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Performance Analysis and Multi-objective Optimization of an Adiabatic CAES System Coupled with Heat Storage Unit

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Abstract. Integrating renewable energy into the grid is essential for combating the greenhouse effect. This paper introduces a high-temperature adiabatic compressed air energy storage system integrated with cascaded thermal energy storage using molten salt and pressurized water to enhance efficiency. The study includes thermodynamic modeling and simulations for the system components. Further, the impacts of key parameters on critical system evaluation criteria are analyzed. Finally, using round-trip efficiency and energy storage density as optimization goals, a particle swarm optimization algorithm was employed for multi-objective optimization. The optimized system achieved a round-trip efficiency of 70.14% and an energy storage density of 3.52 kWh/m^3, resulting in an optimal operational strategy that balances system performance with energy storage capacity.

Keywords: Compressed air energy storage; Performance analysis; Cascaded thermal energy storage; Multi-objective optimization.

1. Introduction

In the context of the global shift towards low-carbon energy systems, the proportion of renewable energy is steadily increasing. IEA [1] predicts that global renewable energy installed capacity will exceed 5,500 GW by 2030. However, the randomness and volatility [2] of renewable energy pose severe challenges to power system stability. Large-scale energy storage technology and efficient thermal energy storage have emerged as effective solutions to enhance grid stability.

Current large-scale energy storage technologies primarily include pumped hydro storage and compressed air energy storage (CAES) [3]. Pumped hydro storage is widely used for its mature technology and large storage capacity, but is constrained by geographic limitations. CAES has become a research hotspot due to its advantages in low cost and long lifespan [4].

In recent years, numerous researchers have conducted analyses and improvements on the configuration of CAES systems. Wang et al. [5] conducted research through conventional and advanced entropy analysis to evaluate the energy conversion efficiency and heat loss of underwater CAES systems. Researchers have attempted to enhance performance by introducing multi-stage compression, isothermal compression, thermal storage coupling, and other methods [6]. The thermodynamic performance directly influences key performance indicators of CAES systems. Traditional CAES systems often struggle to recover heat generated during air compression, leading to low round-trip efficiency (RTE). In adiabatic compressed air energy storage (A-CAES) systems, thermal energy storage technology has become critical to overcoming performance bottlenecks. Xu [7] proposed a new water-circulating compressed air energy storage system, and the simulation results showed that the round-trip efficiency of the system was improved by 1.6% compared to the conventional CAES system.

The influence of key system parameters on performance evaluation indices often exhibits divergent trends, making multi-objective optimization algorithms a viable solution for complex thermodynamic system optimization problems widely adopted by researchers. Shi et al. [8] used the Particle swarm optimization (PSO) algorithm to optimize parameters of a CAES system, achieving an increase in round-trip efficiency from 63.2% to 69.5%. Budt et al. [9] reviewed critical factors affecting the economy and performance of CAES systems, emphasizing the decisive role of optimization strategies in large-scale engineering implementation. Tayyeban et al. [10] researched

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reciprocating expanders in CAES systems. By employing the Pareto solutions approach, they investigated the optimal parameters for reciprocating expanders under inlet pressures of 8 and 10 bar.

It can be seen from this that lots of researchers have conducted studies on the coupling design and optimization of the CAES system at present, proving the feasibility of the combination of this system with other systems. But only a limited number of studies have investigated the system design and thermodynamic performance analysis of CAES systems integrated with cascade heat storage units.

To address these issues, this study proposes a high-temperature adiabatic CAES (HTA-CAES) system. The system employs cascaded thermal energy storage with molten salt and pressurized water, enabling more efficient heat recovery and utilization while expanding the operational temperature range. By leveraging thermal storage, HTA-CAES reduces reliance on fossil fuels, decreases fluctuations from renewable energy grid integration, and provides a technical pathway for large-scale energy storage.

2. System Description and Modeling

2.1 System Description

The HTA-CAES system integrates graded compression and expansion with a cascaded thermal energy storage scheme using molten salt and pressurized water for efficient energy management, comprising three core stages: compression, storage, and release, as is shown in Fig. 1.

During low-load periods, air is sequentially compressed by two stages of compressors, with interstage heat recovery through heat exchangers. The first-stage compressed air cools via heat exchangers IC1 and IC2 before entering the next compressor. After compression, the high-pressure air undergoes further heat exchange and is then stored in underground salt caverns. Molten salt and pressurized water serve as thermal media, stored in HST and HWT. The cascaded system enables molten salt to handle high-temperature heat storage, while pressurized water manages thermal regulation in lower temperature segments during compression. During peak demand, high-pressure air is released, absorbing stored heat from both media through HE1 and HE2 to regain high-temperature and high-pressure states. The heated air expands through high-pressure TURB1 to generate power, with exhaust gas further processed by low-pressure TURB2 for residual energy recovery, completing the release cycle.

