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Sensitivity Analysis on the Impact Factors of the GSHP System Considering Energy Generation and Environmental Impact Using LCA

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Abstract: The world is facing a crisis due to energy depletion and environmental pollution. The ground source heat pump (GSHP) system, the most efficient new/renewable energy (NRE) system that can reduce the load of heating/cooling equipment in a building, can be used to address this crisis. Designers and contractors have implemented such systems depending on their experience, although there are many factors that affect the performance of the GSHP system. Therefore, this study aimed to conduct a sensitivity analysis on the impact factors in terms of energy generation and environmental impact. This study was conducted as follows: (i) collecting the impact factors that affect the GSHP system's performance; (ii) establishing the GSHP system's scenarios with the impact factors; (iii) determining the methodology and calculation tool to be used for conducting sensitivity analysis; and (iv) conducting sensitivity analysis on the impact factors of the GSHP system in terms of energy generation and environmental impact using life cycle assessment. The results of this study can be used: (i) to establish the optimal design strategy for different application fields and different seasons; and (ii) to conduct a feasibility study on energy generation and environmental impact at the level of the life cycle.

Keywords: ground source heat pump system; sensitivity analysis; energy generation; environmental impact; building

1. Introduction

Today, the world is facing a crisis caused by energy depletion and environmental pollution. The world's energy consumption is expected to be three-fold higher than its present level by 2035, with 60% of the energy to be consumed by developing countries, like China, India and Middle East countries, with the current rapid increase in global energy consumption. Alongside this rapid increase in global energy consumption is a dearth of fossil fuels. The reserves to production ratios are 52.5 years for oil, 54.1 years for natural gas and 110 years for coal, as calculated by British Petroleum in 2015 [1]. This suggests that the world's fossil fuel reserves can be depleted [2,3]. In response to this, the world's major developed countries organized the United Nations Framework Convention on Climate Change based on the recognition of the need for greenhouse gas (GHG) reduction and energy savings. In the Conference of Parties 21 held on 12 December 2015, the "Parties' Agreement" was adopted to replace the existing Kyoto Protocol, which is to expire in 2020. Consequently, various countries around the world established a national carbon emission reduction target (CERT) (*i.e.*, 20% by 2020 compared to the 1990 level in the EU, 34% by 2020 compared to the 1990 level in the U.K., 17% by 2020 compared to the 2005 level in the U.S., and 15% by 2020 compared to the 2005 level in Japan) and have established policies to achieve their respective targets. To keep pace with such a global trend, the South Korean government established a plan to reduce the country's GHG emissions by 37% (850.6 million tons CO_2-eq) by 2030 compared to the current estimates [4–12].

Along with the efforts to overcome the crisis due to the depletion of energy resources and to achieve the goal of reducing the GHG emissions, there has been a surge of interest globally in new/renewable energy (NRE) [13–18]. NRE accounted for 18% of the global electricity generation based on the level in 2009, and the energy-generating facilities constituted 25% (1230 GW of 4800 GW). According to the "NRE Medium-Term Market Report" released by International Energy Agency (IEA), the power generation from NRE is expected to increase by 40% compared to the 2011 level. This is a high growth rate, exceeding the growth rate from 2006 to 2011, and two-thirds of the new power plants are expected to be owned and operated by non-OECD countries. As the NRE-related technologies are entering a virtuous cycle of cost reduction owing to global competition, it is now possible to transfer these technologies to developing countries [19–23].

Meanwhile, the U.S. and EU have put more emphasis on NRE-related power stations than on fossil energy-related power stations since 2008. According to a report released by the United Nations Environment Program, NRE has already accounted for more than 50% of the power generation in the U.S. and Europe [24–28]. In other words, IEA forecasted that the NRE production will be double the present amount in 2035. That is, the proportion of electricity production through NRE is expected to increase by 33%, similar to the power generation from fossil fuels, by 2035 [29,30].

The South Korean government has proceeded with a number of projects for the revitalization and institutional stabilization of NRE dissemination in South Korea in line with the global trend. The basic direction of the projects is to expand the NRE market and to thus induce private investment. It also established the New and Renewable Energy Centre under the control of the Korea Energy Management Corporation (KEMCO) and implemented a system of investment incentives, such as the provision of financial support for NTE businesses, the "1 Million Green Homes Project" and feed-in-tariff. In addition, it promoted a mandatory system of public institutions and a renewable portfolio agreement to enhance the leading role of the public sector in NRE promotion. Furthermore, it built a foundation for the support of research and industrialization, such as the establishment of Core Technology Development Center to improve technologies and enhance product qualities and designated specialized colleges by area to foster skilled manpower systematically [31–36].

The ground source heat pump (GSHP) system can reduce the load of heating/cooling equipment in a building most efficiently and is regarded as a system that ensures reasonable operation and maintenance costs of the NRE systems [37,38]. Despite these advantages, however, the GSHP system also has a disadvantage: it involves excessive initial investment costs. Therefore, it is very important to accurately predict the energy load reduction of the target facility through the introduction of the GSHP system prior to the introduction of the said system and, thus, to evaluate the return on investment.

However, the reduction of the load of heating/cooling equipment effects varies depending on: (i) the regional factors (*i.e.*, ground heat capacity, ground temperature, ground thermal conductivity); (ii) the system factor; and (iii) the design factors (*i.e.*, borehole length, number of boreholes) in the case of load reduction by the GSHP system. There is no accurate analysis of the design variables and prediction performance, and in most cases, the analysis depends on the experience of the GSHP system design and construction companies in the existing GSHP system introduction process. It is considered that this trend exists until today, as the introduction rate of the system is relatively low, but as the rate of mandatory NRE introduction increases, an accurate analysis of the alternatives by key impact factor will be more important.

In the previous relevant studies, the factors affecting the GSHP system performance were analyzed in terms of: (i) energy generation; (ii) economic effect; and (iii) environmental impact [39–46]. Fujii *et al.* (2012) conducted a study for the optimization model of the slinky-coil horizontal ground heat exchanger (GHE) to be applied in the U.S. and Canada. They measured the average supply temperature by fraction to be applied to the burial depth of the GHE and the GSHP system and conducted a sensitivity analysis in terms of energy generation by measuring the seasonal heat exchange rate according to the soil type and supply direction of the fluid within the GHE [39]. Casasso *et al.* (2014) selected the impact factors that affect the GHE performance and conducted sensitivity analysis. The GHE length selection was found to be the most important factor in terms of the economic effect, and the U-pipe spacing and grout materials turned out to have an effect on the entire system's performance [40]. Kim *et al.* (2015) performed an economic and environmental assessment for the optimization design of GHE. They conducted an analysis in terms of life cycle cost and LCA by creating a total of five scenarios according to the entering water temperature (EWT). In terms of the environmental impact, the best result was obtained at 25 °C, and in terms of the economic effect, it was achieved at 30 °C [41]. Cosentino *et al.* (2015) analyzed the variables of the thermal energy storage system of boreholes and presented the optimal heat charging system considering a variety of design conditions. In the study, the analysis period was assumed to be 10 and 20 years, and in the case of 10 years, the case in which the borehole length was set to 125 m and the interval to 7 m showed a 76% better result in terms of energy efficiency than the case where the interval was set to 3 m. In the case of 20 years, when the borehole length was set to 125 m and the interval to 7 m, the energy efficiency was further enhanced by 81.4% compared to the case where the interval was set to 3 m [42]. Hepbasli (2002) evaluated the operating performance of the heating/cooling system on the target facility, in which the GSHP system was installed, to analyze the economic effect of the actual system. Compared to the conventional heating/cooling system, the GSHP system was disadvantageous in terms of the initial investment cost, but it was found to be more economical than the conventional system in terms of energy consumption [43]. Boyaghchi *et al.* (2015) constructed a new combined cooling heating and power (CCHP) system and analyzed its heating/cooling performance using the GSHP and solar photovoltaic systems through optimization. It was found through the analysis that the performance of the system varies greatly depending on the type of refrigerant used inside the CCHP system [44]. Essen and Inalli (2009) predicted the energy performance through artificial neural networks by utilizing the experiment data on the heating/cooling performance of the GSHP system [45]. Alavy *et al.* (2013) analyzed the heating/cooling energy savings according to the applicable percentage of the GSHP system with ten target facilities. The analysis of the initial investment cost, payback period and operating costs revealed that the GSHP system is highly economical, as it assumes more than 80% of the entire load of heating/cooling equipment on average [46].

As mentioned earlier, various studies have been conducted on several variables that affect the GSHP system performance, but no research has been done that comprehensively considers energy generation and environmental impact in the sensitivity analysis. In addition, the study on the environmental impact analysis was limited to evaluating the CO_2 emission reduction due to the change in performance that occurs when the GSHP system is installed. Sensitivity analysis is the study of how the uncertainty in the output of a system can be apportioned to different sources of uncertainty in its inputs [47–49]. Therefore, this study aimed to conduct sensitivity analysis on the impact factors of the GSHP system in terms of energy generation and environmental impact. This study was conducted as follows: (i) collecting the impact factors affecting the GSHP system's performance; (ii) establishing the GSHP system's scenarios with the impact factors; (iii) determining the methodology and calculation tool to be used for conducting sensitivity analysis; and (iv) conducting sensitivity analysis on the impact factors in terms of energy generation and environmental impact using LCA (refer to Figure 1). The results of this study can be used in future research (*i.e.*, development of an analysis model for the GSHP system) as the impact factors to be intensively considered for the efficient design and analysis of the GSHP system.

