Research on a compressed air energy storage system with variable pressure ratio and geothermal-solar cascade heating

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Introduction

Although compressed air energy storage (CAES) is widely regarded as one of the most promising large-scale physical energy storage technologies [1], its overall efficiency is frequently constrained by the relatively low temperature grade of the compression heat [2]. The integration of external heat sources and the implementation of waste heat recovery have been identified as effective pathways for performance enhancement [3]. However, conventional advanced adiabatic CAES systems typically require a throttling valve upstream of the air turbine to maintain a constant inlet pressure, a process that inevitably incurs significant throttling exergy losses. While sliding-pressure operation can circumvent these losses by dynamically adjusting interstage valves [4], the drastic fluctuations in air mass flow rate inherent in variable pressure ratio (VPR) operation often lead to a thermal supply-demand imbalance within traditional heat exchange networks. To address this thermodynamic challenge, this study proposes a multi-energy coupled VPR-CAES system. This architecture leverages geothermal and solar energy for cascade heating, while incorporating an Organic Rankine Cycle (ORC) and a water heater (WH) for comprehensive waste heat recovery, thereby aiming to achieve superior system efficiency.

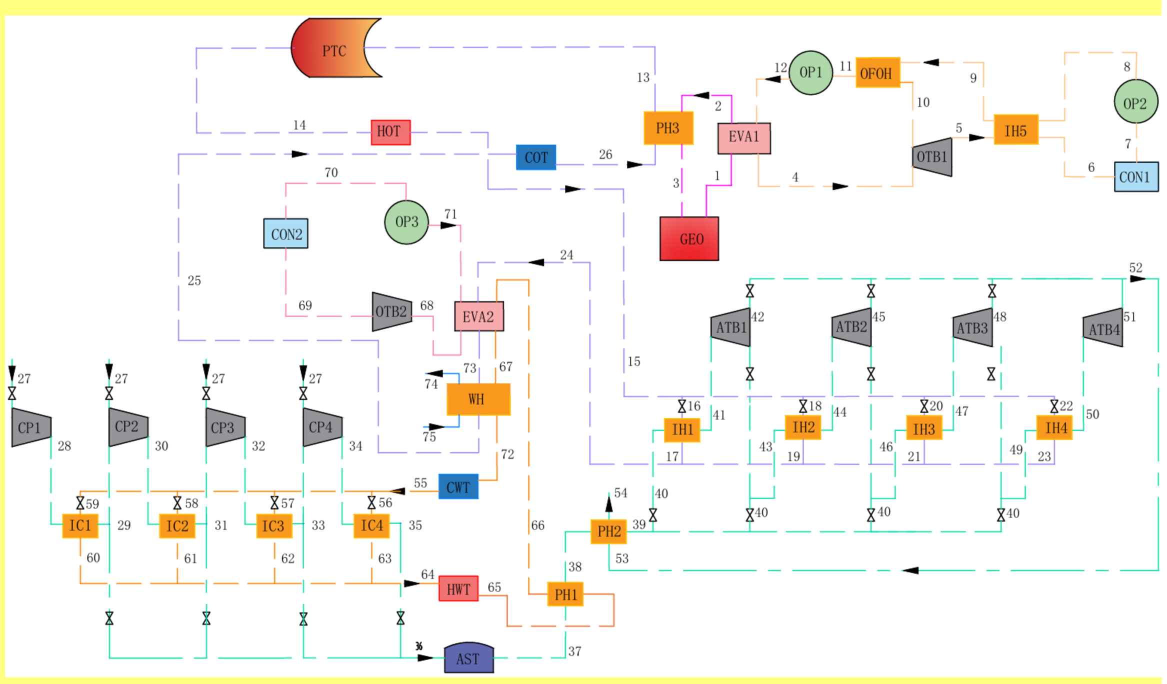

Fig. 1. Schematic diagram of the proposed VPR CAES system.

