compression (1) to (2)

In this stage, the air undergoes adiabatic compression, in which the power consumed by the compressor is denoted as W_{in} [kW].

The power required to compress the air is calculated using the following equation:

$$W_{in} = \dot{m} \cdot C_p \cdot (T_2 - T_1) \quad (1)$$

For an adiabatic compression process, we have the following:

$$P^{1-\gamma} \cdot T^{\gamma} = \text{Constant} \quad (2)$$

Therefore,

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad (3)$$

And,

$$P_2 = P_1 . \pi c \quad (4)$$

The final expression for the power consumed by the compressor is:

$$W_{in} = \dot{m} \cdot C_p \cdot T_1 \cdot \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (5)$$

Where;

- $\dot{m}$ is the mass flow rate of air(kg/s),
- C_p is the specific heat capacity (J/(kg·K)),
- T_1 is the inlet air temperature (K),
- P_1 is the inlet air pressure (Pa),
- P_2 is the outlet air pressure (Pa),
- γ is the specific heat ratio.

The actual work of the compressor is given by:

$$W_{actual} = \frac{W_{in}}{\eta_{is}} \quad (6)$$

Where η_{is} is the isentropic efficiency of the compressor.

Using the expressions of W_{actual} and W_{in}, we can derive the expression of heat losses in the compressor.

2.2. Thermal energy storage (2') to (4')

The heat lost during the charging process is calculated as:

$$Q_{losses} = W_{actual} - W_{in} \quad (7)$$

$$Q_{losses} = \dot{m} \cdot C_p \cdot T_1 \cdot \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right] \cdot \left(1 - \frac{1}{\eta_{is}}\right) \quad (8)$$

The thermal energy stored in the TES is given by:

$$Q_{stored} = \dot{m} \cdot C_p \cdot (T_{Stock} - T_{env}) \quad (9)$$

Where:

- T_{env} is the ambient temperature (°K),
- T_{stock} is the storage temperature, also it is typically the temperature at the compressor outlet (°K).

The thermal energy recovered from the TES is given by:

$$Q_{recovered} = \dot{m} \cdot C_p \cdot (T_{recovered} - T_{env}) \quad (10)$$

$T_{recovered}$ is the temperature after heat recovery.

The efficiency of the TES is defined as the ratio of recovered energy to stored energy:

$$\eta_{TES} = \frac{Q_{recovered}}{Q_{stored}} \quad (11)$$

$$\eta_{TES} = \frac{\dot{m} \cdot C_p \cdot (T_{recovered} - T_{env})}{\dot{m} \cdot C_p \cdot (T_{Stock} - T_{env})} \quad (12)$$

The formula of $T_{recovered}$ is expressed as:

$$T_{recovered} = T_{env} + \eta_{TES}.(T_2 - T_{env}) \quad (13)$$

Thus,

$$T_{recovered} = T_{env} + \eta_{TES} \cdot \left(T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - T_{env}\right) \quad (14)$$

For, $T_{env}=T_{ambiant}=T_1$, we have:

$$T_{recovered} = T_1 \cdot \left[1 + \eta_{TES} \cdot \left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \quad (15)$$

2.3. Compressed air storage (2) to (4)

The storage volume $V_{storage}$ is an essential part of the energy storage system. This volume provides storage for compressed air or other fluids at a specific pressure and temperature.

The storage volume can be expressed as:

$$V_{storage} = \frac{m.R.T}{P} \quad (16)$$

Where:

- m is the mass of stored fluid (kg).
- R is the specific gas constant (J/mol.K°).
- T is the absolute temperature of the fluid (°K).
- P is the absolute pressure of the fluid (bar).

Drop in temperature and pressure can occur during storage.

These losses can be calculated as follows:

The pressure in the storage volume varies over time according to the equation:

$$P_3(t) = (P_2 - \Delta P_{out}) \cdot e^{-kt} \quad (17)$$

Where k is a leakage constant and ΔP_{out} reflects the pressure drop caused by the extracted mass or volume.

The temperature in the storage volume varies over time according to the equation:

$$T_3(t) = T_2.e^{-aht} + T_1.(1 - e^{-aht}) \quad (18)$$

Where h is the heat transfer coefficient and is geometry and thermal factor.

