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Performance of an above-ground compressed air energy storage#

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ABSTRACT

Compressed air energy storage technology has become a crucial mechanism to realize large-scale power generation from renewable energy. This essay proposes an above-ground compressed air energy storage and the thermo-economic performance are analyzed. The advantages of discharge pressure and mechanical efficiency have positive effects on round-trip efficiency of the system. Levelized Cost of Storage has a lowest value about 0.173 $/kWh as varying discharge pressure and mechanical efficiency. At the same time, internal rate of return has peak values as varying discharge pressure and mechanical efficiency. The thermo-economic performance of the system is linearly related with the pressure loss of the heat exchanger. When the charging pressure is 10MPa and the discharge pressure is 3.5MPa, the system has the best performance.

Keywords: above-ground compressed air energy storage system, renewable energy, thermo-economic analysis

NONMENCLATURE

Abbreviations	
CAES	Compressed Air Energy Storage
Symbols	
$\dot{W}$	Power (W)
h	Specific enthalpy (J/kg)
m	Mass flaw rate (kg/s)
$\dot{Q}$	Heat transfer rate (W)
t	Time (s)
RTE	Round-trip efficiency (%)
LCOS	Levelized Cost of Storage ($/kWh)
NPV	Net Pressure Value (Million $)
IRR	Internal Rate of Return

1. INTRODUCTION

With the improvement of human living standards, the energy consumption mainly based on fossil fuel combustion is hard to satisfy the requirements of sustainable development. The transformation of the energy structure is imminent. Renewable energy has gained wide attention as a pragmatic approach on above issues [1]. However, there are many issues with renewable energy grid connection. In this context, energy storage can solve these problems well [2].

Compressed air energy storage (CAES), as a large-scale energy storage technology, benefits from low investment cost and short construction time [3]. It can be classified as above-ground CAES system and underground CAES system.

Many researches on underground CAES have been conducted. Han et al. [4] proposed a CAES with cavern. The results showed that high injection pressure could reduce the temperature and pressure of cave air. Perazzelli et al. [5] went deeply into the cavities of CAES. The results indicated that the prerequisite for the feasibility of CAES cavities is that the rock mass has the ability to resist uplift failure.

However, underground chambers have high geological requirements, which limits the development of underground CAES. Thus, the above-ground CAES technology is studied and developed. Tian et al. [6] analyzed the large-scale adiabatic CAES system. The final results suggested that the third-stage heat exchanger accounts for 13.15% of the avoidable heat energy damage in the system. Chen et al. [7] drew an iso-voltage insulation CAES system. The outcomes indicated that the round-trip efficiency of the system approaches to 80%. Yu et al. [8] advanced a novel indirect heating adiabatic CAES system. The research expressed that this system has better thermodynamic performance.

In order to enrich the research on the field of above-ground CAES, this article proposes an above-ground CAES system and conducts a comprehensive analysis of the system. Focus is placed on how many important parameters affect system performance.

2. REQUIREMENTS OF PAPER STRUCTURE

Fig.1 shows an abridged drawing of this system. The system consists of heat exchangers, turbines, compressors, an air holder and tanks. In the charging

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stage, the air is pressurized by compressors. Coolers recovers the compression heat and stores it in hot tank. Then, the air enters the air holder for storage. In the discharging stage, the compressed air is released by air holder. It enters the heaters to be absorbed compression heat. Finally, preheated air enters the turbine to be expanded.

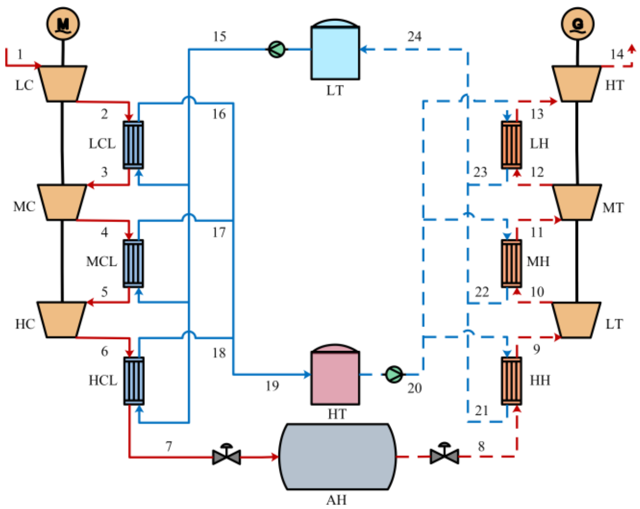

Fig. 1 Abridged drawing of the proposed system.

