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# Combining direct ground cooling with ground-source heat pumps and district heating: Borehole sizing and land area requirements

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ABSTRACT

This article studies the potential combination of direct ground cooling (DGC) with district heating (DH) and ground source heat pumps (GSHP) to compare the required borehole depths and needed drilling areas. It also examines two different borehole sizing approaches to optimize investment costs and drilling areas. The results show that the required borehole depths in most cases are shorter for the DGC and DH combination than for the DGC and GSHP combination. It is also demonstrated that the optimal range of borehole outlet temperatures could be chosen based on the trade-off between borehole installation and terminal units' costs.

## 1. Introduction

Direct ground cooling (DGC) systems use vertical borehole heat exchangers to move heat between the building and the ground (Arghand, 2019). The natural ground temperature is used to cool the building during the summer, and heat is extracted from the ground during the winter to balance the ground loads. DGC systems operate independently of heat pumps. They use only a modest amount of electricity to circulate a working fluid between the building and the ground in comparison to systems with electric-driven heat pumps (chillers) which use a significantly larger amount of electricity. DGC systems are viable alternatives to the mechanically driven cooling systems in Sweden and other cold-climate countries, as the building cooling loads are low enough to be offset by the ground loads. Low underground temperatures in Sweden, ranging from 2 °C to 9 °C (Rosén et al., 2001), ensure a large temperature difference between the heat source and heat sink and thus offer a considerable cooling potential.

DGC systems are often used in combination with district heating (DH). DH networks are developed in almost all major cities and towns in Sweden (Frederiksen and Werner, 2013). DH is traditionally sourced from combined heat and power plants, excess heat from waste incineration and industrial processes, and more recently from biomass, geothermal wells, and solar collectors (Werner, 2017). Therefore, it is considered a low $CO_2$ emission and an efficient heating technology in Sweden. The DH system is typically connected to buildings via heat exchangers. Therefore, it requires a small space in the installation rooms and its investment and installation costs are generally low.

Grounds source heat pumps (GSHPs) utilize the ground as a heat source and heat sink to provide cooling and heating to buildings. The GSHP uses heat pump(s) to elevate the borehole outlet fluid temperature to heat the building during winter. When using the GSHPs, cooling can be provided either by operating the heat pumps in the reverse mode as chillers or by the DGC method without using heat pumps. Typically in Sweden, between 50% and 75% of the maximum design peak cooling load is covered by the DGC method (Andersson and Gehlin, 2018).

There are several examples of using GSHPs in commercial and office buildings in Sweden. The Astronomy Centre at Lund University uses 20 boreholes to generate 300 MW h heating and 150 MW h cooling per year (Naumov, 2005). The system's thermal performance, defined as the ratio of delivered heating and/or cooling to the electricity used, which was 4.8 and 50 for heating and cooling, respectively. The GSHP at Karlstad University consists of 204 boreholes (Olsson, 2014). The annual heating and cooling demands are estimated to be 5500 MW h and 1000 MW h, respectively. The ground-coupled system for the new student centre at Stockholm University is equipped with 20 boreholes and has a heating and cooling performance of about 3.7 and 27, respectively (Spitler and Gehlin, 2019). GSHP technology offers high energy performance for these projects however, using a significant amount of electricity to run the heat pump in heating mode restricts the energy efficiency of the GSHPs.

Only a few studies to evaluate the energy performance of the DGC systems have been conducted. Li et al. (Li et al., 2009) and Eicker et al.

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(Eicker and Vorschulze, 2009) used DGC systems in their experiments to cool small commercial spaces. The measured cooling performance of the system, described by the seasonal performance factor (SPF), ranged between 10 and 20. Such a high SPF was possible due to the small percentage share of the electricity demand for the pumps and the ventilation system. On a large scale, Filipsson et al. (Filipsson et al., 2020) and Liu and Zhang (Liu and Zhang, 2020) studied the energy performance of the Entre Lindhagen office building (~ 83,000 $m^2$) in Stockholm, Sweden. The building used a DGC and had an SPF of about 17. The Ympäristötalo office building in Helsinki, Finland, is another example of an office building equipped with DGC. The electricity demand to operate the building installations is as low as 10.6 kW h/$m^2$.y (Kurnitski, 2012). Arghand et al. (Arghand et al., 2019, Arghand et al., 2021, Arghand et al., 2021) showed that reducing the building's peak cooling loads is a key factor for achieving high energy performance and low operational electricity use when using the DGC systems.