2.4. Compressed air expansion (4) to (5)

In this case, we have an adiabatic expansion:

$$W_{out} = \dot{m} \cdot C_p \cdot (T_4 - T_5) \quad (19)$$

T_4 calculated using the following formula:

$$T_4 = T_3 + \eta_{TES}.(T_{Stock} - T_3) \quad (20)$$

Thus, using the expression of T_3 and T_{stock}, we can establish the final formula of the temperature at the turbine inlet:

$$T_4 = T_2 \cdot e^{-ht} + T_1 \cdot (1 - e^{-ht}) + \eta_{TES} \cdot (T_2 - T_2 \cdot e^{-ht} + T_1 \cdot (1 - e^{-ht})) \quad (21)$$

$$T_4 = T_1 \cdot \pi_c^{\frac{\gamma-1}{\gamma}} \cdot e^{-ht} + T_1 \cdot (1 - e^{-ht}) + \eta_{TES} \cdot \left(\begin{array}{l} T_1 \cdot \pi_c^{\frac{\gamma-1}{\gamma}} - T_1 \cdot \pi_c^{\frac{\gamma-1}{\gamma}} \cdot e^{-ht} + \\ T_1 \cdot (1 - e^{-ht}) \end{array}\right) \quad (22)$$

$$T_4 = T_1 \cdot \left[\pi_c^{\frac{\gamma-1}{\gamma}} \cdot e^{-ht} \cdot (1 - \eta_{TES}) + (1 - e^{-ht}) \cdot (1 - \eta_{TES}) + \left(\eta_{TES} \cdot \pi_c^{\frac{\gamma-1}{\gamma}}\right)\right] \quad (23)$$

Finally, we obtain:

$$T_4 = T_1 \cdot \left[\left(\left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1\right) \cdot e^{-ht} + 1\right) \cdot (1 - \eta_{TES}) + \left(\eta_{TES} \cdot \pi_c^{\frac{\gamma-1}{\gamma}}\right)\right] \quad (24)$$

For adiabatic expansion, we have:

$$T_5 = T_4 \cdot \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}} \quad (25)$$

And,

$$P_4 = P_5 . \pi t \quad (26)$$

The final expression of the power generated by the turbine is:

$$W_{out} = \dot{m} \cdot C_p \cdot T_4 \cdot \left[1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}\right] \quad (27)$$

2.5. System efficiency

The system efficiency is the ratio of the output energy/work to the input energy/ work.

$$\eta_{System} = \frac{W_{out}}{W_{in}} \quad (28)$$

Therefore,

$$\eta_{System} = \frac{T_4 \cdot \left[1 - \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}\right]}{T_1 \cdot \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (29)$$

2.6. Response time of the compressed air energy storage system

The response time of a compressed air energy storage system can be calculated using the following equation.

$$\tau = \frac{V}{\dot{V}} \quad (30)$$

The continuity equation and energy equation help to determine the expression of the response time:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{d\rho V}{dt} \quad (31)$$

$$\dot{Q} - \dot{W} = \frac{dU}{dt} \quad (32)$$

Where:

- $\dot{m}_{in}$ is the incoming mass flow rate (kg/s),
- $\dot{m}_{out}$ is the outgoing mass flow rate (kg/s),
- ρ is the air density (kg/m3),
- V is the storage reservoir volume (m3),
- $\dot{Q}$ is the heat transferred (W),
- $\dot{W}$ is the work done (W),
- U is the internal energy(J),
- τ is the response time (s),
- $\dot{V}$ is the rate of change of the reservoir volume (m^3/s).

From the expressions of the incoming mass flow rate $\dot{m}_{in}$ and outgoing mass flow rate $\dot{m}_{out}$, and by assuming that the volume is constant, we can derive:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{\rho V}{\tau} \quad (33)$$

$$\dot{m}_{in} = \frac{P_{in} \cdot \dot{V}_{in}}{R \cdot T_{in}} \quad (34)$$

$$\dot{m}_{out} = \frac{P_{out} \cdot \dot{V}_{out}}{R \cdot T_{out}} \quad (35)$$

By substituting these expressions into the continuity equation obtained, we get:

$$\frac{P_{in} \cdot \dot{V}_{in}}{R \cdot T_{in}} - \frac{P_{out} \cdot \dot{V}_{out}}{R \cdot T_{out}} = \frac{\rho V}{\tau} \quad (36)$$

Therefore, the final expression for calculating the system's response time becomes:

$$\tau = \frac{\rho V}{\frac{P_{in} \cdot \dot{V}_{in}}{R \cdot T_{in}} - \frac{P_{out} \cdot \dot{V}_{out}}{R \cdot T_{out}}} \quad (37)$$

2.7. Economic feasibility of the system

To assess the economic feasibility of the system, we must calculate the installation costs and various economic parameters. The following formulas are used:

The LCOE (Levelized Cost of Energy) is defined by the following equation:

$$LCOE = \frac{I_{tot} + \sum (O\&M + F)}{\sum E} \quad (38)$$

Where:

- I_{tot} is the total investment cost ($),
- O&M is the operation and maintenance cost($/kWh),
- F is the fuel cost($/kWh),
- E is the energy produced each year (kWh).