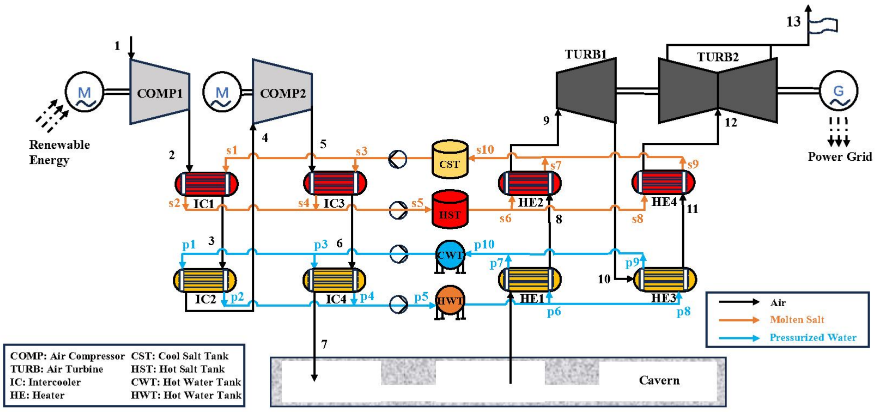

Fig. 1 HTA-CAES system workflow diagram

The HTA-CAES system developed in this study reduces compression energy consumption and improves energy storage density through stage-wise pressure elevation and stepwise heat recovery. Meanwhile, the cascaded thermal energy storage technology broadens the system’s operating temperature range and minimizes heat loss. Additionally, the collaborative design of molten salt-air

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and pressurized water-air heat exchangers optimizes heat transfer efficiency, ensuring efficient coupling between thermal storage media and air working fluid.

2.2 Thermodynamic modeling

2.2.1 Assumptions of the model

To simplify the development of the coupling system model, the following assumptions are included in this study:

(1) The thermal process is regarded as steady state.

(2) The working processes of the compressor and expander are corrected based on the isentropic efficiency calculation.

(3) The system heat loss is ignored, and the pipeline pressure loss is set at 2%.

(4) The molten salt is selected as HITEC.

2.2.2 Modular modeling calculation formula

The input power of the compressor can be expressed as:

$$\dot{W}_c = \dot{M}_{air}(h_{out} - h_{in}) \tag{1}$$

where *m* represents the air quality flow rate, and *h* represents the enthalpy of the working medium. The subscripts *in* and *out* denote the inlet and outlet parameters, respectively.

All the heat exchangers use counter-flow heat exchangers. The heat exchange occurs between the heat storage medium and air. The energy balance equation is as follows:

$$\dot{Q} = \dot{m}_{cold}(h_{cold,out} - h_{cold,in}) = \dot{m}_{hot}(h_{hot,in} - h_{hot,out}) \tag{2}$$

where *Q* represents the heat transfer quantity, and the subscripts *cold* and *hot* represent the cold fluid and the hot fluid, respectively.

The output power of the turbine can be expressed as:

$$\dot{W}_t = \dot{M}_{air}(h_{in} - h_{out}) \tag{3}$$

The evaluation indicators for measuring the performance of the CAES system mainly include RTE for measuring the energy conversion effect of the system, heat recovery rate (HRE) for measuring the utilization efficiency of waste heat, exergy storage density (ESD) for measuring the energy storage capacity, and total exergy efficiency (TEE) for measuring the energy quality. The definitions of these indicators are as follows:

$$RTE = \frac{\dot{W}_t t_{re}}{\dot{W}_c t_{st}} \tag{4}$$

where *t* represents time, and the subscripts *re* and *st* represent the discharging and charging period, respectively.

$$HRE = \frac{\dot{Q}_{\exp} t_{re}}{\dot{Q}_{\text{abs}} t_{st}} \tag{5}$$

where the subscripts *exp* and *abs* represent heat expansion and heat absorption, respectively.

$$ESD = \frac{\dot{W}_t t_{re}}{V} \tag{6}$$

where *V* represents the volume of the salt carven.

$$TEE = \frac{\dot{E}x_P}{\dot{E}x_F} \tag{7}$$

where *Ex* represents the exergy, and the subscripts *P* and *F* represent product and fuel exergy.

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2.3 Desgin conditions

This paper builds a simulation model of the HTA-CAES system based on the MATLAB platform, and uses the REFPROP software to obtain the thermophysical property parameters of the working medium at each node, thereby ensuring the calculation accuracy. The parameter settings of the system are shown in Table 1.