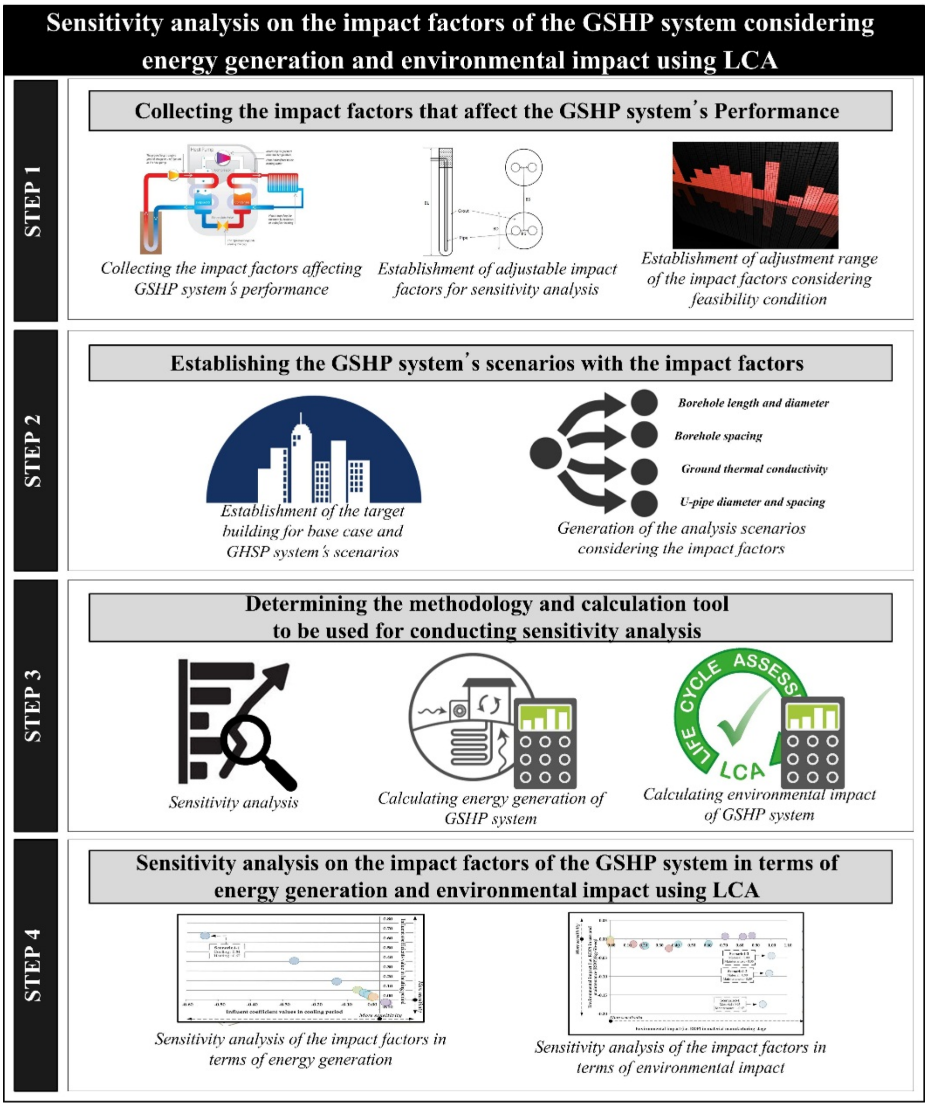

Figure 1. Framework of the sensitivity analysis on the impact factors of the GSHP system considering energy generation and environmental impact.

2. Materials and Methods

2.1. Collecting the Impact Factors Affecting the GSHP System's Performance

The GSHP system is a highly efficient NRE system that uses the ground heat energy through the GHE connected to the ground to reduce the load of heating/cooling equipment in a building and provides heat through a heat pump. In this study, the adjustable impact factors to be considered in the design of the GSHP system were divided as follows: (i) regional factors; (ii) system factors; and (iii) design factors (refer to Table 1) [41]. In addition to the above factors, operation factors and other factors (e.g., control type, schedule of operation and setting of EWT) exist, and those could critically affect the energy generation and environmental impact of the GSHP system [50]. In this study, however, the impact factors affecting the GSHP system independently are selected. Of the aforementioned factors, control type and schedule of operation are influenced by the combination of the other factors and an operating environment according to the type of buildings. Because those are impact factors of a different level, other methods are required to analyze them. Therefore, the study of aforementioned factors should be conducted in future research.

Table 1. Overview of the impact factors.

Classification	Impact Factor (Unit)
Regional factors	Ground temperature (°C), soil type, ground thermal conductivity (W/m· K), ground heat capacity (kJ/K· m^3) [51–54]
System factors	Capacity (kW), power input (kW), heat of rejection (kW), heat of extraction (kW), coefficient of performance, energy efficiency rating [55–57]
Design factors	Borehole length (m), borehole spacing (m), borehole diameter (mm), U-pipe position (mm), number of boreholes, arrangement, grout conductivity (W/m· K), borehole thermal resistance (K/(W/m)), U-pipe type, U-pipe diameter, fluid type, flow rate (L/s), EWT (°C) [58–67]

First, the regional factors were classified as non-adjustable impact factors because they are external factors that affect the performance of the GSHP system in a given environment (*i.e.*, ground temperature, soil type, ground thermal conductivity and ground heat capacity). Second, the system factors were classified as non-adjustable impact factors because the capacity is determined by the heading/cooling load of a building, and the manufacturer's technical capability determines the cost and coefficient of performance. Third, the design factors were classified as impact factors that can adjust the detailed parameters in the design. Among the design factors, however, borehole thermal resistance was classified as a non-adjustable factor, as it appears in the form of a combination of the borehole diameter, borehole thermal conductivity, U-pipe diameter and U-pipe position. The EWT was also classified as a non-adjustable factor, as it is a result value obtained by the combination of all of the design factors. Meanwhile, the fluid type was excluded as it has an insignificant effect on the energy generation and environmental impact of GHE [41]. The borehole arrangement was also excluded because it is limited to the installation site area and site type, and the flow rate was excluded, as it is determined by the total installation capacity of the GSHP system. Accordingly, the adjustable maximum/minimum range of the detailed parameters was calculated with the rest of the impact factors, except for the above-mentioned factors (refer to Table 2).

Table 2. Adjustable range of impact factors.

Impact Factors	Unit	Range			
Borehole Length	m	50	100	150	200
Grout Thermal Conductivity	W/m· K	0.875	0.99	1.2116	1.6
Borehole Spacing	m	4	5	6	7
Borehole Diameter	mm	125	150	175	200
U-pipe Diameter	mm	25	32	40	50
U-pipe Position	-	A	AS	B	C

- Category 1 (borehole length): The borehole length represents the installed capacity of GHE. In this study, the installation range was set to 50 to 200 m. The GSHP system uses geothermal energy and shows a tendency for an up to a 50 m change in the temperature of the ground surface due to the solar radiation to occur, but an increase in temperature due to the ground heat occurs linearly from less than 50 m. The maximum design length of the GHE of the vertical closed loop is limited to 200 m, and the GHE length design programs used globally, such as "Ground loop design (GLD)" and "professional ground loop heat exchanger design (GLHEPro)", show that the design of less than 200 m represents a reliable result [68].
- Category 2 (grout thermal conductivity): This represents the degree of heat transfer of GHE. As the higher the thermal conductivity is, the lower the borehole resistance, the efficiency of GHE increases. The degree of grout thermal conductivity varies depending on the mixing ratio of bentonite, silica sand and water. Table A1 shows the grout thermal conductivity according to the silica sand ratio at 20% bentonite.

- Category 3 (borehole spacing): As the heat capacity varies depending on the soil type, the optimal distance where the performance of GHE does not decrease due to the crossing of the range of the ground heat that each borehole releases and absorbs is required. In the existing study results and construction field, it was designed to be more than 4 m, and if it is less than 4 m, the severe heat interference that occurs between the boreholes (the ground temperature rises due to the heat generated from GHE in the ground) will have an adverse effect on the performance of the GSHP system. In addition, it is impossible to perform construction in a very wide range due to the restrictions on the area. Therefore, in this study, the maximum borehole spacing was limited to 7 m after an interview with experts and based on the existing records on the installation [69].
- Category 4 (borehole diameter): It is designed considering the volume of the grout that fills the borehole and U-pipe through which the fluid flows. As the higher the thickness is, the higher the borehole thermal resistance and the lower the performance and, if it is too thick, the borehole or internal components that protect the grout can be damaged, it should be designed to have an appropriate thickness. The borehole diameter can be adjusted according to the technical skills applied in the construction, and as the wider the borehole diameter is, the higher the material costs, the higher the resistance of the borehole, the lower the thermal conductivity and, therefore, the lower the efficiency. The minimum borehole diameter size is normally determined by the diameter of the U-pipe, and the maximum borehole diameter is calculated to ensure that the U-pipe is safely embedded and that proper heat exchange is done. In this study, as the maximum size of the U-pipe diameter is 50 mm, the minimum size of the borehole diameter was calculated to be 125 mm in order to exceed the sum of the two sides of the U-tube diameter. The maximum range was limited to 200 mm based on the standards of the GHSP association in the U.K., the International Ground Source Heat Pump Association (IGSHPA) [70,71].
- Category 5 (U-pipe diameter): There is a need for a combination that satisfies the heat load considering the low velocity of the fluid that flows inside the pipe and the subsequent heat transfer. Strength and durability exceeding a certain level are required for the part with which the fluid has direct contact. The U-pipe diameter is determined based on the standard predetermined at the time of construction. The currently-used U-pipe diameters are 25 mm, 32 mm, 40 mm and 50 mm, and 32 mm is mainly used.
- Category 6 (U-pipe position): This refers to the interval at which the U-pipe is installed, and the proper interval is needed to achieve sufficient heat exchange. Figure 2 shows the U-pipe position that can be introduced, and it is normally designed as the B type.