The total investment cost is given by:

$$I_{CAES} = I_{compressor} + I_{storage} + I_{turbine} + I_{TES} \quad (39)$$

The investment cost of the CAES system depends on π_c:

$$I_{tot} = I_{CAES} . (1 + \log(\pi_c)) \quad (40)$$

By varying, π_c we get:

$$LCOE(\pi_c) = \frac{I_{tot}(\pi_c) + \sum (O\&M + F)}{\sum E(\pi_c)} \quad (41)$$

3. Result & discussion

3.1. Simulation of the system without thermal energy storage system

In this case, the compressed air storage system is designed without a thermal energy storage system.

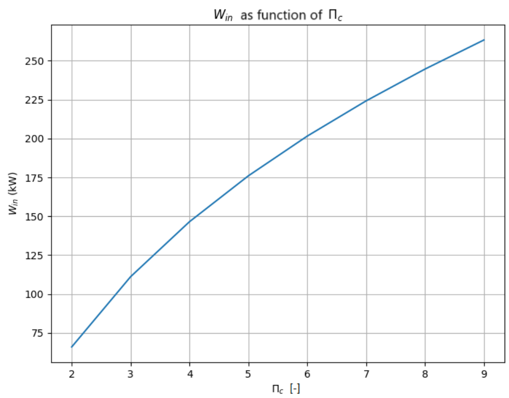

Figure 2. Compressor works as a function of the compression ratio

Figure 2 illustrates the evolution of compressor work as a function of the compression ratio. Input power increases with compression ratio. Since Win is directly linked to the compression ratio, the compressor work follows its evolution.

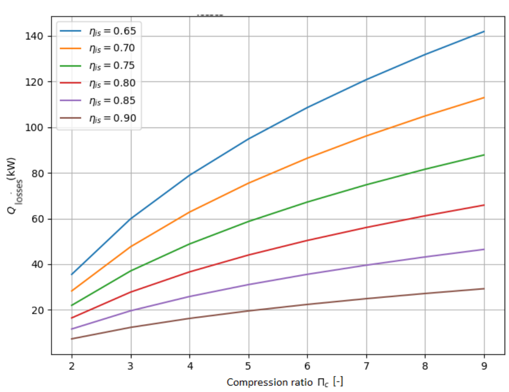

Figure 3. Compressor thermal losses as a function of compression ratio and isentropic efficiency

Figure 3 shows the development of the thermal energy degraded by the compressor. The loss of heat increases as compression ratio increases, indicating that the high ratio leads to more significant thermal damage. In addition, it has decreased heat loss, which is accompanied by an increase in isentropic efficiency. High isentropic efficiency enables a more efficient conversion of work during compression, thereby reducing the generation of excess thermal energy. This explains why the loss of heat is reduced, as is the loss of isentropic efficiency.

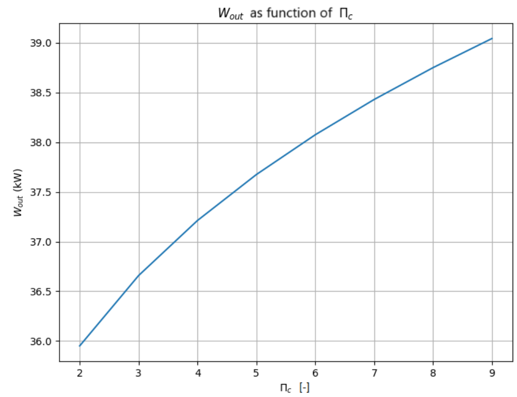

Figure 4. Work provided by the turbine as a function of compression ratio

Figure 4 shows that the output power W_{out} increases with π_c, however with a less steep slope compared to W_{in}. This reflects the efficiency of recovering thermal energy converted into mechanical work at the turbine outlet, depending on temperature T_4 and expansion ratio π_t.

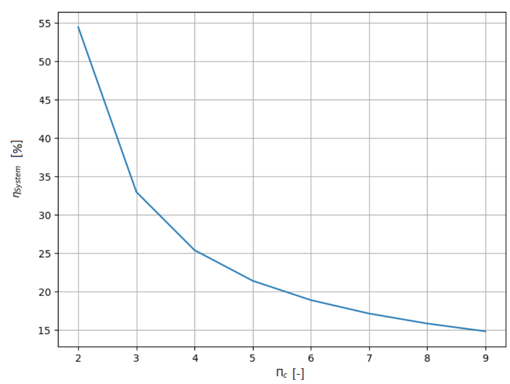

Figure 5. Overall system efficiency as a function of compression ratio

Figure 5 shows how system efficiency varies with compression ratio. System efficiency decreases significantly as the compression ratio increases. This is mainly due to increased energy degradation associated with high compression ratios, including increased thermal losses and inefficiencies in the compression process. As the compression ratio increases, the air requires more energy to compress, and the efficiency of energy conversion drops, leading to a decline in overall system performance. The optimal design of a CAES system should therefore strike a balance between measures that reduce heat loss, achieve an adequate compression ratio, and maximize overall efficiency for storage. These results identify the problems and approach we need to address to improve the performance of compressed air energy storage systems. We must consider how to manage the compression and thermal-recovery components of a Compressed Air Energy Storage system.

