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Combining direct ground cooling with ground-source heat pumps and district heating: Energy and economic analysis

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ABSTRACT

Direct ground cooling (DGC) is a method used in cold climates to provide cooling to buildings without the use of any mechanical refrigeration. When DGC is utilized for providing cooling, ground-source heat pumps (GSHPs) and district heating (DH) are the two commonly used technologies for providing heating to the buildings. This article investigates the coupling of DGC with GSHPs and DH in terms of purchased energy and lifecycle costs. An office building equipped with active chilled beams for cooling and radiators for heating is used as a reference. Six cases based on different combinations of building envelope characteristics and thus different building heating and cooling loads are considered. The results show that using DGC-DH significantly reduces the amount of purchased electricity. However, the total energy cost is lower when DGC-GSHP is used. In addition, the DGC-GSHP can be more viable when the ground loads are well balanced. Investment costs, including borehole installation and equipment costs, are lower for the DGC-DH in the majority of the investigated cases. The lifecycle cost is lower for the DGC-DH in most of the investigated cases due to lower equipment costs.

1. Introduction

Direct ground cooling (DGC) is a method used in cold climates to provide cooling to buildings without the use of any mechanical refrigeration. In a DGC system, cooling is provided by circulating a heat carrier fluid through an array of ground heat exchangers [1]. The heat from the warm heat carrier fluid is rejected to the ground, which is at a lower temperature. DGC only requires a modest amount of electricity for driving the circulation pump(s). This technology is mainly viable in cold and mild climates as the difference between ground and room temperatures is high enough to compensate for the building cooling loads [2–4]. When using DGC, space heating and domestic hot water are provided by a supplementary source.

Two commonly used heating sources in Sweden are district heating (DH) and ground source heat pumps (GSHPs). DH is the most common heating source in Sweden. DH systems use heat from solid biofuel boilers and combined heat and power plants, waste incineration and industrial processes, and renewable sources like solar, geothermal, and biomass, among others, to provide heating and domestic hot water [5–7]. GSHPs are the second most commonly used heating source in Sweden. GSHPs use electricity to drive the heat pump compressor and use the ground as the heat source.

Energy comparison on the building level is complicated for a building using either the DGC coupled with DH or DGC coupled with the GSHPs. This is mainly because the energy plants based on the two combinations rely on different energy sources to provide heating and cooling to buildings. The energy plant based on the combination of DGC and GSHP uses electricity to drive the heat pump and run the circulation pump(s). The electricity is predominantly used by the GSHP as the DGC system requires only a modest amount of electricity to drive the circulation pump(s) [8–11]. On the other hand, the energy plant based on the combination of DGC and DH uses both thermal and electrical energies. The main energy cost is related to the purchased heat from the DH network. The lifecycle cost analysis and comparisons of the two combinations require taking into account not only the energy demand of each combination but also the present and future energy tariffs of electricity and DH.

Most existing techno-economic studies on the topic have been focused on the application of the GSHPs in residential buildings. These studies have mainly addressed technical aspects [12–14], energy performance [15–17], and LCC [18–23]. Only a handful of studies have investigated the energy demand of office/commercial buildings

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equipped with GSHPs or DGC systems. Spitler and Gehlin [24] performed a comprehensive study on a building with a GSHP and direct-ground cooling. The study discussed the importance of considering appropriate boundary schemes to define the energy performance of the heating and cooling systems. Liu and Zhang [25] investigated an office building equipped with a DGC and the DH. They analyzed the energy demand of the building for heating and cooling applications and pointed out the considerable influence of the DGC on reducing the purchased energy for comfort cooling. Arghand et al. [26] carried out a simulation-based study and compared the energy demand of a building with a DGC or a chiller. A substantial reduction in electricity use was achieved by replacing the chiller with the DGC, which resulted in a significantly higher building energy performance in the cooling mode.

The above-mentioned studies have only investigated one system, i.e., DGC with DH or DGC with GSHP(s). Moreover, the systems were studied from the energy performance perspective, but the economic analysis was not included. In reality, both energy and economic analysis are crucial when choosing between the two combinations. However, the existing literature lacks a sufficient understanding of these topics.

Some other studies have had a somewhat different focus and have analyzed the techno-economic challenges associated with the inclusion of heat pumps in district heating networks [27–30]. Examples of these challenges include developing cost-effective business models for incorporation of heat pumps in district heating networks [31], implementing demand-side management solutions to facilitate the inclusion of distributed heat pumps [32], and optimizing heat pumps in district heating systems to lower production costs [33]. However, these studies are not directly applicable to the scope of the current study.

The aim of the current article is to compare a DGC integrated with a DH system or a GSHP system from the purchased energy and life cycle cost perspectives for office buildings in cold climates, like Sweden. To the best of the authors' knowledge, no study has been conducted to compare the DGC systems with DH and DGC systems with GSHPs from energy and economic perspectives. In this study, a side-by-side comparison is performed between the two system combinations considering the total purchased energy and lifecycle cost of the energy plants for each combination. A sensitivity analysis is made on the lifecycle costs of the two combinations for Swedish conditions considering various scenarios of future energy prices. The methodology of this study is detailed in Section 2. The results are discussed in Section 3, followed by discussions in Section 4 and the concluding remarks in Section 5.

2. Methods

This section first briefly describes the method used for building and energy systems simulation. Then, the method for the economic analysis is detailed.

2.1. Building and energy systems simulation model

In the absence of reliable and reproducible experimental data from office buildings with studied heating and cooling systems, i.e., DGC with GSHPs and/or DH, the authors chose to use well-established building models. The building model used in this study is based on the medium-sized office building model developed by the U.S. Department of Energy (DOE) [34]. However, certain modifications have been made to the model to represent typical office buildings in cold climates, e.g., Sweden.

The dimension of a building is an important factor in defining its heat balance. Generally, narrower buildings have larger perimeter areas and higher heat exchange rates with their surroundings. The original dimensions of the DOE model were approximately 49.9 m × 33.3 m (L × W). According to the energy analysis performed on the DOE model with various dimensions and presented in Ref. [35], the building with a dimension equal to or wider than 91 m × 18 m leads to a similar design for the building's heating and cooling systems. Buildings narrower than 91 m × 18 m are rare, and using them as case objects is impractical. The number of floors is increased from three to six to investigate the applicability of the DGC and GSHP for buildings with greater heating and cooling loads.

