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Thermodynamic performance analysis and optimization of a solar-assisted combined cooling, heating and power system

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A B S T R A C T

This study aims to present a thermodynamic performance analysis and to optimize the configurations of a hybrid combined cooling, heating and power (CCHP) system incorporating solar energy and natural gas. A basic natural gas CCHP system containing a power generation unit, a heat recovery system, an absorption cooling system and a storage tank is integrated with solar photovoltaic (PV) panels and/or a heat collector. Based on thermodynamic modeling, the thermodynamic performance, including energy and exergy efficiencies, under variable work conditions, such as electric load factor, solar irradiance and installation ratio, of the solar PV panels and heat collector is investigated and analyzed. The results of the energy supply side analysis indicate that the integration of solar PV into the CCHP system more efficiently improves the exergy efficiency, whereas the integration of a solar heat collector improves the energy efficiency. To match the building loads, the optimization method combined with the operation strategy is employed to optimize the system configurations to maximize the integrated benefits of energy and economic costs. The optimization results of demand–supply matching demonstrate that the integration of a solar heat collector achieves a better integrated performance than the solar PV integration in the specific case study.

1. Introduction

The combined cooling, heating and power (CCHP) system is becoming an attractive option because of its advantages, such as high overall efficiency, low greenhouse gas emissions, and high reliability [1]. Renewable energy resources are sustainable alternatives to natural gas in driving conventional CCHP systems [2], which have gradually become popular research topics. Currently, among renewable energy resources, solar energy has attracted considerable attention from academics and researchers due to its advantages of environmental protection and inexhaustibility. The advancement and development of CCHP systems incorporating solar energy have prompted various studies on integrated conceptual design [3], theoretical study [4], system configuration [5], performance evaluation [6], parameter optimization [7], etc., most of which have concentrated on establishing an optimal CCHP system to achieve favorable effects, such as cost savings, energy savings and emission reduction.

The incorporation methods of solar energy into CCHP systems usually include solar photovoltaic (PV) panels and solar heat collectors. Typically, solar heat collectors, including non-concentrated (stationary) and concentrated collectors, are used as the sole heat source to drive a CCHP system to produce electricity, cooling and heating while PV panels transform solar energy to electricity. Because of the limitation of storage technologies, the organic Rankine cycle (ORC) is often integrated with solar heat collectors in CCHP systems to generate electricity. Al-Sulaiman et al. [6] indicated that the total thermal efficiency of a solar CCHP system integrated with ORC for the solar mode reaches 94%. CCHP systems combining ORC with an ejector refrigeration cycle driven by the collected heat from a flat-plate solar collector [7] and parabolic trough solar collector [8] were designed and analyzed, and their key design parameters for improving the thermodynamic performance were optimized using a multi-objective optimization method. Furthermore, from the thermodynamic and thermoeconomic perspectives, Boyaghchi and Heidarnejad [9] optimized five key thermodynamic parameters of a solar CCHP system with ORC using a genetic algorithm. In addition, a CCHP system based on a metal hydride with ORC driven by solar heat energy was proposed by Meng et al. [4], and its performance was theoretically evaluated.

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Nomenclature

APES	annual primary energy saving
ATC	annual total cost
ATCS	annual total cost savings
ATFC	annual total fuel consumption
CCHP	combined cooling, heating and power
COP	coefficient of performance
ETC	evacuated heat collector
FEL	following electricity load
FTL	following heat load
HCPV	high concentrator photovoltaic
HX	heat exchanger
ICE	internal combustion engine
ORC	organic Rankine cycle
PV	photovoltaic
SP	separation production

Symbols

A	area (m^2)
AM	air mass
C	capital (Yuan)
E	electricity (kW)
Ex	exergy (kW)
F	fuel (kW)
G	solar irradiation (W/m^2)
LHV	lower heat value (MJ/Nm^3)
N	capacity (kW)
Q	heat (kW)
R	capital recovery factor
T	temperature (°C)
U	heat loss coefficient
η	efficiency
ω	weight
θ	ratio
τ	transmissivity ratio
α	absorptivity ratio

Subscripts

B	building
c	cooling
e	electricity
etc	evacuated heat collector
ex	exergy
f	fuel
g	exhaust gas
h	heating
hw	hot water
jw	jacket water
pv	photovoltaic
s	storage
sol	solar
0	reference state

In addition to the integration of ORC, Wang et al. [10] proposed a solar CCHP system based on the Brayton cycle and transcritical CO_2 refrigeration with an ejector-expansion device and discussed the effects of several key thermodynamic parameters on system performance.

To maintain the continuity of a solar CCHP system, an energy storage system is necessarily installed. Alternatively, a supplementary configuration between solar energy and fossil fuels is efficient. The simple supplement of solar PV panels with a natural gas CCHP reduces the generated electricity from the gas engine. Based on a conventional PV unit, Brandoni et al. [11] analyzed and compared the management strategies and system performance of a hybrid CCHP system with a high concentrator PV (HCPV) device, and the analysis indicated that HCPV becomes competitive with PV technology when the level of solar radiation is high. In contrast to the electricity supplement of the PV unit, several methods to integrate the heat supplement from solar heat collectors into CCHP systems are available. Ebrahimi and Keshavarz [12] integrated a solar heat collector to heat water with a basic internal combustion engine (ICE) CCHP system and analyzed the optimal collector direction, type and size for the hybrid CCHP system in 5 climate zones. Additionally, supplementing solar heat through chemical reactions is an efficient solar utilization method. Based on the solar energy thermochemical process and methanol decomposition through which heat collected by the parabolic trough concentrator drives the decomposition reaction of methanol into syngas, Li et al. [13] and Xu et al. [14] presented a full chain energy analysis and an off-design performance analysis of solar hybrid CCHP systems, respectively.

Moreover, both solar PVs and heat collectors are integrated into natural gas CCHP systems. Baniasad Askari et al. [15] designed a hybrid CCHP system integrated with solar PVs, solar collectors and a natural gas generator and discussed how its economic performance was affected by solar equipment and fuel prices. Wang et al. [5] introduced solar PVs and collectors to assist a CCHP system and optimized their installation ratios using the life cycle assessment optimization methodology. Sanaye and Sarrafi [16] optimized CCHP system configurations equipped with solar PV, concentrated photovoltaic/thermal and evacuated tube collectors to achieve the highest values of relative net annual benefit and exergy efficiency. In particular, the studies on solar CCHP systems have been extended to micro-grid operation and management. Brahman et al. [17] proposed a residential energy hub model that consists of a CCHP system, PV panels, plug-in hybrid electric vehicles and thermal energy storage and optimized the energy management to minimize the total energy cost.

In summary, solar CCHP engineering adopting concentrated heat collectors is not common due to the high cost and the lack of development of concentrated heat technologies, especially in buildings. Conversely, solar PV and non-concentrated heat collectors have been widely used in engineering applications, and they are easily integrated into CCHP systems. Differently to the integration of solar PV and collectors in CCHP system in the literatures [5,15,16], the originality of this work lies in designing an integrated CCHP system with solar PV and a flat-plate heat collector, and proposing an optimization method for demand–supply matching between the CCHP system and the building at the base of thermodynamic analysis of CCHP system. Section 2 proposes the solar-assisted hybrid CCHP system and presents operation strategies for variable building loads. Section 3 analyzes its thermodynamic performance from the supply side and reveals the energy efficiency enhancement mechanism of the energy complementarity between solar energy and natural gas. Section 4 proposes an optimization method to maximize the energy and economic benefits from demand–supply matching. Section 5 presents the study's conclusions.