3.2. Simulation of the system with thermal energy storage system

In this section, the effect of thermal energy storage (TES) on a compressed air energy storage (CAES) system will be explored, specifically the transition of the CAES from diabatic to adiabatic operation. This can be achieved by using a TES system to store the heat generated during compression and reusing it to reheat the air before it enters the turbine.

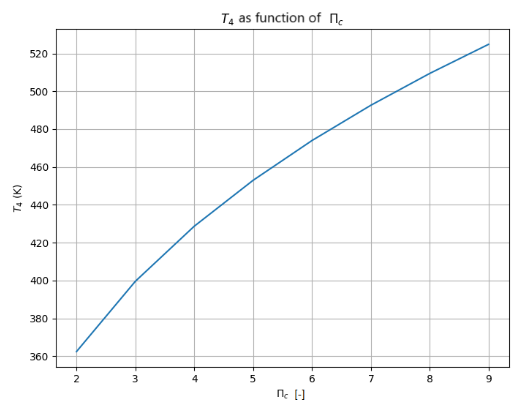

Figure 6. Turbine inlet temperature as a function of compression ratio

Adding the TES system enables reheating of compressed air before it enters the turbine, thus increasing T_4 the turbine inlet temperature. Figure 6 shows an improvement in turbine inlet temperatures as the compression ratio increases. This temperature increase is due to the heat recovered by the TES system.

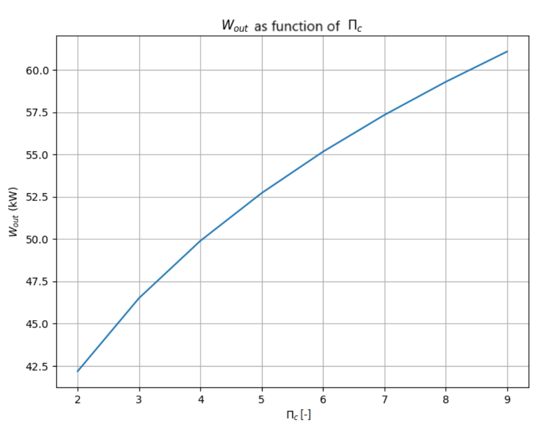

Figure 7. System output works as a function of compression ratio

Figure 7 shows that the output power increases with the compression ratio. Furthermore, the addition of TES increases power output relative to a system without TES. TES maximizes the recovery of thermal energy, which, in turn, increases the turbine's energy output because that output is directly linked to temperature T_4.

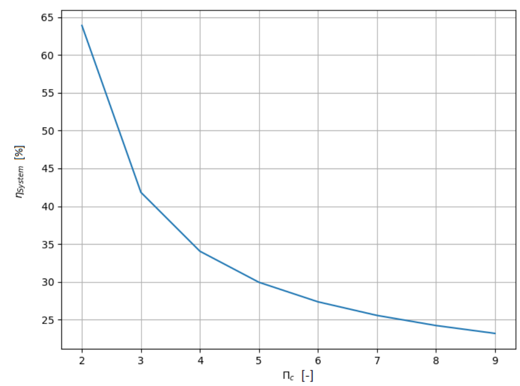

Figure 8. Overall system efficiency as a function of compression ratio

The improvement in turbine power output resulting from the addition of TES directly influences overall system efficiency. The system has two advantages: increased power output at the system exits and constant input power because it is not influenced by TES. As a result, there was a significant improvement in system efficiency of 10%. However, Figure 8 shows that efficiency decreases as compression ratio increases, although this decrease may be less pronounced than in the case without TES. In summary, an adiabatic CAES system enables recovery and reuse of heat generated during the compression phase, in addition to TES, which improves system efficiency and increases the air Temperature before it enters the turbine. This results in higher energy production. Despite these benefits, the overall efficiency may still decrease as the compression ratio increases

