Energies **2015**, *8*, 7752-7776; doi:10.3390/en8087752

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

An Environmental and Economic Assessment for Selecting the Optimal Ground Heat Exchanger by Considering the Entering Water Temperature

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Academic Editor: Hossam A. Gabbar

Received: 29 June 2015 / Accepted: 23 July 2015 / Published: 29 July 2015

Abstract: In order to solve environmental problems such as global warming and resource depletion in the construction industry, interest in new renewable energy (NRE) systems has increased. The ground source heat pump (GSHP) system is the most efficient system among NRE systems. However, since the initial investment cost of the GSHP is quite expensive, a feasibility study needs to be conducted from the life-cycle perspective. Meanwhile, the efficiency of GSHP depends most significantly on the entering water temperature (EWT) of the ground heat exchanger (GHE). Therefore, this study aims to assess the environmental and economic effects of the use of GHE for selecting the optimal GHE. This study was conducted in three steps: (i) establishing the basic information and selecting key factors affecting GHE performances; (ii) making possible alternatives of the GHE installation by considering EWT; and (iii) using life-cycle assessment and life-cycle cost, as well as comprehensive evaluation of the environmental and economic effects on the GHE. These techniques allow for easy and accurate determination of the optimal design of the GHE from the environmental and economic effects in the early design phase. In future research, a multi-objective decision support model for the GSHP will be developed.

Keywords: ground source heat pump; ground heat exchanger; entering water temperature; life-cycle assessment; life-cycle cost

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1. Introduction

Excessive carbon dioxide (CO_2) emissions are currently becoming the major cause of climate change problems such as global warming and abnormal climates. Efforts to reduce CO_2 are being established across the world through the strengthening of environmental regulations such as the Kyoto Protocol. Meanwhile, South Korea imports around 97% of the total amount of energy presently used domestically. As more than 25% of these imports are used for buildings, CO_2 emissions from buildings can no longer be neglected. According to the 2013 Annual End-Use Energy Statistics, the total energy consumption of high energy consumption buildings that use 2,000 tons of equivalent (toe) each year reached 2,307,000 toe and 10,083,000 ton-CO_2, respectively. School facilities showed energy consumption of 336,000 toe and CO_2 emission of 1,397,000 ton-CO_2, which accounted for around 15% of the total amount used by buildings [1].

As the seriousness of the energy problem grows, the importance of alternative energy or new renewable energy (NRE) systems become more urgent [2–14]. In particular, a ground source heat pump (GSHP) system is a highly efficient NRE system for heating and cooling the building [15–18]. This system relies on a relatively constant ground temperature and can transfer the earth's heat into a building during the winter, and transfer heat out of the building during the summer [19–25]. A typical GSHP system consists of a ground heat exchanger (GHE) to collect/reject heat to the ground heat pump to heat/cool the building, and pump(s) to circulate a thermal fluid between the heat pumps and the GHE [26–30].

There have been various studies on the environmental and economic effects of GSHP systems in a building from the following three perspectives: (i) the environmental effects of the GSHP systems were analyzed under various conditions; (ii) the economic effects of the GSHP systems in a building were analyzed; and (iii) the environmental and economic effects of GSHP systems were analyzed at the same time.

First, various studies have focused on the environmental effects of the GSHP system in a building [31–35]. Genchi *et al.* [36] assessed CO_2 payback of a GSHP system in Shinjuku, Tokyo, Japan that consumed a large amount of electric energy. The total CO_2 emissions from the installation and operation of GSHP system were estimated to be 67,701 and 33,935 tons respectively. That means the GSHP system would result in a reduction of 54% of the CO_2 emissions (39,519 ton-CO_2) compared with air source heat pumps (ASHP). If an ASHP system installed within an area of 1 km^2 in this region is replaced with a GSHP system, CO_2 payback-time is estimated at 1.7 years. Blum *et al.* [37] conducted an analysis of unit-area CO_2 savings from a GSHP system. Its scope was limited to 1105 installed GSHP systems. Compared with conventional heating systems, the minimum average total annual CO_2 savings of all installed GSHP systems is up to 2000 tons/year due to the subsidy program which promoted GSHP systems for private one-family, two-family, and terraced houses for which the heating demand is less than 17 kW in Baden-Wurttemberg, Germany. The additional CO_2 emissions are primarily associated with the affluent suburbs of the most densely populated area in the region. Saner *et al.* [38] conducted not only an analysis of CO_2 and energy, but also life-cycle assessment (LCA) of overall environmental damages in terms of resource depletion, human health and ecosystem quality. The analysis result showed that, although a GSHP system normally contributes to the reduction of CO_2 emissions, the GSHP system can cause water pollution.

Second, the economic effects of the GSHP system were analyzed under various conditions [39–44]. Zhu *et al.* [45] analyzed the economic effect of a GSHP system including life-cycle cost analysis. Life-cycle cost analysis is based on the Monte Carlo simulation. A GSHP system installed in Pensacola, U.S. was selected as a case. According to the analysis results, the effectiveness was highest when the subsidy for initial investment cost and operation cost was provided, compared with a conventional single-zone split system using heat pumps. However, where an incentive system did not exist, the feedback period was analyzed as more than 15 years. Sekine *et al.* [46] introduced a cast-in-place concrete pile (energy pile) method to reduce the high initial investment cost, and to improve the efficiency of the GSHP system. According to the analysis result, this system gained a competitive advantage with US$0.79/W, compared with US$3/W of the conventional system.

Third, the environmental and economic effects of GSHP systems were analyzed at same time [47–49]. Nagano *et al.* [47] developed a tool to analyze GSHP system performances, life-cycle cost (LCC) and life-cycle CO_2 ($LCCO_2$).They conducted a comparative evaluation of residential buildings in Sapporo, Japan using thermal response tests. For the case that the building energy loads during the winter are satisfied, they also compared the facility systems of other heat sources and their consumptions and conducted a cost analysis accordingly. Results of the calculations showed that the $LCCO_2$ of the GSHP system is 2038 kg-CO_2/year which is less than half compared to conventional oil boiler systems. Also, the GSHP system can reduce LCC by 50,000–90,000 Japanese yen/year. Self *et al.* [49] compared GSHP systems with facility systems of other heat sources in terms of LCC and $LCCO_2$. According to the analysis result, the GSHP system was by far lower in CO_2 emissions than other heat source systems.

In summary, there are several limitations in the previous studies: (i) most previous studies focused only on CO_2 emissions of a GSHP system; (ii) there are no previous studies focusing on the comparison analysis of the environmental and economic assessments of different entering water temperatures (EWT) of a ground heat exchanger (GHE); and (iii) there are no previous studies on the optimal GHE design alternative in terms of integrated environmental and economic assessment. This study aimed to solve these limitations.