Table 1. Parameter setting of the HTA-CAES system

Parameter	Symbol	Value	Parameter	Symbol	Value
Rated power	W_t	200MW	Ambient pressure	P_0	101kPa
Ambient Temperature	T_0	288.15K	Compression ratio 1	π_1	13.5
Compression ratio 2	π_2	10.0	Expansion ratio 1	β_1	9.2
Expansion ratio 2	β_2	6.8	Air flow rate	M_{air}	1635.08t/h
Energy storage duration	t_{st}	8h	Energy discharge duration	t_{re}	8h
Pressure loss	ΔP	2%	Heat exchanger effectiveness	η_{ex}	87%

3. Results and Discussion

3.1 System performance in designed condition

Table 2 presents the values of the system's thermodynamic performance evaluation indicators under the design conditions. It can be seen that the HRE and RTE of the system are superior to those of the traditional CAES system.

Table 2. System thermodynamic performance evaluation indicators

Indicator	Unit	Value
RTE	%	61.43
HRE	%	66.49
ESD	kWh/m^3	3.43
TEE	%	90.59

3.2 Thermodynamic analysis of HTA-CAES system

3.2.1 Impact of compression ratio 1 on system performance

The influence of the compression ratio distribution of one and two-stage compressors is investigated by varying the compression ratio 1. The total compression ratio is determined to be 135.

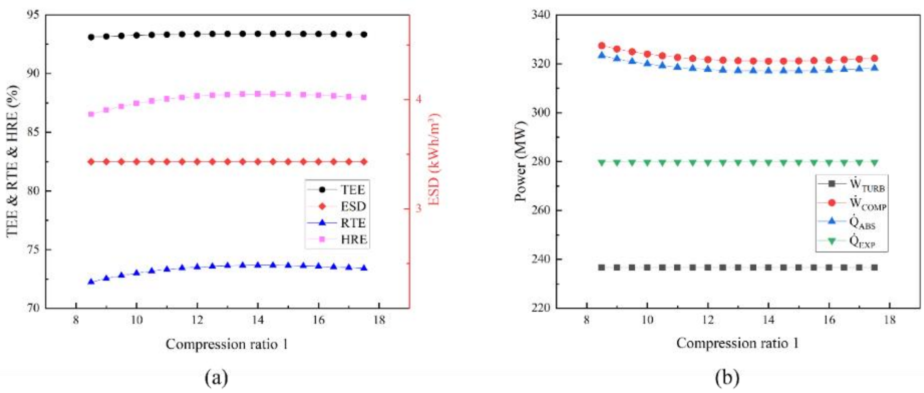

Fig. 2 Impact of compression ratio 1 on system performance

The effect of the first stage compression ratio on the system performance index is shown in Fig. 2(a), and the effect on the system power is shown in Fig. 2(b). The results show that the RTE increased and then decreased with the increase of the first-stage compression ratio, and the RTE

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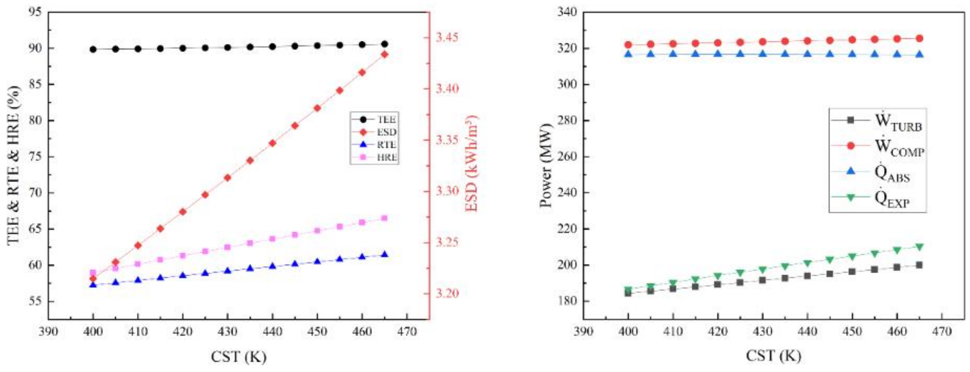
reaches a maximum of 73.63% at the first-stage compression ratio of 13. At the initial stage, the increase in compression ratio made the compression power decrease and RTE increase. However, high compression ratio led to an imbalance in the distribution of the two-stage compressor, and ultimately a decrease in RTE.

3.2.2 Impact of CST temperature on system performance

The effect of the CST on the system performance metrics is shown in Fig. 3(a), and the trend of the system power is shown in Fig. 3(b). As the CST temperature increased, the RTE, HRE, and ESD increased proportionally. The ESD and HRE increased by 6.85% and 12.73%, respectively, and the RTE increased by 2.5%. In the energy release stage, high-temperature molten salt can more fully heat the air in front of the turbine, increasing the reheater heat release and improving the HRE, thereby improving the RTE.



