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Thermodynamic and economic assessment of a novel CCHP integrated system taking biomass, natural gas and geothermal energy as co-feeds

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ABSTRACT

The combined cooling, heating and power (CCHP) system based on biomass, geothermal energy and fossil energy contributes to less fossil fuel-dependent, alleviate the climate change and improve the flexibility of integrated system. Therefore, this paper presents a novel combined cooling, heating and power (CCHP) system based on biomass, natural gas and geothermal energy. The CCHP system consists of an air-biomass gasification subsystem, steam turbine electricity generation subsystem, gas turbine electricity generation subsystem, waste heat utilization subsystem and ground source heat pump subsystem. The thermodynamic and economic analysis of proposed system are investigated, and the influences of some key operating parameters (gas mass ratio and flue gas split ratio) and economic factors (such as biomass and natural gas price, interest rate, operating time coefficient and service life) on integrated system performances are also carried out. The results indicate that the introduction of natural gas contributes to improve the overall energy efficiency of proposed CCHP system and reduce the levelized cost of energy significantly. In the case study (gas mass ratio: 0.5, flue gas split ratio: 0.5), the overall energy efficiency and electricity generation efficiency of CCHP system can be reached at about 97.05% and 30.89%, respectively; the levelized cost of energy is 0.0315 $/kWh. The proposed system provides a new way for utilization of renewable energy and fossil fuels based poly-generation system, which is a promising approach for the utilization of biomass, natural gas and geothermal energy in the rural of China.

1. Introduction

With the rapid development of global society and economy, energy issues are gaining increasing attention. According to the statistics of International Energy Agency (IEA), the world energy demand rose by 2.1% in 2017, more than twice the rate of 2016. The fossil fuels, such as oil, natural gas and coal, accounted for about 81% of the total energy demand in 2017. Accordingly, the world energy-related carbon dioxide emissions increased, which reached a historical high of 32.5 gigatonnes in 2017 [1]. Besides that, the utilization of fossil fuels also results in the environment pollution and ecological destruction. Hence, it is imperative to consider the clean and efficient energy as the alternatives, and the renewable energy is an attractive option. In order to further improve energy efficiency and realize the energy cascade utilization, the selection of energy supply system is also important.

In recent years, the distributed energy system has been widely developed due to their high energy efficiency, environmental protection and high reliability [2]. There are many different structures considering the distinct energy inputs and outputs, such as combined heat and power (CHP) system [3], combined cooling, heating and power (CCHP) system [4], trigeneration system [5] and polygeneration system [6]. Currently, more and more renewable energy is adopted in the distributed energy system so as to decrease the fossil fuels-dependent and enlarge the applications of renewable energy. The related investigations have been carried out from different issues, such as the analysis of thermodynamic performance [7], economic feasibility [8], the optimization of system structure and operation [9,10].

Among the above renewable energy resources, biomass and geothermal energy have attracted more attention for their unique advantages [11]. As a carbon neutral resource, biomass can efficiently reduce the carbon dioxide (CO_2) emission compared with fossil fuels [12]. Through different utilization methods (combustion, fermentation, pyrolysis, gasification), the biomass can be converted into various products directly or indirectly: synthetic gas [13], methanol [14], heat

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Nomenclature

Abbreviations

ANN	artificial neural network
ATC	annual total cost
CCHP	combined cooling, heating and power
CCP	combined cooling and power
CGE	cold gas efficiency
CHP	combined heating and power
COE	cost of electricity
COH	cost of heat
COP	coefficient of performance
ER	equivalence ratio
GCU	gas conditioning unit
GMR	gas mass ratio
GSHP	ground source heat pump
GT	gas turbine cycle
HX	heat exchanger
ICE	internal combustion engine
LCOE	levelized cost of energy
LHV	lower heating value
MGT	micro gas turbine
NG	natural gas
O&M	operation & maintenance
ORC	organic rankine cycle
SR	split ratio
ST	steam turbine cycle

