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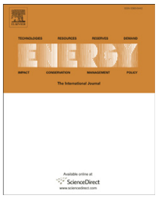

Modelling and optimal operation of a small-scale integrated energy based district heating and cooling system

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ABSTRACT

This paper presents a comprehensive model of a small-scale integrated energy based district heating and cooling (DHC) system located in a residential area of hot-summer and cold-winter zone, which makes joint use of wind energy, solar energy, natural gas and electric energy. The model includes an off-grid wind turbine generator, heat producers, chillers, a water supply network and terminal loads. This research also investigates an optimal operating strategy based on Group Search Optimizer (GSO), through which the daily running cost of the system is optimized in both the heating and cooling modes. The strategy can be used to find the optimal number of operating chillers, optimal outlet water temperature set points of boilers and optimal water flow set points of pumps, taking into account cost functions and various operating constraints. In order to verify the model and the optimal operating strategy, performance tests have been undertaken using MATLAB. The simulation results prove the validity of the model and show that the strategy is able to minimize the system operation cost. The proposed system is evaluated in comparison with a conventional separation production (SP) system. The feasibility of investment for the DHC system is also discussed. The comparative results demonstrate the investment feasibility, the significant energy saving and the cost reduction, achieved in daily operation in an environment, where there are varying heating loads, cooling loads, wind speeds, solar radiations and electricity prices.

1. Introduction

Two of the major global challenges facing the world are responding to global warming and ensuring energy security. Apart from the energy demand due to climatic conditions, rapid economic development, growing population and higher living standards have increased building energy consumption, a significant fraction of which is used for building heating. Hence, it is necessary and important for a heating system to reduce fossil fuel consumption while ensuring the quality of heating. As an important type of heating system, a district heating system is widely used to meet the increasing heat demand from the viewpoint of energy saving [1–3]. A considerable amount of research has been conducted to reduce the fossil fuel consumption of a district heating system [4–11]. In the previous study [12], we have presented an integrated energy based direct district water-heating system. Such an integrated energy based system is more sustainable than a heating system which only relies on fossil fuels, and is more reliable than a heating system which just makes use of renewable energy resources.

However, heat generated by a large number of energy consuming apparatuses also increases the energy need for building cooling. The peaks of electric power demand appearing in summer are partly due to the use of electricity-driven cooling facilities. The rising number of cooling facilities increases the already strong daily variations in electricity demand and thereby also the need for peak load power generation, which is associated with high operating costs. Therefore, except from electricity-driven compression cooling, heat-driven absorption cooling (AC) should be paid more attention. This is because absorption cooling not only decreases the electric power used for cooling, but also raises district heating (DH) demand during low-demand periods and may thus contribute to a more efficient resource utilisation [13].

In practice, a higher resource efficiency can be achieved by combining heating and cooling in a system instead of providing

