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An integrated design for hybrid combined cooling, heating and power system with compressed air energy storage

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HIGHLIGHTS

- Integration of CAES with trigeneration characteristics enriches a CCHP system's operation mode.
- Integrated design method can solve operation mode uncertainty introduced by renewable energy.
- Active storing strategy for CAES exhibits significant superiority in peak sheaving and efficiency increase.
- Novel algorithm C-NSGA-II provides accurate and efficient solutions for the multi-objective optimization model.

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ABSTRACT

The inherent characteristics of renewable energy, such as highly random fluctuation and anti-peak, are essential issues that impede optimal design of a combined cooling, heating and power (CCHP) system. This study presents a novel hybrid CCHP system integrated with compressed air energy storage (CAES). The operation mode of the new system is enriched by the trigeneration characteristic of CAES when compared with a traditional CCHP system. Additionally, an integrated design method based on a tri-level collaborative optimization strategy is proposed for the new scheme. An active storing strategy is introduced to maximize the utility of the superiority of CAES for peak sheaving and efficiency increase. Thus, a novel algorithm based on a hybrid algorithm of Non-Dominated Sorting Genetic Algorithm-II and Multi-Objective Particle Swarm Optimization is employed to solve the multi-objective optimization model with the aim of minimizing the total cost and emissions. A case study shows the effectiveness of the above methods. The implementation of the study fundamentally improves the overall energy utilization degree and the ability for renewable consumption to thereby provide a guiding principle for CCHP system design.

1. Introduction

Since the turn of the 21st century, energy shortages, air pollution and climate change, coupled with sustained and rapid economic development and social progress, have placed increased importance on efficient energy sources with low environmental impact [1]. A combined cooling, heating and power (CCHP) system is a comprehensive production distributed system based on energy cascade utilization that produces heat, cooling, and electricity in an integrated manner by burning fuel sources in addition to recovering waste heat. It possesses the potential to decrease fuel consumption by 20–30% when compared with that of a separate production (SP) system [2–5]. Nevertheless, a traditional CCHP uses natural gas as prime energy and can barely maximize advantages related to energy-saving and emission-reduction [6]. Additionally, the large-scale development of renewable energy generation technology constitutes an important strategy in coping with the fossil energy crisis and the resulting environmental pollution problems. Therefore, a hybrid CCHP system with renewable energies can significantly improve energy efficiency and energy cascade utilization in addition to reducing air pollutant emissions, and therefore has attracted considerable research attention worldwide [7–9].

However, uncertainty and anti-peak characteristics associated with renewable energy and especially wind and solar energy causes the increasing penetration of renewable energy generation to challenge security and reliable operations in addition to generating a significant amount of renewable energy waste [10–12]. It is not possible to use a traditional CCHP to solve this issue due to its inertia and thermoelectric coupling characteristics. Researchers indicated that the introduction of energy storage presents a

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Nomenclature

Abbreviations

CAES	compressed air energy storage
CCHP	combined cooling heating and power
COP	coefficient of performance
DE	dispatching evaluation
DM	decision making
EB	environmental benefit
FED	following electrical demand
ICE	internal combustion engines
MOPSO	multi-objective particle swarm optimization
MPPT	maximum power point tracking
NSGA	non-dominated sorting genetic algorithm
PESR	primary energy savings ratio
PGU	power generation unit
PLR	part-load ratio
PV	photovoltaic cells
SOC	state of charge
SP	separate production
TOU	time of use
TS	thermal storage
WT	wind turbine

Symbols

C	cost
d	discount rate
E	electricity
e	heat exchanger efficiency
Ex	exergy
Ep	energy price
G	gas
g	solar radiation
$gbest$	the global best position
I	electric current
L	load
l	lifespan
p	pressure
P	power
P	population
Q	heat
q	air mass flow rate
T	temperature
t	time
U	voltage
W	technical work
α	on–off coefficient of PGU
γ	polytropic index
θ	electric cooling ratio
η	efficiency
λ	compression ratio
τ	expansion ratio

Subscripts

a	air
ac	absorption chiller
b	boiler
com	compressor
cool	cooling
ec	electricity
exh	exhaust heat
ex	extra
grid	electricity grid
gas	biogas
h	heat
in	inlet
jw	jacket water
l	lower
loss	heat loss
m	mechanical
out	outlet
op	operation
pe	electrical efficiency
r	rated
re	recovery waste heat
sr	solar radiation
stor	storage tank
th	throttle
tur	turbine
te	thermal efficiency
u	upper
w	water

significant alternative to realizing load following, peak shaving, and improvements in power quality [13–17]. Among all the energy storages, adiabatic compressed air energy storage (A-CAES) is considered as a promising technology that can be integrated with a hybrid CCHP system due to its long working life, emission-free and multi-interface of cooling, heating, and power [18–20].

Recently, several studies focused on the CCHP based CAES system. However, the integration of CAES in a hybrid CCHP makes parameters design, capacity configuration and optimal operation extremely difficult due to its complex structure and multi-interface of power, cooling, and heating. This results in the failure to realize expected high energy, economic, and environmental potentials [21,22]. Furthermore, the coupling extent of the forementioned three difficulties deepens with the high penetration of renewable energy that significantly increases the difficulty [23,24].

Parameters of CAES influence the efficiency and the coupling mode directly. Current studies on CAES focus on the optimal design of key parameters with the aim of improving the efficiency of the CAES without considering the overall performance of the CCHP system [25–28]. The parameters that make CAES function at the highest efficiency may decrease the overall efficiency or even cause a mismatch in the energy grade. Yao et al. [29,30] focused on exergy efficiency and total specific cost of the overall system and presented a multi-objective optimal design for the parameters. Nevertheless, its process is conducted without considering complicated operation conditions and especially the influence of renewable energy. Thus, it is important to explore a design method that considers the overall performance as well as the conditions as a whole.

Additionally, a reasonable configuration is an important premise and guarantee for stable and efficient operation of a hybrid CCHP system. Most studies were promoted with the given capacity and there is a paucity of studies examining CAES involved in optimal configuration. Li et al. [24] proposed a bi-level program (BLP) to determine the optimum configuration of a microgrid with CAES. However, it used an over-simplified model and ignored the heating and cooling power of CAES. Several studies on traditional CCHP system focused on the optimal configuration based on intelligence algorithm [22,31–34]. Wang et al. [35] optimized the capacity as well as the on–off coefficient of a power generation unit (PGU) and the ratio of electric cooling to cool load with the aim of maximizing energetic, economic, and environmental benefits. These

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