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A hybrid operating strategy of combined cooling, heating and power system for multiple demands considering domestic hot water preferentially: A case study

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A B S T R A C T

A hybrid electric-thermal (HET) following method is proposed for a combined cooling, heating and power (CCHP) system driven by natural gas and solar energy, focusing on the supply matching of domestic hot water, space cooling/heating and electricity. The domestic hot water thermal demand (Class A) is set to be met preferentially due to its immediateness and timeliness, and the space cooling/heating (Class B) thermal demand matching condition will be discussed from the view of comfort reliability. Detailed strategy methods under summer and winter conditions are presented. Variable electric-thermal ratio (R_A, the ratio of the thermal demand of domestic hot water to the electric demand, R_B, the ratio of the thermal demand of space cooling/heating to the electric demand) load conditions are analyzed and a comparison of HET between the base following electric load and following thermal load strategies is discussed for hotel applications. The criteria including primary energy consumption, carbon dioxide emission, operation cost and exergy efficiency is employed to evaluate the performances in the HET strategy. The results indicate that HET can achieve more benefits than the base operation strategies.

1. Introduction

A combined cooling, heating and power (CCHP) system is an energy application method that utilizes the principle of energy graded use in accordance with the popular concept of regional multi-energy prosumers (RMEP), whose energy demands are met by interconnected energy hubs [1]. Under the background of energy structure adjustment, the CCHP systems in recent studies are generally supported by multi-energy that contains more than one kind of driven energy source. The integration of traditional fossil fuels and clean energy or several kinds of pure clean energy combination are mostly applied, such. as utilizing wind and solar photovoltaic energy to drive the solid oxide fuel cells complementarily [2], gasifying the biomass to drive the ICE while extracting heat from solar energy to actuate absorption chiller [3], employing natural gas as the primary driven source while adding the auxiliary ground source heat pump to produce chilled and hot water [4], integrating solar thermal energy with the typical natural gas CCHP system [5] and co-firing natural gas and biogas to driven the ICE [6]. Since CCHP system products are typically attributed to different energy properties, e.g., thermal and electric properties, exploration of the relations among multiple energy products is essential for optimal operation strategy selection. Generally, the most characteristic operation strategies of CCHP systems are the following electric load (FEL), following thermal load (FTL) and hybrid electric-thermal load following (HET) [7]. FEL means that the generated electricity is equal to the electric load; when the thermal demand is larger, the auxiliary heat equipment complements the deficiency, and when the demand is lower, the surplus heat is rejected to the environment. FTL means that the useful thermal output is equal to the thermal load at any time, so when the electric demand is larger, the excess energy is obtained from the grid [8]. It is important note that if policy permits electricity to be sold back to the grid under the FTL mode [9], when the electric demand is lower, surplus electricity is then sold back; otherwise, electricity storage equipment is needed.

Nevertheless, problems accompany the simplex strategy operation. Previous studies have indicated that when the thermal load is not much, excess heat output is wasted under the FEL mode. When the electric load is low, redundant electricity generation may only lead to a slight benefit if it can be sold [7]; if not, the cost of small-

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Nomenclature

AC	absorption chiller
AHP	absorption heat pump
CCHP	combined cooling heating and power
CDE	carbon dioxide emission
COP	coefficients of performance
EE	exergy efficiency
FEL	following electric load
FTL	following thermal load
HX	heating exchanger
ICE	internal combustion engine
OC	operation cost
PEC	primary energy consumption
RMEP	regional multi-energy prosumers

Symbols

E	electricity (kW)
F	fuel (kW)
Q	energy (kW)
R	load thermal-electric ratio
T	temperature (K)
η	efficiency
φ	price ratio (kW·h/m^3)

Subscripts

A	class A
AC	absorption chiller
AHP	absorption heat pump
B	class B
b	intercept
bld_dD	domestic hot water thermal demand of the building
bld_D	space cooling/heating thermal demand of the building
C	for cooling
CD	cooling demand
C_AB	recovered heat for space cooling/heating afterburning
C_FT	recovered heat for space cooling/heating at the thermal following condition
C_lack	lack of recovered heat for space cooling/heating
C_store	store of recovered heat for space cooling/heating
dD	domestic hot water demand
ED	electric demand
elec	electricity
H	recovered heat or heating
HD	heating demand
HE	waste heat of ICE
HG	high generator
HX	heat exchanger
ICE	internal combustion engine
k	slope
m	metered
r, rexh	recovery of exhaust gas
R	recovered heat
RC	recovered heat for cooling
RH	recovered heat for heating
s	summer
sol,hw	solar hot water
w	winter

scale electricity storage may exceed its benefit. Consequently, some researchers have concentrated on strategy transformation, and HET is the most typical strategy that has been proposed because it combines the mutually complementary advantages of FEL and FTL. Current research focuses on these following aspects of operation strategies:

(1) Considering single electric-thermal proportional relationship.

The ratio of electric and heat produced by the power generation unit (PGU) is relatively fixed. However, the electric-thermal ratio of users varies hourly. The well matching between them is helpful to improve the system performances. Some researchers have developed some different integrated CCHP systems and analyzed the benefits on different operation strategies, such as the typical natural gas CCHP system by Han et al. [7] and Mago et al. [10], biogas-driving CCHP system [11], and the CCHP system integrated ground heat source [12]. Their system energy flow are similar that the electricity was generated from the PGU while the thermal product were consist of waste heat from PGU and the heat production of auxiliary boiler or assisted heat pump. In these explorations, the thermal product was merely employed for space cooling/heating, didn't contain the subsequent recovery process or divide partial waste heat for domestic hot water. During the researches on HET, these researches merely focused on the electric-thermal relationship between electric load and the thermal demand for space cooling/heating, while rarely considering the electric-thermal relationship between electric load and thermal demand for domestic hot water and the multi-relation between these three demands.

(2) Comparing different strategies based on various evaluation criteria.

In order to comprehensively compare the advantages and disadvantages of HET with FEL and FTL, researchers selected various parameters of CCHP system. The common criteria mainly includes primary energy consumption (*PEC*) [13], primary energy saving ratio (*PESR*) [11], operation cost (*OC*) [14], economic saving [15], carbon dioxide emission (*CDE*) [16], exergy efficiency (*EE*) [7] and so on.

(3) Taking the government policies into consideration.

Based on the traditional evaluation criteria, there have appeared some researches on the adaptability of HET from the perspective of government taxation and tariff policy. Such as considering carbon tax and electric feed in tariff when calculating the operation cost [16], proposing a feed in tariff policy that ensure both energy and economic performance are both optimal [17].

(4) Exploring the adaptation of HET in different building categories and climates.

Li et al. [18] from the energetic, economic and environmental viewpoints explored the HET application in hotels, offices and residential buildings, respectively. The results indicated that the local climate data was an essential factor that influences the design and operation optimization of CCHP system. Smith et al. [19] modeled a large hotel building in 16 cites, and Hajabdollahi et al. [20] performed its procedure for hot, cold and moderate climates, which have compared the operation performance between