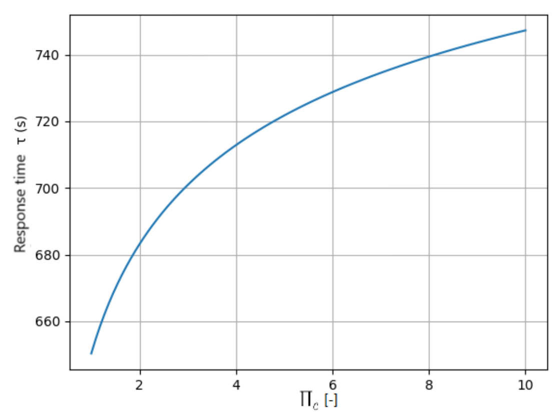

Figure 9. System response time as a function of compression ratio

Figure 9 shows the relationship between the response time and the compression ratio. It is observed that as π_c increases, τ increases, indicating a nonlinear behavior. The increase in τ is slight as the compression ratio increases. This means that the system's response time increases as the compression ratio increases, but this effect diminishes at higher ratios. The curve's exponential rise demonstrates that the pressure and temperature calculations depend on the exponential components.

The practical application of the system shows that higher compression ratios lead to longer response times because larger energy storage systems need extended periods for stabilization.

To improve our system, the following actions could be implemented:

- Extending the time range for τ beyond 100 seconds might be useful to observe long-term behavior.
- Impact of variables: adding graphs that vary other parameters η_{TES} (such ask or h) could help visualize their influence on τ and better understand their impact on response time.

3.3. Proposed system improvements

This part focuses on altering the storage material of the TES system to enhance TES performance and thus the overall efficiency of the system.

To estimate the efficiency of the TES system, it is necessary to determine both the amount of heat stored and the amount recovered.

The heat stored in the TES is calculated from the thermal capacities of the materials, their masses, and the temperature change experienced by each material.

$$Q_{stored} = m_{material}.Cp.\Delta T \quad (42)$$

$$Q_{stored} = \rho_{material}.V.Cp.(T_{air} - T_{material}) \quad (43)$$

The recovered heat depends on the efficiency of the TES and on thermal losses. For simplicity, we will assume that thermal losses are proportional to the temperature difference and to time.

$$Q_{losses} = h.A.\Delta T.t \quad (44)$$

Where:

- $T_{material}$ is the initial temperature of materials;
- T_{air} is compressed air temperature;
- h is the convective energy heat transfer coefficient;
- A is the contact area;
- t is the storage duration

To calculate the efficiency of the thermal energy storage (TES) system, we use Equation 11.

We also have:

$$Q_{recovered} = Q_{stored} - Q_{losses} \quad (45)$$

$$\eta_{TES} = \frac{Q_{stored} - Q_{losses}}{Q_{stored}} \quad (46)$$

$$\eta_{TES} = 1 - \frac{Q_{losses}}{Q_{stored}} \quad (47)$$

Therefore, to improve the efficiency of the thermal storage system, we need to increase the percentage of heat stored. The amount of stored heat depends on T_{air} (equal to T_2 in our case). Alternatively, it also depends on: $m_{material}$, C_p, and $T_{material}$, which are directly related to the nature of the material used for thermal storage.

Table 1 illustrates the values of density ρ, initial temperature $T_{material}$, and specific energy heat capacity C_p for 20 materials commonly used for thermal storage, including volcanic rocks.

Table 1. Thermal Properties of Various Materials for Thermal Storage [26-40]

Material	Density (kg/m³)	Initial Temperature (K°)	Specific energy Heat Capacity (J/(kg·K°))
Volcanic Rocks	3000	300	840
Granite	2650	300	790
Basalt	2900	300	840
Sand	1600	300	830
Concrete	2400	300	880
Refractory Brick	2200	300	1000
Steel	7850	300	490
Aluminum	2700	300	900
Copper	8960	300	385
Iron	7200	300	550

Water	1000	300	4186
Ethylene Glycol	1110	300	2470
Paraffin	900	300	2100
Thermal Oil	900	300	2000
Molten Salt (nitrate)	1800	300	1500
Quartz	2650	300	730
Cement	3100	300	900
Graphite	2260	300	710
Zirconium	6500	300	270
Lithium	534	300	3570

The evolution of heat losses generated by the compressor as a function of compression ratio for several materials used in thermal energy storage systems. The graph reveals that losses increase progressively with compression ratio, consistent with the idea that higher pressures or thermal stresses cause greater heat losses. Thermal losses are independent of the materials used in thermal energy recovery. However, the stored energy depends on the material used.

