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Optimal design and operation strategy for integrated evaluation of CCHP (combined cooling heating and power) system

Miao Li [a,*], Hailin Mu [b], Nan Li [b], Baoyu Ma [c]

[a] School of Mechanical Engineering, Dalian Polytechnic University, Dalian, 116034, PR China
[b] Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian, 116024, PR China
[c] Liaoning Zhongyu Construction (Group) Limited Liability Company, Fushun, 113000, PR China

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ABSTRACT

With the encouragement of LNG (liquefied natural gas) application in China, CCHP (combined cooling heating and power) system fueled by natural gas has been receiving increasing attention. This paper presents optimization of CCHP system on their design and operation from energetic analysis, economic operation and environment effect viewpoints. CCHP system for hotels, offices and residential buildings in Dalian (China) is given to ascertain the effectiveness of the model. Weighting method and fuzzy optimum selection theory are employed to evaluate the integrated performances of CCHP systems with various operation strategies. Results show that: (1) Hotels have the greatest contribution (42.28%) to the energy savings based on energetic analysis sub-model because of their relatively stable electricity loads. (2) CCHP systems reduce the annual total costs for all operation cases compared with the reference system for hotels and offices. However, CCHP system achieves no economic merits for residential buildings. (3) The applications of the CCHP system decrease pollutant emissions in all operation cases for the studied buildings. (4) CCHP system driven by gas engine has better performance than driven by gas turbine. Coupled with renewable energy sources and with thermal storage tank are mostly optimum operation cases from energetic, economic and environment criteria.

1. Introduction

In traditional power plants, the electricity conversion efficiency is about 30%. The majority loss of energy in traditional power plant is the discharge of waste heat. Further energy losses also occur in the transmission and distribution process [1]. CCHP (combined cooling heating and power) system, close to demand sites, allows waste heat to be recovered to meet thermal loads and enable overall system energy efficiency to be higher [2]. Over the past few years, LNG (liquefied natural gas) is recognized as preferred fuel in many countries [3] and CCHP system fueled by natural gas has been receiving increasing attention [4]. Recently, many terminal LNG receiving stations have been established in China including Dalian receiving station. Therefore CCHP system has been recognized as a good energy system option for sustainable development and low-carbon society construction in Dalian [5].

The energy performance characteristics of CCHP system are strongly influenced by equipment capacity and operational strategy [6]. Therefore, in order to realize the expected high energetic, economic and environmental potentials, it is necessary to determine appropriate capacity of selected equipments so that they can match customer's load demands well [7]. However, how to design such a certain system is a complex and hard work. The energy consumption is greatly dependent upon the capacity of energy equipments [8]. According to the analysis, it can be found that correct sizing of PGU is a key design variable that determines the capacities of other equipments such as heating exchanger, auxiliary natural gas boiler and supplement electricity [9]. A variety kinds of PGU in CCHP system have already been studied by researchers [10]: gas-turbine, micro-turbine, gas-engine [11], string engine [12], fuel cells, etc. Operational strategy is another important design variable. Two traditional operation modes (FEL and FTL) are usually chosen to run the prime mover in accordance to either electrical or thermal demand. However, the two simple operation modes cannot fully provide advantages of CCHP system. Under these specifications, an optimization model is necessary for above two design variables [13]. In the past, most work in optimization of PGU is focus on

* Corresponding author. Tel.: +86 13234068712; fax: +86 0411 84708095.
E-mail address: limiaolaile@163.com (M. Li).

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Nomenclature

NG	natural gas
LNG	liquefied natural gas
CCHP	combined cooling heating power
HVAC	heating, ventilating, and air conditioning
FEL	following electric load
FTL	following thermal load
PGU	power generation unit
PESR	primary energy saving ratio
ATCS	annual total cost savings
GARR	Pollutant emissions reduction ratio
PEC	Primary energy consumption
CER	CO_2 emissions reduction ratio

Symbols

COP	Coefficient of performance
L	load fraction
τ	on–off coefficient of power generation unit
CO	cooling demand
Q	heat consumption
E	electricity
I	gas engine
T	gas turbine
HPR	heat to power ratio
PV	photovoltaic power
η	efficiency
PMax	the rated capacity of each equipment
C	cost
OGen	power generation of each equipment
FPur	purchased fuel
EPur	purchased electricity
P	installed power of equipment
FUEL	fuel
EL	electricity
l	the numbers of total equipments
i	interest rate
n	the service life of the equipment
R	recovery factor
m	month
d	day
h	hour
Em	pollutant emission
F_j	fuel consumption
ξ_z	emission factor

subscripts

GWE	global warming effect
AE	acidification effect
RE	$PM_{2.5}$ emission
λ	conversion factors
ec	electric chiller
Grid	electricity grid
co	cooling
pgu	power generation unit
p	pump
th	thermal
b	boiler
e	electricity
h	heat
ch	absorption chiller
rh	recovered thermal energy for heating
rc	recovered thermal energy for cooling
nom	rated capacity
hc	heating coil
rec	waste heat recovery system
building	the studied buildings
i	hour
in	input
out	output
storage	storage tank
f	fuel
cap	capital cost
MAN	maintenance cost
FC	energy charge cost
INV	Investment cost
load	load
capacity	the capacity of equipment
fix	fix costs
var	variable costs
peak-load	peak demand
demand	demand load
excess	the excess electricity

superscript

CCHP	combined cooling, heating and power
HVAC	heating, ventilating, and air conditioning
sum, demand	total heat demand
ecl	cooling load produced by electricity

single objective, and over 50% of the works on building optimization were concerned with economic achievements objective [14]. Benonysson et al. [15] formulated a mathematical model where the objective is to minimize the operational costs of district heating system. Soderman et al. [16] proposed a MILP (mixed integer linear programming) to minimize the system overall cost, the sum of the running costs and the investment costs, for structural and operational optimization. Ren et al. [17] developed a MINLP (mixed integer nonlinear programming) model to minimize annual cost of the energy system for a given residential customer. Li et al. [18] also established a MINLP model to evaluate optimization of facility scheme and operation strategy of BCHP system. The indices of feasibility evaluation include annual cost and annual cost saving rate. Facci et al. [19] minimized the total cost using another mathematical model, backward dynamic programming, whose computational effort is compatible with real practical applications. Bischi et al. [20] gave a design of a cogeneration system to determine an operating schedule that minimizes the total operating and maintenance costs. Yang et al. [21] focused on the optimal design of DER (distributed energy resource) systems. The optimization function is the annual total cost for investing, maintaining, and operating the system. All above studies optimized the design and operation strategy of CCHP system based on minimal annual total cost. While some researchers considered maximum NPV (net present value) as another economic optimization objective. Sheikhi et al. [22] introduced concept of DCF (discounted cash flow) analysis for the derivation of project performance using NPV criteria. Li et al. [23] presented a MINLP problem which was solved by GAs (Genetic Algorithms). System NPV was also taken as the objective to be maximized in the paper. In Tichi et al.'s paper [24], for the economic analysis, all costs in the objective function were all converted to the NPV, and Moradi et al. [25] offered an EMS (energy management system) strategy to determine the optimum ranges for boiler and CHP capacities which maximized an objective