System Description

The proposed system operates in independent charging and discharging modes. During the charging phase, ambient air is compressed and cooled by a multi-stage compressor before being stored in an air storage tank, with the compression heat stored in a hot-water tank. Concurrently, deep geothermal fluid drives a single-stage regenerative ORC to generate base-load electricity, and its tail water preheats the thermal oil to share the thermal load of a parabolic trough solar collector (PTC). Ultimately, the thermal oil is superheated by the PTC and subsequently stored in a hot-oil tank. During the discharging phase, to mitigate the thermodynamic impacts induced by air flow fluctuations under VPR operation, the high-pressure air undergoes cascade superheating sequentially via the compressed hot water, the air turbine exhaust, and the high-temperature thermal oil before entering the air turbine. Finally, the residual heat at the end of the pipeline network is sequentially recovered by a basic ORC and the WH, accomplishing the utilization of low-grade waste heat. The proposed architecture provides three core thermodynamic advantages:

1) the VPR operation eliminates irreversible throttling exergy destruction and broadens the operational pressure range; 2) the cascade heating mitigates heat transfer exergy destruction while elevating turbine inlet temperatures; and 3) the BORC and WH recover low-grade residual heat, maximizing the total electrical output.

Thermodynamic Analysis

The fundamental thermodynamic assumptions of the system are as follows[4]:

1) Heat dissipation and pressure drop in the heat exchangers and pipes are negligible.

2) The isentropic efficiencies of compressors, turbines and pump are all constant.

3) The air storage chamber (ASC) is isothermal during the charging and discharging processes

Energy storage efficiency (ESE): The ratio of the electric energy generated during the discharging phase to the electric energy consumed by the compressor train during the charging phase:

$$ESE = \frac{W_E + W_{BORC}}{W_C} = \frac{\sum_{i=1}^{N} W_{e,i}\, t_{e,i} + W_{BORC}}{\sum_{i=1}^{N} W_{c,i}\, t_{c,i}} \quad (1)$$

Roundtrip efficiency (RTE) : The ratio of the total energy output during the discharging process to the total energy input during the charging process:

$$RTE = \frac{W_E + W_{BORC} + W_{SRORC} + Q_{WH}}{W_C + Q_{geo} + Q_{PTC}} \quad (2)$$

Exergy roundtrip efficiency, defined as the ratio of revenue exergy to expenditure exergy of the system:

$$ERTE == \frac{W_E + W_{BORC} + W_{SRORC} + Ex_{WH}}{W_C + Ex_{geo} + Ex_{PTC}} \quad (3)$$

Energy storage density (EPV): Defined as the ratio of the total electric energy output during the discharging phase to the volume of the air storage cavern.

$$EPV = \frac{W_E + W_{BORC}}{V_{ASC}} \quad (4)$$

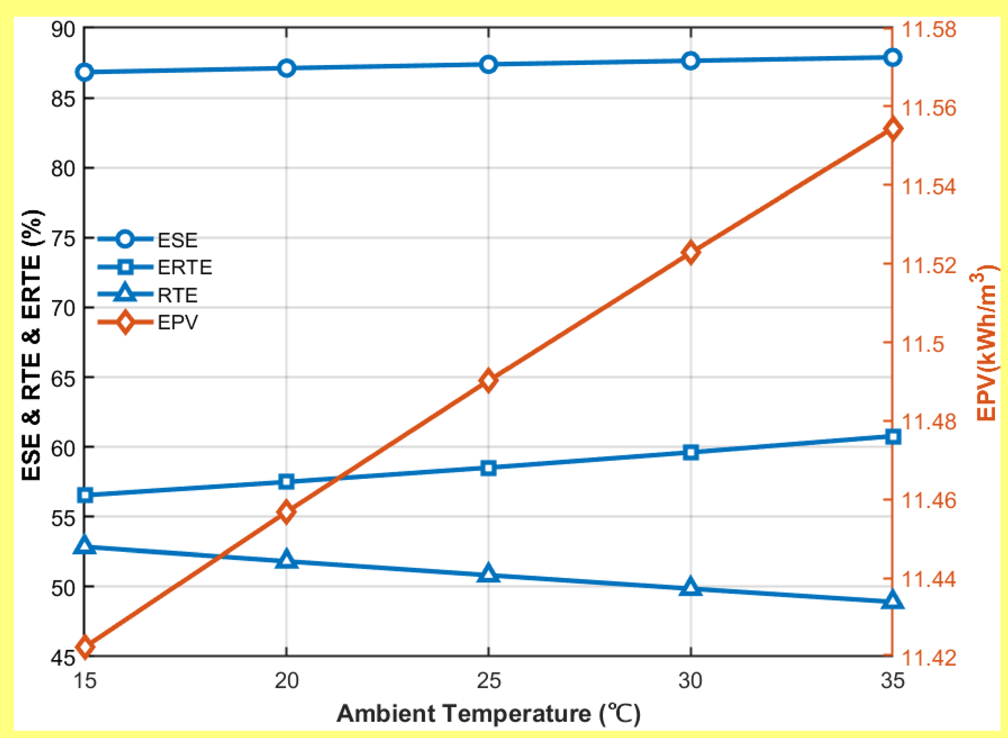

Fig. 2. Influence of ambient temperature on ESE, ERTE, RTE and EPV.