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Nomenclature

A_c	area of a solar collector (m^2)
A_fac	annuity factor
$A_{\mathrm{r}j}$	radiators' heat radiating area of building j (m^2)
B_g	natural gas consumption rate (m^3/s)
$c_{\mathrm{comf}i}$	fixed O&M costs coefficient of unit i ($/kW)
$c_{\mathrm{comv}i}$	variable O&M costs coefficient of unit i ($/kW)
c_elec	electricity tariff rate ($/kWh)
c_g	unit cost of natural gas ($/$\mathrm{m}^3$)
c_w	specific heat of water (J/(kg °C))
C_annu	annual capital cost ($)
C_elec	cost of purchasing electricity ($)
C_g	cost of natural gas ($)
C_inv	present investment ($)
COP_1	COP of a reciprocating chiller
COP_2	COP of an absorption chiller
C_om	operation and maintenance cost ($)
$\overline{G}$	relative water flow ratio
$h_{\mathrm{a,in}j}$	specific enthalpy of air at the inlet of AHU in building j (kJ/kg)
$h_\mathrm{w,in}$	specific enthalpy of saturated air at the temperature of inlet water (kJ/kg)
H_0	head of a pump installed in main pipeline (m)
H_j	head of a pump installed in jth branch (m)
H_T	total solar flux incident on the collector (W/m^2)
I	interest rate
K_p	heat transfer coefficient unit length (W/(m °C))
$K_{\mathrm{r}j}$	radiator's heat transfer coefficient in building j (W/(m^2 °C))
l	length of a pipe (m)
M_0	water flow rate of heat units (kg/s)
$M_{\mathrm{a}j}$	AHU airflow of building j (m^3/h)
M_c1	chilled water flow of a reciprocating chiller (kg/s)
M_c2	chilled water flow of an absorption chiller (kg/s)
M_p	water flow of a pipe (kg/s)
M_s	water flow rate of main pipeline (kg/s)
$M_{\mathrm{w}j}$	water flow of jth branch pipeline (kg/s)
n	number of buildings
N_col	number of solar collectors at site
$P_{\mathrm{cap}i}$	capacity of heat unit i (W)
P_H1	heat production of a gas boiler (W)
P_H2	heat production of an electric boiler (W)
P_H3	heat production of a solar water heater (W)
P'_p	rated power of a pump (W)
P_pur	purchasing electric power (W)
P_WG	wind generator output power (W)
q_g	calorific value of natural gas (J/m^3)
$q_{\mathrm{V}j}$	volumetric heat index of building j (W/(m^3°C))
$Q_\mathrm{a,rated}$	rated capacity of an absorption chiller (W)
Q_c1	cooling rate of a reciprocating chiller (W)
Q_c2	cooling rate of an absorption chiller (W)
$Q_{\mathrm{CL}j}$	cooling load of building j (W)
Q_gen	thermal power input to an absorption chiller's generator (W)
$Q_{\mathrm{HL}j}$	heating load of building j (W)
$Q_{\mathrm{net}j}$	heat transferred from network to radiators (W)
$Q_{\mathrm{rad}j}$	radiators' heat release rate of building j (W)
$Q_\mathrm{r,rated}$	rated capacity of a reciprocating chiller (W)
S_DHCS	flow resistance of heat units or chillers
S_j	flow resistance of jth branch pipeline
$S_\mathrm{p,tol}$	flow resistance of fittings around pumps
S_r	flow resistance of return pipeline
S_s	flow resistance of supply pipeline
T_a	ambient temperature (°C)
$T^\mathrm{in}_\mathrm{cond1}$	condenser inlet temperature of a reciprocating chiller (°C)
$T^\mathrm{in}_\mathrm{cond2}$	condenser inlet temperature of an absorption chiller (°C)
T_chwr	chilled water return temperature (°C)
T_chws	chilled water supply temperature (°C)
$T^\mathrm{in}_\mathrm{evap1}$	evaporator inlet temperature of a reciprocating chiller (°C)
$T^\mathrm{in}_\mathrm{evap2}$	evaporator inlet temperature of an absorption chiller (°C)
$T^\mathrm{out}_\mathrm{evap1}$	evaporator outlet temperature of a reciprocating chiller (°C)
$T^\mathrm{out}_\mathrm{evap2}$	evaporator outlet temperature of an absorption chiller (°C)
$T^\mathrm{in}_\mathrm{gen}$	generator inlet water temperature (°C)
$T^\mathrm{out}_\mathrm{gen}$	generator outlet water temperature (°C)
T_il	inlet temperature of a gas boiler (°C)
T_i2	inlet temperature of an electric boiler (°C)
T_i3	inlet temperature of a solar water heater (°C)
T_ip	inlet temperature of a pipe (°C)
$T_{\mathrm{n}j}$	indoor temperature set point of building j (°C)
T_ol	outlet temperature of a gas boiler (°C)
T_o2	outlet temperature of an electric boiler (°C)
T_o3	outlet temperature of a solar water heater (°C)
T_op	outlet temperature of a pipe (°C)
$T_\mathrm{w,in}$	terminal unit inlet temperature (°C)
$T_{\mathrm{w,out}j}$	terminal unit outlet temperature (°C)
V_j	peripheral volume of building j (m^3)
η_1	operation efficiency of a gas boiler
η_2	operation efficiency of an electric boiler
η_c	efficiency of a solar collector

these energy services separately [14–16]. A district heating and cooling (DHC) system, which produces hot and cold fluids, and then distributes them throughout the residents with underground pipes, can ensure the security of supply, increase efficiency and reduce fuel costs. This has been demonstrated in some Northern European countries, for instance Denmark, where innovative technologies related to district heating and cooling have been developed and implemented for decades. There has also been a quantity of studies on DHC systems [17–23]. Using such an energy production and distribution system, less energy consumption can be achieved in heating and cooling, leading to more efficient use of energy resources. Furthermore, it has been proved that the integrated utilisation of energy resources, including both non-renewable energy and renewable energy, can make energy supply sustainable and reliable concurrently [12]. Therefore, as an extension of the district heating system presented in Ref. [12], an integrated energy based DHC system, which utilizes both non-renewable energy and renewable energy, is proposed in this paper.

The rest of the paper is organized as follows: Section 2 models the integrated energy based DHC system. The models of a district heating and cooling station, a water supply network and terminal loads are described respectively in this section. Section 3 investigates an optimal operating strategy through which the running cost of the system in daily operation is optimized. In Section 4, simulation studies of the proposed model and optimal operating strategy, including parameter settings, simulation results

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