The studied building has dimensions of 91 m × 18 m × 22.2 m (L × W × H) and has an area of 1660 m^2, see Fig. 1. The building has 6 floors, and each floor consists of a large interior zone surrounded by four perimeter zones. The building envelope design parameters are aligned with the suggestions of the Swedish National Board of Housing (Boverket) and databases of Swedish commercial buildings [36–38].

Internal heat loads consist of heat from occupants (8.0 W/m^2), office equipment (7.4 W/m^2), and lights (8.6 W/m^2), based on the recommendations from ASHRAE Handbook- Fundamentals [39]. All the internal loads are scheduled from 8:00 to 17:00 only on weekdays. The use factor of equipment and occupancy is set at 80%. Lights have a use factor of 50% from June 1st until August 31st and 80% for the rest of the year. These use-factors are commonly used by designers in Sweden.

Table 1 lists the cases and the design parameters for each case. The cases differ from each other in the thermal properties of envelope materials (U-value) and solar transmittance of the glazing parts (G-value). The cases are formulated to represent different heating and cooling characteristics of a building. For a more complete description of these cases, readers are referred to Arghand et al. [35].

Fig. 2 shows the effect of various U-values and G-values on the building's annual energy and daily peaks [35]. G-value appears to be highly influential for the annual energy and peak cooling loads. However, it has an insignificant impact on the building heating demand. This is because the G-value determines the amount of solar heat gain in the zones. U-value affects both the cooling and heating demands. U-values are generally inversely proportional to the annual energy and peak cooling loads. Gothenburg has a cold climate and outdoor temperature, even in summer the outdoor temperature is often below the room cooling setpoint of 24 °C.

The building cooling terminal units are active chilled beams (ACBs). ACBs use on-off feedback controllers to regulate the water flow to meet the room air temperature setpoint of 24 °C. The supply water has a temperature of 16 °C and an "on-state" flow rate of 0.5 l/min per beam. The primary air from the air handling unit has a flow rate of 1.5 l/s.m^2 (0.5 air change rate per hour (ACH)) and a temperature of 20 °C. The air handling unit is equipped with a rotary heat recovery unit with a thermal efficiency of 75%. The cooling system operates from 6:00 until 17:00 only on weekdays.

The heating system uses water radiators designed for the hot water supply and return temperatures of 45 °C and 30 °C at the design condition, respectively. The radiators are equipped with thermostats with a setpoint temperature of 21 °C. The heating system is off from June to September.

The domestic hot water system is designed to provide the occupants

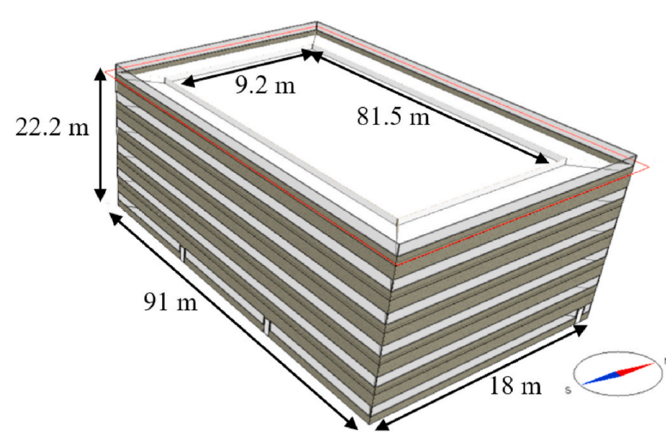

Fig. 1. Isometric view of the reference building.

Table 1
Main features of the external structure of the simulated building for each case.

Design parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Avg building U-value (W/ m^2. k)	0.2	0.2	0.4	0.4	0.6	0.6
Windows G-value	0.6	0.3	0.6	0.3	0.6	0.3
Internal gains (W/m^2)	11.7 (June–September) – 16 (Oct–May)					
Air temperature set-point winter/summer (°C)	21/24					
Cooling terminal unit	Active chilled beams (see Table 2)					
Heating terminal unit	Water radiators (see Table 2)					
Plant type	GSHP + DGC or DH + DGC					

with 3.8 l/person per day during the occupancy period from 8:00 to 17:00. The domestic hot water is provided at 55 °C. Table 2 summarizes the main input design parameters of the heating and cooling systems.

Two types of plants are used to provide heating and cooling to the building. The first plant uses DGC for cooling and DH system for heating. The main parts of the DGC are ground heat exchangers, circulation pumps, and a ground-load balancing system. The borehole field consists of groundwater-filled boreholes drilled in hard rock and fitted with double U-tubes. The boreholes are drilled at a depth ranging between 260 m and 300 m and a spacing of 6 m or 7 m, depending on the case. The heat carrier fluid for the DGC is water. Fig. 3 shows the schematic of the DGC.

The DGC is designed as a thermally balanced system in which the annual heat rejected to and extracted from the ground is equal. The rejected heat to the ground for providing cooling is extracted by the ground-load balancing system for pre-heating the ventilation air. A dry-cooler is also supplemented in some cases to extend the heat extraction if needed, see Fig. 3.

For the combination of DGC with DH, heating is provided by the DH network via a heat exchanger. At the design conditions, the heating system is designed to provide hot water to the radiators at 45 °C and the domestic hot water system at 55 °C, see Fig. 3.

For the combination of DGC with GSHP, the building heating and domestic hot water demands are provided using one or more GSHPs, and cooling using the DGC system. The GSHP consists of brine-to-water heat pumps connected to the ground heat exchangers, see Fig. 4. The nominal heating power of each heat pump is 100 kW with a nominal seasonal COP of 4.0. Depending on the design load, one or more heat pumps are used. Heat pumps are sized to provide 100% of the buildings' peak heating load. The minimum designed brine entering fluid temperature to the ground heat exchangers is −2 °C. Under design heating conditions, a temperature difference of 3 K is expected between the inlet and outlet borehole fluid temperature. The heating supply temperature from the heat pump is 45 °C.

The GSHP system mainly relies on direct cooling from the ground heat exchangers for space cooling. In addition, a cold recovery system utilizes the cold fluid leaving the heat pump. If the fluid temperature is lower than the liquid in the distribution tank, the control valve directs the fluid to circulate through a heat exchanger in the fluid tank, see Fig. 4. If the refrigerant temperature is higher than the liquid in the tank, it is directed back to the borehole system.