To address these challenges, this study defined the research scope as follows: (i) the scope of environmental impact assessment was defined by life-cycle stages (including material manufacturing, use and maintenance); (ii) the scope of environmental impact categories were placed into six categories (including resource depletion potential (RDP), global warming potential (GWP), ozone layer depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidation potential (POCP)); and (iii) the scope of analysis focused on GHE. Based on the defined research scope, this study aims to assess the environmental and economic effects of the use of GHE for selecting the optimal GHE. This study was conducted in three steps: (i) Establishing the basic information and selecting key factors affecting GHE performances; (ii) Creating possible alternatives for GHE installation while considering EWT; (iii) Using life-cycle assessment and life-cycle cost, as well as comprehensive evaluation of the environmental and economic effects on the GHE (refer to Figure 1).

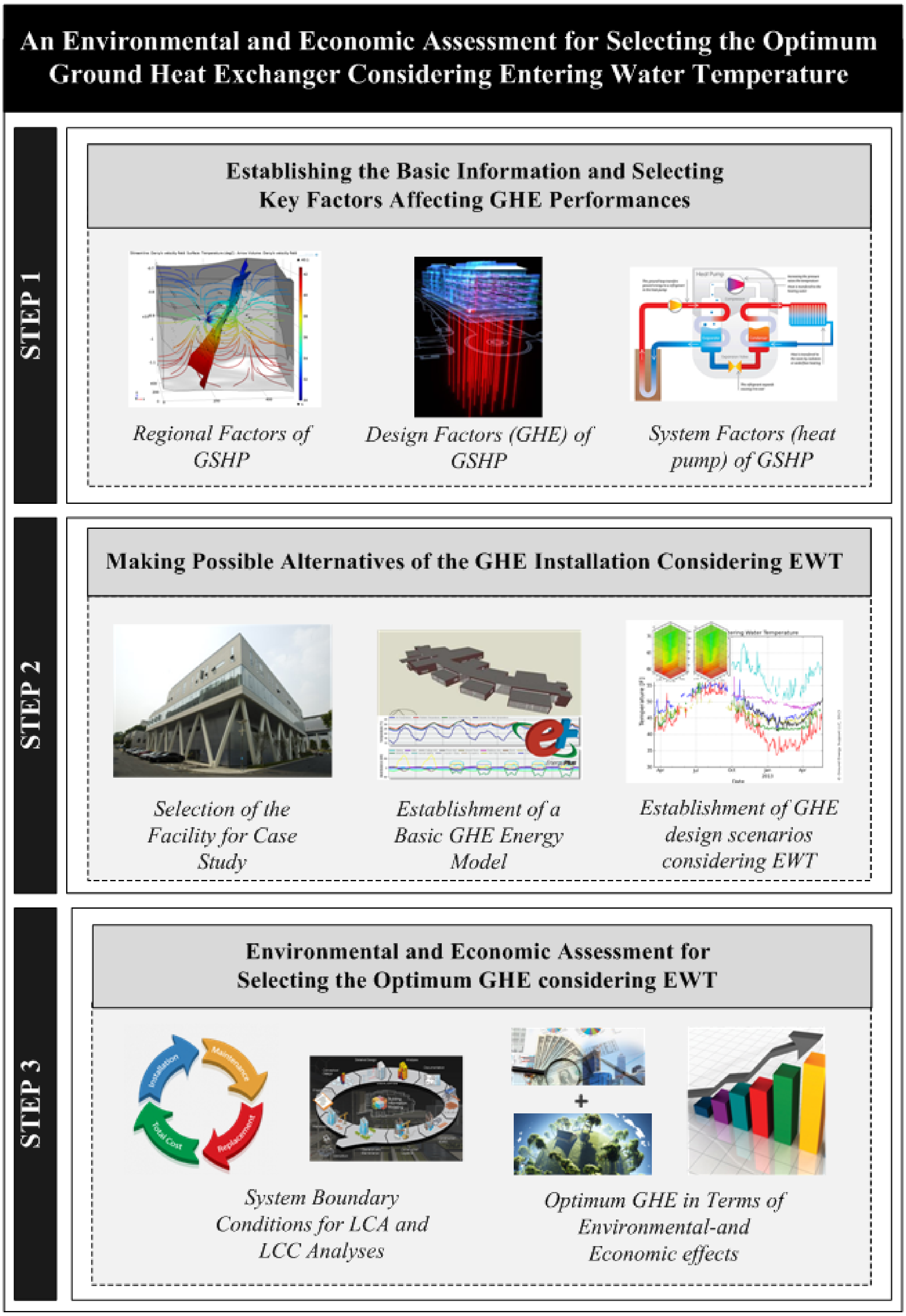


Figure 1. Framework of the research.

2. Establishing the Basic Information and Selecting Key Factors Affecting Ground Heat Exchanger (GHE) Performances

Prior to designing the GSHP system, the basic information for the GSHP system installation needs to be established. The study defines the region, facility type, and power supply system type where the system is to be implemented. Furthermore, the study selects key factors affecting GSHP system performances. The study establishes the information of regional factors, design factors (GHE), and system factors (heat pump) linked with the facility to design the optimal alternative.

2.1. Regional Factors of a Ground Source Heat Pump (GSHP) System

Ground thermal conductivity, ground heat capacity and ground temperature are considered regional factors. These factors affect GSHP system performances, and the value varies depending on regions. In addition, as borehole drilling costs incurred in construction are different according to the types of soil, these factors should be investigated prior to GSHP system installation.

2.2. Design Factors of GHE for a GSHP System

GHE is largely assessed by the characteristics of the borehole, such as the number and arrangement of boreholes, borehole spacing, grout conductivity, U-tube type and size, EWT, *etc.* and accounts for a large proportion of cost in the initial investment of GSHP system. Each component affects the GSHP system performances individually and decides GHE performances through interaction. The details of each factor are as follows (refer to Figure 2 and Table 1):

- Borehole length (BL): Borehole length usually affects largely the performances and cost of GHE, and, accordingly, multi-studies are being conducted on the design of optimal length. The optimal length is decided by all the factors affecting GHE such as underground environment, GHE components and G-function.
- Number of boreholes and arrangement: The number and arrangement of boreholes is a factor that can affect the total length of the borehole and accounts for a significant portion of the cost. Besides, as the distribution of temperature transferred to underground varies according to a type of arrangement such as L-, U- and rectangle types, this factor affects the performances of boreholes.
- Borehole spacing (BS): As heat capacity differs according to the type of ground, optimal spacing should be designed to prevent a reduction in GHE performances caused by intersection of the scopes of ground-source heats emitted and absorbed by each borehole.
- Borehole diameter (BD): Borehole diameter is designed in consideration of the U-pipe through which fluid flows and the volume of grout that fills a borehole. As borehole thermal resistance is higher with an increase in the volume of grout, the performance decreases. If its volume is too small, the inner components protected by grout can be impaired. Thus, it is necessary to make proper thickness.
- U-pipe spacing (PS), pipe size and pipe type: It is necessary to combine these factors to meet temperature load in consideration of the speed of fluid that flows inside a pipe and its related heat transfer capacity. These factors, which are related to the flowing fluid the pipe directly touches, require a strength and durability above a certain level.
- Grout conductivity: Grout conductivity is an element that constitutes a borehole. The higher its thermal conductivity, the lower the overall borehole resistance.
- Fluid type, flow rate: Fluid type and flow rate are variables of heat transfer that occur while fluid flows in a pipe. The usual mix with other material keeps fluid from freezing.

