

COMPRESSED AIR ENERGY STORAGE OPTIMIZATION – ADVANCED PROCESS IMPROVEMENT

Abstract

Intermittency and high cost were the main barriers to the large-scale commercialization of renewable energy decades ago. The cost of renewable energy has decreased dramatically in the last decade. The intermittency of renewable energy, however, remains a serious challenge to be overcome. Compressed Air Energy Storage (CAES) is widely considered to be a promising energy storage technology at utility-scale and receives increasing attention from both academic and industrial communities. In this study, two novel CAES systems are proposed and a thorough investigation and comparison of the thermodynamic performance of both conventional and novel CAES systems have been performed. The turbine inlet temperature and the maximum cavern storage pressure are identified as the bottlenecks of CAES plants. The round-trip efficiency and energy density are chosen as the conflicting objectives. Pareto fronts are obtained based on the simulation-based multi-objective optimization framework developed in this study. The energy density of a diabatic CAES plant is within the range between 4.24 and 11.58 kWh/m³, while that value becomes 1.28–7.96 kWh/m³ for a conventional adiabatic CAES system. The novel two-pressure level adiabatic CAES system can improve the round-trip efficiency by at least 3.5% compared with the conventional adiabatic CAES system. The novel indirect heating diabatic CAES system can improve the round-trip efficiency by at least 2%. The Pareto fronts can be a useful tool for the grassroot design or retrofit of a CAES plant. Solutions to improve the CAES system performance have been proposed based on the optimization results of this study.

Introduction

The Paris Agreement established an international framework to limit average global temperature rise to below 2 °C (Williams et al., 2012), in which the electricity supply will be largely decarbonized by 2050. The costs of leading sources of renewable energy, solar panels and wind farms, have plummeted over the last decade, spurring increased rates of adoption (Patil et al., 2017). However, their power output is not stable and dispatchable like conventional power plants. To meet future decarbonization goals, the grid requires energy storage to enable increased adoption of intermittent renewable energy sources.

A variety of energy storage technologies are either deployed or under consideration for the future including pumped-hydro (PHES) (Ahmad and Moubayed, 2012), compressed air (CAES) (Lund and Salgi, 2009), liquid air (LAES) (Liu et al., 2020), battery (Divya and Østergaard, 2009), carbon storage cycle (Gençer et al., 2014), hydrogen (Ozarslan, 2012), ammonia-based (Wang, G. et al., 2017b), and thermal energy storage systems (Sharma et al., 2009). Among all of the energy storage technologies, PHES and CAES have been recognized as reliable grid-scale energy storage technologies (Wang, J. et al., 2017).

CAES systems promise several advantages over other storage systems, such as high power and energy capacity, long lifetime, fast response time, and relatively low capital, and maintenance costs (Mozayeni et al., 2020). If they can be developed and economically deployed, CAES systems can be operated not only for daily and weekly storage but also perhaps for inter-seasonal storage (Mouli-Castillo et al., 2019). A detailed techno-economic analysis of advanced adiabatic CAES system was performed based on life cycle cost (Zhou et al., 2020). And the advanced adiabatic CAES system is found to be a viable solution. Foley and Lobera investigated the impacts of CAES on electricity markets with a large renewable energy portfolio (Foley and Díaz Lobera, 2013). They concluded that a CAES plant could successfully optimize energy arbitrage opportunities, increase the revenues for power suppliers, and decrease CO₂ emissions. In addition, CAES is one of the energy storage technologies with the least environmental impact (Sternberg and Bardow, 2015). CAES plants have excellent operational performance characteristics such as ramping, frequency regulation, and spinning reserve. A CAES plant can typically be built in less than 3 years and have an estimated lifespan of 35 years. Up to now only two grid-scale CAES systems have been deployed: the first in Huntorf, Germany with a 290 MW capacity and a 3 h discharge time, commissioned in 1978, and the second in McIntosh, Alabama with a 110 MW capacity and a 26 h discharge time, commissioned in 1988. The main reason for such small deployment is that less expensive combined cycle power plants with low-cost natural gas are at present the most widely used option to firm up and balance variable renewable power generation (Khorshidi et al., 2016).

Current literature primarily focuses on high round-trip efficiency as a measure of the thermodynamic performance of CAES; however, in addition to round-trip efficiency, energy density and techno-economic performance Current literature primarily focuses on high round-trip efficiency as a measure of the thermodynamic performance of CAES; however, in addition to round-trip efficiency, energy density and techno-economic performance are also of great importance (Gençer and Agrawal, 2016). Han et al. carried out a multi-objective optimization of an adiabatic compressed air energy storage system under four operation modes (Han et al., 2018). However, the diabatic CAES system is not discussed in that study. Yao et al. performed multi-objective optimization of a combined cooling, heating and power system with a CAES system (Yao et al., 2017). The objective functions were exergy efficiency and total product unit cost, focusing on the integration between different energy systems, and only a single stage diabatic CAES system is considered. For a large-scale CAES system, the storage volume requirement is of great importance to the implementation of the system. The cavern of a large-scale CAES system should be sized to supply adequate electricity during peak hours. Other than high round-trip efficiency, high energy density is also desirable. In previous studies, however, the energy density is not considered along with the round-trip efficiency. In this study, the energy storage density and the round-trip efficiency are investigated simultaneously. Novel CAES systems are proposed to facilitate the carbon capture or improve the round-trip efficiency. This study performs a thorough optimization of different types of CAES systems, and the resulting optimal Pareto front is intended to be used as a guideline for the preliminary design of a CAES system.

Section snippets

Compressed air energy storage system investigated

In any energy storage system, there are two separate processes, charging and discharging. The principle of CAES system is easy to understand. In the CAES system, the charging process involves the compression of air to convert electricity into mechanical and thermal energy. During the discharging process when electricity is needed, the pressurized air can be heated and expanded through a turbine to generate electricity. CAES can be classified into multiple categories based on various criteria.

Process simulation

In this study, the process simulation of the CAES system is performed using Aspen Hysys (2013), which is widely used for chemical process and energy conversion process simulation (Yu et al., 2021). The following assumptions are made for the process simulation. The natural gas is assumed to be pure methane and the lower heating value (LHV) is 50.17 MJ/kg. The adiabatic efficiencies of compressors and turbines are assumed to be 80% and 75% respectively.

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Results and discussion

In this section, the results of the multi-objective optimization of the conventional and novel CAES systems proposed in this study are presented. The key parameters and the suggestions on improving the CAES systems based on the optimal Pareto fronts are also discussed. All of the Pareto fronts are obtained with the variable bounds listed in Table 1.

Conclusion

This study investigates process improvements and optimization of the conventional diabatic and adiabatic CAES systems. Two novel CAES plant configurations are proposed. The trade-off between round-trip efficiency and energy density is determined based on a multi-objective simulation-based optimization framework. The round-trip efficiency of the system depends on the operating conditions and the energy storage capacity. For the diabatic CAES system, the maximum cavern storage pressure and the....

CREDIT authorship contribution statement

Haoshui Yu: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Seijiss Engelkemier:** Conceptualization, Methodology, Formal analysis, Validation, Writing – review & editing. **Emre Gençer:** Investigation, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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OBJECTIVES OF THE STUDY:

- To Characteristics the Higher Round Trip Efficiency - it Makes CAES complete directly with Li-ion batteries for grid storage.
- To Comparative analysis of Low cost Long- Duration Energy Storage (LDES)Leader.
Optimization improves:
 - Charging/ discharging schedule.
 - Component life.
- To Developed Environmental – Friendly Storage Option.

Future CAES will be much greener than battery storage.