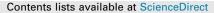
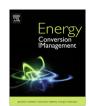
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Mathematical modelling and optimization of a large-scale combined cooling, heat, and power system that incorporates unit changeover and time-of-use electricity price

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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 CO₂ 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 CO₂ 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 CO2 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.

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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

http://dx.doi.org/10.1016/j.enconman.2016.10.056 0196-8904/© 2016 Elsevier Ltd. All rights reserved. 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,

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Nomenclature

Sets		θ	thermal efficiency
DI	{ <i>di</i> all candidate capacities of unit <i>i</i> }		
I	{ <i>i</i> all selected units}	Variables	
IC	<i>ic</i> candidate condensing turbines}	C	annual cost (\$)
IFB	{ <i>ifb</i> candidate fuel fired steam boilers}	CAN	annual capital cost (\$)
IG	{ig candidate gas turbines}	CL	cooling output (MW)
IHB	<i>{ihb</i> candidate hot water boilers <i>}</i>	E	annual CO_2 emission (ton)
IT	{ <i>it</i> candidate back pressure turbines}	EISC	isentropic enthalpy drop of the condensing turbine
J	{ <i>j</i> seasonal operation scenarios}	LISC	(k]/kg)
ј Т	$\{t \mid \text{hourly operation scenarios}\}$	F	flow rate of natural gas (kg/s)
•		HL	heat output (MW)
Paramet	tore	пL M	flow rate of steam and water (kg/s)
		IVI PH	power input for EC and heat input for HWAR and SAR
A, B	regression parameters	rп	
CCR	refrigerating capacity ratio of the icing mode to the air	0	(MW)
CNC	conditioning mode	Q	waste heat of GT (MW)
CNG	carbon content of natural gas	W	output power (MW)
CNC	carbon content of coal		
COP	coefficient of performance	Binary vo	
Ср	specific heat (kJ/(kg °C))	у	1 if a unit is selected or a unit is on and 0 if a unit is not
EISB	isentropic enthalpy drop of the back pressure turbine		selected or a unit is off
	(kJ/kg)	Ζ	denotes the start-up status of unit
Н	operating hours per year (h)		
ΔH	low heat value of natural gas (kJ/kg)	Superscripts and subscripts	
ir	annual interest rate	a	air
k	annual coefficient	buy	power importation
l	flow ratio of natural gas to air	cc	capital cost
LHVC	lower heat value of coal (kJ/kg)	degn	maximum design load of GT, BT, CT, FB, and HWB
LPE	average efficiency of the local power plants	е	selection
n	power loss ratio of GT	in	inlet of the hot water boiler
Р	unit price of electricity and natural gas (\$)	let-down	let-down valve
q	specific heat load of the steam generated in the boiler	max	maximum
6	(kJ/kg)	0	operation
S	single start-up cost of gas turbine, back pressure	OC	operating cost
_	turbine, and condensing turbine (\$)	out	outlet of the hot water boiler
T	time fraction	R	refrigeration
T^a_{-f}	inlet air temperature of the gas turbine (°C)	sat	saturation
T ^f	inlet fuel temperature of the gas turbine (°C)	st	start-up
ΔT^{sat}	temperature difference of the saturation temperature	tot	total
	(°C)	U	users
yr	durable years (a)	W	waste heat
φ	constant parameter ensuring the minimum operating		
	load of GT, BT, and CT		

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 CO₂ 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

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