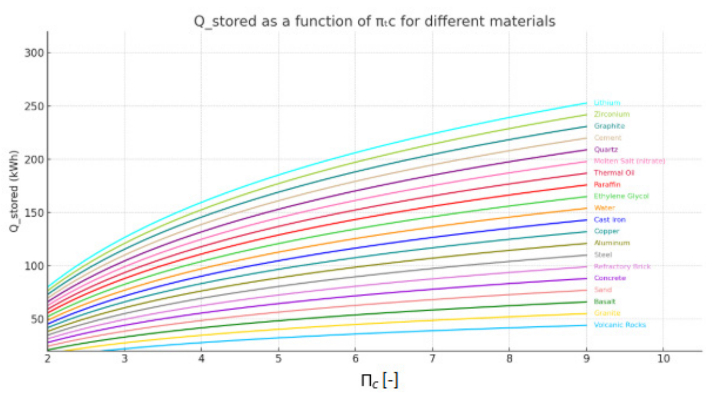

Figure 10. Amount of Thermal Energy Recovered by TES as a function of Compression Ratio

Figure 10 illustrates the stored energy as a function of compression ratio for different storage materials. Stored energy increases with the compression ratio, but the rate of increase varies with the materials used. Volcanic rocks and materials, such as steel and copper, exhibit higher levels of stored energy, making them potentially useful in applications that require high thermal capacity. Materials such as quartz and paraffin, although efficient, have moderate energy storage capacities.

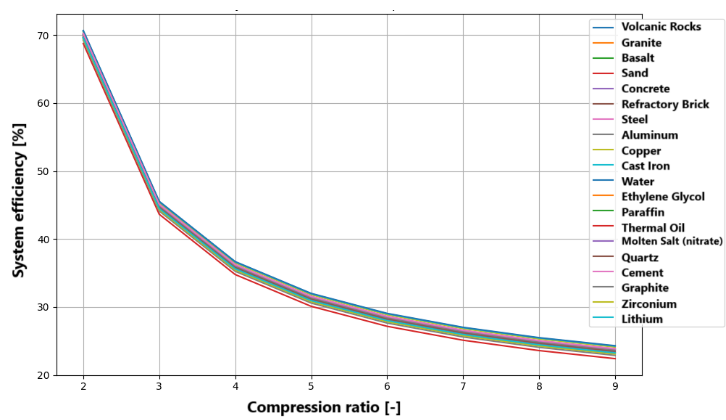

Figure 11. System Efficiency as a function of Compression Ratio

Figure 11 presents the evolution of system efficiency as a function of the compression ratio. TES efficiency remains generally constant with increasing compression ratios for most materials. This suggests that the efficiency of TES systems depends less on variations in compression ratio than on intrinsic material properties. System efficiency differs slightly (Fig.11). Volcanic rocks and granite exhibit thermal efficiencies of up to 71%, whereas other materials have lower efficiencies. The thermal performance of concrete and steel is insufficient for applications that require minimizing thermal losses. The TES system demonstrates material performance through its thermal losses, storage capacity, and efficiency, as shown in Figures 10 and 11. The right material selection should follow the system requirements because thermal losses, stored energy, and overall efficiency need to be evaluated together. The different criteria require trade-off decisions, as shown by the results.

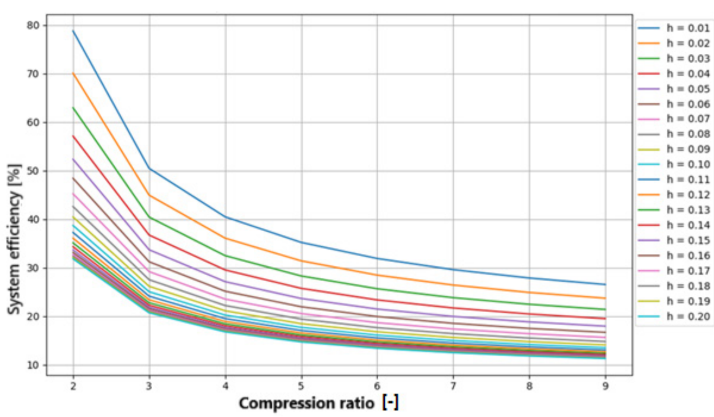

Figure 12. System efficiency as a function of expansion ratio for different values of the heat transfer coefficient

Figure 12 shows how system efficiency varies with different compression ratios that were tested at multiple values of h. Efficiency decreases with increasing h, indicating that higher convective losses reduce overall system performance. The convective heat transfer coefficient, h, represents thermal losses due to convection, which in turn affect the compressed-air storage volume. Indeed, this phenomenon reduces the air temperature. For high values of h, thermal losses are significant, leading to a decrease in overall efficiency. The figure shows that, to maintain high efficiency, it is crucial to minimize convective losses, especially at high compression ratios.