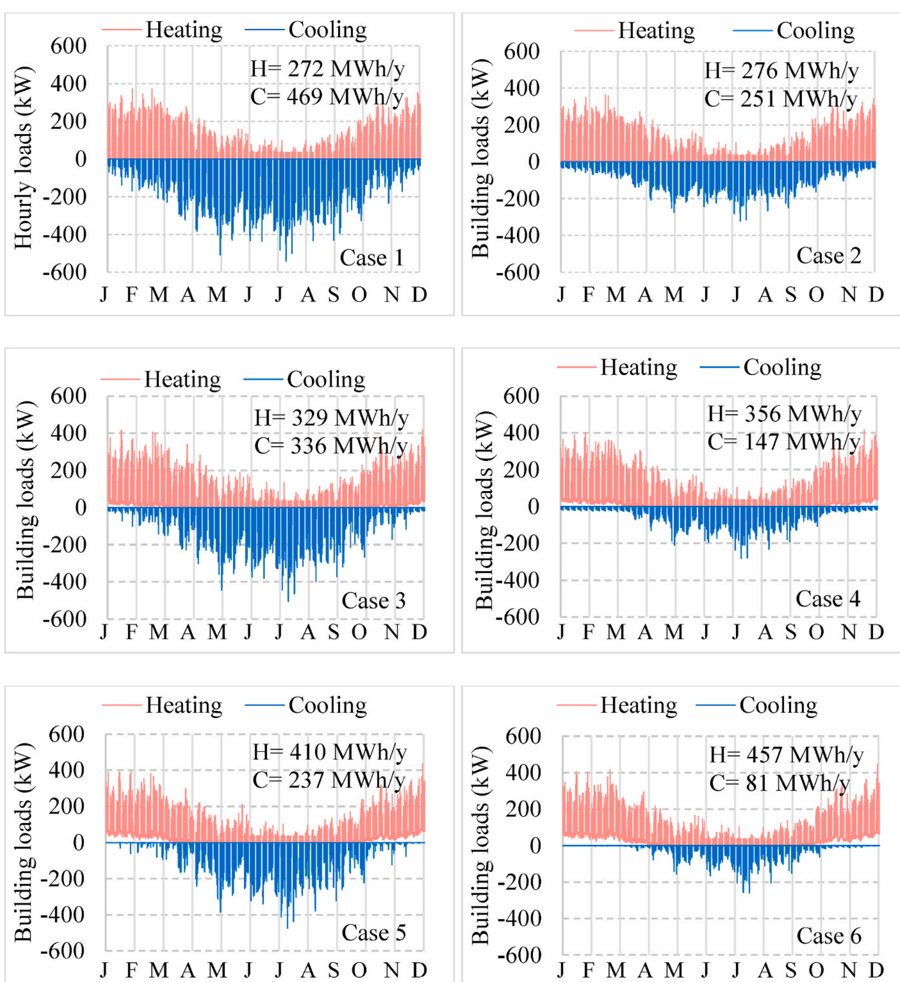

Fig. 2. Hourly heating and cooling loads for six cases summarized in Table 1.

Table 2
Specifications of the building heating, cooling, and air conditioning systems.

Active chilled beams	
Primary airflow rate (l/s.m^2)	1.5
Supply water temperature (°C)	16
Primary air temperature (°C)	20.0
$T_{return,\ water} - T_{supply,\ water}$ at maximum power (K)	3
Room temperature setpoint for cooling (°C)	24.0
Operation period (–)	06:00–17:00, weekdays
Water radiators	
Supply water temperature (°C)	45
Room temperature setpoint for heating (°C)	21.0
Temperature difference at design condition (K)	15
Operation period (–)	Always (except Jun–Sep)
Air handling unit	
System type	Balanced ventilation with rotary heat recovery
Primary/exhaust air flow rate (l/s.m^2)	1.5
Primary air temperature (°C)	20.0
Operation period	06:00–17:00, weekdays
Heat recovery efficiency (%)	75

2.2. Simulation tools and design considerations

Three simulation tools used in this study are IDA ICE building energy simulation version 4.8, the "IDA ICE borehole" extension, and Earth Energy Design (EED) borehole design software. IDA ICE and "IDA ICE borehole" are used to perform hourly simulations of the building and the ground-coupled system [40,41]. The outputs of these simulations are building heating and cooling loads and purchased electricity and heating demands on an hourly and yearly basis. Other simulation outputs are room temperature (air and operative) and thermal comfort levels in spaces.

The building hourly heating and cooling loads from the IDA ICE simulations are used as inputs for calculating the ground loads and sizing the boreholes. Sizing of the boreholes is carried out using the EED simulation tool [42]. EED uses precomputed step-response functions, also known as g-functions, to determine the required borehole lengths by iteratively adjusting the borehole configurations to meet the prescribed fluid temperature levels. The borehole sizing simulations are carried out for a life period of 30 years.

After performing borehole field simulation, the borehole sizes and design characteristics are used as inputs to the "IDA ICE borehole" extension. Using this extension allows for predicting the thermal and energy performance of the ground-coupled system [40,43]. It is important to note that the IDA ICE borehole extension in this study is not used for sizing boreholes since it is very time-consuming. The extension is only used to calculate the annual electrical energy demand of the borehole system and the building energy systems.

The ground heat exchangers for the DGC with DH are sized based on the building's hourly cooling demand with the maximum and minimum fluid temperature limits at 14 °C and 0 °C, respectively. The maximum temperature is set according to the building's peak hourly cooling loads and the sizing of the ACBs. The minimum temperature limit is set to prevent the water in the building loop from freezing. The design borehole fluid temperature limits for the DGC with GSHP are 14 °C and −2 °C. This minimum temperature limit is chosen to prevent the groundwater in the boreholes from freezing. Using ethanol 28% allows for decreasing the minimum borehole fluid temperature for the GSHP.

2.3. Economic analysis

Lifecycle cost (LCC) analysis is used to investigate and compare the energy plants based on the combinations of DGC with GSHPs and DH from an economic point of view. LCC in this study is calculated using the net present value (NPV) method. The LCC analysis considers only the energy plant part, and the building heating and cooling systems' costs are not included. This is because the building heating, cooling, and ventilation systems are the same and are designed with the same design parameters. The differences are related to the plants (DGC coupled with GSHP or DH). All prices and costs are given without value-added tax for ease of comparison with other countries.