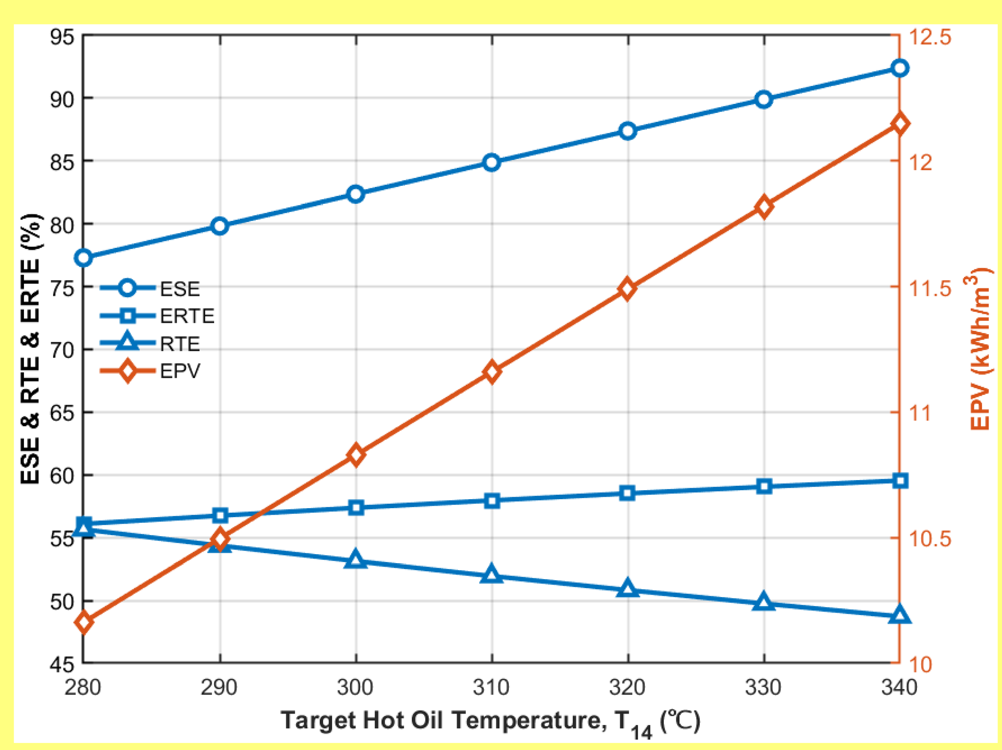

Fig. 3. Influence of target hot oil temperature on ESE, ERTE, RTE and EPV.

Result And Discussion

THERMODYNAMIC SIMULATION RESULTS

During the charging phase, the compressor train consumes 6574 kWh, with concurrent geothermal and solar thermal inputs of 4461 kWh and 7460 kWh, respectively. In the discharging phase, the cascade-heated high-pressure air drives the ATB to generate 4825 kWh, while the bottoming BORC recovers waste heat to provide a net output of 920 kWh. The results an ESE, EPV, RTE, and ERTE of 87.39%, 11.49 kWh/m³, 50.83%, and 58.52%, respectively.

PARAMETERS ANALYSIS

Fig.2 illustrate the ambient temperature impact. Rising temperatures elevate the cold oil's dead-state temperature, reducing PTC heat demand from 8.07 to 6.85 MWh while increasing BORC recovery from 0.72 to 1.11 MWh. This energy compensation helps ESE and ERTE reach 87.89% and 60.78%, respectively, indicating a potential to buffer high-temperature performance degradation.

Fig.3 display target hot oil temperature effects. Elevated heating enhances air work potential, boosting ATB generation to 5.00 MWh. Concurrently, BORC waste heat recovery contributes 1.07 MWh, assisting ESE and EPV to reach 92.40% and 12.15 kWh/m³, respectively. This deep recovery appears to offset internal exergy destruction, promoting a steady ERTE rise to 59.54%.

