ARTICLE IN PRESS

Energy Conversion and Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Mathematical modelling and optimization of a large-scale combined cooling, heat, and power system that incorporates unit changeover and time-of-use electricity price

Qiannan Zhu [a], Xianglong Luo [a,b,*], Bingjian Zhang [c], Ying Chen [a,b,*]

[a] School of Material and Energy, Guangdong University of Technology, No. 100 Waihuan Xi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou 510006, China
[b] Soft Matter Center, Guangdong Province Key Laboratory on Functional Soft Matter, No. 100 Waihuan Xi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou 510006, China
[c] School of Chemistry and Chemical Engineering, Key Lab of Low-carbon Chemistry & Energy Conservation of Guangdong Province, Sun Yat-Sen University, No. 135, Xingang West Road, Guangzhou 510275, China

ARTICLE INFO

Article history:
Received 10 July 2016
Received in revised form 17 October 2016
Accepted 24 October 2016
Available online xxxx

Keywords:
CCHP
Changeover
CO_2 emission
MINLP
Multi-objective

ABSTRACT

Building energy systems, particularly large public ones, are major energy consumers and pollutant emission contributors. In this study, a superstructure of large-scale combined cooling, heat, and power system is constructed. The off-design unit, economic cost, and CO_2 emission models are also formulated. Moreover, a multi-objective mixed integer nonlinear programming model is formulated for the simultaneous system synthesis, technology selection, unit sizing, and operation optimization of large-scale combined cooling, heat, and power system. Time-of-use electricity price and unit changeover cost are incorporated into the problem model. The economic objective is to minimize the total annual cost, which comprises the operation and investment costs of large-scale combined cooling, heat, and power system. The environmental objective is to minimize the annual global CO_2 emission of large-scale combined cooling, heat, and power system. The augmented ε–constraint method is applied to achieve the Pareto frontier of the design configuration, thereby reflecting the set of solutions that represent optimal trade-offs between the economic and environmental objectives. Sensitivity analysis is conducted to reflect the impact of natural gas price on the combined cooling, heat, and power system. The synthesis and design of combined cooling, heat, and power system for an airport in China is studied to test the proposed synthesis and design methodology. The Pareto curve of multi-objective optimization shows that the total annual cost varies from 102.53 to 94.59 M$ and the annual CO_2 emission varies from 407390.4 to 328632.3 ton. The total annual cost of the scheme without simultaneously incorporating unit start-up cost is 1.23% higher than that of the scheme simultaneously incorporating unit start-up cost. The natural gas price sensitivity analysis results show that the natural gas-based combined cooling, heat and power system is superior to power importation in both economic and environmental performance when the natural gas price is lower than 500 $/t.

1. Introduction

The increase of world population and decrease of fossil energy reserves have resulted in the popularity of energy efficiency improvement and greenhouse gas emission reduction as research topics. Over 40% of global energy consumption and approximately 33% of global greenhouse gas emissions are attributed to the building sector [1]. China is the world's second largest energy consumer and building energy user [2]. Moreover, the energy consumption associated with buildings in China has reached an equivalent of 1.66 billion tons of coal in 2013. Accordingly, building energy consumption has experienced a stable annual growth rate of 7% since 2001 [3]. Building energy efficiency has been regarded as a key element of energy security to reduce the energy costs and energy dependence for end-users [4].

Although coal is the main source of energy in China, the traditional coal-based energy system is no longer allowed for most of the building sector because of its serious environmental performance. Currently, natural gas is becoming the main energy source for building energy systems. Natural gas-based combined cooling,

* Corresponding authors at: School of Material and Energy, Guangdong University of Technology, Guangzhou 510006, China.
E-mail addresses: lxl-dte@gdut.edu.cn (X. Luo), chenying@gdut.edu.cn (Y. Chen).

http://dx.doi.org/10.1016/j.enconman.2016.10.056
0196-8904/

Please cite this article in press as: Zhu Q et al. Mathematical modelling and optimization of a large-scale combined cooling, heat, and power system that incorporates unit changeover and time-of-use electricity price. Energy Convers Manage (2016), http://dx.doi.org/10.1016/j.enconman.2016.10.056