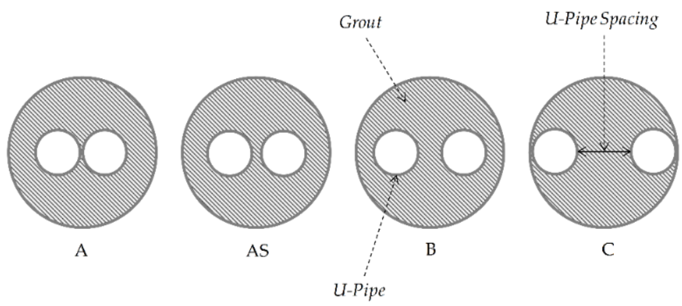

Figure 2. U-pipe installation position.

2.2. Establishing the GSHP System's Scenario Considering the Range of Impact Factors

2.2.1. Establishment of the Target Building for the Base Case and the Analysis Scenarios

In this study, the target building was selected to fix the regional and system factors, in addition to the adjustable impact factors. The target building was selected based on the following criteria:

- Among the buildings that require the introduction of the NRE system, a building that facilitates the construction of the GSHP system was selected. According to the 2013 statistics of the Korea Energy Agency, energy-intensive buildings, which use energy of more than 2000 TOE (tons of oil equivalent) per building annually, consumed a total of 2,307,000 TOE and emitted a total of 10,083,000 t CO_2 in 2012. Among various types of buildings, universities consumed a total of 336,000 TOE and emitted a total of 1,397,000 t CO_2, which accounts for about 15% of the energy consumed in the entire building sector [72]. In addition, in most cases, the newly-constructed buildings within a university have adopted the NRE system, and especially, the GSHP system has actively been introduced [73].
- In this study, the GSHP system was analyzed, with a focus on the vertical closed-loop type among the several existing GSHP system types. This is because the vertical closed-loop type can yield more accurate simulation results compared to the other types, and the vertical closed-loop type accounts for more than 60% of all of the types used, especially in South Korea [74–77]. Therefore, a building in which the vertical-closed-loop-type GSHP system is installed was selected as the target building in this study.
- For sensitivity analysis, a building where the daily use of the GSHP system is nearly constant, *i.e.*, a residential building in which the daily electricity consumption does not change significantly, was selected as the target building [78].

Finally, a dormitory building in a university in Seoul where the GSHP system had been installed was selected for the sensitivity analysis. The regional factors, like the underground environment and the building heating/cooling load, were defined, and the specifications of the heat pump system were also defined. Meanwhile, the specifications of the existing GSHP system were set as a base case for the sensitivity analysis with respect to the target building in which the GSHP system had been installed. The lot area of the target building is 26,298 m^2, and the gross area is 6612 m^2. The heating and cooling loads are 283.1 and 349.2 kW, respectively, and the installation capacities of the existing GSHP system are 352.206 kW (heating) and 364.42 kW (cooling), respectively (refer to Tables 3 and 4). The GSHP system's scenarios were established with GSHP system's base case and the range of impact factors (refer to Table 5).

Table 3. Overview of the target building.

Category	University Facility
Year established	2014
Location	Seoul
Building type	Residential facility
Electricity system	On-grid
Heating system	Individual heating
Progressive tax	No
Gross floor area	6612 m^2
Major energy service	GSHP system
Installation of capacity	Heating: 352.2 kW/cooling: 364.4 kW
Borehole	Length: 150 m/ Number of borehole: 40

Table 4. Overview of the GSHP system's base case.

Classification	Borehole Length (m)	Grout Thermal Conductivity (W/m· K)	Borehole Spacing (m)	Borehole Diameter (mm)	U-Pipe Diameter (mm)	U-Pipe Spacing (mm)
Base case	150	0.99	5	150	32	B

Table 5. The GSHP system's scenarios with the impact factors.

Classification		Borehole Length (m)	Grout Thermal Conductivity (W/m· K)	Borehole Spacing (m)	Borehole Diameter (mm)	U-Pipe Diameter (mm)	U-Pipe Spacing (mm)
Category 1 Borehole Length (m)	Scenario 1-1	50	0.99	5	150	32	B = 28.67
	Scenario 1-2	100	0.99	5	150	32	B = 28.67
	Scenario 1-3	150	0.99	5	150	32	B = 28.67
	Scenario 1-4	200	0.99	5	150	32	B = 28.67
Category 2 Grout Thermal Conductivity (W/m· K)	Scenario 2-1	150	0.875	5	150	32	B = 28.67
	Scenario 2-2	150	0.99	5	150	32	B = 28.67
	Scenario 2-3	150	1.2116	5	150	32	B = 28.67
	Scenario 2-4	150	1.6	5	150	32	B = 28.67
Category 3 Borehole spacing (m))	Scenario 3-1	150	0.99	4	150	32	B = 28.67
	Scenario 3-2	150	0.99	5	150	32	B = 28.67
	Scenario 3-3	150	0.99	6	150	32	B = 28.67
	Scenario 3-4	150	0.99	7	150	32	B = 28.67
Category 4 Borehole diameter (mm)	Scenario 4-1	150	0.99	5	125	32	B = 28.67
	Scenario 4-2	150	0.99	5	150	32	B = 28.67
	Scenario 4-3	150	0.99	5	175	32	B = 28.67
	Scenario 4-4	150	0.99	5	200	32	B = 28.67
Category 5 U-Pipe Diameter (mm)	Scenario 5-1	150	0.99	5	150	25	B = 28.67
	Scenario 5-2	150	0.99	5	150	32	B = 28.67
	Scenario 5-3	150	0.99	5	150	40	B = 28.67
	Scenario 5-4	150	0.99	5	150	50	B = 28.67
Category 6 U-Pipe spacing (mm)	Scenario 6-1	150	0.99	5	150	32	A = 0
	Scenario 6-2	150	0.99	5	150	32	AS = 3.17
	Scenario 6-3	150	0.99	5	150	32	B = 28.67
	Scenario 6-4	150	0.99	5	150	32	C = 86

Scenarios 1-3, 2-2, 3-2, 5-2, 6-3 stand for the base case; scenarios were established by considering the range of impact factors.

2.2.2. Validation of the Designed Model

This was analyzed via CV(RMSE) to verify the validity of the model [79]. The CV(RMES) was calculated by Equation (1):

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{n} (MEC_i - SEC_i)^2 \times \frac{1}{n}}}{\sum_{i=1}^{n} MEC_i \times \frac{1}{n}} \times 100 \quad (1)$$

where MEC is the measured energy consumption (kWh); SEC is the simulation-based energy consumption (kWh) during 40 years; and n is the number of compared data (months).

The actual energy consumption data of the building do not exist, because the service life of the building is less than one year. Therefore, in this study, the actual heating/cooling load of the building and the COP data of GSHP that was installed in the building were used to predict the energy consumption data of the actual building. The validation was conducted as the following steps: (i) estimating the monthly actual load of the facility (refer to Table A2); (ii) using the coefficient of performance measured through the experiment with GSHP installed in the building; during the cooling period, the COP were measured as 6.46, 5.09 and 4.16, respectively, when the EWT was at 15, 25 and 32 °C; during the heating period, the COP were measured as 3.83, 4.2 and 4.63, respectively, when the EWT was at 5, 10 and 15 °C (refer to Figures A1 and A2); (iii) estimating monthly electricity consumption for 40 years through simulation (refer to Table A3); (iv) predicting the electricity consumption with the result of Steps (i) and (ii); and (v) comparing the value of predicting and comparing the predicted value with the simulation result (refer to Figure 3). The CV(RESE) value was measured as 8.39%; therefore, it was proven that the model for the GSHP system's scenario was feasible.