Although using DGC combined with DH can potentially improve energy efficiency and reduce $CO_2$ emissions, statistics do not indicate a growing trend in the application of this combination (Gehlin et al., 2020, Lund and Toth, 2021, Lund and Boyd, 2016, Lund et al., 2011). To discern the reasons behind this trend, interviews were conducted with several practitioners and designers in Sweden (Arghand, 2021). The key survey questions were related to the application of the DGC combined with DH and the GSHP in office buildings. According to the survey results, the potential financial and technical benefits of the DGC are not obvious to designers and practitioners. Decisions are predominantly made based on past experiences and design traditions. In addition, a literature review performed in this article on the comparison between the two systems showed a general lack of literature on a systematic comparison of DGC with GSHP and DH. To the best of the authors' knowledge, no study has been conducted to compare DGC systems with DH and GSHPs from design and economic perspectives.

The primary objective of this study is to analyse the technical and economic potential of DGCs integrated with DH for office buildings in the Swedish market. This study investigates the design scenarios where the combination of the DGCs and DH becomes competitive with GSHPs with DGC. A twofold objective has been addressed and explained in two parallel articles. The current article compares the two energy plants from the perspectives of borehole size and required land area. This article also suggests two methods for sizing the boreholes to optimize the installation costs and land area constraints. The first method focuses on minimizing the land area needed to drill the boreholes, whereas the second method aims at optimizing the costs of borehole heat exchangers. A paper parallel to this one elaborates upon the energy performance and life-cycle cost analyses of the combination of the two alternatives. This article is a simulation-based investigation of a typical Swedish office building using either DGC with a DH plant or DGC with GSHPs. The design approach and methodology are explained in Sections 2 and 3. The results are discussed in Section 3, followed by the discussion in Section 4 and the concluding remarks in Section 5.

## 2. Methods

This section first describes the reference building model and an approach to define the building dimensions to generalize the model. The building's heating and cooling systems are then described in detail. Finally, the simulation tools, modelling procedure, and design criteria for sizing the borehole ground heat exchangers are described.

### 2.1. Building selection

To achieve a high level of generality and to yield outcomes that go beyond a specific case, it is imperative that the case building selected in this study is appropriate and adheres to the required standards of validity, reliability, and functionality. 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 and make certain modifications to them to attain typical office buildings in cold climates, e.g., Sweden.

The U.S. Department of Energy (DOE) has developed several reference building energy simulation models to provide descriptions for whole buildings' energy simulation analysis (Deru et al., 2011). These buildings have been used in several simulation-based research studies. Among the available commercial building models, the medium-sized office building is used as the reference model for this study. The building has three floors, and each floor consists of a large interior zone surrounded by four perimeter zones and has an area of 1660 $m^2$.

The thermal characteristics of the medium-office developed by DOE are not common for Swedish office buildings. Therefore, a combination of common materials in the Swedish construction market for walls, windows, the roof, and the floor are used to determine three common average building U-values for the simulation model. The U-values are taken based on the suggestions of the Swedish National Board of Housing (Boverket) and Swedish commercial building databases (EU Building Stock Observatory 2016, Boverket 2018, LÅGAN 2021). Table 1 lists the case studies and the design parameters for each case study.

Internal heat loads include 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 ASHRAE Handbook-Fundamentals (ASHRAE 2017). The occupancy and the office equipment are scheduled from 8:00 to 17:00 on weekdays with an 80% use factor. Lights are also scheduled from 8:00 to 17:00 on weekdays with a 50% use factor from June 1st until August 31st and 80% for the rest of the year. The use factors are based on experience and educated guesswork and are commonly used among practitioners in Sweden.