Symbols

A	heat transfer area (m^2)
C	investment cost of component ($)
c	fuel price ($/ton, $/m^3)
c_p	specific heat capacity (kJ/(kmol·K))
d	service life (year)
E	electricity (kW)
h	specific enthalpy (kJ/kg)
I	capital recovery factor
K	heat transfer coefficient (W/(m^2·K))
m	mass flow rate (kg/h)
n	poly-tropic exponent
P	pressure (Pa)
Q	heat (kW)
q	specific heat (kW/kg)
R	universal gas constant (kJ/kmol·K)
r	interest rate (%)
T	temperature (°C)
t	annual operation hour (h)
V	volume flow rate (Nm^3/h)
w	specific electricity (kW/kg)
η	efficiency (%)

Subscripts

C	cooling
c	condenser
e	evaporator
H	heating
mix	mixture gas
wf	working fluid

[3], power [15], etc. At the same time, the ground source heat pump (GSHP) is usually adopted to utilize the geothermal energy [16], which has the stable heat source from the Earth's interior and not influenced by season and weather conditions. Some researchers have studied the integrated energy system base on biomass and geothermal energy. Malik et al. [17] assessed the energetic and exergetic performances of a biomass combustion and geothermal power generation based multi-generation system, providing electricity, hot water, cooling, liquefied gas and hot drying air for residential buildings; and the influences of key parameters on system performances are also investigated. Patarau et al. [18] presented a techno-economic analysis of a hybrid renewable energy system for a vegetable greenhouse in Oradea region, Romania. The hybrid energy system mainly consists of: solar panels, a geothermal generator and a biogas generator. Seethamraju et al. [19] integrated a biomass combustor with an existing geothermal electricity generation plant, utilized the combustion heat from biomass combustor to further heat the geothermal steam. In order to select an optimal alternative, three different scenarios have been adopted to demonstrate the integration performances of different scenarios. Moret et al. [20] presented an appropriate methodology for urban energy systems combined with deep geothermal energy and woody biomass, and validated the model performance by an application case study in Switzerland. Lukawski et al. [21] studied a geothermal-biomass hybrid renewable energy system to achieve the Cornell's transformation energy plan, the proposed system adopted biomass boiler to generate the heat production and combined with geothermal energy and ORC to provide electricity. According to the above literature survey, the researches mainly concentrated on the energy power generation or CHP system integrated with biomass combustion and geothermal power generation, and rarely focused on biomass gasification and ground source heat pump (GSHP) based integrated energy system. To date, the authors have investigated a novel combine heating and power (CHP) system integrating with biomass and geothermal energy in terms of exergetic and exergoeconomic aspects [22]. Moreover, a multi-objective optimization model of the proposed system was investigated in order to obtain the optimal capacity and operation strategy [23]. Although the above CHP system provides a new way for biomass and geothermal based energy integration system, it has adjustability limitation to a certain extent and cannot meet the multiple load demands of users.

In addition, the biomass cannot meet the energy requirement of users throughout the whole year considering the low energy density and limited utilization efficiency. Therefore, some researchers proposed the concept of co-firing to alleviate the above problems. Fan et al. [24] investigated a biomass and coal co-feed chemical looping combustion for combined cooling, heating and power generation system from the perspective of thermodynamic and environmental assessment. Walter and Llagostera [25] analyzed the feasibility of co-fired combined-cycles utilizing sugarcane residues-derived gas and natural gas in terms of economic aspects, the authors compared with the current and middle term costs of combined cycle through calculating the capital, operation and maintenance costs. Wang et al. [26] studied the thermodynamic and exergoeconomic performances of a novel co-fired CCHP (combined cooling, heating and power) system taking natural gas and biomass product gas as co-feeds, the presented system mainly contains a gasifier, internal combustion engine (ICE), absorption chiller and heat exchangers. The results showed that the co-firing of natural gas and biogas can decrease the primary energy consumptions considering the high energetic and exergetic efficiencies. Agbor et al. [27] presented a techno-economic model to analyze the technical potential and economic feasibility of 60 scenarios for co-firing biomass with coal and natural gas, and the environmental performances are also determined. Fiaschi and Carta [28] analyzed a co-firing of natural gas and biomass-