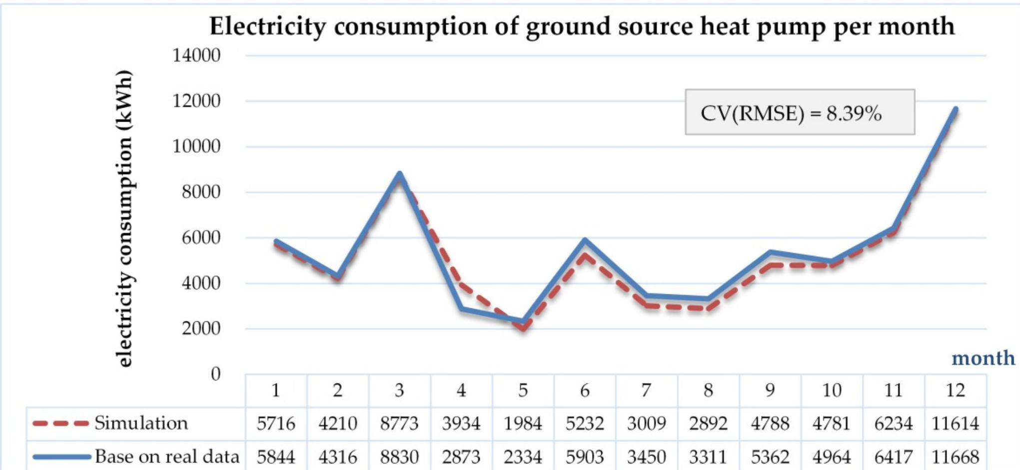

Figure 3. Comparing the electricity consumption of the ground source heat pump for CV(RMSE).

2.3. Sensitivity Analysis on the Energy Generation and Environmental Impact of the GSHP System

2.3.1. Sensitivity Analysis

The previous relevant studies defined sensitivity analysis as consisting of a quantitative comparison of the changes in the outputs to the changes in the inputs [80–83]. In this study, the regional and system factors of the GSHP system were fixed, and the design factors (e.g., borehole length, grout thermal conductivity, borehole spacing, borehole diameter, U-pipe diameter and U-pipe position) of the base case were configured as inputs (e.g., scenarios by category) according to the range to establish the GSHP system's scenarios (refer to Table 5). The sensitivity analysis on the environmental impact and energy generation of the GSHP system was performed by changing only one design factor. The sensitivity influence coefficient (IC) has been used in several studies as one of the most adequate forms of sensitivity coefficients in the assessment of sensitivity (refer to Equation (2)) [80–83].

$$IC = (\Delta OP/OP_{BC})/(\Delta IP/IP_{BC}) \tag{2}$$

where IC is the influence coefficient, $\triangle OP$ is the change in output resulting from a $\triangle IP$ change in input, OP_{BC} is the base case output value and IP_{BC} is the base case output value.

This approach resulted in a unit-less form of sensitivity coefficient, which was important for comparing parameters with different units (e.g., m for the borehole length, W/m· K for the grout thermal conductivity, m for the borehole spacing and mm for the borehole diameter). For example, an IC value of +0.2 for the borehole length means that a 1% increase in borehole length will lead to a 0.2% increase in the performance of the GSHP system. Meanwhile, a negative IC value of −0.2 for the borehole diameter means that a 1% increase in the borehole diameter will lead to a 0.2% decrease in the performance of the GSHP system.

2.3.2. Calculating the Energy Generation of the GSHP System

The process of calculating the energy generation of the GSHP system is presented herein for the sensitivity analysis on the impact factors of the GSHP system in terms of energy generation. The EWT generated from GHE and supplied to the heat pump was measured to calculate the heat efficiency of the GSHP system. EWT is an indicator of the final performance resulting from the combination of impact factors and serves as the heat pump inlet temperature from GHE that satisfies the energy demand of a facility. EWT exhibits higher efficiency when provided as a higher temperature during the heating season and as a lower temperature during the cooling season. Therefore, the load of the heat pump can be reduced, and thus, it is possible to reduce the electricity energy consumption of a building. In this study, "GLHEPro", the GHE simulation and design program, was used to calculate the EWT and analyze the scenarios [84,85]. "GLHEPro", which is used internationally, uses the combination of a variety of formulas and a database of the various materials of the GSHP system to design the borehole depth. In addition, through "GLHEPro", the energy generation of GHE and the annual/monthly energy consumption of the heat pump of a building can be analyzed. In this study, the energy consumption pattern, the result of the simulation, was established to come up with the GSHP system's analysis scenarios.

2.3.3. Calculating the Environmental Impact of the GSHP System

The LCA methodology is still under discussion and continues in the ISO meeting; the basic configuration is as Figure 4. In this study, LCA was used to analyze the environmental impact of the GSHP system, and the method of assessment consists of the following steps that the ISO 14040 defined [86–88].

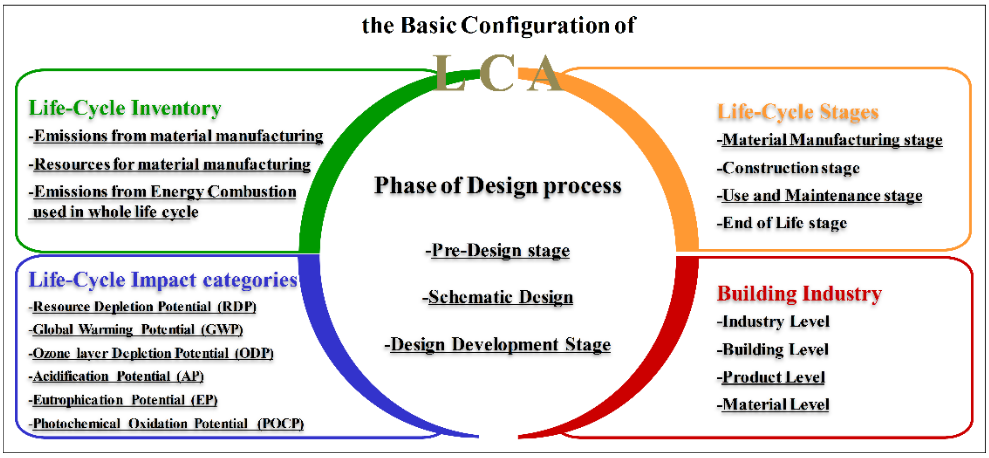

Figure 4. The basic configuration of LCA.

- Step 1. Practical unit and scope: The target and scope to conduct LCA should be clear. In this study, the GSHP system supplied from the material manufacturing and the use and maintenance phase for the whole life cycle is defined as the practical unit, and the relevant data for the whole life cycle is defined as the scope to conduct LCA.
- Step 2. Life cycle inventory (LCI) analysis: The environmental impact substances can be calculated by following LCI steps. First, the energy source amount used to manufacture the components of the GSHP system over the life cycle was calculated using input-output LCA. Second, the environmental impact substances produced in the contaminant and energy production process were measured using the process-based LCA method studied in former research with the domestic LCI database established in South Korea [87,88].
- Steps 3 and 4. Life cycle impact assessment (LCIA) and results: LCIA defines the environmental impacts using following phases: (i) classification; (ii) characterization; (iii) normalization; and (iv) weighting [86,87]. The characterization factor of each category is required for calculating the characterized impact. In this study, the scenarios of the GSHP system were analyzed in terms of environmental impact with the following categories (e.g., resource depletion potential (RDP), global warming potential (GWP), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP) and photochemical oxidation potential (POCP)). The characterized impacts are calculated using Equation (3).

$$ICC_n = \sum_n E_s \times CF_{s,n} \quad (3)$$

where ICC_n is the impact category's (n) characterized impact, E_s is the emission of substance (s) and $CF_{s,n}$ is the substance's characterization factor (s) to impact category (n).

3. Results and Discussion

The impact factors of the GSHP system were analyzed through sensitivity analysis, considering the energy generation and environmental impact. Sensitivity analyses were performed on one base case and 24 scenarios in six categories. Based on the simulation results, the average maximum and minimum EWT and the monthly electricity consumption were analyzed to compare the performance of the GSHP system in the average heating period with that in the average cooling period to calculate in terms of energy generation. Furthermore, the environmental impact was calculated using LCA for the material manufacturing and use and maintenance stages.

3.1. Sensitivity Analysis on Impact Factors of the GSHP System in Terms of Energy Generation

The results of the sensitivity analysis on the impact factors of the GSHP system in terms of energy generation are summarized in Figure 5 and Table 6, which show the average minimum/maximum EWT and IC values calculated for the different categories of impact factors. These IC values showed the changing influence of the impact factors on energy generation (*i.e.*, EWT) of the GSHP system, where the EWT exhibits higher efficiency if provided as a high temperature in the heating period and as a low temperature in the cooling period. Accordingly, as the IC values of the cooling period become greater as negative values, the influence level is large, and as the IC values of the heating period become greater as positive values, the influence level is large. For the results, Category 1 (borehole length) showed the most influential impact factors for the GSHP system. Specifically, the IC of Scenario 1-1 in the cooling and heating periods was −0.54 and 0.67, respectively. In the cooling period, when the borehole length was reduced by as much as 100 m (66.7%), the EWT increased by as much as 6.82°C (36%) compared to that of the base case. In the heating period, when the borehole length was reduced by as much as 100 m (66.7%), the EWT decreased by as much as 5.63 °C (44.5%) compared to that of the base case.