Another important factor when simulating a building model is its compactness. Building compactness is the ratio of a building's volume to its external surface area. Buildings with lower compactness ratios are narrower and have larger perimeter areas. The compactness ratio of a building affects its heat balance, which is of great importance to the design of ground-coupled systems as their design is sensitive to both intense peaks (Arghand et al., 2021, Pahud et al., 2012, Arghand et al., 2021) and imbalanced annual energy (You et al., 2016, Chen et al., 2021, Bae and Nam, 2022).

The impact of a case building's compactness on its energy demand has been investigated using the relative compactness (RC) approach, which has been used in several previous studies (Ourghi et al., 2007, AlAnzi et al., 2009, Straube, 2012). The RC of a case building is the ratio of its compactness to the compactness of the building model developed by DOE. RC is defined as follows:

$$RC = \frac{(V/A_{ext})_{building}}{(V/A_{ext})_{ref}} \tag{1}$$

where V is the building volume ($m^3$), $A_{ext}$ is the building perimeter area ($m^2$), $(V/A_{ext})_{building}$ is the compactness of the study case, and $(V/A_{ext})_{building}$ is the compactness of the building model developed by DOE.

**Table 1**
Main features of the external structure of the simulated building with the floor dimension of 91m × 18m and 9 600 $m^2$ floor area for each case study.

| Design parameter | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|---|
| Mean 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 with DGC or DH with DGC | | | | | |

The dimensions of the investigated study cases are 259 m × 6 m, 152 m × 11 m, 91 m × 18, 64 m × 25 m, 50 m × 32 m, and 40 m × 40 m (L × W). The DOE building model dimensions are 50 m × 32 m. The height of all buildings investigated is 11.1 m, according to the reference model height. Buildings' have an average U-value of 0.4 W/m$^2$ k and a G-value of 0.3, based on case 4 in Table 1.

Fig. 1 shows the maximum hourly peak and the annual heating and cooling energy relative to the RC. Both the annual energy and peak show a sharp decrease with the increase in the RC. This is mainly because narrow buildings have a much larger perimeter area compared to square-shaped ones. A larger perimeter area increases the heat exchange rates between the building and its surroundings.

Although the annual energy and peak powers are high, buildings narrower than 91 m × 18 m are rare, and using them as case objects is impractical. According to the results shown in Fig. 1, choosing any 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. 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 selected building dimensions are 91 m × 18 m × 22.2 m (L × W × H). The isometric view of the simulation model is shown in Fig. 2.

### 2.2. Building heating and cooling systems

The cooling system in the building uses active chilled beams (ACBs) for thermal conditioning and for ventilating the spaces. ACBs are convective-based terminal units using high-temperature chilled water as the main cooling fluid. The ACBs are connected to an on-off feedback control system to maintain the room air temperature at the setpoint of 24 °C. The water flow is adjusted at either the "on" or "off" state, relative to the setpoint. If the room temperature rises above the setpoint, water starts circulating in the beam(s) until the room temperature drops below the setpoint. Table 2 summarises the main design parameters of the ACBs.

The supply airflow rate from the ACBs is taken to be 1.5 l/s m$^2$ (0.5 air change rate per hour (ACH)). A total flow rate of 1.2 l/s m$^2$ is considered for air quality requirements of a low-pollution landscaped office (0.7 l/s m$^2$ and 0.5 l/s m$^2$ for emissions from building materials and people, respectively) (CEN 2019). An additional flow rate of 0.3 l/s m$^2$ is also considered to establish the designed induction ratio for the ACB.

A central air handling unit provides ACBs with 100% fresh outdoor air. The air handling unit uses a rotary heat recovery system with an efficiency of 75% to preheat the outdoor air before entering the heating coil. This system is designed as a balanced supply and exhaust ventilation system.

