Journal of Cleaner Production 186 (2018) 68–80

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Multi-criteria analysis of a self-consumption strategy for building sectors focused on ground source heat pump systems

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ARTICLE INFO

Article history:
Received 23 November 2017
Received in revised form
8 March 2018
Accepted 12 March 2018
Available online 13 March 2018

Keywords:
Ground source heat pump system
Self-consumption
Life cycle energy
Life cycle cost
Life cycle assessment

ABSTRACT

This study aims to conduct the multi-criteria analysis of a self-consumption strategy for building sectors focused on ground source heat pump (GSHP) systems that simultaneously considers the energy generation, economic, and environmental effects of the system in the planning and design phases. In this study, an education facility, a sports facility, and a residential facility are selected as the target facilities. The GSHP system is analyzed at all the target facilities considering the self-consumption of 0–100%, with 25% intervals. The results of this study are as follows. The energy generation rate is increased with increasing self-consumptions in all the target facilities. In terms of the economic effects, the higher self-consumption is, the higher net present value is in all target facilities. However, the savings-to-investment ratio differs by building types due to the energy policy (i.e., the education facility: from 2.68 to 2.39. and the sports facility: from 2.33 to 1.95), however, SIR increased in a residential facility (i.e., the education facility: from 2.65 to 3.32). In terms of the environmental effects, the abiotic depletion, global warming, acidification, and eutrophication potentials decrease in all the target facilities, but the ozone layer depletion potential increases. The proposed model may be useful for decision makers (i.e., architects, owners, construction managers, etc.) or policymakers to determine the percentage of self-consumption when introducing the GSHP system to buildings.

1. Introduction

There has been a growing interest worldwide in the reduction of the total energy and fossil fuel consumption (Koo et al., 2014; UNFCCC, 2015). To solve the foregoing, it is necessary to implement a clean-energy system in buildings instead of the conventional energy system. As such, new/renewable energy (NRE) is currently being used in buildings as a clean-energy system (Dincer and Acar, 2015; Hamdy et al., 2013; Kharseh et al., 2015). In particular, among the several NRE systems, the ground source heat pump (GSHP) system is energy-efficient considering its air pollutant reduction ability and energy efficiency as the cost in terms of life cycle is compared to the wind system, solar system and biomass system (Self et al., 2013). However, the conventional systems often perform much better because of low-ground heat exchanger (GHE) or waste heat (Bayer et al., 2012; Dincer and Acar, 2015). The GSHP system provides heating and cooling energy to buildings with a high-energy-efficiency system that utilizes the temperature difference of the ground heat (Bayer et al., 2012; Dincer and Acar, 2015; Esen and Inalli, 2009; Hanova and Dowlatabadi, 2007; Huang and Mauerhofer, 2016). The GSHP system has used much earlier in the U.S. and Europe, and many other countries that are interested in introducing such system to their buildings aim to raise such system's self-consumption in their buildings. The term of "self-consumption" is the proportion of renewable energy (i.e., GSHP system and photovoltaic system) that meet the building energy load instead of the conventional heating and cooling system (Allaerts et al., 2015; Franco and Fantozzi, 2016; Thygesen, 2016; Thygesen and Karlsson, 2014). The GSHP system supplies 174,347 kW

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https://doi.org/10.1016/j.jclepro.2018.03.121
0959-6526/

applied to all the building sectors (i.e., public institution facility, education facility, residential facility, commercial facility, social welfare facility, and others) in South Korea. In particular, South Korea aims to raise the GSHP system's self-consumption by 20–30% yearly (KOSIS, 2017; Renewables, 2015). The GSHP system's self-consumption is increasing at an average annual rate of 18.0%. Such system is more expensive than the other NRE systems, however, due to the initial investment cost (IIC) and operation and maintenance cost (Dincer and Acar, 2015; Kim et al., 2015c).

The GSHP system is categorized into two types (Kim et al., 2016a; Korea Energy Agency, 2017): (i) the open-type system, which directly obtains heating and cooling energy using ground and surface water; and (ii) the closed-type system, which obtains heating and cooling energy through the circulating water that passes a ground heat exchanger (Kim et al., 2016a). The closed-type system is further classified into vertical- and horizontal-borehole-type ground heat exchangers (Korea Energy Agency, 2017). The vertical-borehole-type ground heat exchanger is applied in this study because it is widely used owing to its high heat exchange rate (Huang and Mauerhofer, 2016; Kim et al., 2016a). Its IIC is very high and has a significant environmental impact in the construction, operation, and maintenance phases due to the accompanying borehole drilling cost (Saner et al., 2010). Therefore, it is necessary to develop a decision support tool that simultaneously considers the energy generation, economic, and environmental effects of the GSHP system in the planning and design phases.

Several previous studies investigated the optimal GSHP system. In terms of the energy generation rate, the GSHP system is examined considering various parameters. In terms of the economic effects, the GSHP system is analyzed to reduce the construction and maintenance costs. Lastly, in terms of the economic and environmental effects, the system is analyzed from the life cycle perspective (Table S1 in supplementary data).

