Energy Conversion and Management 135 (2017) 244–255

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Complementary configuration and performance comparison of CCHP-ORC system with a ground source heat pump under three energy management modes

Ligai Kang, Junhong Yang, Qingsong An *, Shuai Deng, Jun Zhao, Zelin Li, Yongzhen Wang

Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), MOE, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 19 June 2016
Received in revised form 1 November 2016
Accepted 18 December 2016

Keywords:
CCHP system
Organic Rankine cycle
Ground source heat pump
Operational mode
Performance analysis
Sensitivity analysis

ABSTRACT

The variation of the end-user load and the constant output of power generation units (PGUs) results in a mismatch between energy supply and demand. To reduce the difference and to avoid an excess output of electricity or heat, a complementary combined cooling, heating and power- organic Rankine cycle system (CCHP-ORC) system with a ground source heat pump is configured. In this study, the CCHP-ORC system, which is operated in thermal demand management (TDM) or electricity demand management mode, is employed to analyze the operational cost (OC), annual total cost (ATC), carbon dioxide emission (CDE), primary energy consumption (PEC) and system efficiency based on a case study of a regional energy system in Sino-Singapore eco-city. Meanwhile, the performance analysis of an improved operational mode is also conducted in this study. Following this mode, the waste heat and electricity imported from grid can be minimized by controlling the operation condition of PGU and ORC with a thermal management controller (TMC-ORC mode). Monthly and annual results in the case study show that the proposed system performed well on OC, CDE and PEC reductions and the ATC are both increased except for the ATC of TMC-ORC mode. However, the total efficiency of TDM is the highest among the three operational modes. Finally, for TMC-ORC mode, sensitivity analysis is performed and results are presented with varying electricity and gas price.

1. Introduction

The energy crisis and environmental concerns are two of the principal motivations for introducing "energy hubs" that integrate energy production, conversion and storage technologies, such as combined cooling, heating and power (CCHP) systems, renewable energy resources, batteries and thermal energy storage [1]. Energy demand, such as cooling, heating and electric demand, and the decentralization of energy production have continuously increased. By placing power generation units (PGUs) near the site or onsite, waste heat expelled by PGUs is cascaded utilized to meet the heating demand of end user. Thus, a CCHP system is an alternative that mitigates negative environmental impacts and improves energy utilization efficiency and energy supply security [2–5].

Many researchers have studied CCHP systems on the aspects of modeling, optimization, feasibility analysis and evaluation. Most of these studies [6,7] found that the performance of a CCHP system is determined according to its design. In the design phase, the operational mode should be taken into account. Typically, a CCHP system can be operated in two modes: thermal demand management (TDM) and electricity demand management (EDM) [8]. These two modes are also described as following the thermal load (FTL) and following the electric load (FEL). Wang et al. [9–11] evaluated the performances of a CCHP system with TDM and EDM including the following parameters: primary energy consumption (PEC), operational cost (OC) and carbon dioxide emissions (CDE). Chen et al. [12] investigated the energy and exergy analysis of the CCHP system with the EDM mode under the rated and part load conditions. Mago et al. [13,14] also studied the system performance using FTL and FEL, based on PEC, CDE and OC for different climate conditions. The results showed that the CCHP-FTL mode reduced the PEC for all of the studied cities.

Nevertheless, some researchers proposed that two such basic operational modes could not yield superior integrated performance. Therefore, other modes based on TDM and EDM have been developed. For instance, Hajabdollahi et al. [15] compared a new operational strategy named variable electric cooling ratio with constant electric cooling ratio for different climates including hot, cold and moderate. To avoid the excess heat in FEL or excess

* Corresponding author.
E-mail address: anqingsong@tju.edu.cn (Q. An).