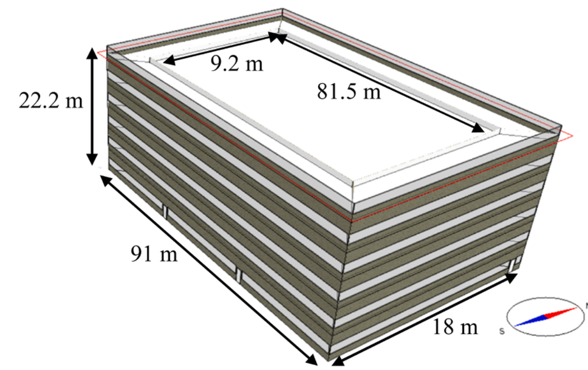


**Fig. 2.** Isometric view of the reference building.

**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 time period (-) | 06:00 - 17:00 on weekdays |
| ***Water radiators*** | |
| Supply/return water temperature ( °C) | 45/30 |
| Room temperature setpoint for heating ( °C) | 21.0 |
| Temperature difference at design condition (K) | 10 |
| 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 time period | 06:00 - 17:00 on weekdays |
| Heat recovery efficiency (%) | 75 |

The air handling unit operates from 6:00 to 17:00 only on weekdays. The air handling unit is initiated two hours before the occupancy. Pre-ventilation ensures a complete change of air volume before the spaces are reused by the occupants, according to (Boverket 2018, CEN 2019).

The heating system uses larger-than-usual water radiators designed for the hot water supply and return temperatures at 45 °C and 30 °C at design conditions, respectively. The control system is equipped with

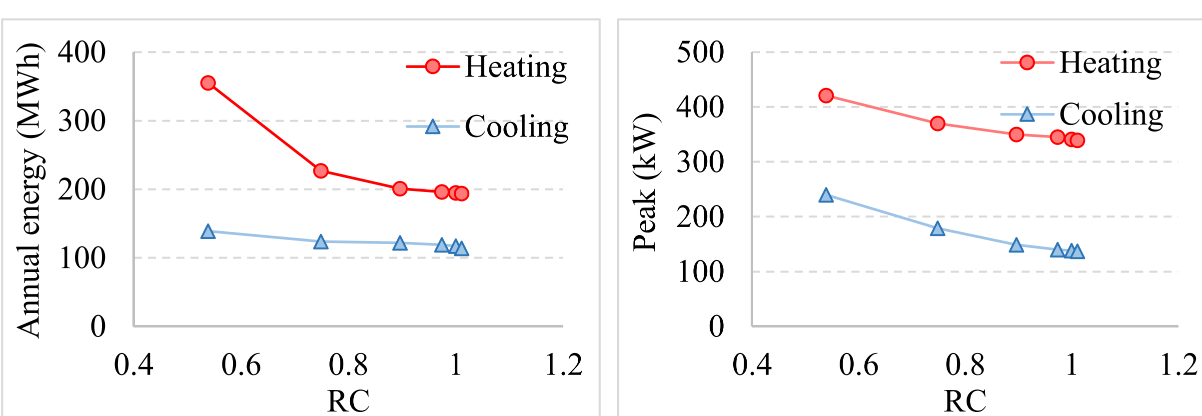


**Fig. 1.** Influence of buildings' RC on the annual heating and cooling energy and daily peak loads. All buildings have three floors and have the same floor area (~ 1660 m$^2$) according to the original building model developed by DOE.

thermostats, with the setpoint air temperature at 21 °C. The heating system is off between June and September.

The domestic hot water system is designed to provide the occupants with 3.8 l/person per day during the occupancy period from 8:00 to 17:00. This corresponds to the annual heating demand of 2 kW h/m$^2$.y and is aligned with the recommended design parameters by the Swedish National Board of Housing (Boverket) (Boverket 2017). The domestic hot water has a temperature of 55 °C. Domestic hot water is provided to the building by the DH when using the DGC and DH plant, and by GSHP, when using the DGC and GSHP plant.

### 2.3. Heating and cooling plants

The combinations of DGC with GSHPs and DH are considered to be providing heating and cooling to the building. The first plant uses a DGC system for cooling and a DH system for heating the building. The DGC consists of vertical ground heat exchangers, circulation pumps, and a ground-load balancing system. The DGC is designed as a thermally-balanced system wherein the annual heat rejected to and extracted from the ground is equal. Thus, the annual ground temperature is approximately unchanged during the operational life of this system.