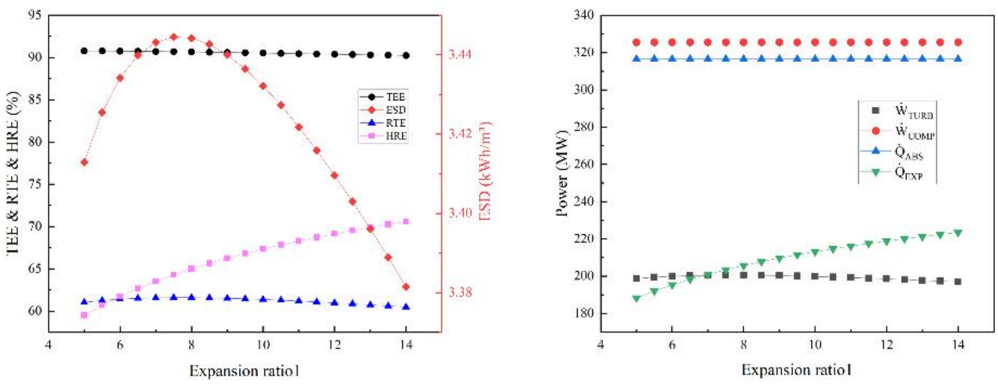
(a) (b)

Fig. 3 Impact of CST temperature on system performance

3.2.3 Impact of expansion ratio 1 on system performance

The expansion ratio 1 is varied to study the distribution of expansion ratios in turbines and to investigate the influence. The total expansion ratio is 62.56.

As shown in Fig. 4, when expansion ratio 1 was in the range 4-8, increasing the expansion ratio enhanced turbine output power, and the RTE increased slightly. Once the expansion ratio exceeded 8, however, the compressor must overcome a higher storage pressure, resulting in a gradual decrease in RTE. At high expansion ratios, the reheaters' heat transfer capacity approached the upper limit, the growth rate of heat release slowed down and the increase in the HRE decreased. Initially, ESD increased significantly with the increase in expansion ratio 1, reaching a maximum. At the expansion ratio of 7.5, the ESD reached a maximum value of 3.44 kWh/m^3.



(a) (b)

Fig. 4 Impact of expansion ratio 1 on system performance

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3.3 Multi-objective optimization of HTA-CAES system

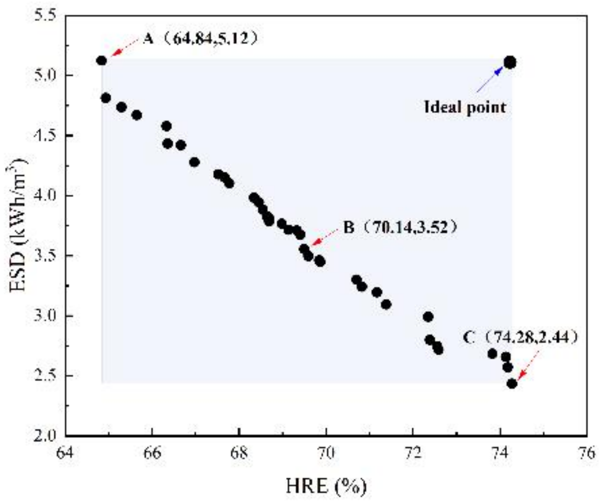

Fig. 5 Optimization results of the HTA-CAES system

In this study, MOPSO algorithm is utilized to optimize the HTA-CAES system over the decision variables in the feasible range. It was determined that point B was the point optimized by the Pareto optimal solution determined by the LPDMMPA method. This point had the closest Euclidean distance to the ideal point. It was established that point B had the ESD of 3.52 kWh/m³ and the RTE of 70.14%.

4. Summary

To enhance the energy storage capacity and heat recovery rate of CAES systems, this study proposes and investigates an HTA-CAES system integrated with cascaded thermal energy storage units. The influence of key parameters on the system's thermodynamic performance is analyzed, and multi-objective optimization is conducted to obtain an optimal system design scheme. The main work and research conclusions are as follows:

(1) A high-temperature adiabatic compressed air energy storage system is proposed, and a thermodynamic model of the system is established based on the MATLAB platform. System evaluation indices are derived from the laws of thermodynamics.

(2) The influence of key parameters on the system's thermodynamic performance was studied. Results show that reasonable allocation of compression and expansion ratios can maximize the system's thermodynamic performance.

(3) Taking system output power and exergy efficiency as optimization objectives, MOPSO algorithm is used to analyze the key parameter distributions corresponding to Pareto solutions. The optimal operating point of the system is determined, with ESD of 3.52 kWh/m³ and RTE of 70.14%.

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