Nomenclature

Sets

DI	{*di* | all candidate capacities of unit *i*}
I	{*i* | all selected units}
IC	{*ic* | candidate condensing turbines}
IFB	{*ifb* | candidate fuel fired steam boilers}
IG	{*ig* | candidate gas turbines}
IHB	{*ihb* | candidate hot water boilers}
IT	{*it* | candidate back pressure turbines}
J	{*j* | seasonal operation scenarios}
T	{*t* | hourly operation scenarios}

Parameters

A, B	regression parameters
CCR	refrigerating capacity ratio of the icing mode to the air conditioning mode
CNG	carbon content of natural gas
CNC	carbon content of coal
COP	coefficient of performance
Cp	specific heat (kJ/(kg °C))
EISB	isentropic enthalpy drop of the back pressure turbine (kJ/kg)
H	operating hours per year (h)
ΔH	low heat value of natural gas (kJ/kg)
ir	annual interest rate
k	annual coefficient
l	flow ratio of natural gas to air
LHVC	lower heat value of coal (kJ/kg)
LPE	average efficiency of the local power plants
n	power loss ratio of GT
P	unit price of electricity and natural gas ($)
q	specific heat load of the steam generated in the boiler (kJ/kg)
S	single start-up cost of gas turbine, back pressure turbine, and condensing turbine ($)
T	time fraction
T^a	inlet air temperature of the gas turbine (°C)
T^f	inlet fuel temperature of the gas turbine (°C)
ΔT^{sat}	temperature difference of the saturation temperature (°C)
yr	durable years (a)
φ	constant parameter ensuring the minimum operating load of GT, BT, and CT
θ	thermal efficiency

Variables

C	annual cost ($)
CAN	annual capital cost ($)
CL	cooling output (MW)
E	annual CO_2 emission (ton)
EISC	isentropic enthalpy drop of the condensing turbine (kJ/kg)
F	flow rate of natural gas (kg/s)
HL	heat output (MW)
M	flow rate of steam and water (kg/s)
PH	power input for EC and heat input for HWAR and SAR (MW)
Q	waste heat of GT (MW)
W	output power (MW)

Binary variables

y	1 if a unit is selected or a unit is on and 0 if a unit is not selected or a unit is off
z	denotes the start-up status of unit

Superscripts and subscripts

a	air
buy	power importation
cc	capital cost
degn	maximum design load of GT, BT, CT, FB, and HWB
e	selection
in	inlet of the hot water boiler
let-down	let-down valve
max	maximum
o	operation
oc	operating cost
out	outlet of the hot water boiler
R	refrigeration
sat	saturation
st	start-up
tot	total
U	users
w	waste heat

heat, and power (CCHP) is a promising technology for building energy systems. The cooling, heat, and power generating processes in a CCHP system are integrated into a poly-generation system from the viewpoint of the cascade utilization of primary energy. CCHP is effective in simultaneously reducing primary energy consumption and CO_2 emission compared with the conventional separate production energy system. Although the natural gas-based energy system is superior to the traditional coal-based energy system in terms of environmental performance, the former is not competitive in terms of economic performance in China. Many incentive policies for CCHP systems have been issued in the European Union, the US, and Japan [5,6]. Over the past few decades, China has also explored motivation policies to develop CCHP systems; these policies include investment tax credit, direct subsidy for energy savings, and tax exemption. However, the development of synthesis, design, and operation strategy of CCHP remains an open research issue.

The synthesis, design, and operation optimization of CCHP has been drawn great interest among researchers. Many works have focus on the design capacity and operation optimization with predetermined technologies. Abdollahi and Meratizaman [7] proposed a multi-objective design approach of a small-scale CCHP system with risk analysis. Three objective functions (i.e., total levelized cost rate, environmental impact, and exergetic efficiency) were considered. The genetic algorithm (GA) was used to obtain the set of Pareto optimal solutions. Gu et al. [8] proposed an integrated assessment framework to give a comprehensive understanding of four types of CCHP technologies following three design and management modes. Li et al. [9] performed an analysis and optimization of the CCHP system in office and residential buildings in Dalian, China. The configuration of this system was optimized by adding an air-conditioning system and a heat storage tank. A nonlinear model was formulated and solved using GA. Yao et al. [10] proposed a novel CCHP system based on a small-scale compressed air energy storage with artificial air vessels. They applied an evolutionary multi-objective algorithm to investigate the compromise between economic and thermodynamic performances. Chen et al. [11] presented an innovative, hybrid residential CCHP system that is based on solar and fuel cell technologies. The effects of the key operating parameters on the thermodynamic