Table 1. Overview of key factor.

Category	Key Factor (Unit)	References
Regional Factor	Ground temperature (°C), Soil type, Ground thermal conductivity (W/mK), Ground heat capacity (kJ/K·m^3)	[50–53]
Ground Heat Exchanger	Borehole length (BL) (m), Borehole spacing (BS) (m), Borehole diameter (BD) (mm), U-pipe spacing (PS) (mm), Number of boreholes: arrangement, Grout conductivity (W/mK), Borehole thermal resistance (K/(W/m)), Pipe type, Pipe size, Fluid type, Flow rate (L/s), Entering water temperature (°C)	[54–62]
Heat Pump	Capacity (kW), Power input (kW), Heat of rejection (kW), Heat of extraction (kW), Coefficient of performance, Energy efficient rating, Entering water temperature (°C)	[27,63–65]

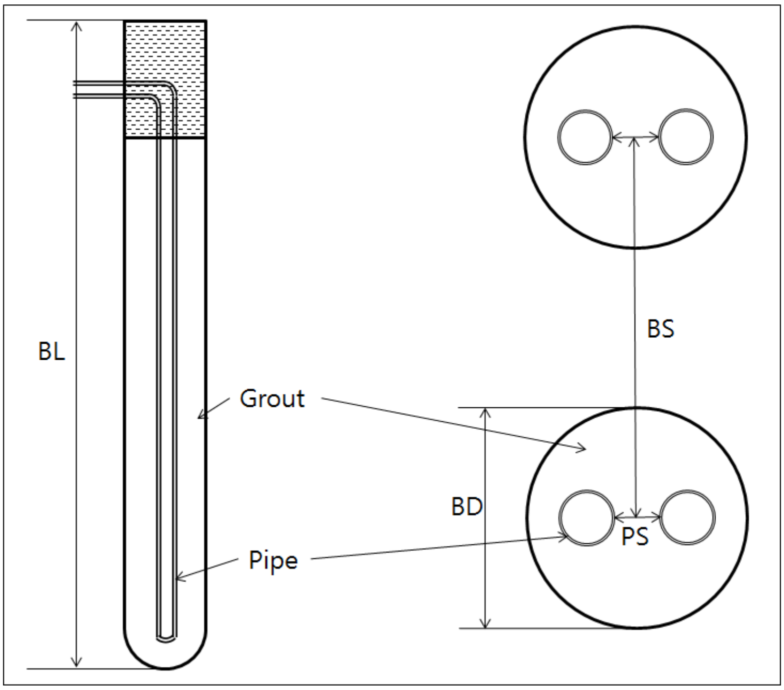


Figure 2. Components of Ground Source Heat Pump (GSHP) system.

- Borehole thermal resistance: Borehole thermal resistance, which is the thermal resistance of the overall borehole determined by a mix of the above factors, affects the design of a borehole.
- Entering water temperature (EWT): EWT, which is an indicator that can evaluate the final performance by a mix of each key factor, is the GHE outlet temperature that meets the energy demand of the building [66]. To calculate the EWT, Equation (1) was used [67]. EWT is designed to provide water at a high temperature in the case of heating, and at a low temperature in the case of cooling, which can minimize the load of a heat pump. Hence, the design process of the GHE will be a core factor in the design of the overall GSHP system.

$$EWT = T_g + \frac{q_i}{2mc_p} + \frac{Q_i R_b}{H} + \frac{1}{2\pi L}\sum_{i=1}^{N}(Q_i - Q_{i-1})g\left\{\frac{(t_i - t_{i-1})}{t_s}, \frac{r_b}{H}\right\} \tag{1}$$

where, EWT is GHE outlet temperature, T_g is ground temperature, q is the net heat rejection rate, i is the index to denote the end of a time step, m is mass flow rate, C_p is specific heat of the water, Q_i is step heat rejection pulse, R_b is borehole thermal resistance, L is borehole length, H is borehole depth, t is time, t_s is time scale, r_b is borehole radius, k is ground thermal conductivity.

In this case, the total length of a borehole can be calculated by taking into account the energy and EWT necessary for the cooling and heating of the building (refer to (Equations (2) and (3))) [67].

$$L_C = \frac{(Capacity_{Cooling})\left(\frac{COP_C - 1}{COP_C}\right)(R_p + R_s \cdot RunFraction_h)}{EWT_{Max} - T_{g.Max.Annual}} \tag{2}$$

$$L_H = \frac{(Capacity_{Heating})\left(\frac{COP_H - 1}{COP_H}\right)(R_p + R_s \cdot RunFraction_h)}{T_{g.\min.Annual} - EWT_{\min}} \tag{3}$$

where, L_c is required bore length for cooling, L_h is required bore length for heating, Capacity is capacity of ground source heat pump, *COP* is coefficients of performance of ground source heat pump, R_p is thermal resistance of pipe, R_s is thermal resistance of soil, $RunFraction_h$ is runtime of heat pump, EWT is the heat pump entering liquid temperature

2.3. System Factors (Heat Pump) of GSHP System

A heat pump is directly linked to GHE; therefore, the heating and cooling loads of a target facility should be first identified. In this case, a design of heat pump can be conducted by taking into account hourly load, average daily load or average monthly load. Meanwhile, the EWT, which is the temperature of water entering from the GHE, has a considerable effect on the efficiency of a heat pump. Thus, a proper heat pump should be designed in conjunction with EWT and the energy demand of the building.

3. Creating Possible Alternatives for the GHE Installation by Considering Entering Water Temperature (EWT)

3.1. Selection of a Facility for Case Study

To conduct an environmental- and economic-effect assessment for the GHE in this study, a facility that has actually applied the GSHP system was selected as a case study. The following criteria were applied to selection:

- According to the 2013 Annual End-Use Energy Statistics, the total energy and CO_2 emissions from high energy consumption buildings that use 2000 toe per year reached 2,307,000 toe and 10,083,000 ton-CO_2, respectively. The energy used by the schools among them reached 336,000 toe with CO_2 emissions of 1,397,000 ton-CO_2, which accounted for around 15% of the total amount used by buildings [1].
- The GSHP system among an NRE system can be installed underground and designed around the systematic characteristics. Accordingly, the region with the lowest high building density should be selected.
- A building that fully uses an air cooling and heating GSHP system was selected to calculate the environmental and economic effects of a GSHP system according to GHE scenarios.