Meanwhile, Category 6 (U-pipe spacing) showed the least influential impact factors for the GSHP system. Specifically, the IC of Scenario 6-1 in the cooling and heating periods was −0.02 and 0.03, respectively. In the cooling period, when U-pipe spacing was reduced by as much as 25.5 mm (88.8%), the EWT was increased by as much as 0.39 °C (2.1%) compared to that of the base case. In the heating period, the U-pipe spacing was reduced by as much as 25.5 mm (88.8%), and the EWT was decreased by as much as 0.39°C (3.1%) compared to that of the base case.

The results of other impact factors are as follows. In the case of Category 2 (grout thermal conductivity), the IC of Scenario 2-1 in the cooling and heating periods was −0.07 and 0.10, respectively. When grout thermal conductivity was reduced by as much as 0.115 W/m· K (11.6%) in the cooling period, the EWT was increased by as much as 0.15 °C (0.8%) compared to that of the base case. When the grout thermal conductivity was reduced by as much as 0.115 W/m· K (11.6%) in the heating period, the EWT was decreased by as much as 0.15 °C (1.1%) compared to that of the base case. In the case of Category 3 (borehole spacing), the IC of Scenario 3-1 in the cooling and heating periods were −0.07 and 0.10, respectively. When the borehole spacing was reduced by as much as 1 m (20%) in the cooling period, the EWT was increased by as much as 0.26 °C (1.4%) compared to that of the base case. When the bore spacing was reduced by as much as 1 m (20%) in the heating period, the EWT was decreased by as much as 0.26 °C (2.1%) compared to that of the base case. In the case of Category 5 (U-pipe diameter), the IC of Scenario 5-1 in the cooling and heating periods were −0.05 and 0.07, respectively. When the U-pipe diameter was reduced by as much as 7 mm (21.9%) in the cooling period, the EWT was increased by as much as 0.2 °C (1.1%) compared to that of the base case. When the U-pipe diameter was reduced by as much as 7 mm (21.9%) in the heating period, the EWT was decreased by as much as 0.2 °C (1.6%) compared to that of the base case. In the case of Category 4 (borehole diameter), the IC of Scenario 4-1 in the cooling and heating periods was 0.02 and −0.03, respectively. When the bore diameter was reduced by as much as 25 mm (17%) in the cooling period, the EWT was decreased by as much as 0.07 °C (0.4%) compared to that of the base case. When the bore diameter was reduced by as much as 25 mm (16.7%) in the heating period, the EWT was increased by as much as 0.07 °C (0.6%) compared to that of the base case.

To sum up, the borehole length was determined to be the most influential impact factor, and the borehole diameter and U-pipe spacing were determined to be the least influential impact factors in terms of the energy generation of the GSHP system (refer to Figure 5).

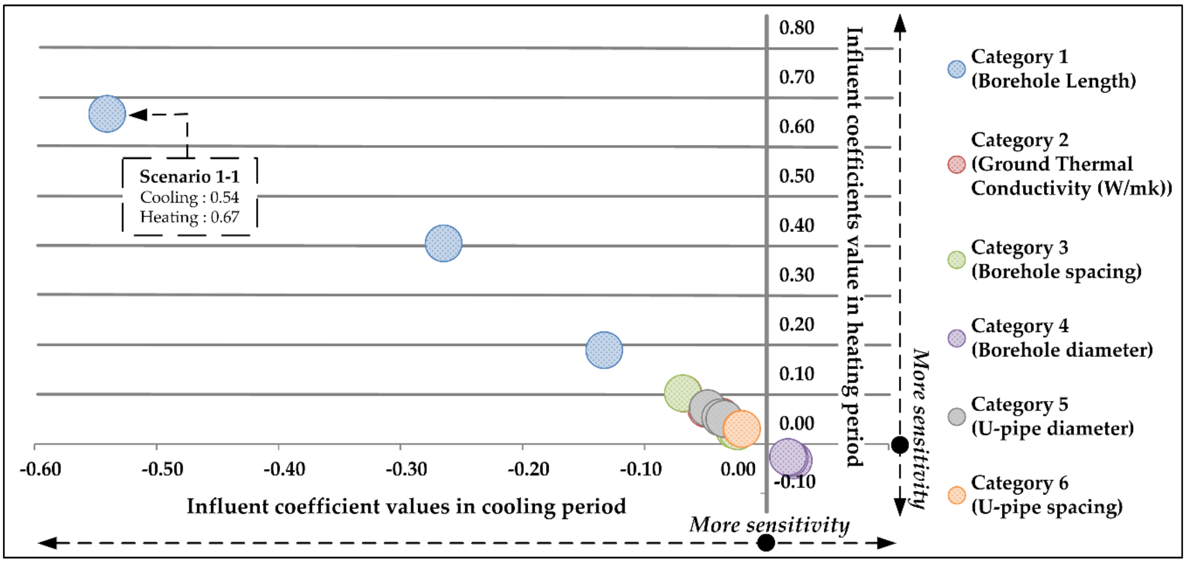

Figure 5. Influence coefficient values of different impact factors in terms of energy generation.

Table 6. Influence coefficient values of different impact factors in terms of energy generation.

Classification of Impact Factors		Avg Min. EWT (°C)	Avg. Max. EWT (°C)	Influence Coefficient Values	
		Cooling Period	Heating Period	Cooling Period	Heating Period
Category 1 borehole length (m)	Scenario 1-1	25.75	7.02	−0.54	0.67
	Scenario 1-2	20.6	10.94	−0.26	0.41
	Scenario 1-3	18.93	12.65	-	-
	Scenario 1-4	18.09	13.45	−0.13	0.19
Category 2 grout thermal conductivity (W/m·K)	Scenario 2-1	19.08	12.5	−0.07	0.10
	Scenario 2-2	18.93	12.65	-	-
	Scenario 2-3	18.72	12.85	−0.05	0.07
	Scenario 2-4	18.5	13.08	−0.04	0.06
Category 3 borehole spacing (m)	Scenario 3-1	19.19	12.39	−0.07	0.10
	Scenario 3-2	18.93	12.65	-	-
	Scenario 3-3	18.83	12.72	−0.03	0.03
	Scenario 3-4	18.75	12.78	−0.02	0.03
Category 4 borehole diameter (mm)	Scenario 4-1	18.86	12.72	0.02	−0.03
	Scenario 4-2	18.93	12.65	-	-
	Scenario 4-3	18.99	12.59	0.02	−0.03
	Scenario 4-4	19.04	12.54	0.02	−0.03
Category 5 U-pipe diameter (mm)	Scenario 5-1	19.13	12.45	−0.05	0.07
	Scenario 5-2	18.93	12.65	-	-
	Scenario 5-3	18.75	12.82	−0.04	0.05
	Scenario 5-4	18.56	13.01	-0.03	0.05
Category 6 U-pipe spacing (mm)	Scenario 6-1	19.32	12.26	−0.02	0.03
	Scenario 6-2	19.27	12.31	−0.02	0.03
	Scenario 6-3	18.93	12.65	-	-
	Scenario 6-4	18.32	13.21	−0.02	0.02

Scenarios 1-3, 2-2, 3-2, 5-2 and 6-3 stand for the base case; each scenario is described in Table 5.

3.2. Sensitivity Analysis on the Impact Factors of the GSHP System in Terms of the Environmental Impact

The results of the sensitivity analysis on the impact factors of the GSHP system in terms of the environmental impact (*i.e.*, six impact categories) are summarized in Figure 6, Figure A3 and Tables 7, A4–A7. In Section 2.3.3, the practical unit of LCA is defined as "the GSHP system supplied from the material manufacturing and use and maintenance stages for the whole service life." Therefore, the environmental impact was assessed in two stages: (i) the material manufacturing stage; and (ii) the use and maintenance stage. Table 7 shows the results of the sensitivity analysis in terms of RDP. Tables A4–A7 show the results of the sensitivity analysis on the other environmental impact categories.

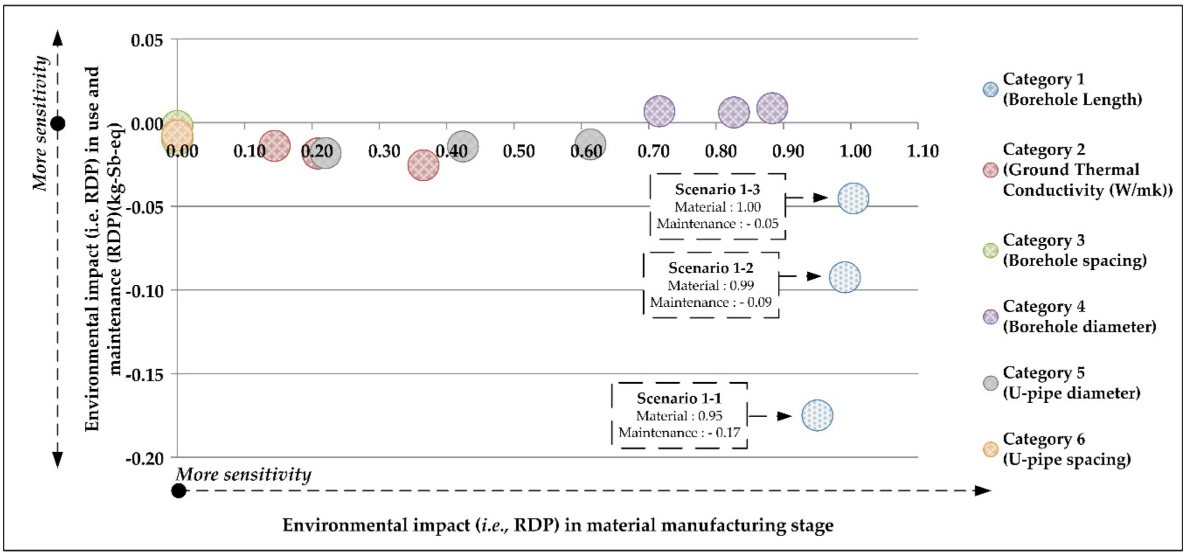

Figure 6. Influence coefficient values of different impact factors in terms of environmental impact (*i.e.*, resource depletion potential (RDP)).