LCC calculations primarily account for the investment costs and the operation costs of the two combinations, based on Eq. (1):

$$LCC = \sum \left(C_{investment} + C_{operation}\right)$$

The LCC includes boreholes' drilling and installation costs,

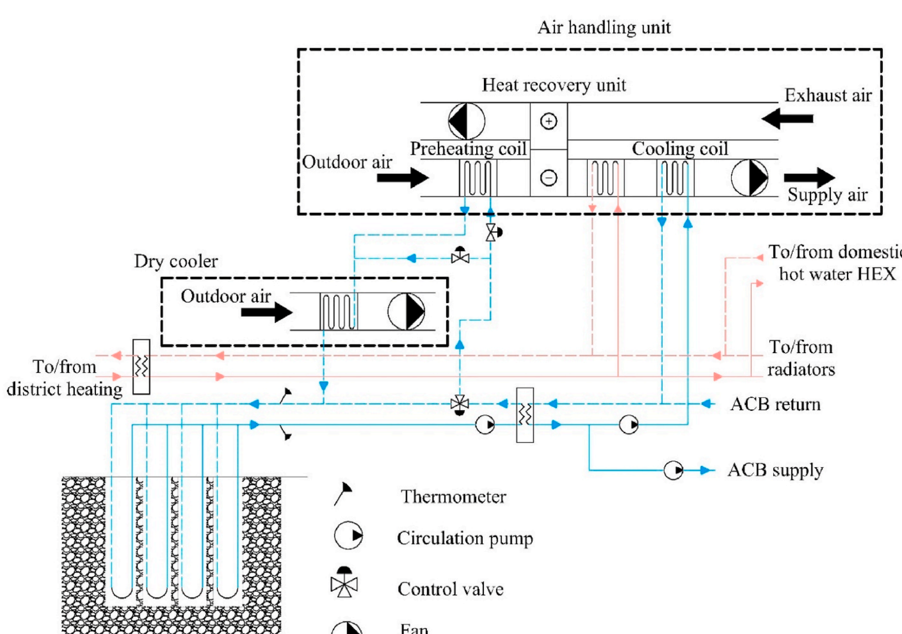

Fig. 3. Schematic of the plant consisting of the DGC and DH.

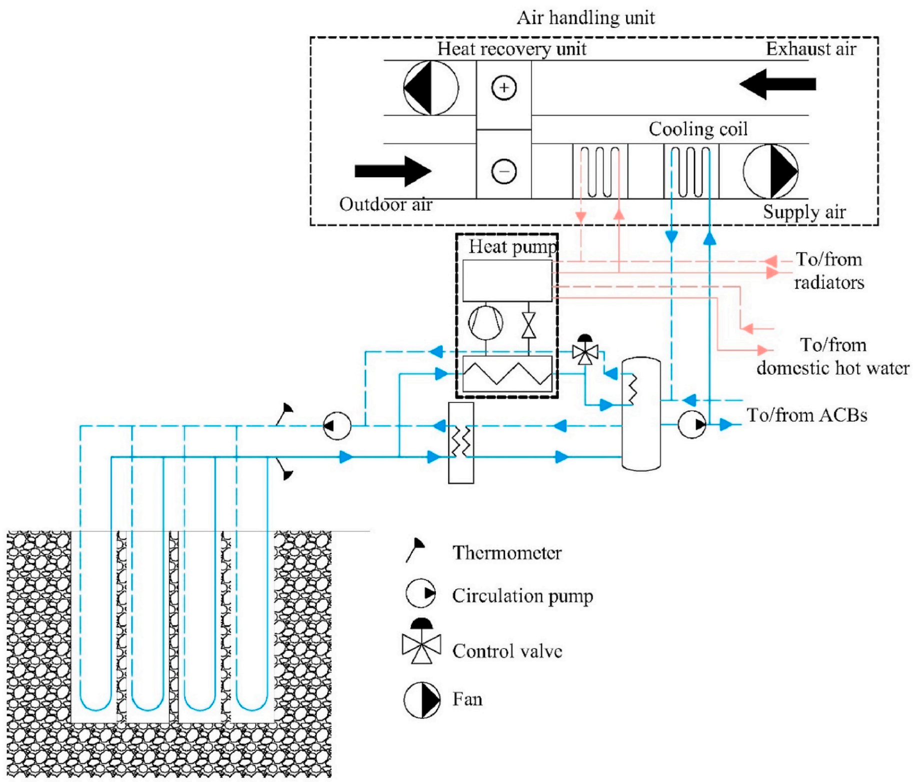

Fig. 4. Schematic of the GSHP plant consisting of a heat pump and DGC from the boreholes.

equipment purchased and maintenance costs, and purchased energy costs, given in Eqs. (1) and (2):

$$LCC_{investment} = (C_{BH} + C_{EQ}) \tag{1}$$

$$LCC_{operation} = (C_E + C_M) \tag{2}$$

where C_{BH} and C_{EQ} are total costs for drilling and installation of ground heat exchangers, and equipment costs, respectively, and C_E, and C_M are total costs for purchased energy, and maintenance respectively. The calculations are carried out in Swedish kronor (SEK) (1 SEK ≈ 0.1 EUR) for a period of 20 years.

In Sweden, the boreholes are drilled in the bedrock and sealed at the top. The ground heat exchangers are fitted with a bottom weight. The space between the ground heat exchangers and the bedrock is naturally filled with groundwater, and thus, is uncontrolled. The uppermost section of the borehole where the ground heat exchanger is surrounded by soil is protected using a steel casing. The length of this uppermost section should be a minimum of 6 m, according to Swedish guidelines for borehole heat exchangers [44]. Boreholes drilling and installation costs (C_{BH}) are calculated based on Eq. (3):

$$C_{BH} = (C_{BH-1} + C_{BH-2} + C_{BH-3}) \tag{3}$$

where $C_{BH\text{-}1}$ is the cost for casing and drilling the uppermost section, $C_{BH\text{-}2}$ is the cost of drilling the rest of a borehole and $C_{BH\text{-}3}$ is the cost of installing the ground heat exchangers and implementation of the well-top and bottom weight as well as trenching and collectors. All costs are sourced from Swedish companies and are detailed in Table 3.

Equipment costs (C_{EQ}) include the investment cost to purchase the heat pump (for the GSHP system) and the dry cooler (for the DGC with DH plant), see Table 3.

Purchased energy is used to quantify the required heat from the district heating network and electricity from the grid. Note that the purchased electricity ($C_{E,1}$) only accounts for the demand for the equipment in the plant part, and electricity use for the building's heating

Table 3
LCC input variables.