Based on the above criteria, the "Y" university gym facility located in Seoul, South Korea was selected. "Y" university gym facility introduced a 422 kW GSHP system (installation capacity: 204 kW for cooling; and 218 kW for heating) in December 2012 and has replaced 100% of the annual heating and cooling energy consumption with the GSHP system. Table 2 provides data about the gym of "Y" university with regard to its characteristics and energy consumption.

Table 2. Overview of Target facility.

Category	University Facilities
Year established	2012
Location	Seoul
Building type	Educational facility
Electricity system	On-grid
Heating system	Individual heating
Progressive tax	No
Floor space of gym	1197.54 m^2
Major energy service	Ground source heat pump (GSHP)
Installation of capacity	Cooling: 204 kW/Heating: 218 kW
Borehole	Length: 143 m/hole: 22 EA

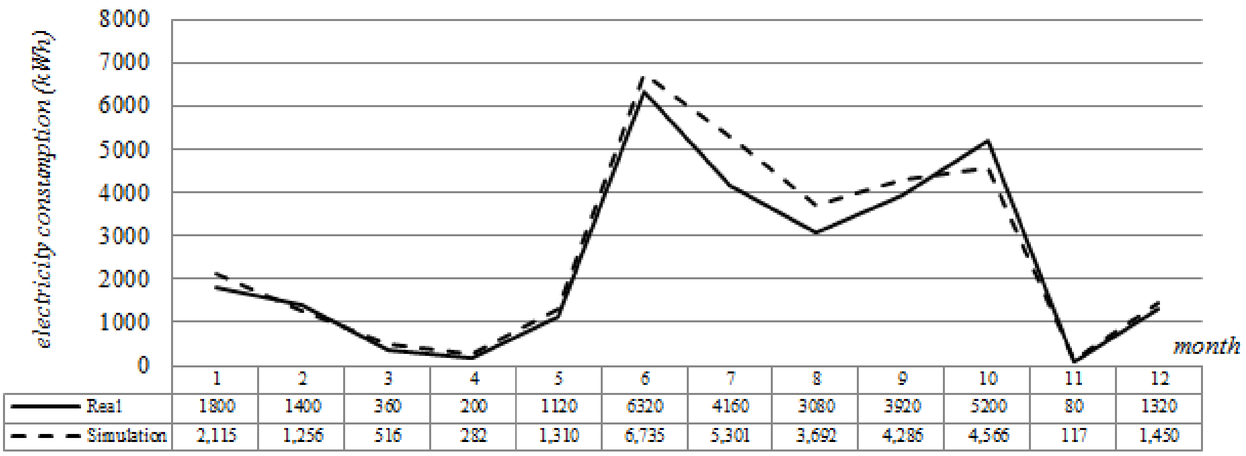
3.2. Establishment of a Basic GHE Energy Model

To analyze the effect of the GSHP system on the target building, a basic energy model that reflects the current energy consumption pattern should be established. Toward this end, this study used the energy simulation software program: (i) GLHEpro which was developed by the International Ground Source Heat Pump Association (IGSHPA) in the U.S. [68]; (ii) EnergyPlus which was developed by the U.S. Department of Energy [69]. GLHEpro uses an incremental search method to change the borehole depth and then runs a simulation. The max and min EWT results are compared with the desired values, iterating until it finds a solution that matches EWT requirements. EnergyPlus was developed to be available at any stage of the design process. In this study, "Y" university gym facility has replaced 100% of the annual heating and cooling energy consumption with the GSHP system. As a result, electric energy is consumed only by a heat pump that connects GHE to the "Y" university gym facility. Therefore, in this study, a basic energy model should be established for electricity energy consumption of the heat pump.

To verify the feasibility of the energy simulation results, the coefficient of variation of the root mean square error (CV(RMSE)) wasused (Equation (4)). As shown in Figure 3, the CV(RMSE) values were 19.26% within the tolerance limits (25%) [7]. Thus, it was determined that the basic model was feasible.

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(y_{\mathrm{estimate\_usage},i} - y_{\mathrm{actual\_usage},i})^2}{n-1}}}{\bar{y}_{\mathrm{actual\_usage}}} \times 100 \quad (4)$$

where, $y_{\mathrm{estimate\_usage},i}$ is electricity consumption of each month (simulation-based data), $y_{\mathrm{actual\_usage},i}$ is electricity consumption of each month (actual data), $\bar{y}_{\mathrm{actual\_usage}}$ is average of actual electricity consumption for 1 year, *n* is the number of data (months).



	1	2	3	4	5	6	7	8	9	10	11	12
——— Real	1800	1400	360	200	1120	6320	4160	3080	3920	5200	80	1320
– – – Simulation	2,115	1,256	516	282	1,310	6,735	5,301	3,692	4,286	4,566	117	1,450

Figure 3. (CV)RMSE: electricity consumption of heat pump ("Y"university gym facility).

3.3. Establishment of GHE Design Scenarios Considering EWT

In Section 2, this study established the basic information and selecting key factors affecting GHE performances. In this case, GHE is a system that provides heat to the heat pump in the building or recovers heat through direct heat exchange from heat sources. GHE should be designed to satisfy the energy demand of the building and comprehensively consider the effects of key factors in order to create an optimal scenario in terms of environmental and cost effectiveness.

In order to design a GSHP system that can satisfy the energy demand of the target facility, scenarios for GHE were created in a condition of the existing facility (*i.e.*, heat pumps and land). As mentioned above, GHE is designed based on EWT and the characteristics of boreholes. The number of GHE scenarios available in a situation when EWT fluctuates, increases considerably with by taking into account the energy demand of the target facility, the EWT and the characteristics of boreholes (refer to Table 3, Tables A1–A4). For a direct comparison with a case with an existing GHE (Scenario #4), GHE scenarios were selected on the basis of borehole length according to a change in EWT for a GHE that satisfies the energy demand of target facility. Furthermore, the characteristics of a borehole except for the length were fixed to analyze the change (refer to Table 4). Based on five scenarios as follows, an environmental and economic assessment was conducted to select the optimal GHE in terms of environmental and economic effects.

4. Environmental and Economic Assessment for Selecting the Optimal GHE by Considering EWT

4.1. System Boundary Conditions for Life-Cycle Assessment (LCA) and Life-Cycle Cost (LCC) Analyses

Since the initial investment cost of the GSHP system is quite expensive, the feasibility study needs to be conducted from the life-cycle perspective. Moreover, in recent years, environmental implication has become one of the primary concerns of many governments. Therefore, this study conducted the life-cycle environmental and economic assessment and the following two methods were used: (i) Life-cycle assessment (LCA), a method of calculating the environmental impacts throughout the whole life cycle of a product; (ii) Life-cycle cost (LCC) analysis, a method of calculating the economic value throughout the whole life cycle of a product.

Table 3. Scenarios (length of borehole) of ground heat exchanger (GHE) taking into consideration (entering water temperature) EWT (23 °C) and characteristics of borehole.