As shown in Table 7, Category 1 (borehole length) showed the most influential impact factors for the GSHP system in the material manufacturing and use and maintenance stages. Specifically, the IC of Scenario 1-4 in the material manufacturing stage and the IC of Scenario 1-1 in the use and maintenance stage were 1.00 and −0.17, respectively. In the material manufacturing stage, when the borehole length increased by as much as 50 m (33.3%) compared to that of the base case (150 m), the RDP increased by as much as 170 kg-Sb-eq (33.7%) compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the borehole length was reduced by as much as 100 m (66.7%) compared to that of the base case (150 m), the RDP decreased by as much as 320 kg-Sb-eq (11.6%) compared to that of the base case (2168 kg-Sb-eq). Meanwhile, Category 3 (borehole spacing) showed the least influential impact factors for the GSHP system. Specifically, the ICs of Scenario 3-4 in the material manufacturing and use and maintenance stages were 0.00 and −0.002, respectively. In the material manufacturing stage, even when the borehole spacing increased by as much as 2 m (40%) compared to that of the base case (5 m), the RDP showed no change compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the borehole spacing was reduced by as much as 2 m (40%) compared to that of the base case (5 m), the RDP decreased by as much as 2 kg-Sb-eq (0.2%) compared to that of the base case (2168 kg-Sb-eq).

Table 7. Influence coefficient values of different impact factors in terms of environmental impact (*i.e.*, resource depletion potential (RDP)).

Classification		Values	Environmental Impact (RDP) (kg-Sb-eq)			Influent Coefficient (IC) of Environmental Impact (RDP)		
			Material Manufacturing	Use and Maintenance	Sum	Material Manufacturing	Use and Maintenance	Sum
Category 1 borehole length (m)	Scenario 1-1	50	185	2421	2606	0.95	−0.17	0.04
	Scenario 1-2	100	338	2235	2573	0.99	−0.09	0.11
	Scenario 1-3	150	505	2168	2673	-	-	-
	Scenario 1-4	200	675	2135	2810	1.00	−0.05	0.15
Category 2 grout thermal conductivity (W/m· K)	Scenario 2-1	0.875	484	2174	2658	0.37	−0.03	0.05
	Scenario 2-2	0.99	505	2168	2673	-	-	-
	Scenario 2-3	1.2116	529	2159	2688	0.21	−0.02	0.02
	Scenario 2-4	1.6	550	2149	2700	0.14	−0.01	0.02
Category 3 borehole spacing (m)	Scenario 3-1	4	505	2172	2678	0	−0.01	−0.01
	Scenario 3-2	5	505	2168	2673	-	-	-
	Scenario 3-3	6	505	2167	2672	0	−0.002	−0.002
	Scenario 3-4	7	505	2166	2672	0	−0.002	−0.002
Category 4 borehole diameter (mm)	Scenario 4-1	125	431	2165	2596	0.88	0.01	0.17
	Scenario 4-2	150	505	2168	2673	-	-	-
	Scenario 4-3	175	566	2170	2736	0.72	0.01	0.14
	Scenario 4-4	200	645	2172	2817	0.83	0.01	0.16
Category 5 U-pipe diameter (mm)	Scenario 5-1	25	481	2176	2657	0.22	−0.02	0.03
	Scenario 5-2	32	505	2168	2673	-	-	-
	Scenario 5-3	40	559	2160	2719	0.42	−0.01	0.07
	Scenario 5-4	50	680	2152	2832	0.61	−0.01	0.11
Category 6 U-pipe spacing (mm)	Scenario 6-1	0	505	2185	2690	0	−0.01	−0.01
	Scenario 6-2	3.17	505	2182	2688	0	−0.01	−0.01
	Scenario 6-3	28.37	505	2168	2673	-	-	-
	Scenario 6-4	86	505	2142	2647	0	−0.01	0

Scenarios 1-3, 2-2, 3-2, 5-2 and 6-3 stand for the base case; Sb stands for Antimony (stomic number 51); each scenario is described in Table 5.

The results of other impact factors are as follows. In the case of Category 2 (grout thermal conductivity), the ICs of Scenario 2-1 in the material manufacturing and use and maintenance stages were 0.37 and −0.03, respectively. In the material manufacturing stage, even when the grout thermal conductivity was decreased by as much as 0.115 W/m·K (11.6%) compared to that of the base case, the RDP was decreased by as much as 21 kg-Sb-eq (4.2%) compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the grout thermal conductivity was reduced by as much as 0.115 W/m·K (11.6%) compared to that of the base case, the RDP was increased by as much as 6 kg-Sb-eq (0.3%) compared to that of the base case (2168 kg-Sb-eq). In the case of Category 4 (borehole diameter), the ICs of Scenario 4-1 in the material manufacturing and use and maintenance stages were 0.88 and 0.01, respectively. In the material manufacturing stage, even when the borehole diameter was decreased by as much as 25 mm (16.7%) compared to that of the base case, the RDP was decreased by as much as 74 kg-Sb-eq (14.7%) compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the borehole diameter was reduced by as much as 25 mm (16.7%) compared to that of the base case, the RDP was decreased by as much as 3 kg-Sb-eq (0.1%) compared to that of the base case (2168 kg-Sb-eq). In the case of Category 5 (U-pipe diameter), the IC of Scenario 5-4 in the material manufacturing stage and the IC of Scenario 5-1 in the use and maintenance stage were 0.61 and −0.02, respectively. In the material manufacturing stage, when the U-pipe diameter was increased by as much as 18 mm (56.3%) compared to that of the base case, the RDP was increased by as much as 175 kg-Sb-eq (34.7%) compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the U-pipe diameter was reduced by as much as 7 mm (21.9%) compared to that of the base case, the RDP was increased by as much as 8 kg-Sb-eq (0.4%) compared to that of the base case (2168 kg-Sb-eq). In the case of Category 6 (U-pipe spacing), the ICs of Scenario 6-2 in the material manufacturing and use and maintenance stages were 0.00 and −0.01, respectively. In the material manufacturing stage, even when the U-pipe spacing was decreased by as much as 25.2 mm (88.8%) compared to that of the base case, the RDP showed no change compared to that of the base case (505 kg-Sb-eq). In the use and maintenance stage, when the U-pipe spacing was reduced by as much as 25.2 mm (88.8%) compared to that of the base case, the RDP was increased by as much as 14 kg-Sb-eq (0.6%) compared to that of the base case (2168 kg-Sb-eq). As shown in Tables A4–A7 other environmental impact categories showed similar trends.

In summary, the borehole length was determined to be the most influential impact factor, and the borehole spacing and U-pipe spacing were determined to be the least influential impact factors in terms of the environmental impact of the GSHP system (refer to Figure 6).

4. Conclusions

This study aimed to conduct sensitivity analysis on the impact factors of the GSHP system in terms of energy generation and environmental impact. This study was conducted as follows: (i) collecting the impact factors affecting the GSHP system's performance; (ii) establishing the GSHP systems' scenarios with the impact factors; (iii) determining the methodology and calculation tool to be used for conducting sensitivity analysis; and (iv) sensitivity analysis on the impact factors in terms of energy generation and environmental impact using LCA. A dormitory building in a university in Seoul where the GSHP system had been installed was selected for the sensitivity analysis. The average maximum and minimum EWT and the monthly electricity consumption were analyzed, which could enable the comparison of the performances of the GSHP system during the heating and cooling periods based on the simulation results. Furthermore, the environmental impact was calculated using LCA for the material manufacturing and use and maintenance stages.