	Explanation	Abbreviation (unit)	Cost
Borehole drilling and installation (C_{BH})	Drilling and casing the uppermost section (6 m)	$C_{BH\text{-}1}$ (SEK/m)	950
	Drilling the main body of a borehole	$C_{BH\text{-}2}$ (SEK/m)	330
	Well-top and bottom weight installation, trenching, and collectors	$C_{BH\text{-}3}$ (SEK/borehole)	2800
Purchased energy (C_E)	Averaged electricity price only for the plant (GSHP, pumps, dry cooler, etc.)	$C_{E\text{-}1}$ (SEK/MWh)	1.5 [45–47]
	Annual district heating energy	$C_{E\text{-}2}$ (SEK/MWh)	87 (May–Sep) 346 (Apr, Oct, Nov) 508 (Dec-Mar) [48]
	Peak district heating power (fixed cost)	$C_{E\text{-}3}$ (SEK/y)	12,865 (p < 250 kW) 35,455 (251 < p < 500 kW) [48]
	Peak district heating power (variable cost)	$C_{E\text{-}4}$ (SEK/kW)	805 (p < 250 kW) 715 (251 < p < 500 kW) [48]
Equipment and maintenance (C_{EQ})	Equipment investment	C_{EQ} (SEK/kW)	Heat pump: 5000 Dry cooler: 1500
maintenance (C_M)	Equipment maintenance (heat pump and dry cooler)	C_M (SEK)	1% of the investment cost per year
Discount rate	Real discount rate	d (%)	5
Growth rate	Real growth rate	g (%)	1.5
Period of analysis	–	n (year)	20

and cooling systems is excluded. Purchased heat is calculated based on the combined effect of the annual energy demand ($C_{E,2}$), a fixed annual fee for peak demand ($C_{E,3}$), and a variable fee based on the peaks' intensity ($C_{E,4}$). District heating rates are based on the supplier company in Gothenburg, GöteborgEnergi [48]. The current electricity price is taken to be 1.5 SEK/kWh, which includes energy and distribution costs, and corresponds to a typical electricity purchase contract between 2010 and 2020 [45–47]. The market price is assumed fixed over the year for simplicity. Future electricity prices are calculated using a price growth rate of 1.5%. Purchased energy cost is calculated for a period of 20 years (n) and is given in Eqs. (3) and (4):

$$C_E = C_{E,1} + C_{E,2} + C_{E,3} + C_{E,4} \tag{4}$$

$$C_{E,1-4} = P_{E,1-4} + \left[\frac{F_{E,1-4}}{(d-g)} \cdot \left(1 - \left(\frac{1+g}{1+d}\right)^n\right)\right] \tag{5}$$

where P_E is the present value of energy, F_E is the first-year cost of energy, d is the discount rate, g is the growth rate of energy and n is the period of analysis.

Maintenance costs (C_M) for the equipment are taken to be 1% of the equipment investment cost for the first year with a growth rate of 1.5%. Maintenance cost is given in Eq. (6):

$$C_M = \frac{F_M}{(d-g)} \cdot \left(1 - \left(\frac{1+g}{1+d}\right)^n\right) \tag{6}$$

where C_M is the equipment investment cost, F_M is the maintenance cost for the first year and n is the period of analysis which in this study is 20 years. Equipment costs are sourced from Swedish suppliers.

3. Results

3.1. Investment costs

The investment cost only includes the borehole installation and equipment costs. The distribution system and the heating and cooling systems in the building are the same and are hence not included in the investment cost analysis. Fig. 5 shows the initial investment for each case and each studied plant.

The major investment cost for all cases is the borehole installation costs. Borehole installation costs are relative to the required depth of the boreholes and the total number of boreholes in a borehole field. Cases using the DGC-DH plant require fewer boreholes and thus, have lower installation costs compared to that with the DGC-GSHP plant. This is because the ground loads for the DGC-GSHP are imbalanced and/or have high peaks. Therefore, additional boreholes are required to meet the prescribed borehole fluid temperature levels.

In general, the DGC with DH plant has lower borehole installation costs for all cases except for cases 4 and 5. The equipment costs are significantly lower for the DGC. Thus, the DGC-DH plant has the lowest investment costs for all cases.

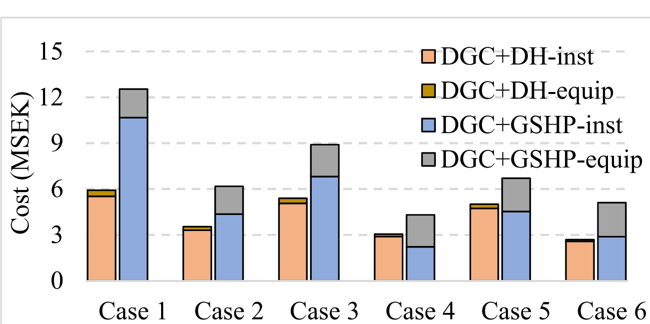

Fig. 5. Investment costs for each case are based on the plant type. Cost calculations include borehole installation costs (inst) and equipment costs (equip) (1 SEK ≈ 0.1 EUR).

3.2. Purchased energy

The energy demand of the plants comprises the purchased electricity and the purchased heat. The purchased electricity includes the demand for the borehole's circulation pump, heat pump and dry cooler. Fig. 6 shows a comparison of the annual purchased electricity for all cases. The electricity demand of the heat pump has the largest contribution to the total electricity demand for the cases with the GSHP. The heat pump electricity demand increases from case 1 to case 6 by about 68% since the heating demand increases due to the increase in the U-value of the building. In addition, the circulation pump energy demand decreases from 0.25 kWh/m^2 in case 1 to 0.1 kWh/m^2 in case 6. This is because the annual operation hours of the circulation pumps are reduced.

The boreholes' circulation pump demand is higher for the DGC-DH. This is partly due to the long operation period of the circulation pump to extract heat from the boreholes even out of office hours, and partly due to the higher friction losses of the ground loop for this particular combination. The higher pressure drops are due to the circulation of the fluid through the pre-heating coil and the dry cooler, see Fig. 3.

Fig. 7 shows the annual purchased heat from the DH for heating and domestic hot water in cases with the DGC-DH plant. For the cases using the GSHP, all the required heat is provided by the GSHP. The domestic hot water demand is the same for all cases. A twofold increase from 25 kWh/m^2 to 49 kWh/m^2 in the purchased heat can be seen in cases 1 to 6 due to the increase of the U-value of the building.