3. MATHEMATICAL MODEL

This section establishes mathematical models to estimate the thermo-economic performance of the system.

3.1 Thermodynamic analysis model

Power consumption of the compressors are:

$$\dot{W}_{LC} = m_{air}(h_2 - h_1) \quad (1)$$

$$\dot{W}_{MC} = m_{air}(h_4 - h_3) \quad (2)$$

$$\dot{W}_{HC} = m_{air}(h_6 - h_5) \quad (3)$$

Power consumption of the turbines are:

$$\dot{W}_{HT} = m_{air}(h_{13} - h_{14}) \quad (4)$$

$$\dot{W}_{MT} = m_{air}(h_{11} - h_{12}) \quad (5)$$

$$\dot{W}_{LT} = m_{air}(h_9 - h_{10}) \quad (6)$$

The energy equations in the heat exchangers are:

$$\dot{Q}_{LCL} = m_{air}(h_2 - h_3) = m_{water,16}(h_{16} - h_{15}) \quad (7)$$

$$\dot{Q}_{MCL} = m_{air}(h_4 - h_5) = m_{water,17}(h_{17} - h_{15}) \quad (8)$$

$$\dot{Q}_{HCL} = m_{air}(h_6 - h_7) = m_{water,18}(h_{18} - h_{15}) \quad (9)$$

$$\dot{Q}_{LH} = m_{air}(h_{13} - h_{12}) = m_{water,23}(h_{20} - h_{23}) \quad (10)$$

$$\dot{Q}_{MH} = m_{air}(h_{11} - h_{10}) = m_{water,22}(h_{20} - h_{22}) \quad (11)$$

$$\dot{Q}_{HH} = m_{air}(h_9 - h_8) = m_{water,21}(h_{20} - h_{21}) \quad (12)$$

The power consumption during the charging stage is expressed as:

$$\dot{W}_{ch} = \dot{W}_{LC} + \dot{W}_{MC} + \dot{W}_{HC} \quad (13)$$

The power consumption during the discharging stage is expressed as:

$$\dot{W}_{dis} = \dot{W}_{HT} + \dot{W}_{MT} + \dot{W}_{LT} \quad (14)$$

Round-trip efficiency (*RTE*) can be depicted as：

$$RTE = \frac{W_{dis}t_{dis}}{W_{ch}t_{ch}} \times 100\% \quad (15)$$

3.2 Economic analysis model

The investment cost of each component of the system is：

The purchased cost of components is：

$$Z_{PC} = Z_C + Z_T + Z_{HE} + Z_{Tank} + Z_{AH} \quad (16)$$

The system installation cost is：

$$Z_{IC} = 0.9 Z_{PC} \quad (17)$$

The system operation and maintenance cost is ：

$$Z_{OM} = 0.04 Z_{PC} \quad (18)$$

The system charging cost is:

$$Z_{ch} = C_{ch}\left(W_{ch}t_{ch}\right)cycle \quad (19)$$

The levelized Cost of Storage (*LCOS*) can reflect the comprehensive economic performance:

$$LCOS = \frac{\sum_{y=1}^{Life}\frac{Z_{OM}+Z_{ch}}{(1+d_r)^y} + Z_{PC} + Z_{IC}}{\sum_{y=1}^{Life}\frac{cycle W_{dis}t_{dis}}{(1+d_r)^y}} \quad (20)$$

The electricity price during peak hours is：

$$Z_{dis} = C_{dis}(W_{dis}t_{dis})cycle \quad (21)$$

Net Present Value (NPV) is defined as：

$$NPV = \sum_{y=1}^{Life}\frac{Z_{dis} - Z_{OM} - Z_{ch}}{(1+d_r)^y} - Z_{PC} - Z_{IC} \quad (22)$$

The Internal Rate of Return (IRR) can directly reflect the economic situation of the project during the whole calculation period：

$$IRR = \frac{NPV}{Z_{PC} + Z_{IC}} \quad (23)$$

4. RESULTS AND DISCUSSION

This section presents a thermo-economic analysis of the proposed CAES system. Table 1 shows the specific operating parameters.