Maximum Entering Water Temperature: 23 °C, Minimum Entering Water Temperature: 5 °C														
Number of Boreholes: Arrangement (U)	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size** PN10, DN25				**U-Tube Type and Size** PN10, DN32				**U-Tube Type and Size** PN10, DN40			
			Borehole Diameter				**Borehole Diameter**				**Borehole Diameter**			
			125 mm		150 mm		125 mm		150 mm		125 mm		150 mm	
			U-Pipe Spacing				**U-Pipe Spacing**				**U-Pipe Spacing**			
			3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm
22 (EA): 8 × 8	4 m	1 W/mK	249.1	227.3	251.9	232.6	212.1	194.1	215.1	198.7	182.5	168.3	185.2	173.3
		1.4 W/mK	216.7	196.9	217.7	199.7	189.0	174.6	189.8	177.1	166.2	154.2	167.0	156.5
		1.8 W/mK	195.8	181.1	195.8	182.4	174.7	162.1	166.6	163.0	155.8	145.3	155.2	145.9
	5 m	1 W/mK	247.6	225.4	250.5	231.1	210.4	192.5	213.4	197.2	180.3	166.0	183.1	170.8
		1.4 W/mK	214.9	195.2	216.1	198.1	187.3	172.2	188.2	174.8	164.0	152.2	164.8	154.4
		1.8 W/mK	194.4	179.0	194.3	180.2	172.3	159.8	172.0	160.7	153.8	143.6	153.3	144.2
	6 m	1 W/mK	246.6	224.0	249.5	229.9	209.1	191.4	207.8	195.8	179.2	165.1	181.9	169.7
		1.4 W/mK	212.8	194.3	214.7	196.9	186.0	171.1	182.3	173.9	163.0	151.1	163.8	153.4
		1.8 W/mK	193.2	177.9	193.1	179.0	171.5	158.7	166.6	159.6	152.7	142.5	152.2	143.1

Table 4. Target scenarios (length of borehole) of GHE considering EWT and characteristics of borehole.

Number of Scenario	**Max./Min. Entering Water Temperature**	**Number of Boreholes: Arrangement (U)**	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size**	**Borehole Diameter**	**U-Pipe Spacing**	**Borehole Length**
Scenario #1	30/5 °C	22 (EA): 8 × 8	6 m	1.8 W/mK	PN10, DN25	150 mm	20 mm	90 m
Scenario #2	27/5 °C							107 m
Scenario #3	25/5 °C							123 m
Scenario #4 (exist GHE)	23/5 °C							143 m
Scenario #5	20/5 °C							195 m

4.1.1. Establishment of System Boundary and Assumptions for LCA

To assess the life-cycle environmental effect, the LCA process was conducted by following four steps defined by ISO 14040: (i) Goal and scope definition; (ii) Life-cycle inventory (LCI) analysis; (iii) Life-cycle impact assessment (LCIA); (iv) Results and interpretations [70–72]. The system boundary of the LCA showed the depth and breadth as follows (refer to Figure 4): (i) Life-cycle stages (including material manufacturing, use and maintenance stage); (ii) Building industry (including building level, product level, and material level); (iii) Life-cycle inventory (including emissions from material manufacturing, resources use for material manufacturing, and emissions from energy combustion used in whole life cycle); (iv) Phase of design process (including design development stage); (v) Life-cycle impact categories (including RDP, GWP, ODP, AP, EP, and POCP).

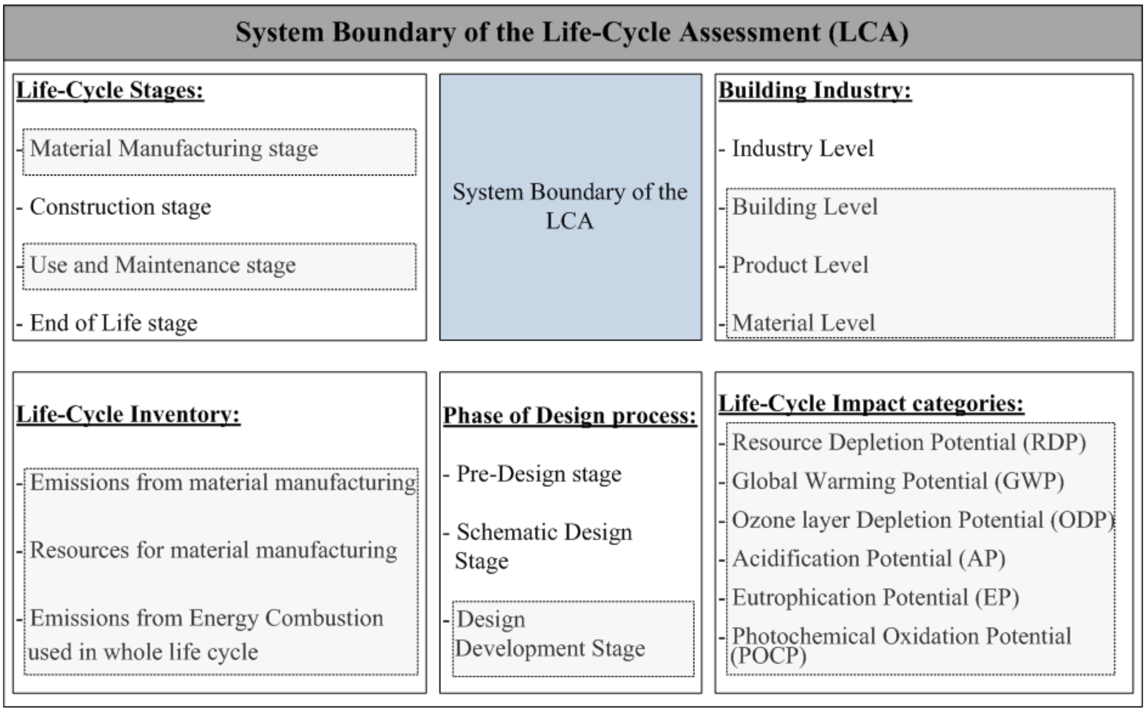


Figure 4. System boundary of the LCA.

- Step 1. Goal and scope definition: Based on the information available in whole life cycle, environmental impact generated from the material manufacturing phase and use and maintenance stage are analyzed. The functional unit is defined as "the entire building supplied from design and use and maintenance for a whole service life".
- Step 2. LCI analysis: Using the LCI analysis results by life-cycle phase, the environmental-impact substances can be calculated. First, using input-output (I-O) LCA, energy source quantity utilized to produce the material for each life-cycle phase was calculated. Second, employing a process-based LCA, the national LCI database of South Korea established that the environmental-impact substances produced in the material and energy production process can be calculated (refer to Equation (5)) [71,72].

$$E_i = \sum_k (QE_k \times EP_{ik} + QE_k \times EC_{ik}) \tag{5}$$

where E_i is the emission of substance (i), QE_k is the quantity of energy source (k), EP_{ik} is the emission factor of substance (i) emitted in producing one unit of energy source (k), and EC_{ik} is the emission factor of substance (i) emitted in consuming one unit of energy source (k).