In terms of the energy generation of the GSHP system, the borehole length was determined to be the most influential impact factor, showing influence coefficient values of −0.54 and 0.67, respectively, during cooling and heating period. These values are relatively high compared to those of other impact factors, such as the grout thermal conductivity (−0.07 and 0.10, respectively, during the cooling and heating period), borehole spacing (−0.07 and 0.10, respectively, during the cooling and heating period), borehole diameter (0.02 and −0.03, respectively, during the cooling and heating period) and U-pipe diameter (−0.05 and 0.07, respectively, during the cooling and heating period), which indicate that the borehole length influences the energy generation of the GSHP the most. On the other hand, the U-pipe spacing was determined to be the least influential impact factor, showing influence coefficient values of −0.02 and 0.03, respectively, during the cooling and heating period. In terms of the environmental impact of the GSHP system, the borehole length was again determined to be the most influential impact factor, showing influence coefficient values of 1.00 and −0.17, respectively, in the material manufacturing and use and maintenance. These values are relatively high compared to those of other impact factors, such as the grout thermal conductivity (0.37 and −0.03, respectively, in the material manufacturing and use and maintenance), borehole spacing (−0.07 and 0.10, respectively, in the material manufacturing and use and maintenance), borehole diameter (0.88 and 0.01, respectively, in the material manufacturing and use and maintenance) and U-pipe diameter (0.61 and −0.02, respectively, in the material manufacturing and use and maintenance), which indicate that the borehole length influences the environmental impact of the GSHP the most. On the other hand, the borehole spacing and U-pipe spacing were determined to be the two least influential impact factors, showing influence coefficient values of zero and −0.01, respectively, in the material manufacturing and use and maintenance for both impact factors. To sum up, the borehole length was determined to be the most influential impact factor in terms of both energy generation and environmental impact. Meanwhile, U-pipe spacing was determined to be the least influential impact factor in terms of both energy generation and environmental impact

The results of this study can be used: (i) to establish the optimal design strategy for different application fields and different seasons; and (ii) to conduct a feasibility study on energy generation and environmental impact at the level of the life cycle.

Research on the following is recommended for future studies: (i) economic and environmental assessment for selecting the optimal implementation fraction of the GSHP system using the above-analyzed factors; and (ii) a multi-objective optimization system for the ultimate decision maker to analyze the uncountable scenarios in terms of several impact factors.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

IEA	International Energy Agency
OECD	Organization for Economic Cooperation and Development
GHG	Greenhouse gas
CERT	Carbon emission reduction target
NRE	New/renewable energy
KEMCO	Korea Energy Management Corporation
GSHP	Ground source heat pump
GHE	Ground heat exchanger
IGSHPA	International Ground Source Heat Pump Association
CCHP	Combined cooling heating and power

LCA	Life cycle assessment
EWT	Entering water temperature
CV(RMSE)	Coefficient of variation of the root-mean-square error
COP	Coefficient of performance
IC	Influence coefficient
ISO	International Organization for Standardization
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
RDP	Resource depletion potential
GWP	Global warming potential
ODP	Ozone layer depletion potential
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical oxidation potential

Appendix

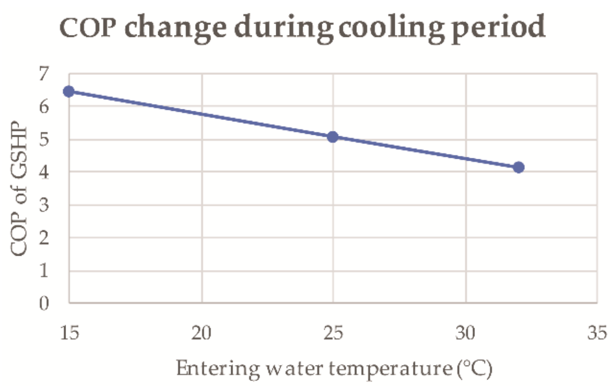

Figure A1. The coefficient of performance measured through experiment during the cooling period.

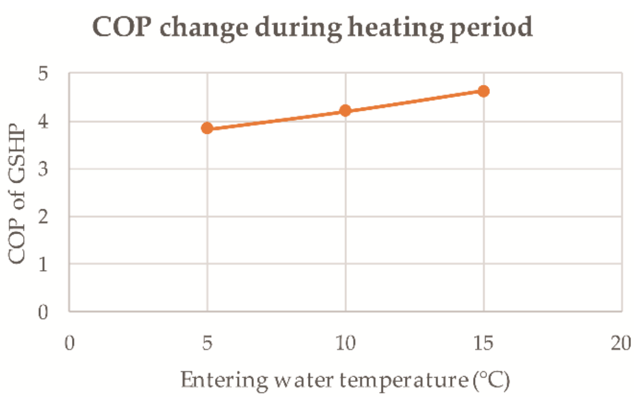

Figure A2. The coefficient of performance measured through experiment during the heating period.

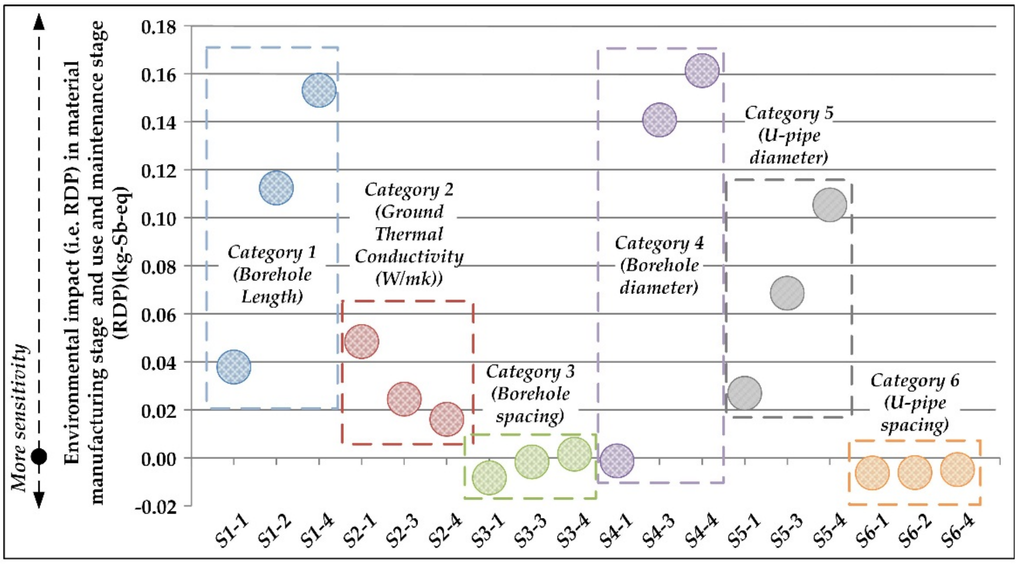

Figure A3. Influence coefficient values of different impact factors for environmental impact (*i.e.*, resource depletion potential (RDP)), sum of material manufacturing and use and maintenance stage.

Table A1. Ground thermal conductivity according to silica sand mass fraction.

20% Bentonite	Silica Sand Mass Fraction (%)										
	0	5	10	15	20	25	30	35	40	45	50
DY-100	0.7746	0.8619	0.9055	0.9408	0.9738	1.0567	1.1373	1.233	1.3438	1.4967	1.6107
DY-100S	0.7937	0.9072	0.9279	0.964	1.0157	1.0828	1.1653	1.2634	1.3769	1.5059	1.6504
Montigel F	0.7879	0.8831	0.9211	0.957	1.0082	1.0748	1.1508	1.2542	1.3668	1.4949	1.6383
EZ-SEAL	0.8067	0.9221	0.9431	0.9798	1.0323	1.1005	1.1844	1.32841	1.3995	1.5306	1.6774
Thermal Grout	0.8374	0.9571	0.979	1.0348	1.0716	1.1598	1.2295	1.3504	1.4527	1.5888	1.7531
Volcay Grout	0.7615	0.8746	0.9159	0.9554	0.9897	1.0884	1.1286	1.2116	1.2997	1.4839	1.6052

Table A2. The actual monthly load of the facility.

Month	Total Load (kWh)	Peak Load (kW)
January	26,946	236
February	19,913	193
March	40,572	142
April	18,521	67
May	14,800	85
June	35,807	213
July	21,312	306
August	20,424	293
September	32,226	191
October	22,965	80
November	29,633	107
December	53,586	188

Table A3. Monthly electricity consumption for 40 years through simulation.

Month	Electricity Consumption (kWh)	EWT (°C)
January	5716	13.9
February	4210	14.1
March	8773	13.0
April	3934	15.1
May	1984	15.9
June	5232	17.9
July	3009	17.1
August	2892	17.1
September	4788	18.3
October	4781	14.8
November	6234	14.3
December	11,614	12.8

Table A4. Influence coefficient values of different impact factors for environmental impact (*i.e.*, global warming potential (GWP)).

