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# Optimization analysis of a novel combined heating and power system based on biomass partial gasification and ground source heat pump

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ABSTRACT

The thermodynamic performance of a novel combined heating and power system integrated with biomass partial gasification and ground source heat pump has been investigated previously, while system performances are greatly dependent on system component capacity and operation strategy. In this paper, a multi-objective optimization model of proposed integration system is presented, which considers the energetic, economic and environmental performances. The optimal parameters are mainly consists of three parts: the rated power of power generation unit, carbon conversion ratio and the temperature of warm water. Genetic algorithm is adopted to optimize the component capacity and operation strategy of proposed system. In order to demonstrate the optimal model, a case study is adopted. The optimal results show that the primary energy saving ratio, annual total cost saving ratio, carbon dioxide emission reduction ratio and performance indicator are 7.61%, 23.62%, 66.52%, 32.58%, respectively. In addition, the influences of related economic factors on proposed system performances are also analyzed. Finally, the research shows that the multi-objective optimization model provides a new way for the optimization design of the integration system.

## 1. Introduction

As is well known, combined heating and power system (CHP) has drawn more and more attention due to its high energy utilization, environmental-friendly, high reliability and economic benefits [1]. Considering the diversified products, there are many derived configurations so as to meet the requirements of different users. Bai et al. [2] proposed a polygeneration system of producing methanol and electricity, in which the proposed system took solar and biomass energy as co-feeds. Wu and Wang [3] summarized the different combined cooling, heating and power (CCHP) technologies, typical systems and the developments. Han et al. [4] presented the current application and prospects of distributed energy system (DES) in China and the comparison with other countries. In 2016, the world total primary energy consumption was 13267.3 Mtoe - 1% more than in 2015, and the average growth in the past ten years is 1.8% [5]. The primary energy consumption by fossil fuels, such as coal, oil and natural gas, accounts for about 85%. Accordingly, the carbon dioxide emissions increases, the total world $CO_2$ emissions from energy consumption have reached at 33432.0 Mt of $CO_2$, and the average growth in the past ten years is 1.6%. The $CO_2$ emissions derived from fossil fuels are in the majority [6]. With the increasing of energy demand and the stringent emission rules, combined heating and power system (CHP) based on renewable resource has gradually become the alternative option for energy utilizations and widely investigated.

In 2015, about 13.4% of world total primary energy supply is generated from renewable energy resources, which have increased at an average annual rate of 2.0% [7]. In all the renewable energy resources, the biogases and geothermal energy grow at the average annual rate of 12.6% and 3.1% respectively, which are higher than the average rate of renewable resource, 2.0% [7]. For the biomass and geothermal energy based integration system, some researchers have studied from different aspects. Østergaard et al. [8] analyzed the possibility of 100% renewable energy scheme for Aalborg Municipality, in which the renewable energy resources consists of three parts: the low-temperature geothermal heat, wind power and biomass. Moret et al. [9] presented a multi-period Mixed-Integer Linear Programming (MILP) model to evaluate the potential for coupling deep geothermal energy with woody

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**Nomenclature**

*Abbreviation*

| | |
|---|---|
| BCHP | building cooling heating and power |
| CCHP | combined cooling, heating and power |
| CCR | carbon conversion ratio |
| CGE | cold gas efficiency |
| CHP | combined heating and power |
| COP | coefficient of performance |
| DES | distributed energy system |
| ER | equivalence ratio |
| GA | genetic algorithm |
| GCU | gas conditioning unit |
| GSHP | ground source heat pump |
| HP | heat pump |
| HPR | heat to power ratio |
| HX | heat exchanger |
| LCA | life cycle assessment |
| MILP | mixed-integer linear programming |
| MINLP | mixed-integer nonlinear programming |
| ORC | organic rankine cycle |
| PEMFC | polymer electrolyte membrane fuel cell |
| PGU | power generation unit |
| PI | performance indicator |
| PSO | particle swarm optimization |
| RC | rankine cycle |
| SP | separated production |