- Step 3. Life-cycle impact assessment: LCIA converts the environmental-impact substances from the LCI analysis into the environmental impacts. LCIA is made up four categories: (i) Classification; (ii) Characterization; (iii) Normalization; (iv) Weighting [70,71]. In this study, classification and characterization were used to calculate the characterized environmental impact. The process of classification and characterization was calculated by Equation (6) [71,72]. To calculate characterized impacts (CCI_l), the characterization factor ($CF_{l,i}$) of each substance is required. Based on the "environmental labeling type III" standard, the characterized environmental impacts on six environmental-impact categories (*i.e.*, RDP, GWP, ODP, AP, EP, and POCP) were presented.

$$CCI_l = \sum_i E_i \times CF_{l,i} \tag{6}$$

where CCI_l is the characterized impact of impact category (l), E_i is the emission of substance (i), and $CF_{l,i}$ is the characterization factor of substance (i) to impact category (l).

- Step 4. Results and interpretations: Using the estimated environmental impact, environmental and economic values are calculated. Environmental cost signifies the cost generated using end-point LCA methodology [70,73,74]. In this study, the environmental-cost conversion factor proposed in EPS 2000 was used to convert the environmental impact to environmental cost [75] (refer to Table A5). By analyzing the relative degree of the impact on the global environment of the environmental-impact categories, all the environmental impacts can be converted into environmental cost.

4.1.2. Establishment of System Boundary and Assumptions for LCC

For the calculation of the life-cycle economic value using LCC analysis, the following system boundaries and assumptions were established: (i) analysis approach; (ii) analysis period; (iii) interest rate; and (iv) significant cost of ownership (refer to Table A6) [71].

- Analysis approach: For the analysis approach, net present value (NPV) was selected for the LCC analysis. NPV is the method used to convert the future value of a design alternative into the present value by considering the discount rate and the time value (refer to Equation (7)). If NPV > 0, the project is deemed feasible; if NPV = 0, the break-even point is deemed to have been reached [76].

$$NPV = \sum_{t=0}^{n} \frac{BES_t + BET_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{CI_t + CRr_t + CRt_t}{(1+r)^t} \tag{7}$$

where NPV is the net present value, BES_t is the benefit from the energy savings in year t, BET_t is the benefit from the emissions trading in year t, CI_t is the cost of the initial investment in year t, $\mathrm{CR}r_t$ is the cost of the repair in maintenance phase in year t, $\mathrm{CR}t_t$ is the cost of the replacement in maintenance phase in year t, r is the real discount rate, and n is the period of the life-cycle analysis.

- Analysis period: Generally, the analysis period for the LCC analysis can be established based on the service life of a product, which is based on the building's structural type [71]. In this study, a 40-year time frame was used for the analysis period of the LCC.
- Interest rate (refer to Equation (8)): In this study, the real discount rate was calculated using the nominal interest rate and various inflation rates (refer to Table A6) [71]. It can be used for converting various benefits and costs into present values.

$$i = \frac{(1+i_n)}{(1+f)} - 1 \tag{8}$$

where i is the real discount rate, i_n is the nominal interest rate, and f is the inflation rate (*i.e.*, electricity price growth rate, gas price growth rate, carbon dioxide emission trading price growth rate).

- Significant cost of ownership: From the life-cycle perspective, the initial investment cost and the use and maintenance cost need to be considered. The material consumption information was collected from the bill of quantities of the GHE and heat pump. The energy consumption information, on the other hand, was established through energy simulation, which was allocated to the energy cost among the use costs. Meanwhile, the repair rate, repair cycle, and replacement cycle of each material should be considered to calculate the cost in the maintenance phase. In this study, resources such as "Public Procurement Service", "Ministry of National Defense" and "Implementing Regulations of the Housing Act in Korea (Appendix 5)", which are provided by respectable institutions, were used [71].

4.2. Optimal GHE in Terms of Environmental and Economic Effects

Among the 540 GHE design alternatives (U arrangement and 22 EA borehole) (refer to Table 3 and Tables A1–A4), the analysis results of five scenarios including existing GHE system are presented as an example (refer to Table 4). As shown in Table 4, the existing GHE (scenario #4) has a maximum EWT of 23 °C and the characteristics of the borehole are 22 EA boreholes, 6 m borehole spacing, 1.8 W/mK grout conductivity and 143 m borehole length. For a direct comparison with the existing GHE (Scenario #4), GHE scenarios were selected on the basis of borehole length according to a change in EWT; furthermore, the characteristics of the borehole except for the length were fixed to analyze the change.

Table 5 shows the results of the design alternative analysis on the GHE in the target facility. The analysis results can be presented in the following three aspects: (i) life-cycle environmental cost; (ii) life-cycle economic cost; and (iii) life-cycle environmental and economic cost. Table A6 shows the boundary conditions of LCC and LCA.

- First, life-cycle environmental cost: Saving effect of life-cycle environmental cost of Scenario #3 was determined at 2.2% compared with the existing GHE (Scenario #4). Although the initial investment environmental cost is higher than that of the existing GHE, the operation and maintenance environmental cost is lower than that of the existing GHE.

Table 5. Life-cycle environmental and economic cost of scenarios.

Scenario	**Classification**	**Environmental Impact Category**						**Environmental Cost**	**Economic Cost**	**Total Cost**
		RDP (kg-Sb-eq)	**GWP (kg-CO$_2$-eq)**	**ODP (kg-CFC11-eq)**	**AP (kg-SO$_2$-eq)**	**EP (kg-PO$_4^{3}$-eq)**	**POCP (kg-C$_2$H$_4$-eq)**			
Scenario #1	Initial cost	260	151,144	-	804	62	227	23,136	94,638	117,774
	O and M cost	1275	724,427	-	1244	231	2	108,246	104,664	212,909
	Total cost	1535	875,572	-	2047	293	229	131,381	**199,302**	330,683
Scenario #2	Initial cost	288	168,762	-	898	69	250	25,819	103,296	129,115
	O and M cost	1150	653,432	-	1122	209	2	97,638	96,079	193,716
	Total cost	1437	822,194	-	2020	277	252	123,457	199,375	**322,831**
Scenario #3	Initial cost	315	186,416	-	993	76	274	28,508	111,969	140,477
	O and M cost	1096	622,723	-	1069	199	2	93,049	92,421	185,469
	Total cost	1411	809,139	-	2062	275	276	**121,557**	204,390	325,947
Scenario #4	Initial cost	352	210,223	-	1121	85	305	32,133	123,610	155,743
	O and M cost	1085	616,970	-	1059	197	2	92,189	91,824	184,014
	Total cost	1437	827,193	-	2180	282	307	124,322	215,434	339,756
Scenario #5	Initial cost	439	265,811	-	1419	107	379	40,600	150,977	191,578
	O and M cost	966	549,094	-	943	175	2	82,047	83,713	165,760
	Total cost	1405	814,905	-	2362	282	381	122,647	234,690	357,337

Notes: Unit (US$); operation and maintenance phase (O and M); resource depletion potential (RDP); global warming potential (GWP); ozone layer depletion potential (ODP); acidification potential (AP); eutrophication potential (EP); and photochemical oxidation potential (POCP).