Classification		Values	Environmental Impact (GWP) (kg-CO_2-eq)			Influent Coefficient (IC) of Environmental Impact (GWP)		
			Material Manufacturing	Use and Maintenance	Sum	Material Manufacturing	Use and Maintenance	Sum
Category 1 borehole length (m)	Scenario 1-1	50	54,479	1,375,833	1,430,312	0.96	−0.17	−0.05
	Scenario 1-2	100	101,103	1,270,132	1,371,235	1.00	−0.09	0.03
	Scenario 1-3	150	151,374	1,232,166	1,383,539	-	-	-
	Scenario 1-4	200	201,926	1,213,583	1,415,509	1.00	−0.05	0.07
Category 2 grout thermal conductivity (W/m· K)	Scenario 2-1	0.875	148,573	1,235,809	1,384,382	0.16	−0.03	−0.01
	Scenario 2-2	0.99	151,374	1,232,166	1,383,539	-	-	-
	Scenario 2-3	1.2116	154,455	1,227,077	1,381,532	0.09	−0.02	−0.01
	Scenario 2-4	1.6	157,255	1,221,589	1,378,844	0.06	−0.01	−0.01
Category 3 borehole spacing (m)	Scenario 3-1	4	151,374	1,234,689	1,386,063	0.00	−0.01	−0.01
	Scenario 3-2	5	151,374	1,232,166	1,383,539	-	-	-
	Scenario 3-3	6	151,374	1,231,652	1,383,026	0.00	0.00	0.00
	Scenario 3-4	7	151,374	1,231,219	1,382,593	0.00	0.00	0.00
Category 4 borehole diameter (mm)	Scenario 4-1	125	123,985	1,230,380	1,354,365	1.09	0.01	0.13
	Scenario 4-2	150	151,374	1,232,166	1,383,539	-	-	-
	Scenario 4-3	175	169,503	1,233,546	1,403,050	0.72	0.01	0.08
	Scenario 4-4	200	194,961	1,234,689	1,429,649	0.86	0.01	0.10
Category 5 U-pipe diameter (mm)	Scenario 5-1	25	148,904	1,237,056	1,385,960	0.07	−0.02	−0.01
	Scenario 5-2	32	151,374	1,232,166	1,383,539	-	-	-
	Scenario 5-3	40	156,807	1,227,781	1,384,588	0.14	−0.01	0.00
	Scenario 5-4	50	169,058	1,223,115	1,392,172	0.21	−0.01	0.01
Category 6 U-pipe spacing (mm)	Scenario 6-1	0	151,374	1,241,712	1,393,086	0.00	−0.01	−0.01
	Scenario 6-2	3.17	151,374	1,240,452	1,391,825	0.00	−0.01	−0.01
	Scenario 6-3	28.37	151,374	1,232,166	1,383,539	-	-	-
	Scenario 6-4	86	151,374	1,217,255	1,368,629	0.00	−0.01	−0.01

Table A5. Influence coefficient values of different impact factors for environmental impact (*i.e.*, acidification potential (AP)).

Classification		Values	Environmental Impact (AP) (kg-SO_2-eq)			Influent Coefficient (IC) of Environmental Impact (AP)		
			Material Manufacturing	Use and Maintenance	Sum	Material Manufacturing	Use and Maintenance	Sum
Category 1 borehole length (m)	Scenario 1-1	50	296	2362	2658	0.98	−0.17	0.16
	Scenario 1-2	100	569	2181	2749	0.99	−0.09	0.22
	Scenario 1-3	150	851	2115	2966	-	-	-
	Scenario 1-4	200	1135	2083	3219	1.00	−0.05	0.26
Category 2 grout thermal conductivity (W/m· K)	Scenario 2-1	0.875	829	2122	2950	0.22	−0.03	0.05
	Scenario 2-2	0.99	851	2115	2966	-	-	-
	Scenario 2-3	1.2116	875	2107	2982	0.13	−0.02	0.02
	Scenario 2-4	1.6	897	2097	2994	0.09	−0.01	0.02
Category 3 borehole spacing (m)	Scenario 3-1	4	851	2120	2970	0.00	−0.01	−0.01
	Scenario 3-2	5	851	2115	2966	-	-	-
	Scenario 3-3	6	851	2114	2965	0.00	0.00	0.00
	Scenario 3-4	7	851	2114	2965	0.00	0.00	0.00
Category 4 borehole diameter (mm)	Scenario 4-1	125	709	2112	2822	1.00	0.01	0.29
	Scenario 4-2	150	851	2115	2966	-	-	-
	Scenario 4-3	175	943	2118	3061	0.65	0.01	0.19
	Scenario 4-4	200	1074	2120	3193	0.79	0.01	0.23
Category 5 U-pipe diameter (mm)	Scenario 5-1	25	829	2124	2952	0.12	−0.02	0.02
	Scenario 5-2	32	851	2115	2966	-	-	-
	Scenario 5-3	40	900	2108	3007	0.23	−0.01	0.06
	Scenario 5-4	50	1010	2100	3109	0.33	−0.01	0.09
Category 6 U-pipe spacing (mm)	Scenario 6-1	0	851	2132	2983	0.00	−0.01	−0.01
	Scenario 6-2	3.17	851	2130	2980	0.00	−0.01	−0.01
	Scenario 6-3	28.37	851	2115	2966	-	-	-
	Scenario 6-4	86	851	2090	2941	0.00	−0.01	0.00

Table A6. Influence coefficient values of different impact factors for environmental impact (*i.e.*, eutrophication potential (EP)).

Classification		Values	Environmental Impact (EP) (kg-PO_4^3-eq)			Influent Coefficient (IC) of Environmental Impact (EP)		
			Material Manufacturing	Use and Maintenance	Sum	Material Manufacturing	Use and Maintenance	Sum
Category 1 borehole length (m)	Scenario 1-1	50	30	440	469	0.97	−0.17	0.03
	Scenario 1-2	100	57	406	462	0.99	−0.09	0.10
	Scenario 1-3	150	84	394	478	-	-	-
	Scenario 1-4	200	113	388	500	1.00	−0.05	0.14
Category 2 grout thermal conductivity (W/m· K)	Scenario 2-1	0.875	81	395	476	0.32	−0.03	0.04
	Scenario 2-2	0.99	84	394	478	-	-	-
	Scenario 2-3	1.2116	88	392	480	0.18	−0.02	0.02
	Scenario 2-4	1.6	91	390	481	0.13	−0.01	0.01
Category 3 borehole spacing (m)	Scenario 3-1	4	84	394	479	0.00	−0.01	−0.01
	Scenario 3-2	5	84	394	478	-	-	-
	Scenario 3-3	6	84	393	478	0.00	0.00	0.00
	Scenario 3-4	7	84	393	478	0.00	0.00	0.00
Category 4 borehole diameter (mm)	Scenario 4-1	125	72	393	465	0.92	0.82	0.85
	Scenario 4-2	150	84	394	478	-	-	-
	Scenario 4-3	175	94	394	488	0.89	0.82	0.84
	Scenario 4-4	200	106	394	501	0.88	0.82	0.84
Category 5 U-pipe diameter (mm)	Scenario 5-1	25	81	395	476	0.19	−0.02	0.02
	Scenario 5-2	32	84	394	478	-	-	-
	Scenario 5-3	40	92	392	484	0.36	−0.01	0.05
	Scenario 5-4	50	109	391	500	0.52	−0.01	0.08
Category 6 U-pipe spacing (mm)	Scenario 6-1	0	84	397	481	0.00	−0.01	−0.01
	Scenario 6-2	3.17	84	396	481	0.00	−0.01	−0.01
	Scenario 6-3	28.37	84	394	478	-	-	-
	Scenario 6-4	86	84	389	473	0.00	−0.01	0.00

Table A7. Influence coefficient values of different impact factors for environmental impact (*i.e.*, photochemical oxidation potential (POCP)).

Classification		Values	Environmental Impact (POCP) (kg-C_2H_4-eq)			Influent Coefficient (IC) of Environmental Impact (POCP)		
			Material Manufacturing	Use and Maintenance	Sum	Material Manufacturing	Use and Maintenance	Sum
Category 1 borehole length (m)	Scenario 1-1	50	195	3.97	199	0.97	−0.17	0.96
	Scenario 1-2	100	370	3.66	374	0.99	−0.09	0.98
	Scenario 1-3	150	552	3.55	555	-	-	-
	Scenario 1-4	200	737	3.50	740	1.01	−0.05	1.00
Category 2 grout thermal conductivity (W/m· K)	Scenario 2-1	0.875	522	3.57	526	0.46	−0.03	0.46
	Scenario 2-2	0.99	552	3.55	555	-	-	-
	Scenario 2-3	1.2116	584	3.54	588	0.26	−0.02	0.26
	Scenario 2-4	1.6	552	3.56	555	0.00	0.00	0.00
Category 3 borehole spacing (m)	Scenario 3-1	4	552	3.56	555	0.00	−0.01	0.00
	Scenario 3-2	5	552	3.55	555	-	-	-
	Scenario 3-3	6	552	3.55	555	0.00	0.00	0.00
	Scenario 3-4	7	552	3.55	555	0.00	0.00	0.00
Category 4 borehole diameter (mm)	Scenario 4-1	125	482	3.55	485	0.76	0.01	0.76
	Scenario 4-2	150	552	3.55	555	-	-	-
	Scenario 4-3	175	611	3.56	615	0.64	0.01	0.64
	Scenario 4-4	200	688	3.56	691	0.74	0.01	0.73
Category 5 U-pipe diameter (mm)	Scenario 5-1	25	517	3.57	521	0.29	−0.02	0.28
	Scenario 5-2	32	552	3.55	555	-	-	-
	Scenario 5-3	40	628	3.54	631	0.55	−0.01	0.55
	Scenario 5-4	50	799	3.53	803	0.80	−0.01	0.79
Category 6 U-pipe spacing (mm)	Scenario 6-1	0	552	3.58	555	0.00	−0.01	0.00
	Scenario 6-2	3.17	552	3.58	555	0.00	−0.01	0.00
	Scenario 6-3	28.37	552	3.55	555	-	-	-
	Scenario 6-4	86	552	3.51	555	0.00	−0.01	0.00

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