The boreholes have double U-tube ground heat exchangers and are vertically drilled below the building. The boreholes are drilled into the rock and are naturally filled with groundwater, as per the common practice in Sweden (Arghand, 2019). The heat carrier fluid is water in the DGC. The design and dimensioning principles of the boreholes are explained in Section 2.4. Borehole specifications are outlined in Table 3.

The ground-load balancing system is primarily designed to extract heat from the ground to pre-heat the outdoor air in the air handling unit. Since the AHU only operates from 6:00 to 17:00, a dry cooler is also integrated to increase the duration of the heat extraction process if needed. If the annual heat extraction cannot be fully compensated by the balancing system, the remaining load is added to the next year's load.

The flow rate is always kept around 0.7 l/s in the U-pipes to ensure a turbulent regime. A control system is adopted to drive the control valve in the borehole system based on the outdoor temperature (see Fig. 3). The control system directs the fluid to circulate within the AHU and the dry cooler when the outdoor temperature is between 2 °C and 12 °C. During the period when the AHU is off, the two-way control valve connected to the preheating coil is shut. Therefore, all of the fluid is directed toward the dry cooler. When the outdoor temperature falls below 2 °C, the brine is directed towards boreholes to avoid freezing in the AHU. When the outdoor temperature exceeds 12 °C, the brine is also bypassed towards the boreholes because it is more likely that the warm brine heats the ground than cools it.

**Table 3**
Ground and borehole specifications.

| | |
|---|---|
| ***Borehole*** | |
| Diameter (mm) | 140 |
| Filling material | Groundwater |
| Thermal resistance (m.K/W) | 0.09 |
| ***Ground*** | |
| Undisturbed ground temperature ( °C) | 9.0 |
| Ground thermal conductivity (W/m.K) | 3.0 |
| ***U-tube*** | |
| U-tube type (-) | Double U-tube |
| Pipe type (-) | Polypropylene, PN8 DN40 |
| Inner diameter (mm) | 28.0 |
| Outer diameter (mm) | 32.0 |
| Thermal conductivity (W/m.K) | 0.42 |
| ***Circulating fluid*** | |
| Type | Water (DGC+DH)<br>Ethanol 28% (DGC+GSHP) |
| Flow rate per U-tube (l/s) | 0.3 (water)<br>0.7 (ethanol) |
| Thermal conductivity (W/m.K) | 0.582 (water)<br>0.415 (ethanol) |
| Specific heat capacity (J/kg.K) | 4192 (water)<br>4232 (ethanol) |
| Freezing point ( °C) | 0.0 (water)<br>-18.5 (ethanol) |

All the coils in the AHU are designed for low velocities of approximately 1.0 m/s up to 1.5 m/s. Such a design approach leads to a low air pressure drop ($\Delta P_{max} < 50$ pa) across the heat exchangers and results in low fan power, low electricity demand, and high thermal efficiency.

The heating source in the first plant is DH. The DH is connected to the building heating system via a heat exchanger (Fig. 3). The heating system is designed to provide hot water to the radiators at 45 °C and the domestic hot water system at 55 °C.

In the second plant, space heating and domestic hot water are provided by a GSHP, as shown in Fig. 4. The GSHP consists of a brine-to-water heat pump connected to the boreholes. The nominal heating power of each heat pump is 100 kW with a nominal seasonal COP of 4.0. The minimum designed brine entering fluid temperature to the ground heat exchangers is -3 °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 in the space heating mode and 55 °C in the domestic hot water mode. One or more heat pumps are used depending on the design load. Heat pumps are sized to provide 100% of the buildings' peak heating load. The borehole system specifications are outlined in Table 3.

Cooling is mainly provided by the DGC method from the boreholes. The building cooling system is connected to the ground loop through a heat exchanger (see Fig. 4), which enables provision of cooling to the building from the ground heat exchangers independent of the heat pump operation. However, part of the space cooling can also be provided by circulating the brine leaving the heat pump through the heat exchanger in the tank (see Fig. 4). If the brine temperature is below the water temperature in the tank, the control valve directs the brine to the heat exchanger. Otherwise, the control valve bypasses the tank, and the brine goes towards the ground heat exchangers.