- Second, life-cycle economic cost: Saving effect of life-cycle economic cost of Scenario #1 was determined to be 7.5% as compared to the existing GHE (Scenario #4). Although the initial investment cost is higher than that of the existing GHE, the operation and maintenance cost is lower than that of the existing GHE.
- Third, life-cycle environmental and economic cost: Saving effect of total cost of Scenario #2 was determined to be 5.0% compared with the existing GHE (Scenario #4). Although the initial investment cost is higher than that of the existing GHE, the operation and maintenance cost is lower than that of the existing GHE.

In conclusion, compared to the existing design, the design alternatives of GHE in the target facility were shown to be advantageous in the life-cycle environmental and economic aspects. All of the initial costs tend to decrease when max EWT decreases; however, all of the O and M costs tend to increase when max EWT increases. In other words, as the amount of EWT that enters a heat pump is reduced during the summer, the efficiency of a heat pump becomes higher and borehole length becomes greater.

5. Conclusions

This study aims to assess the environmental and economic effects of the use of GHE for selecting the optimal GHE. This study was undertaken in three steps: (i) establishing the basic information and selecting key factors affecting GHE performances; (ii) making possible alternatives of the GHE installation by considering EWT; and (iii) using life-cycle assessment and life-cycle cost for a comprehensive evaluation of the environmental and economic effects on the GHE.

By conducting a multilateral analysis on the results of the energy simulation, the energy generation effect considering EWT was evaluated by applying the GSHP system. Furthermore, LCA (e.g., RDP, GWP, ODP, AP, EP, and POCP) with the analysis of the LCC was conducted to assess the environmental and economic effects of the implementation of the GSHP system to "Y" university gym facility using NPV methods (refer to Table A6). The analysis results can be summarized as follows:

- Life-cycle environmental cost: Saving effect of life-cycle environmental cost of Scenario #3 was determined to be 2.2% compared with existing GHE (Scenario #4).
- Life-cycle economic cost: Saving effect of life-cycle economic cost of Scenario #1 was determined at 7.5% compared with existing GHE (Scenario #4).
- Life-cycle environmental and economic cost: Saving effect of total cost of scenario #2 was determined at 5.0% compared with existing GHE (Scenario #4).

In conclusion, all of the initial costs tend to decrease when max EWT (for cooling system) decreases; however, all of the O and M costs tend to increase when max EWT increases. In other words, as there is less EWT entering a heat pump during the summer, the efficiency of a GSHP system increases and the borehole lengthens.

The results of this study could benefit potential GSHP system users and give new value in terms of system application in several ways: (i) decide which location is proper for the implementation of the GSHP system considering the characteristics of the regional factor; (ii) maximize the environmental and economic benefit and the efficiency by considering key design factors such as EWT and characteristics of borehole.

Meanwhile, the following research is recommended for future studies: (i) sensitivity analysis of the GSHP system considering the recent trends in the reduction of the initial investment cost and government's subsidy; (ii) a multi-objective optimization system for the ultimate decision maker to analyze uncountable scenarios in terms of several key factors (EWT and characteristics of borehole).

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP; Ministry of Science, ICT & Future Planning) (No.NRF-2015R1A2A1A05001657).

Author Contributions

All authors read and approved the manuscript. All authors contributed to this work, discussed the results and implications and commented on the manuscript at all stages. Jimin Kim discussed the main idea behind the work and reviewed and revised the manuscript. Taehoon Hong gave precious advice on the establishment of framework as well as design process. Myeongsoo Chae made the model with the co-authors and explicated the GSHP system more thoroughly. Choongwan Koo made the LCC and LCA analysis models for assessing the alternative of GSHP system. Jaemin Jeong led the development of the paper and conducted the LCC and $LCCO_2$ analyses.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix

Table A1. Scenarios (length of borehole) of GHE considering EWT (30 °C) and characteristics of borehole.

Maximum Entering Water Temperature: 30 °C, Minimum Entering Water Temperature: 5 °C														
Number of Boreholes: Arrangement (U)	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size** PN10, DN25				**U-Tube Type and Size** PN10, DN32				**U-Tube Type and Size** PN10, DN40			
			Borehole Diameter				**Borehole Diameter**				**Borehole Diameter**			
			125 mm		150 mm		125 mm		150 mm		125 mm		150 mm	
			U-Pipe Spacing				**U-Pipe Spacing**				**U-Pipe Spacing**			
			3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm
22 (EA): 8 × 8	4 m	1 W/mK	157.4	142.4	159.3	145.8	134.1	123.0	135.7	126.3	114.7	105.7	116.4	108.8
		1.4 W/mK	136.5	125.1	137.1	126.9	119.1	109.7	119.7	111.3	104.2	96.9	104.8	98.2
		1.8 W/mK	124.3	113.9	124.3	114.6	109.8	101.5	109.6	102.1	97.9	91.8	97.5	92.2
	5 m	1 W/mK	156.1	141.4	157.9	144.7	133.2	121.9	134.8	125.1	113.5	104.3	115.3	107.5
		1.4 W/mK	135.6	123.9	136.2	125.8	117.9	108.5	118.5	110.1	102.9	95.7	103.4	97.0
		1.8 W/mK	123.2	112.7	123.1	113.4	108.5	100.2	108.4	100.8	96.6	90.6	96.3	91.0
	6 m	1 W/mK	155.4	140.7	157.3	144.0	132.4	120.8	134.0	124.2	112.7	103.8	114.4	106.9
		1.4 W/mK	134.9	123.0	136.5	124.8	117.1	107.8	117.7	109.4	102.3	95.3	102.9	96.6
		1.8 W/mK	122.3	111.9	122.2	112.7	107.9	99.8	107.7	100.3	96.2	90.1	95.9	**90.4**

Table A2. Scenarios (length of borehole) of GHE considering EWT (27 °C) and characteristics of borehole.

