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Thermo-economic optimization of a combined cooling, heating and power system based on small-scale compressed air energy storage

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ABSTRACT

Energy storage systems are important for dealing with the fluctuation of renewable energies in course of their increasing penetration into the energy market. Small-scale compressed air energy storage (CAES) with artificial air vessels can improve the supply capacity of power system and the utilization of renewable energy by storing excess power during off-peak time and releasing it for on-peak power supply and becomes more promising for distributed energy systems. For diabatic CAES, heat usually cannot be efficiently utilized and the low inlet temperature of turbine in an adiabatic-CAES (A-CAES) usually leads to low discharge efficiency. To address these problems, in this paper, we propose a novel combined cooling, heating and power system (CCHP) based on small-scale CAES. The sensitivity analysis performed shows the effectiveness of heat exchanger, and the air temperature and pressure at the turbine inlet have great influence on the system's thermodynamic performance. Then, the trade-off between the thermodynamic and economic performances is investigated by an evolutionary multi-objective algorithm. The total investment cost per output power of the Pareto solutions does not increase significantly when increasing exergy efficiency below 51%, indicating the solutions with an exergy efficiency of around 51% are promising for practical designs.

1. Introduction

With the increasing depletion of traditional fossil fuel, the development of renewable energy technologies, e.g., wind energy and solar energy, has attracted more and more attention [1,2]. Particularly for wind energy, the cumulative installed capacities wind turbines in the two biggest installers, China and USA, by the end of 2014 have reached 114.763 GW and 65.879 GW (31% and 17.8% of the world installed capacity), respectively [3]. However, the random and intermittent nature of renewable energy has greatly challenged the large-scale utilization of renewable energies, mostly for power generation. Large-scale power generation needs the grid transportation to reach the power consumers, while the intermittence of large-scale renewable power may lead to serious problems on the power grid, e.g., shock and instability. Therefore, energy storage technologies are essential to ensure continuous and stable utilization from renewable energies by storing the excess renewable energies and releasing energy to balance the energy supply and demand [4].

At present, there are mainly two energy storage systems suitable for large-scale energy storage applications, i.e., pumped hydro storage (PHS) and compressed air energy storage (CAES) [5,6]. Compared with PHS, CAES is promising for the low investment costs, fast construction time and small geographic restrictions [7]. During the charge period at off-peak time, excess wind energy is used to compress air; the compressed air is then stored in an air storage vessel. During the discharge period at peak time, the compressed air from the air storage vessel is preheated and expanded to produce electricity [8].

There are two different types of CAES systems: diabatic CAES and adiabatic CAES (A-CAES). The diabatic CAES consumes additional natural gas or other fuel by combustion with the compressed air to increase the compressed-air temperature before expansion [9]. The A-CAES, however, reuses the compression heat stored in the charge process to heat up the compressed-air in the discharge process [10]. In addition, some new concepts about CAES systems were proposed and optimization on these systems has been performed in recent years: Ibrahim et al. [11,12] proposed a hybrid wind-diesel-CAES system for heightening diesel power output, increasing engine efficiency, and reducing the fuel consumption and greenhouse gas (GHG) emissions. Yao et al. [13] and Kim et al. [14] proposed hybrid energy storage systems

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Nomenclature

A	area (m^2)
C	investment cost
C_p	specific heat at constant pressure (kJ/kg K)
$\overline{C}_p$	average over cross-section specific heat at constant pressure (kJ/kg K)
d	diameter (m)
E	exergy (kW)
f	Darcy friction factor
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K); enthalpy (kJ/kg)
I_t	Marshall & Swift cost index
j_{sh}	shell side heat transfer factor
k	thermal conductivity (W/m^2 K)
L	length (m)
m	mass flow rate (kg/s)
Nt	number of tubes
Nu	Nusselt number
P	pressure, bar; power (kW)
Pr	Prandtl number
Q	heat rate (kW)
R	universal gas constant (J/(K mol)); fouling resistance
Re	Reynolds number
St	tube pinch (m)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
V	volume (m^3)
W	work (kW)
X_{tt}	Lockhart–Martinelli number

Greek letters

Δt_m	log mean temperature difference between hot side and cold side (K)
Γ	tube loading (kg/(ms))
η	efficiency
κ	adiabatic coefficient
π	pressure ratio
ρ	density (kg/m^3)
v	flow velocity (m/s)
μ	dynamic viscosity (Pa s)
x	dryness of refrigerant
ω	mass entrainment ratio

Subscripts

a	air
b	bulk
c	cold fluid
COMP	compressor
COND	condenser
cooling	cooling
EJ	ejector
EVAP	evaporator
F	exergy fuel
fs	fouling resistances on shell side
ft	fouling resistances on tube side
fuel	fuel
G	generator
g	gas
GE	gas engine
h	hot fluid
HEX	heat exchanger
i	inner
l	liquid
M	motor
max	maximum
min	minimum
o	outer
P	exergy product
PUMP	pump
s	shell-side; isentropic
sc	subcool
sh	subheat
SV	air storage vessel
sw	shell wall
t	tube-side
tot	total system
TURB	turbine
TV	throttle valve
v	vapor
VG	vapor generator
wt	wall
ww	wet wall region
0	ambient

Superscripts

·	rate
ph	physical
ch	chemical

integrated PHS with CAES, which could make the storage vessel keep constant pressure during operation to ensure a high efficiency. Zhao et al. [15] proposed a wind-hybrid energy storage system combining the A-CAES with flywheel energy storage system. The concept could not only fit the load requirement well but also provide an efficient power management for wind power penetration. Wolf and Budt [16] proposed a low-temperature A-CAES system in order to avoid all the technical challenges of A-CAES designs.

Although a number of concepts on CAES have been proposed, currently, there are only two commercial CAES plants in the world: One was built in Huntorf, Germany (1978) with an electricity output capacity of 290 MW and the other one was built in McIntosh, United States (1991) with an output capacity of 110 MW [17]. The main reason for this situation is that large-scale CAES is demanding on the suitable underground geology, which restricts its wide application [18]. Small-scale CAES, however, could use artificial air vessel instead of natural cavern to storage compressed air, thus becoming more applicable, especially for distributed energy systems.

The combined cooling, heating and power (CCHP) concept has been widely used to improve the energy efficiency and to reduce GHG emissions [19]. Wang et al. [20] proposed a CCHP system combining with a Brayton cycle and a transcritical CO_2 refrigeration cycle driven by solar. Badami and Portoraro [21] proposed an innovative natural-gas CCHP system with electrical, heating and cooling capacities of 126/220/210 kW, respectively. Wu et al. [22] simulated, built and tested a micro-CCHP system that mainly consists of an internal combustion engine, an adsorption chiller, a thermal management controller and some other devices. The micro-CCHP system can realize 17.7 kW heating output, 6.5 kW cooling output and 16 kW electric output simultaneously. The concept realizes cascade utilization of waste heat to provide cooling and heating to users [23,24]. Therefore, integrating the small-scale