Table 1

Detailed operation parameters of the proposed system

Parameter	Unit	Value
Ambient pressure	MPa	0.1
Ambient temperature	K	298.15
Charge time	h	8
Discharge time	h	8
Compressor isentropic efficiency	%	84
Turbine isentropic efficiency	%	88

Efficiency of heat exchanger	%	95
Pressure loss of heat exchanger	MPa	0.2
Valley electricity price	$/kWh	0.052
Power station life cycle	Year	30
Annual cycle times of the power station		365
Discount rate		0.05

4.1 Impact of discharge pressure on system performance

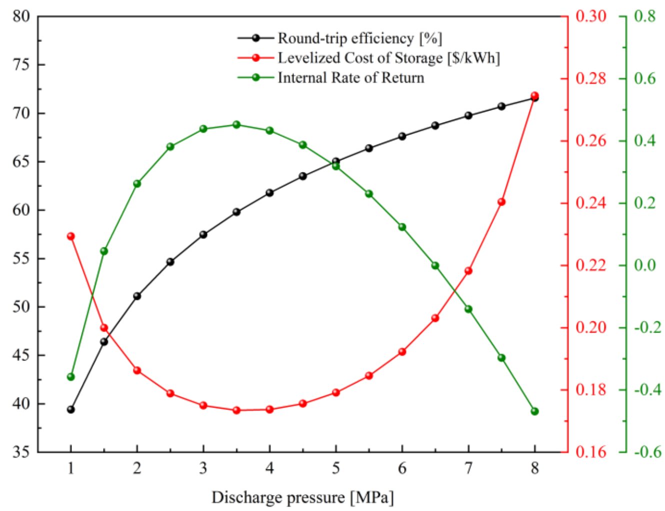

Fig. 2 Impact of discharge pressure on system performance

Fig. 2 shows the impact of discharge pressure on the system performance. It is obviously that discharge pressure has an active impact on the *RTE* of the system. At a discharge pressure of 3.5MPa, the *LCOS* and *IRR* respectively arrive the valley value of 0.1734 $/kWh and the peak value of 0.4523. At this time, the value of RTE is 59.80%.

4.2 Impact of the compressor isentropic efficiency on system performance

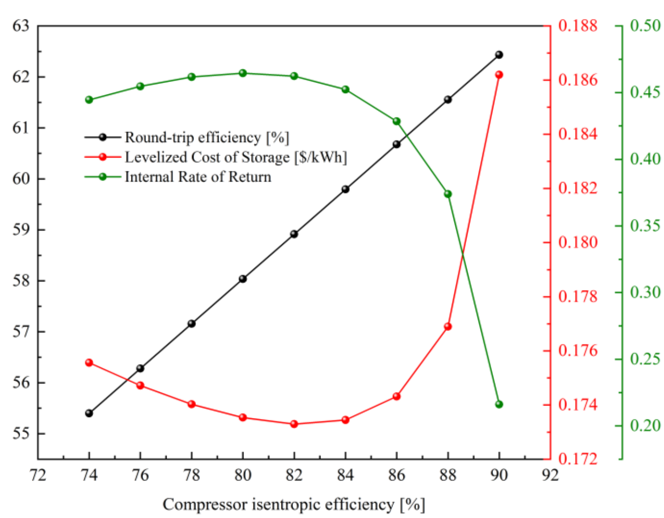

Fig. 3 Impact of the compressor isentropic efficiency on system performance

Fig. 3 shows the impact of the compressor isentropic efficiency on system performance. The compressor isentropic efficiency has a positive effect on the RTE of the system. The peak value of 0.1735 $/kWh for LCOS is achieved at the compressor isentropic efficiency is 80 %. The IRR decreases by 0.25 as the compressor isentropic efficiency increasing from 80 % to 90 %. It has the lowest value of 0.4646 at the compressor isentropic efficiency is 82 %.