Fig.4 reflect compressor pressure ratio influences. Increasing this ratio expands the cavern pressure limit, allowing EPV to reach 26.32 kWh/m³. Although elevated compression power drops RTE from 51.69% to 46.89%, utilizing the BORC to recover abundant exhaust heat yields an additional 1.82 MWh. This compensates for certain compression penalties, inversely raising ERTE to 59.37% and preliminarily suggesting a reasonable thermodynamic synergy.

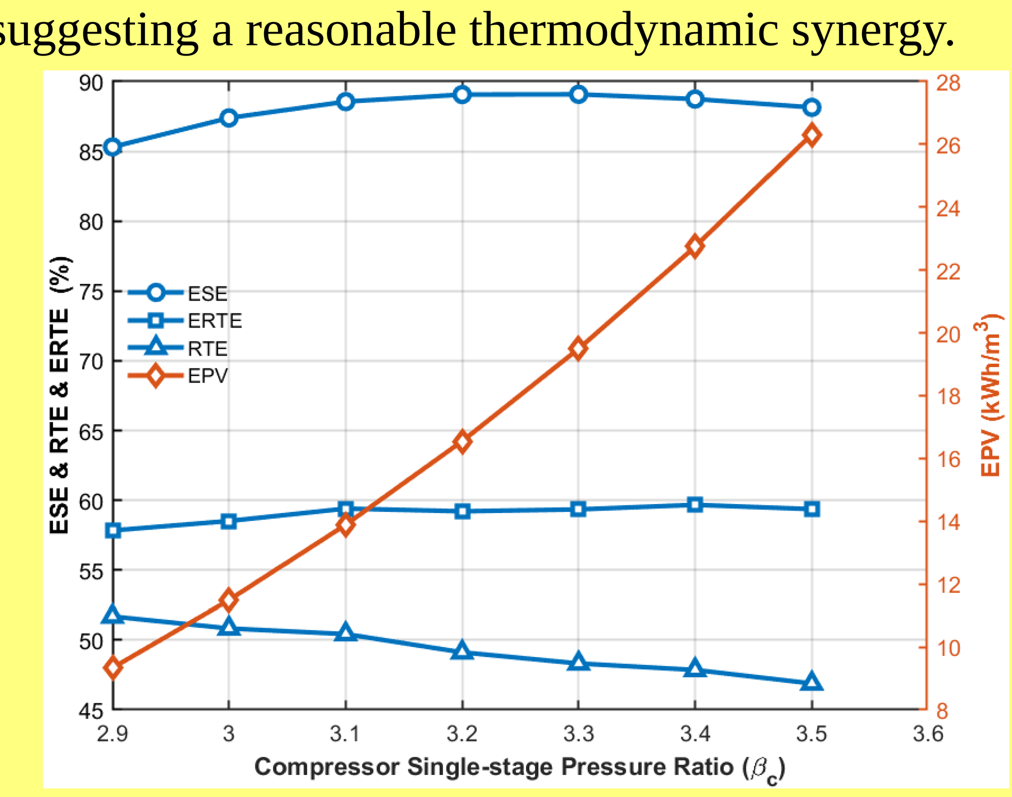

Fig. 4. Influence of compressor single-stage pressure ratio on ESE, ERTE, RTE and EPV.

Conclusions

To alleviate thermal imbalances in VPR-CAES, a geothermal-solar-ORC coupled system is proposed. Analyses indicate:

1) It exhibits adaptability to ambient temperatures from 15 to 35 ℃. Increased ORC recovery and reduced solar demand offset lower air density, helping ESE and ERTE reach 87.89% and 60.78%.

2) Elevating thermal oil temperatures from 280 to 340 ℃ enhances output, allowing ESE and EPV to achieve 92.40% and 12.15 kWh/m³. Waste heat recovery mitigates exergy destruction, promoting a 59.54% ERTE.

3) Increasing pressure ratios from 2.9 to 3.5 improves cavern utilization, propelling EPV to 26.32 kWh/m³. The ORC reasonably offsets compression penalties, recovering ERTE to 59.37%.

These findings provide a preliminary reference for long-duration energy storage.

References

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