### 2.4. Simulation tools and design considerations

Three simulation tools are used in this study: IDA ICE building energy simulation version 4.8, "IDA ICE borehole" extension, and Earth Energy Design (EED) borehole design software. Each simulation tool is dedicated to a specific purpose.

IDA ICE is a building energy model tool being extensively used in Sweden. This tool has been validated against experimental measurements under the framework of various standards, including CIBSE TM33 (Moosberger, 2007), ANSI/ASHRAE 140 (EQUA Simulation Technology Group 2010), and EN 13791 (Kropf and Zweifel, 2001). In this study, IDA ICE is used to simulate the hourly and yearly heating, cooling, and electricity demands of the systems. The heat extraction and rejection loads used in the borehole calculations are obtained from IDA ICE simulations. Other simulation outputs are room temperature levels and thermal comfort status in spaces. IDA ICE uses a climate file provided by the ASHRAE Handbook of Fundamentals 2013 (ASHRAE 2013). The minimum, maximum, and annual average dry-bulb temperatures are -13.2 °C, 26.1 °C, and 7.2 °C, respectively.

Borehole sizing is performed using the EED simulation tool (Hellström and Sanner, 2020). EED uses step-response functions, also known as g-functions, to calculate the ground loads in the form of loop temperatures as a function of time. The temperatures are then iteratively adjusted until meeting the user-defined inlet and outlet borehole temperature constraints. The building loads in form of hourly heating, cooling, and domestic hot water loads are obtained from the IDA ICE simulations and are used as inputs to this program.

In the next step, the borehole sizes and design characteristics are used as inputs to the "IDA ICE borehole". "IDA ICE borehole" is an extension of IDA ICE, which allows for the predicting of the thermal and energy performance of any ground-coupled system (EQUA Simulation Technology Group 2014, Eriksson and Skogqvist, 2017). Using the "IDA

