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Thermodynamic analysis of a compressed carbon dioxide energy storage system using two saline aquifers at different depths as storage reservoirs

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ABSTRACT

Compressed air energy storage (CAES) is one of the leading large-scale energy storage technologies. However, low thermal efficiency and low energy storage density restrict its application. To improve the energy storage density, we propose a two-reservoir compressed CO_2 energy storage system. We present here thermodynamic and parametric analyses of the performance of an idealized two-reservoir CO_2 energy storage system under supercritical and transcritical conditions using a steady-state mathematical model. Results show that the transcritical compressed CO_2 energy storage system has higher round-trip efficiency and exergy efficiency, and larger energy storage density than the supercritical compressed CO_2 energy storage. However, the configuration of supercritical compressed CO_2 energy storage is simpler, and the energy storage densities of the two systems are both higher than that of CAES, which is advantageous in terms of storage volume for a given power rating.

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1. Introduction

In recent years, renewable energy, particularly wind power and solar photovoltaic (PV) generation has demonstrated robust growth-worldwide motivated by concerns about energy security and climate change due to CO_2 emission levels [1,2]. But Renewable energy sources (e.g., solar and wind energy) exhibit significant and uncontrollable intermittency during power production. When these renewable energy sources are connected to an electrical grid, they can cause serious safety problems for the grid; hence, it is difficult to deliver power from renewable energy sources that instantly matches electricity demand [3].

To solve this dilemma and develop renewable energy sources further, viable energy storage systems (ESS) are required. For example, an efficient ESS can increase the penetration of wind power generation by controlling wind power plant output and storage, in addition to providing ancillary services to the power system [4,5].

On a utility scale, compressed air energy storage (CAES) is one of the technologies with the highest economic feasibility with potential to contribute to a flexible energy system with an improved utilization of intermittent renewable energy sources [1]. The feasibility of using CAES to integrate fluctuating renewable power into the electricity grid has been proven by many researchers [6–9]. Bosio and Verda [6] analyzed the thermo-economics of a CAES system integrated into a wind power plant in the framework of the Italian Power Exchange market, which showed that a hydroelectric power plant (HPP)-CAES system was cost-effective in terms of solving local imbalances of the grid. Clearly et al. [7] evaluated the economic benefits of CAES in mitigating wind curtailment. They showed that both wind curtailment levels and wind-farm total annual generation costs could be decreased. Arabkoohsar et al. [8,9] simulated and analyzed CAES equipped with a solar heating system. The results showed that CAES could increase the efficiency and reliability of a PV plant.

However, the main drawbacks of a CAES system include its low thermal efficiency (e.g., Huntorf CAES plant efficiency is 42% and AA-CAES efficiency is about 70% [10]), CO_2 emissions from combustion of natural gas in the recovery system for conventional CAES, the need for high temperature thermal storage and temperature resistant materials for adiabatic CAES (A-CAES). These factors limit further development of CAES. Although large-scale caverns are also required for CAES as it is carried out today, porous media systems such as aquifers and depleted natural gas reservoirs, so-called porous media CAES (PM-CAES) systems, offer much more storage capacity [11].

Thermodynamic analyses of CAES systems have been performed to optimize these systems and improve their thermal efficiency. For example, Buffa et al. [12] conducted an exergy analysis

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Nomenclature

H	enthalpy (kJ/kg)
S	entropy (kJ/(kg K))
P	pressure (MPa)
$\dot{E}$	exergy (kW)
T	temperature (K)
T_s	surface temperature (K)
W	shaft work (kW)
C_p	specific heat capacity at constant pressure (kJ/(kg K))
G	geothermal gradient (K/km)
V	volume (m^3)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer (W)
Z	depth of saline reservoir (m)

Abbreviations

A-CAES	adiabatic CAES
AA-CAES	advanced adiabatic CAES
C	compressor
CAES	compressed air energy storage
CCES	compressed CO_2 energy storage
HE	heater
HS	high pressure reservoir
LS	low pressure reservoir
PM-CAES	porous media CAES
RE	recuperator
SC-CCES	supercritical compressed CO_2 energy storage
SC-CO_2	supercritical CO_2
T	turbine
TC-CCES	transcritical compressed CO_2 energy storage
TC-CO_2	transcritical CO_2