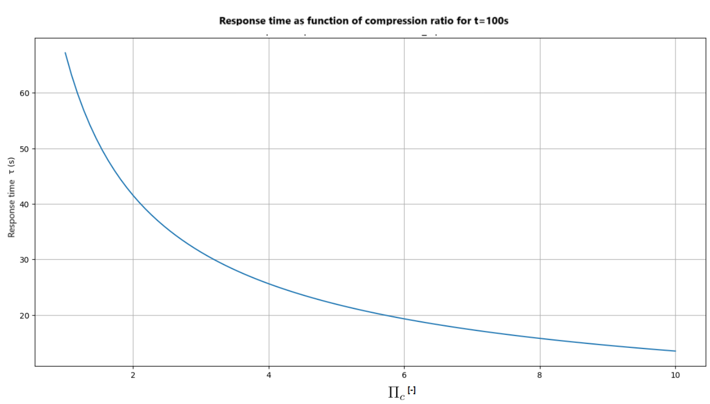

Figure 13. System Response Time as a Function of Compression Ratio (with Improvement)

Figure 13 shows the variation in response time with compression ratio at a time of 100s.

Inverse Trend: Conversely to figure 10 where response time increased with the increase of π_c, Figure 13 shows that response time decreases significantly as π_c increases. This reflects behavior opposite to that previously observed, suggesting a different dynamic resulting from parameter adjustments.

Amplitude: The initial response time in Figure 13 is much higher (around 60 seconds) and decreases to about 20 seconds at a high compression ratio. This rapid reduction suggests an improvement in response π_c time.

The effect of compressible gas dynamics may explain the improvement in results through better modulation of the compression π_c ratio. As input pressure increases, energy storage capacity increases, leading to a faster response time to system disturbances. Therefore, the system reaches equilibrium more rapidly.

More Efficient Energy Storage and Release: By more efficiently managing compression and input/output temperatures, the system can adapt more quickly to pressure changes, reducing the time required to reach a new equilibrium.

Parameter Optimization: By adjusting parameters such as time (t), the convection coefficient (h), and other factors, the system can become more responsive. This is visible as a decrease in τ as the compression ratio increases. This means that improvements in thermodynamic parameters and initial conditions have optimized the process, leading to faster system responsiveness. The modification of the modeling parameters has produced a more physically intuitive result: systems with higher compression ratios are more responsive, thereby reducing response time. This shows that, in an energy storage system such as A-CAES, greater compression can allow faster adjustments in the system, consistent with the behavior of compressible thermodynamic processes.

Wenjun Shi et al. [39] studied a multi-objective optimization approach to improve both thermal and economic performances of an AA-CAES system. The results indicate a thermal efficiency of approximately 70% under optimal conditions. The study demonstrated that higher heat storage capacity improves both efficiency and economic viability.

Nguyen et al. [40] examines the thermodynamic efficiency of near-isothermal CAES system focusing more on pressure release mechanisms using internal combustion engines. The results show an efficiency of up to 75% for near-isothermal CAES systems, compared with 50% for traditional systems. The study also highlights the reduction in energy losses due to improved pressure management. Assumed TES efficiencies align with experimental values reported in [11,15], where volcanic rocks achieved 85% efficiency under similar conditions. In our results, overall efficiency reaches 71%, which compares to [4,7,8,11,15,40] a report of 70% for an AA-CAES system and 75% for near-Isothmal CAES system respectively. Although our system is based on AA-CAES, achieving 71% indicates that our approach not only matches, but is slightly more efficient than the same designs, thereby the effectiveness of our thermal energy storage strategy.

3.4. Economic Analysis

The economic analysis in this paper is based on the estimation of the Levelized Cost of Energy (LCOE).

The LCOE is a key metric for evaluating the economic viability of the CAES system. This metric helps determine whether the system can provide an economically competitive energy source compared to other storage technologies.

Considering the LCOE values observed in our analysis, the adiabatic CAES system has a higher cost than other energy storage solutions. The increase in LCOE with higher compression conditions indicates that, while improvement of system performance can lead to cost-effectiveness, higher compression conditions may not be cost-effective. It is important to consider the cost-benefit balance and assess whether the system's performance gains are sufficient to justify additional costs.

Figure 14 illustrates the variation in LCOE as a function of the compression ratio over a 25-year lifespan. LCOE increases progressively as the compression ratio rises. For low compression ratios, LCOE remains relatively low, but it increases with compression ratio. A high compression ratio results in low system efficiency; because LCOE is inversely related to system efficiency, LCOE increases as the compression ratio increases. This, in turn, leads to a much higher system cost, eventually overtaking benefits.