*Symbols*

| | |
|---|---|
| ATC | annual total cost ($) |
| ATCSR | annual total cost saving ratio (%) |
| C | cost ($) |
| CDE | carbon dioxide emission (g) |
| CO2ERR | carbon dioxide emission reduction ratio (%) |
| d | service life (y) |
| E | electricity (kW) |
| F | fuel (kW) |
| f | load fraction (%) |
| i | interest rate (%) |
| m | mass flow rate (kg/h) |
| N | install capacity (kW) |
| PESR | primary energy saving ratio (%) |
| Q | heat (kW) |
| R | capital recovery factor |
| t | temperature (°C) |
| $\mu$ | conversion factor (g/kWh) |
| $\omega$ | weight coefficient |
| $\eta$ | efficiency (%) |

*Subscripts*

| | |
|---|---|
| ae | auxiliary electricity |
| b | boiler |
| cb | char boiler |
| e | electricity |
| g | gasification |
| grid | electricity grid |
| h | heat |
| he | heating exchanger |
| m | day |
| n | hour |
| r | rated condition |
| rec | recovery heat |
| w | warm water |

biomass in an urban energy system. The above researches mainly analyze the conceptual system combined with geothermal and biomass energy, while some specified integrated systems based on these two renewable energy resources are also investigated. Seethamraju et al. [10] studied and compared the different forms of existing geothermal power plant integrating with biomass combustor, the combustion heat was used to further superheat the geothermal steam so as to improve the geothermal power output. Thain and Dipippo [11] also proposed a hybrid biomass-geothermal power plant, and compared the thermodynamic performances of different configurations. Besides that, Malik et al. [12] investigated a multi-generation system based on biomass and geothermal energy, which is made up of seven parts: a biomass combustion cycle, an organic Rankine cycle, an absorption chiller cycle, a Linde Hampson liquefaction cycle, a geothermal power plant, a water heating system and a dryer. The proposed system generates power, hot water, cooling, liquefied gas and heated drying air, which provides a novel way for integrated system. In general, the above studies focus on the biomass combustion and geothermal energy based integrated system, while the integration system combined with biomass gasification and geothermal energy is relatively fewer. According to the principle of energy cascade utilization, a new CHP system combined with biomass partial gasification and ground source heat pump was proposed by authors in previous study [13]. Moreover, the authors investigated the thermodynamic and exergoeconomic performances of the proposed system [14]. In the proposed system, the biomass is partially gasified compared with the conventional complete gasification, which generates two different products: bio-gas and char. These products are sent into the Brayton gas turbine cycle and Rankine steam turbine cycle for electricity generation, respectively. At the same time, the ground source heat pump (GSHP) is adopted to utilize the geothermal energy, the superiority of the novel utilization of geothermal energy has been carried out in previous studies [15]. The temperature of hot water rises through two steps: The cold water is firstly preheated to an intermediate temperature in the condenser of GSHP, and then reheated to the requirement temperature in heat exchanger of CHP subsystem [16]. These measures decrease the outlet temperature of condenser of GSHP, so as to reduce the compression ratio and improve coefficient of performance (COP) of GSHP accordingly. In the proposed biomass partial gasification and ground source heat pump based CHP system, the hot water is reheated by the exhaust gas derived from Brayton gas turbine cycle.

Optimization of design and operation is one of the critical factors to improve the performance of integrated system [17]. There are various mathematical optimization techniques to settle the optimization problems, and the typical techniques are linear programming and nonlinear programming. Cho et al. [18] used a linear programming to develop an optimal energy dispatch algorithm, so as to decrease the energy cost on the constraint of energy efficiency of each equipment. Somma et al. [19] adopted a multi-objective linear programming method to obtain the optimal operation in terms of energy cost and exergy efficiency. Li et al. [20] conducted a sensitivity analysis of three different energy demands (average, uncertainty and peaks) on performance of CCHP system, in which the mix-integer nonlinear programming (MINLP) model was presented. Savola and Fogelholm [21] carried out a novel mix-integer nonlinear programming (MINLP) for the electricity generation optimization of a biomass based CHP, and the developed MINLP model contributed to improve the electrical efficiencies and power-to-heat ratios of four existing CHP plants. In addition to the above mentioned techniques, there are some other optimization methods. Ji et al. [22] applied a two-stage stochastic robust