http://dx.doi.org/10.1016/j.enconman.2016.12.055
0196-8904/

Nomenclature

c	unit prices (CNY/m^3 or CNY/kg or CNY/kW h)
C	capital cost per unit (CNY/kW)
COP	coefficient of performance
E	electricity (kW)
F	fuel energy (KW)
H	efficiency matrix
i	interest rate
l	number of equipment
n	service life
N	installation capacity (kW)
Q	heat (kW)
r	load ratio
R	capital recovery factor
V	vectors
Symbols	
η	efficiency
α	dispatch factor
μ	the emission conversion factors
k	the site-to-primary energy conversion factors
Γ	dispatch matrix
Subscripts and Superscripts	
ac	absorption chiller
c	cooling
ct	carbon tax
e	electricity
ex	heat exchanger
f	natural gas
g	grid
h	thermal
i	input
k	kth component
max	maximum load
min	minimum load
o	output
opt	optimal
$\_r$	rated parameter
req	required load
$user$	end user
Abbreviation	
ATC	annual total cost
CCHP	combined cooling, heating and power
CDE	carbon dioxide emissions
EDM	electricity demand management
FTL	following the thermal load
FEL	following the electric load
FHL	hybrid load-following method
GSHP	ground source heat pump
OC	operational cost
ORC	organic Rankine cycle
PEC	primary energy consumption
PGU	power generation unit
TMC	thermal management controller
TMC-ORC	energy management mode with TMC and ORC working
TDM	thermal demand management

electricity in FTL, Mago et al. [16] and Smith et al. [17,18] introduced a hybrid load-following method (FHL) that switches between FTL and FEL as required. Zheng et al. [19] proposed a novel operational strategy based on the minimum distance and compared the results of the proposed strategy with FTL, FEL and FHL. Wang et al. [20] proposed an improved operational mode of a CCHP system based on FEL to minimize PEC, in which the PGU operated following the daily average electrical load. Mu et al. [21] modeled a CCHP system to investigate its annual total cost (ATC) reduction, PEC savings and CDE reduction relative to a reference system under five different operation modes: FEL, FTL, FHL, following the seasonal operation strategy and following the electric–thermal load of buildings.

However, no matter which operational mode is employed, the electric or thermal demand is not always satisfied due to the variation of the end-user load. Wu et al. [22–24] presented the concept of a "thermal management controller (TMC)", which was applied to a micro-CCHP system to recover and manage the wasted heat. With the help of TMC, the system was able to realize 17.7 kW heating output, 6.5 kW cooling output and 16 kW electric output simultaneously. Sedghi et al. [25,26] and Ahmadian et al. [27] pointed out that storage units in distributed generation system were used for several objectives, i.e., peak shaving, voltage regulation, and reliability enhancement. Hajabdollahi et al. [28] presented an optimum design of CCHP generation system with ORC for various cooling, heating and electrical load demands. Fang et al. [29] configured a complementary CCHP-ORC system in which the electricity to thermal energy output ratio can be adjusted by dynamically changing the loads of the electric chiller and ORC. Zare [30] presented a comparative thermodynamic analysis and optimization for two different designs of geothermal energy-based tri-generation systems. The two considered systems were distinguished by their power generation units, as ORC was employed in one system while Kalina cycle is used in the other system. Kang et al. [31], Zeng et al. [32] and Liu et al. [33], proposed a CCHP system, in which ground source heat pump (GSHP) is added.

This paper presents a novel configuration of hybrid system which contains CCHP, ORC and GSHP. The GSHP is added to supplying the cooling and heating load to substitute conventional electric chiller and boiler. The ORC is added to use the extra recovered heat of the PGU to produce electricity. Thus, an improved operational mode of TMC and ORC co-operation, called the TMC-ORC mode, is proposed correspondingly. The aim of this mode is to minimize the waste heat and electricity imported from the grid. Then, a case study of an energy system in Sino-Singapore eco-city is conducted with three operational modes based on the criteria of ATC, OC, CDE and PEC. Finally, sensitivity analysis of OC is performed for TMC-ORC mode.

2. Model description

2.1. System matrix modeling

In this section, the system configuration will be presented firstly. Then a comprehensive and intuitive matrix modeling of the system will be introduced.

2.1.1. System configuration

To provide sufficient energy to communities and to improve the flexibility of the energy supply, an optimal CCHP-ORC system is