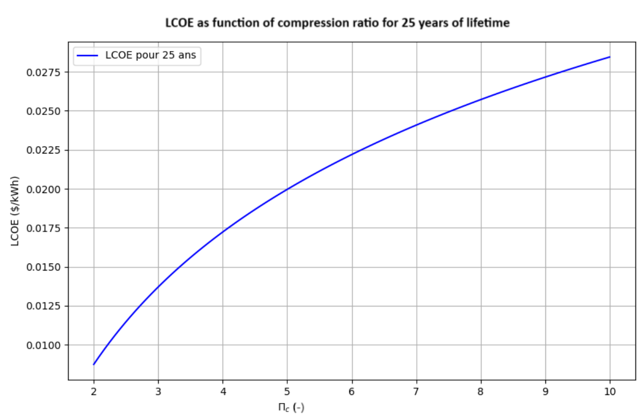

Figure 14. LCOE as a function of Compression Ratio

The levelized cost of energy (LCOE) for the adiabatic CAES system in this study ranges from 0.01–0.03 $/kWh for compression ratios 2–10. This positions A-CAES as competitive with other large-scale energy storage technologies. For context:

Li-ion batteries exhibit higher costs (0.15–0.30$/kWh) due to shorter lifespans and material constraints [50].

Pumped hydro storage, while cheaper (0.05–0.15$/kWh*), faces geographical and environmental limitations [51].

The economic viability of A-CAES is further strengthened by its scalability and fuel independence, offering a balanced solution for grid-scale renewable integration.

4. Conclusion

The adiabatic compressed air energy storage system demonstrates its capacity to store. The system requires solutions to three main challenges: handling temperature control, choosing suitable materials, and creating systems compatible with current facilities. The assessment of thermal characteristics, energy storage capacity and economic performance informs the development of suitable solutions for compressed-air energy storage technologies. The study demonstrated that increasing the compression ratio produced two opposing effects. The first effect results from increased thermal energy loss during the compression process, which reduces system efficiency. The second effect causes delays because the system requires additional time to reach high pressure during compression and decompression of air. The system achieved better performance because response time decreased as a result of previous improvements, enabling faster system operation to handle energy demand and supply changes.

The thermal energy storage system stores more thermal energy as the compression ratio increases. The compression process generates additional heat because higher pressure leads to further compression. The efficiency of the thermal energy storage system remains constant because its performance depends on the system's materials and design rather than on the amount of heat introduced.

The economic analysis shows that higher compression ratios lead to increased energy costs. The need for high-pressure compressors, robust air storage tanks, and efficient heat exchangers increases costs because the system requires these components for both construction and operation. The system requires more labor to operate because employees must handle more complex systems that lead to additional expenses. The system requires full construction through design work; although a high compression ratio benefits thermodynamic performance, in this case the complete system design must be finalized first. According to current research, there are effective ways to address these obstacles. Improved materials development for thermal energy storage systems will increase heat storage and transfer capabilities by enhancing material performance, which will decrease heat loss. The system will maintain its operational speed via efficient operation when we implement advanced control algorithms that determine optimal operational settings linking the compression ratio to system response time. The levelized cost of energy will remain manageable if we develop cost-effective methods for producing high-pressure components using new materials and manufacturing techniques. Advances in adiabatic compressed air energy storage systems will improve operational performance, economic competitiveness, and reliability.

The advanced adiabatic compressed-air energy storage system faces multiple research challenges that must be resolved to increase its operational capabilities. The main problem arises when administrators operate thermal energy storage systems: they must choose among various materials with differing performance capabilities to design effective heat-exchange systems that minimize thermal energy losses. The development of compressor and turbine systems needs to focus on two main research areas: achieving higher energy conversion efficiency and reducing capital and operational expenditures. The system integration process requires additional and economic solutions because it requires advanced control methods and the successful implementation of larger systems to connect stalled and renewable energy sources while maintaining grid stability.

Nomenclature

$\dot{m}$	Mass flow rate of air, kg/s
C_p	Specific heat capacity at constant pressure, J/(kg·K°)
T_1	Inlet air temperature, K°
P_1	Inlet air pressure Pa
P_2	Outlet air pressure, Pa
γ	Specific heat ratio,-
η_{is}	Isentropic efficiency of compressor, %
T_{env}	Ambient temperature,
T_{stock}	Storage temperature, K°
$T_{recovered}$	Temperature after heat recovery, K°
m	Mass of stored fluid, kg
R	Specific gas constant, J/(mol.K°)
$\dot{m}_{in}$	Incoming mass flow rate, kg/s
$\dot{m}_{out}$	Outgoing mass flow rate, kg/s
V	Storage reservoir volume, m3,
$\dot{Q}$	Heat transferred, W
ρ	Density,
$\dot{W}$	Work, W
U	Internal energy, J
τ	Response time, s
$\dot{V}$	Rate of change of the reservoir volume, m³/s
I_{tot}	Total investment cost ($),
O&M	Operation and Maintenance cost, $/kWh
F	Fuel cost, $/kWh
E	Energy produced each year, kWh
$T_{material}$	Initial temperature of materials, K°
T_{air}	Compressed air temperature, K°
h	Convective energy heat transfer coefficient, W/(m2.K°)
A	Contact area, m2
t	Storage duration, s

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