Fig. 8 shows the lifecycle energy costs for the DGC-DH and DGC-GSHP for the six cases considered in this study. The costs are calculated for a period of 20 years based on the assumptions given in section 2.3. In general, energy costs for the DGC-DH plant are significantly higher compared to the DGC-GSHP plant. For both combinations, the total energy cost increases from cases 1 to 6 with building U-values. This is because the purchased energy for space heating increases with increasing U-values. On the other hand, the declining trend of the electricity demand from cases 1 to 6 for the DGC-DH is due to the decreasing cooling demand of the building.

3.3. Building design parameters, investment costs and energy costs

The influence of the building U-value and windows G-value on the initial investment and energy costs can be seen in Figs. 2, Figs. 5 and 8. For the combination of DGC and DH, U-value has little influence on the initial investment (borehole installation cost) but a significant influence on the energy costs (Fig. 9). Increasing the U-value makes the system

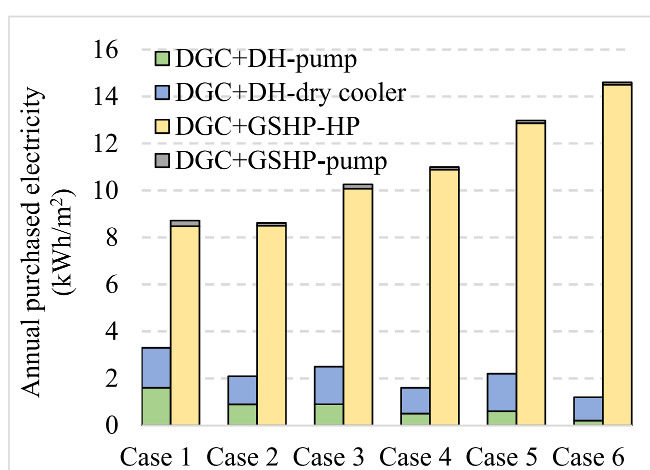

Fig. 6. Annual electricity demand for the boreholes' circulation pump, dry cooler, and heat pump (HP) for the DGC with DH and DGC with GSHP plants.

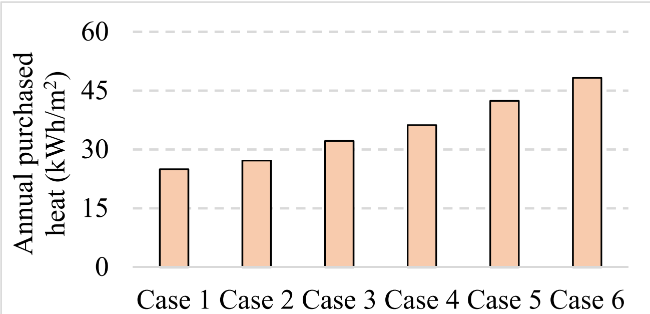

Fig. 7. Annual purchased heat for the DGC coupled with DH.

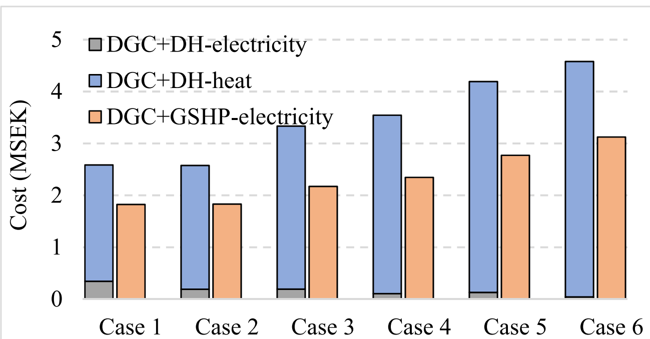

Fig. 8. Lifecycle energy costs based on the plant type (1 SEK ≈ 0.1 EUR).

more dependent on the purchased heat and less dependent on the ground cooling (Fig. 2). On the other hand, G-value is an influential parameter in defining the building cooling demand and thus, plays an important role in the borehole installation costs. When using DGC-DH, heating and cooling demands to the building are provided from different sources independent of each other, and the lowest cost is yielded when both heating and cooling demands are reduced.

For the combination of DGC-GSHP, the influence of the U- and G-values on the investment and energy costs depends on how imbalanced the building heating and cooling loads are. The more imbalanced the loads are, the larger the required borehole length is. For instance, in cases 1, 3, and 5, a higher U-value results in lower heating demand and reduces the imbalanced ratio between the heating and cooling loads (Fig. 2). Although the energy costs increase, the reductions yielded in the investment costs are significantly higher to offset the energy costs. Thus, the sum of the investment and energy costs are reduced when the U-value increases in cases 1, 3 and 5.

3.4. LCC costs

Fig. 9 presents a detailed comparison of LCC for the six cases. LCC for each case considers the investment costs and the operation costs.

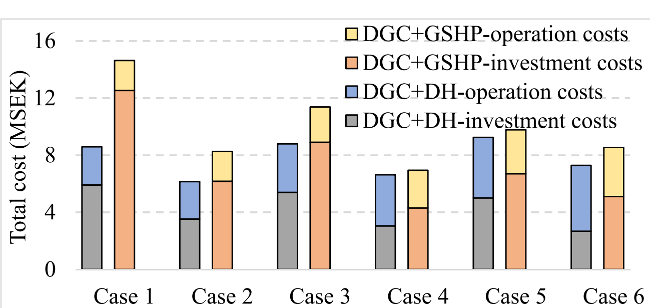

Fig. 9. The total lifecycle cost based on the plant type (1 SEK ≈ 0.1 EUR).

For the DGC-DH plant, while the investment costs for cases 1 to 3 are either higher or nearly equal to the operation costs, they are significantly lower for cases 4 to 6. This is because the cooling demand in cases 1 to 3 is generally high which leads to longer required borehole lengths. On the other hand, the purchased heat in cases 4 to 6 is high, resulting in higher operation costs.

When using the DGC-GSHP, the proportion of the investment costs to the LCC of the system is higher. This is mainly because of the heat pump costs. In those cases where the system is nearly thermally balanced, i.e., cases 2, 4 and 6, the investment costs are highly reduced but still constitute a larger proportion of the LCCs.

Case 2. has the lowest LLC among all cases for the DGC-DH. This is because of the relatively low heating and cooling demands of the building due to lower U- and G-values, respectively. For the DGC-GSHP, Case 2 has imbalanced ground loads, which results in larger borehole length and thus, higher installation costs. For the DGC-GSHP, case 4 has the lowest LCC mainly because of the low borehole installation costs.