4.3 Impact of the turbine isentropic efficiency on system performance

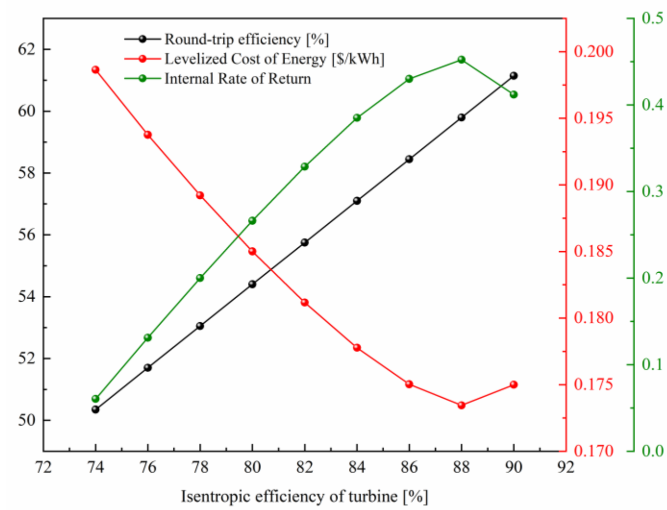

Fig. 4 Impact of the turbine isentropic efficiency on system performance

Fig. 4 shows the impact of the turbine isentropic efficiency on system performance. The RTE of the system increases linearly with the increase of the turbine isentropic efficiency; when the turbine isentropic efficiency reaches 88 %, the minimum value of the *LCOS* is 0.173 $/kWh; the IRR rises first and then falls as the turbine isentropic efficiency increases, and a turning point occurs when the turbine isentropic efficiency is 88%.

4.4 Impact of heat exchanger pressure loss on system performance

Fig. 5 shows the impact of heat exchanger pressure loss on system performance. It is obviously that the LCOS raises by 0.008 $/kWh as heat exchanger pressure loss increasing from 0.05 bar to 0.45 bar. And the RTE and IRR drop by 3.51% and 0.1361 separately as varying heat exchanger pressure loss.

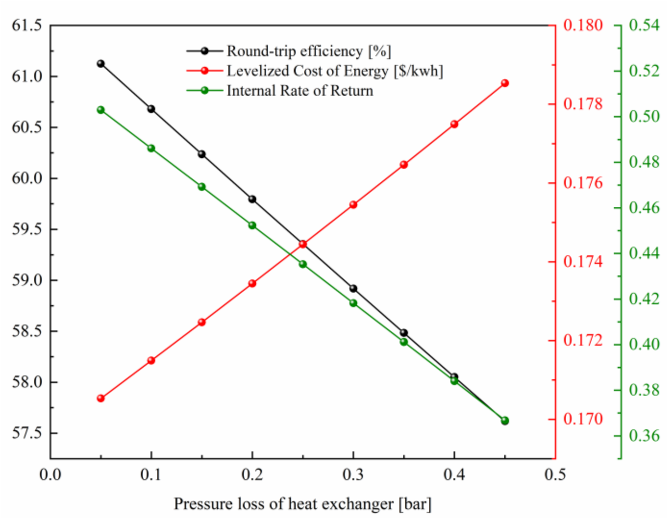

Fig. 5 Impact of heat exchanger pressure loss on system performance

5. CONCLUSIONS

In this paper, the thermodynamic and economic performance of an above-ground compressed air energy storage system are analyzed. The main conclusions are summarized as follows: an optimal discharge pressure of 3.5 MPa can be achieved for the better application feasibility; an appropriate compressor isentropic efficiency and 88% of turbine isentropic efficiency should be selected for better system feasibility; higher discharge pressure, higher compressor efficiency and turbine efficiency and lower heat exchanger pressure loss can improve the system thermodynamic performance.

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