Greek symbols

β_p	pore compressibility (Pa^{-1})
β_w	change in brine density
η	efficiency
ΔT	temperature difference (K)
ρ	density (kg/m^3)

Subscripts

S	isentropic process
Comp	compressor
1	inlet stream
2	outlet stream
T	turbine
NG	nature gas
F	fuel
tot	total
D	destruction
L	loss

of A-CAES and found that exergy destruction mostly occurred in the compressors and coolers. Proczka et al. [13] analyzed the effects of pressure and the efficient sizing of pressure vessels on CAES. Zhang et al. [14,15] analyzed the thermodynamic effects of thermal energy storage (TES) and the air storage chamber model on a CAES system. Jubeh and Najjar et al. [16] explored the effects of operating variables on A-CAES performance. Najjar and Zamout analyzed the effects of dry regions on the performance of a CAES plant [17]. The operation, experience, and characteristics of Huntorf CAES were also investigated [18]. Thermodynamic analyses have shown that, both, decreasing the exhaust temperature and using heat of compression during expansion can significantly improve CAES efficiency.

Several novel CAES systems have been proposed that reduce waste heat. A recuperator was utilized to capture heat from the turbine exhaust, which could reduce the fuel consumption of the McIntosh plant by 25% [19,20]. Safaei and Keith [17] proposed a distributed CAES (D-CAES) system that placed compressors near heat demand loads to recover the heat generated during the compression stage. Liu [2] proposed a modified A-CAES system that used a pneumatic motor instead of a low pressure turbine (LT) to reduce the exhaust temperature caused by LT, and the exergy efficiency can be improved by nearly 3% compared with that of the conventional A-CAES system. Guo et al. [21] proposed a novel A-CAES system in which an ejector was integrated into an A- CAES system to recover pressure reduction losses; energy conversion efficiency could reach 65.36%. Several demonstration A-CAES plants have been built, such as a 1.5 MW A-CAES in China, where initial experimental tests are on-going. An A-CAES technology that uses reversible reciprocating piston machines is being developed by LightSail Energy Ltd. in the U.S. Other new systems include a tri-generation system based on compressed air and thermal energy storage [22], biomass-fueled CAES, isobaric adiabatic CAES with combined cycle [23], combined cooling, heating and power system based on small-scale CAES [24], CAES using a cascade of phase change materials [25], CAES combined with solar thermal capture [26], integrating CAES with diesel engine [27], and compressed carbon dioxide energy storage [28].

Although thermal efficiency can be improved by various methods, CAES has low energy density and requires large-scale storage reservoirs [29]. To overcome these restrictions, several studies have been conducted on novel energy storage technologies. For instance, Kim [30] proposed a constant-pressure CAES system combined with pumped hydro-storage to reduce the cavern volume. Guo et al. [31] presented a supercritical compressed air energy storage (SC-CAES). Oldenburg and Pan [11] modeled a porous media CAES (PM-CAES) system that uses aquifers or depleted natural gas reservoirs for storage. Underwater compressed air energy storage (UWCAES) stores the compressed air under water by using a large elastic bladder [32]. Small scale CAES (SS-CAES) that stores high-pressure air in a tank or an underground pipeline was also proposed [33]. Each of these novel approaches brings with it additional requirements and limitations.

As popularly known, CAES is derived from the Brayton cycles, and gases like CO_2 that are non-ideal at operating conditions are more efficient in a Brayton cycle [34].

Using CO_2 as the working fluid in a compressed gas energy storage system can also achieve better performance than AA-CAES [35]. At the same time geological CO_2 sequestration in deep formations (e.g., saline aquifers, gas and oil reservoirs, and coal beds) is a promising measure for reducing greenhouse gas emissions [36]. Therefore, the combination of compressed gas energy storage in the deep subsurface and large-scale utilization of CO_2 is both possible and beneficial.

Although, some research has been conducted on energy power cycle and energy storage systems based on CO_2 and liquid CO_2 [28,35], we are not aware of published analyses of energy storage systems based on transcritical CO_2 (transition from supercritical to gas) or based on supercritical CO_2 throughout the cycle. Therefore, the innovation of this paper resides in the exergy analysis of a closed-loop gas storage system, conceived by two of us (Borgia and Oldenburg in January of 2012), which comprises two