3.5. Sensitivity analysis

The choice of discount and growth rates introduces uncertainty in the LCC analysis. The LCCs presented in Fig. 9 were calculated based on the nominal discount rate of 5% and the nominal price growth rate of 1.5% for both electricity and heating. However, as both the discount and growth rates are subject to uncertainty and can have profound effects on the LCC, a sensitivity analysis has been carried out to determine the effects of these uncertainties on the results of LCCs.

Fig. 10 presents the results of a sensitivity analysis of the discount and growth rates for the DGC-GSHP. For a prescribed growth rate, a general trend of decreasing LCC with an increasing discount rate can be noticed. This suggests that at higher discount rates, energy costs constitute smaller shares of the LCC. With increasing discount rates, the LCCs for cases 4 and 6 decreases at a faster rate than for cases 1, 2, 3, and 5. This is because the lifecycle costs in cases 4 and 6 mainly comprise the investment costs that are insensitive to changes in discount rates. The analysis also shows that the lifecycle costs are more sensitive to changes in discount rates at higher growth rates.

Fig. 11 presents the results of the sensitivity analysis of the discount and growth rates for the six investigated cases corresponding to the DGC-DH. As seen from the figure, the lifecycle costs are highly dependent on the discount rates due to relatively lower investment and higher energy costs. Cases 2, 4 and 6 are more sensitive to changes in the discount rate as the lifetime costs are higher than the investment costs, see Fig. 9. The most notable change can be seen in case 6 with the largest proportion of energy to the lifecycle cost. A higher discount rate results in lower lifecycle energy costs. Thus, at high discount rates, the cases are mainly different based on their initial investment costs.

Comparing Figs. 10 and 11 indicates a higher decrease in the LCCs at higher discount rates for the DGC-DH system compared to the DGC-GSHP system. Energy costs constitute a major part of the LCCs for the DGC-DH, in contrast to the high influence of the investment costs for the DGC-GSHP. Energy costs are highly dependent on the discount and growth rates and those rates can significantly affect the LCCs of both combinations.

4. Discussion

This article compares the combination of DGC with DH and GSHP from an energy performance and LCC perspective. Various scenarios of electricity and heat prices are considered to provide a comprehensive analysis of the comparison.

The results presented in the preceding section for the six investigated cases indicate that neither of the two combinations has any market economic advantage over the other. The choice should be based on the technical and economic assessment of each case. In general, the DGC-DH

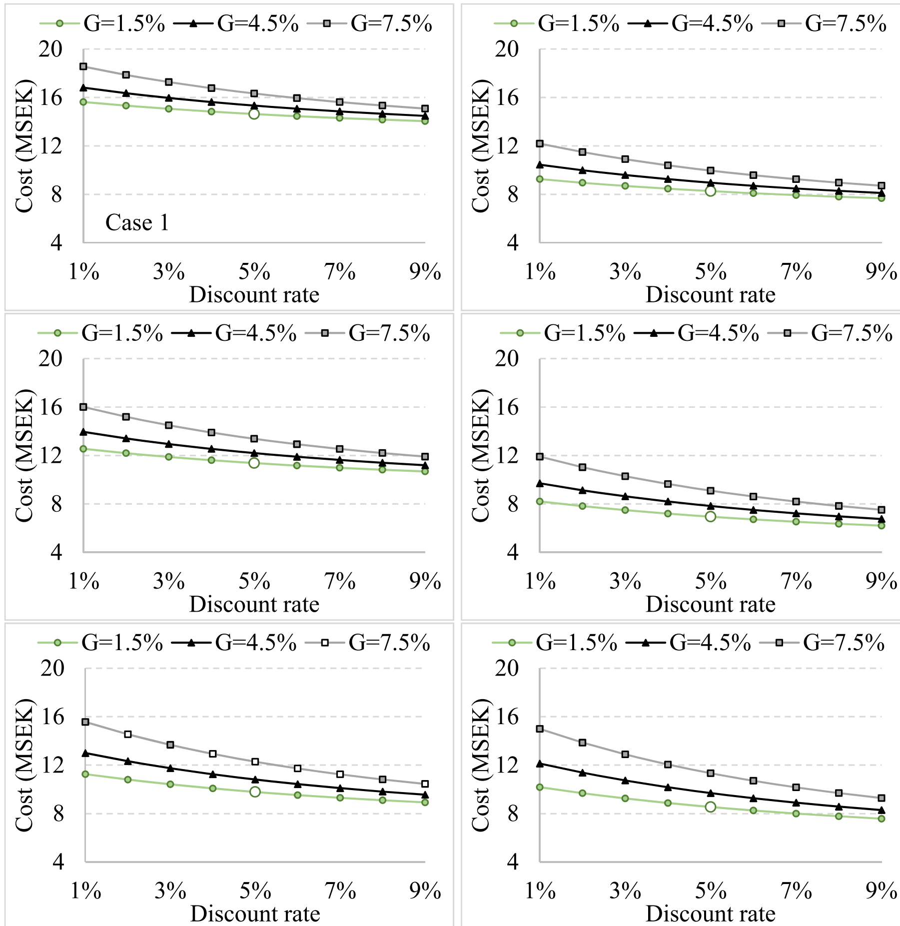

Fig. 10. Sensitivity of LCC for the DGC-GSHP system for various discount rates and energy growth rates. The nominal discount rate used in the study is shown with empty marks at the growth rate of 1.5% and the discount rate of 5% (1 SEK ≈ 0.1 EUR).

is economically a more rational choice when the ground loads are imbalanced. The results suggest that the DGC-DH offers lower investment costs due to lower equipment costs. This choice would yield even greater economic benefits if the design integrates high-temperature cooling to further reduce the overall borehole length [35]. On the other hand, using the DGC-GSHP is more economically viable when ground loads are relatively balanced. In addition, energy cost, mainly purchased heat, is lower for the DGC-GSHP compared to the DGC-DH.

Various scenarios can be thought of for the future Swedish energy market. One likely scenario is the high volatility of electricity prices due to the transformation of the Swedish power system and abandonment of the nuclear power [7,49–51]. Given this scenario, high-electricity-price periods would appear more often. In addition, DH plants and distribution networks would be operating more efficiently in future. Given the likelihood of higher electricity prices in the future, DGC-DH would offer greater flexibility.