First, some previous studies analyze the GSHP system in terms of its energy generation rate (Table S1 in supplementary data). Esen and Inalli (2010), Cosentinoa et al. (2015), and Yekoladio et al. (2015) optimize the GSHP system to predict the energy generation rate of the GSHP system. Esen and Inalli (2010) predict the heating and cooling energy generation rate of the vertical-borehole-type ground heat exchanger using both the artificial neural network and the adaptive neuro-fuzzy inference system, and suggest a model that can predict the GSHP system performance by almost 100%. Michopoulos et al. (2007), Montagud et al. (2011), Ozgener and Hepbasli (2005), and Ozgener et al. (2005) conduct an experiment to analyze the energy of the GSHP system. Ozgener et al. (2005) analyze the overall energy and exergy efficiencies of the geothermal district heating system to evaluate their individual performances, and the geothermal district heating system are determined to be 55.5 and 59.4%, respectively.

Second, there are previous studies that analyze the GSHP system in terms of its economic effects (Table S1 in supplementary data). To analyze the economic effect, Alavy et al. (2013), Arslan (2011), and Retkowski and Thöming (2014) conduct a computerized approach. The IIC and operation cost of the GSHP system are affected by the heat pump and IIC and operation cost are related to each other. Kharseh et al. (2015), Blackler and Iqbal (2006), and Bakirci et al. (2011) conduct optimization. Based on the results, the heat pump and thermodynamic are considered as design variables in order to optimize the GSHP system. When the GSHP system is used, the payback period is estimated to be from 3 years to 7 years.

Third, previous studies analyze the GSHP system in terms of the economic and environmental effects (Table S1 in supplementary data). Kim et al. (2015a,b) analyze five GSHP system scenarios considering the entering water temperature, and conduct a sensitivity analysis of the impact factors (i.e., borehole length, ground thermal conductivity, borehole spacing, borehole diameter, U-tube diameter, and U-tube position) in terms of both energy generation and environmental impact. The borehole length is determined to be the most influential impact factor. Gokcol and Dursun (2013) select the minimum self-consumptions (i.e., 0, 20, 40, 60, 80, 90, and 100%) for calculating the optimal NRE systems in terms of the economic and environmental effects, and suggest the optimal NRE systems by the minimum self-consumption.

As mentioned above, several studies, analyze the GSHP system from various points of view that can be summarized as follows: (i) in terms of the energy generation, few studies analyze the GSHP system considering the self-consumptions; (ii) in terms of the economic effects, few studies analyze the GSHP system considering the building energy policy (i.e., electricity cost), which is variable depending on the building type; and (iii) in terms of the economic and environmental effects, there are few studies that simultaneously consider both the economic feasibility from the life cycle perspective and the environmental impacts.

This study aims to conduct the multi-criteria analysis of a self-consumption strategy for building sectors focused on GSHP systems. In this study, three types of facilities (i.e., education facility, sports facility, and residential facility) are selected as the target facilities by considering their building energy consumption and electricity pricing. To select the optimal GSHP system based on the previous studies, this study considers three objectives such as energy generation, economic effect and environmental effect. This study is conducted in three steps. (Fig. 1): (i) step 1: database establishment; (ii) step 2: generation of GSHP system scenarios; and (iii) step 3: comparative analysis of the GSHP system considering the self-consumptions.

2. Materials and methods

2.1. Step 1: database establishment

2.1.1. Key parameters of the GSHP system

This study establishes the database required for determining the optimal GSHP system by the self-consumption. Information on the GSHP system's parameters from the literature review can be categorized into (i) regional factors and (ii) physical information of the GSHP system (Table S1 in supplementary data).

First, the regional factors include the rock type (CAK, 2017), ground temperature (°C) (Bakirci et al., 2011; Esen et al., 2017) ground thermal conductivity (W/m·K) (Alavy et al., 2013; Balbay and Esen, 2013; Esen et al., 2006; Kim et al., 2015c; Nguyen et al., 2016), and ground heat capacity (kJ/K·m^3) (CAK, 2017). The regional factors affect the drilling cost and energy generation rate of the GSHP system.

Second, the components of the GSHP system generally include the heat pump and the ground heat exchanger, which represent the physical information of the GSHP system in this study (Bakirci et al., 2011; Huang and Mauerhofer, 2016; Kim et al., 2015c). They determine the heating and cooling energy generation of the GSHP system, as well as the IIC and the operation and maintenance cost. The physical information of the heat pump and the ground heat exchanger is as follows:

- Heat pump: The energy generation of the GSHP system is determined by the heat pump's coefficient of performance (COP) (Alavy et al., 2013; Bakirci et al., 2011; Blackler and Iqbal, 2006; Esen et al., 2007; Esen et al., 2008; Esen and Yuksel, 2013; Huang and Mauerhofer, 2016; Islam et al., 2016; Michopoulos et al., 2007; Nguyen et al., 2016; Retkowski and Thöming, 2014). The COP is an efficient index of the heat pump,