Maximum Entering Water Temperature: 23 °C, Minimum Entering Water Temperature: 5 °C														
Number of Boreholes: Arrangement (U)	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size** PN10, DN25				**U-Tube Type and Size** PN10, DN32				**U-Tube Type and Size** PN10, DN40			
			Borehole Diameter 125 mm		150 mm		**Borehole Diameter** 125 mm		150 mm		**Borehole Diameter** 125 mm		150 mm	
			U-Pipe Spacing 3 mm	20 mm	3 mm	20 mm	**U-Pipe Spacing** 3 mm	20 mm	3 mm	20 mm	**U-Pipe Spacing** 3 mm	20 mm	3 mm	20 mm
22 (EA): 8 × 8	4 m	1 W/mK	186.5	169.1	188.5	173.1	158.4	144.6	160.7	148.5	135.7	122.4	133.7	125.8
		1.4 W/mK	161.8	147.0	162.7	149.3	140.3	130.4	141.0	132.2	124.1	112.9	121.5	114.4
		1.8 W/mK	146.1	134.9	146.0	135.7	130.5	120.8	130.3	121.5	114.0	107.0	113.5	107.4
	5 m	1 W/mK	185.0	167.5	187.2	171.5	156.8	143.3	159.0	147.1	132.0	122.1	133.6	125.6
		1.4 W/mK	160.0	145.7	161.0	147.9	139.1	129.1	139.8	131.0	120.5	112.3	121.1	113.9
		1.8 W/mK	144.8	133.8	144.8	134.5	129.2	119.4	129.0	120.0	113.4	106.3	113.0	106.7
	6 m	1 W/mK	184.1	166.9	186.3	170.8	156.0	142.5	158.2	146.3	131.9	121.9	133.6	125.3
		1.4 W/mK	159.3	144.9	160.0	147.1	138.3	128.0	139.0	129.9	120.1	111.9	120.8	113.5
		1.8 W/mK	144.1	132.9	144.0	133.7	128.0	118.3	127.9	118.9	113.0	105.9	112.6	**107.0**

Table A3. Scenarios (length of borehole) of GHE considering EWT (25 °C) and characteristics of borehole.

Maximum Entering Water Temperature: 23 °C, Minimum Entering Water Temperature: 5 °C														
Number of Boreholes: Arrangement (U)	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size** PN10, DN25				**U-Tube Type and Size** PN10, DN32				**U-Tube Type and Size** PN10, DN40			
			Borehole Diameter 125 mm		150 mm		**Borehole Diameter** 125 mm		150 mm		**Borehole Diameter** 125 mm		150 mm	
			U-Pipe Spacing 3 mm	20 mm	3 mm	20 mm	**U-Pipe Spacing** 3 mm	20 mm	3 mm	20 mm	**U-Pipe Spacing** 3 mm	20 mm	3 mm	20 mm
22 (EA): 8 × 8	4 m	1 W/mK	212.6	192.9	215.4	197.0	181.5	166.3	184.1	170.4	155.1	142.6	157.5	146.8
		1.4 W/mK	185.2	168.8	186.1	171.3	161.3	148.1	162.1	150.3	140.8	132.2	141.5	133.8
		1.8 W/mK	168.0	154.0	168.0	155.0	148.1	137.7	147.9	138.3	133.4	125.1	132.9	125.6
	5 m	1 W/mK	211.2	191.5	213.8	195.7	179.8	164.4	182.2	168.6	153.4	141.2	155.7	145.3
		1.4 W/mK	183.5	166.9	184.4	169.5	159.3	146.4	160.2	148.6	139.5	130.8	140.1	132.6
		1.8 W/mK	166.1	152.3	166.1	153.3	146.5	136.5	146.3	137.1	132.1	123.5	131.6	124.0
	6 m	1 W/mK	210.1	190.6	212.8	197.8	178.8	163.6	181.1	167.7	182.9	140.3	154.8	144.4
		1.4 W/mK	182.4	166.3	183.4	168.5	158.4	145.5	159.3	147.7	138.5	129.6	139.2	131.5
		1.8 W/mK	165.3	151.4	165.2	152.4	145.6	135.5	145.4	136.1	130.9	122.1	130.4	**122.6**

Table A4. Scenarios (length of borehole) of GHE considering EWT (20 °C) and characteristics of borehole.

Maximum Entering Water Temperature: 23 °C, Minimum Entering Water Temperature: 5 °C														
Number of Boreholes: Arrangement (U)	**Borehole Spacing**	**Grout Conductivity (W/mK)**	**U-Tube Type and Size** PN10, DN25				**U-Tube Type and Size** PN10, DN32				**U-Tube Type and Size** PN10, DN40			
			Borehole Diameter				**Borehole Diameter**				**Borehole Diameter**			
			125 mm		150 mm		125 mm		150 mm		125 mm		150 mm	
			U-Pipe Spacing				**U-Pipe Spacing**				**U-Pipe Spacing**			
			3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm	3 mm	20 mm
22 (EA): 8 × 8	4 m	1 W/mK	338.8	306.9	342.7	314.1	287.2	263.6	291.4	270.1	247.3	230.1	250.9	236.0
		1.4 W/mK	293.8	267.9	295.4	271.3	255.8	237.6	257.2	240.7	226.7	209.7	228.5	213.0
		1.8 W/mK	266.5	245.9	266.4	247.2	237.7	220.9	237.5	222.1	211.9	198.8	211.1	199.1
	5 m	1 W/mK	337.1	305.4	341.1	312.4	285.5	261.8	289.6	268.7	245.5	227.2	249.0	233.9
		1.4 W/mK	291.6	266.1	293.3	269.9	254.0	235.5	255.4	238.8	224.2	206.9	225.4	210.6
		1.8 W/mK	264.6	243.8	264.5	245.3	235.7	218.3	235.4	219.5	209.6	195.9	208.8	196.6
	6 m	1 W/mK	335.9	304.2	340.0	311.2	284.3	260.5	288.4	267.7	274.3	225.5	247.6	232.3
		1.4 W/mK	290.3	264.9	292.0	268.9	252.8	234.0	254.1	237.0	222.2	205.1	223.7	208.7
		1.8 W/mK	263.4	242.3	263.2	243.8	234.2	216.4	233.9	217.6	207.3	194.1	206.5	**194.9**

Table A5. Environmental cost conversion factor.

Environmental Impact	Environmental Cost Conversion Factor
resource depletion potential (RDP)	2.439 US$/kg-Sb-eq
global warming potential (GWP)	0.167 US$/kg-$CO_2$-eq
ozone layer depletion potential (ODP)	145.172 US$/kg-CFC11-eq
acidification potential (AP)	0.032 US$/kg-$SO_2$-eq
eutrophication potential (EP)	0.029 US$/kg-$PO_4^3$-eq
photochemical oxidation potential (POCP)	2.675 US$/kg-$C_2H_4$-eq

Table A6. Boundary conditions of LCC and LCA.

Classification	Detailed Classification	Detailed Description
Analysis Approach		Present Worth Method (NPV_{40})
Analysis Period		40 years
Realistic Discount Rate	Interest	3.30%
	Electricity	0.66%
	Gas	0.11%
	$KCER_s$	2.66%
Significant Cost of Ownership	Initial construction cost	Initial investment cost
	Operation and maintenance cost	Replacement/repair cost
		Energy consumption cost
	Operation and maintenance benefit	Gas savings, electricity savings
		Benefit from $KCER_s$

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