Other important factors, such as the primary energy demand of the system and the resilience of the energy pant, can also affect the choice between the two combinations. Primary energy is one of the factors being used to assess the environmental impacts on current and new buildings. It is used to denote the total energy needed to produce the final energy, including all fuel inputs and losses along the energy chain. According to the Swedish National Board of Housing (Boverket), the primary energy factor for electricity is 1.8 and is almost 2.5 times greater than that for the DH at 0.7 [52]. Considering these values, the primary energy use for the DGC-DH is still higher than the DGC-GSHP in all considered cases. However, in other recommendations, the primary energy factors for electricity range between 1.6 and 2.6 and for DH between 0.04 and 1.5, depending on the energy source type [53–55]. Therefore, the primary energy use of the system can be in favour of either the combination of DGC and DH or the combination of DGC and GSHP, depending on the origin of the energy supply.

Resilience is an important consideration when analysing heating and cooling systems. Resilience is the capacity of a heating/cooling system that allows the system to overcome, defer or recover the consequences of operational disruptions due to disturbances such as power outages or heatwaves [56]. Both GSHPs and DGCs feature some resilient cooling aspects as they utilize the ground thermal mass to minimize and delay the impacts of disruptive events, such as heatwaves [57]. However, based on the purchased energy analysis, it can be concluded that the DGC-DH is more reliable to withstand power outages as they require a modest amount of electricity for operation. In case of a blackout, a small electricity generator can provide outage protection for the DGC system.

5. Conclusions

This study investigates the economic potential of using the combination of DGC with DH for providing cooling and heating to office buildings in cold climates. The results are compared to a more commonly used combination of DGC with GSHP. The following conclusions can be drawn.

1 DGCs-DH can be regarded as an economical alternative to the DGC-GSHP. Based on the assumptions made, initial investments, including borehole and equipment costs, are lower when using the DGC-DH. Using the DGC-DH instead of the DGC-GSHP is especially

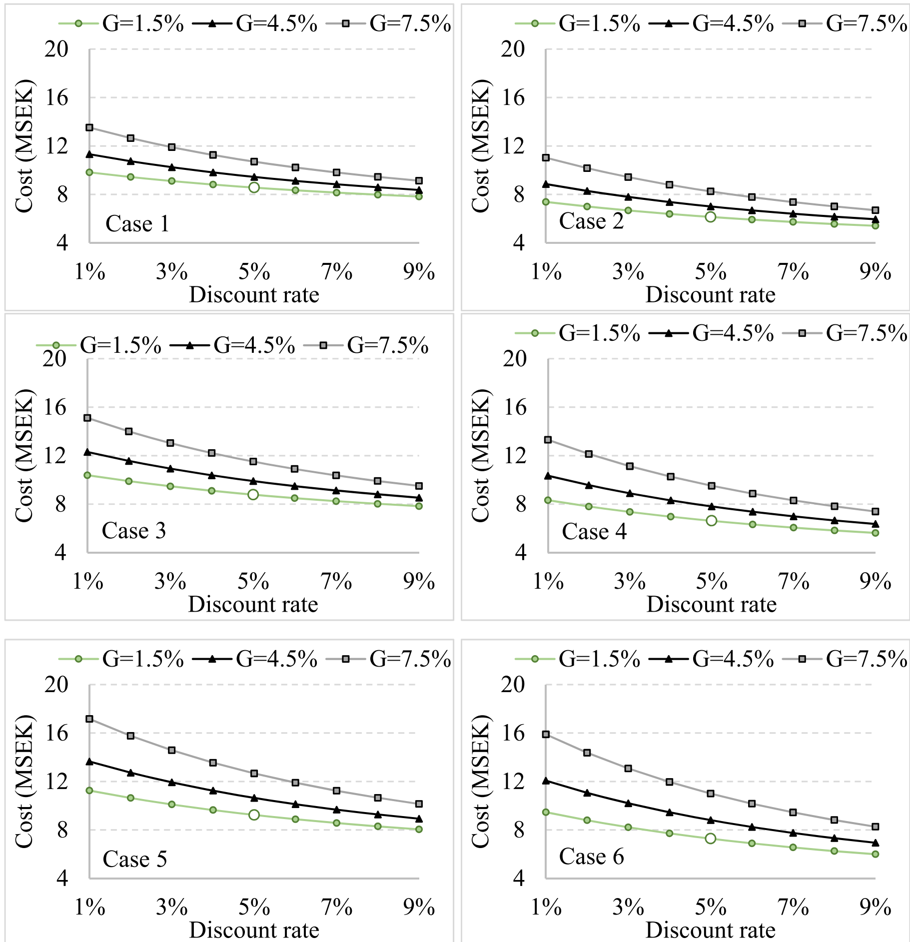

Fig. 11. Sensitivity of LCC for the DGC-DH system for various discount rates and energy growth rates. The nominal discount rate used in the study is shown with empty marks at the growth rate of 1.5% and the discount rate of 5% (1 SEK ≈ 0.1 EUR).

profitable when the building heating and cooling loads are imbalanced towards heating. In addition, LCC is lower for the DGC-DH in most cases mainly due to the lower equipment costs. Using the DGC-GSHPs can be profitable when the building loads are relatively balanced and the borehole costs are lower.

2 The annual purchased electricity for the DGC-GSHP is significantly higher than that for the DGC-DH. However, the purchased energy costs for the DGC-DH are higher, owing to the high purchased heating costs. At higher discount rates, investment costs represent a smaller share of LCCs, as demonstrated in the sensitivity analysis.

3 The results reiterate the importance of optimizing the building design parameters (envelope U-value and windows G-value) for the design and energy demand of the energy plants. For the energy plant based on DGC and DH, increasing the U-value makes the system more dependent on the purchased energy (heating from DH) and less dependent on the ground energy. On the other hand, for the DGC-GSHP, increasing the U-value reduces the thermal losses, resulting in further utilization of the ground energy and reducing the purchased energy. For both energy plants, G-value is an influential parameter in defining the borehole installation costs.

Credit author statement

Taha Arghand: Conceptualization, Methodology, Software, Data curation, Investigation, Formal analysis, Visualization, Writing – original draft (lead), Writing – review & editing (lead). **Saqib Javed**: Supervision, Methodology, Conceptualization, Writing – original draft (supporting), Writing – review & editing (lead). **Jan-Olof Dalenbäck**: Conceptualization, Supervision, Writing – review & editing (lead), Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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