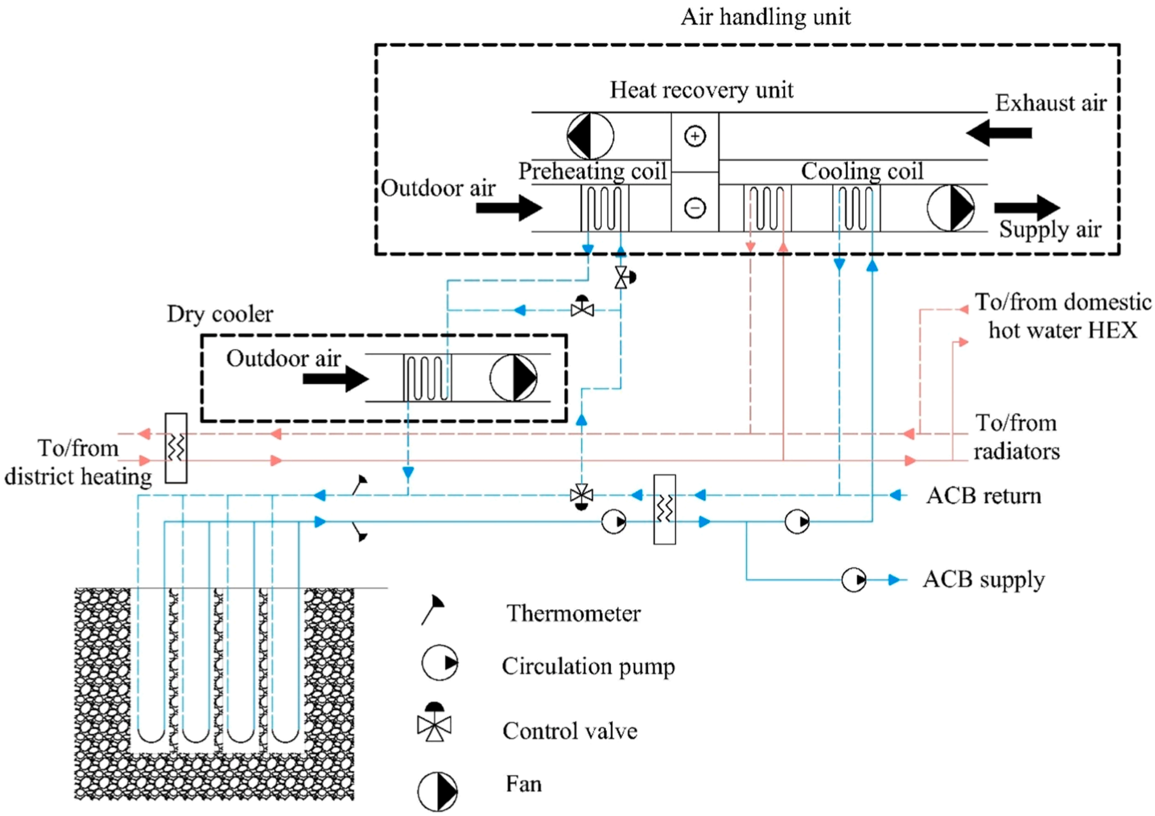


**Fig. 3.** Schematic of the plant consisting of the DGC system and DH.

ICE borehole" extension allows for the execution of coupled simulations between the borehole part and the building part. Such simulations are required to calculate the electrical energy demand of the borehole system and the building energy systems.

The boreholes for the DGC 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 keep the water in the building loop from freezing. The EED program uses the building loads simulated from IDA ICE. The boreholes' required length is iteratively adjusted to reach the targeted borehole temperature constraints. The maximum temperature is aligned with the required supply water temperature to the ACBs, which is 16 °C. The minimum temperature avoids freezing in the U-pipes. The heat carrier fluid is water. It is worth restating that the DGC is a thermally-balanced system. Thus, the annual heat build-up in the ground is insignificant. The boreholes are designed for a 30-year life cycle.

The borehole designs for the GSHP and DGC consider not only the hourly cooling loads but also the hourly heating and the domestic hot water loads. The design borehole fluid temperature limits are 14 °C and -2 °C. This minimum temperature limit prevents the groundwater in the boreholes from freezing. The boreholes are sized using the same approach as for the DGC system.

### 2.5. Borehole sizing optimization

As noted in Section 2.4, the borehole outlet temperature is a crucial parameter in determining the required borehole sizes. The use of high-temperature cooling systems, such as active chilled beams, makes it possible to increase the borehole outlet temperature and thus decrease the borehole sizing. For this study, two approaches for optimizing the borehole sizing have been investigated. In the first approach, the borehole sizing is optimised based on the cost. The objective is to have the best trade-off between the borehole investment and the active chilled beam investment costs for various supply water temperatures. In the second approach, the borehole sizing is optimised based on the available land area. The objective is to minimise the required land area for the borehole system by increasing the supply water temperature of the chilled beam system. This approach is suitable for densely built urban neighbourhoods where land area is scarce.

### 2.6. Borehole and ACB investment costs

In Sweden, boreholes are drilled into the bedrock, sealed at the top, and fitted with a bottom weight for the U-pipe. The space between the ground heat exchangers and the bedrock is naturally filled with groundwater, and thus, is free. 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 is taken to be 6 m, according to Swedish guidelines for borehole heat exchangers (The Swedish Geological Survey (SGU) 2008). All costs are calculated in Swedish Kronor (SEK) (1 SEK ≈ 0.1 EUR).

Borehole investment costs consist of three parts. The first part is drilling and casing the uppermost layer part, which is 6 m long and costs approximately 950 SEK per meter of a borehole. The second part is drilling the main body of the borehole which costs approximately 330 SEK per meter of a borehole. The third part includes installing and performing the well-top and bottom-weight for the U-pipe, trenching, and installing the collectors. This part costs 2800 SEK per borehole.

Investment costs for the ACB are sourced from the Swedish manufacturer and are calculated as roughly 2000 SEK per ACB meter. The ACBs simulated in this study are 2.4 m long.

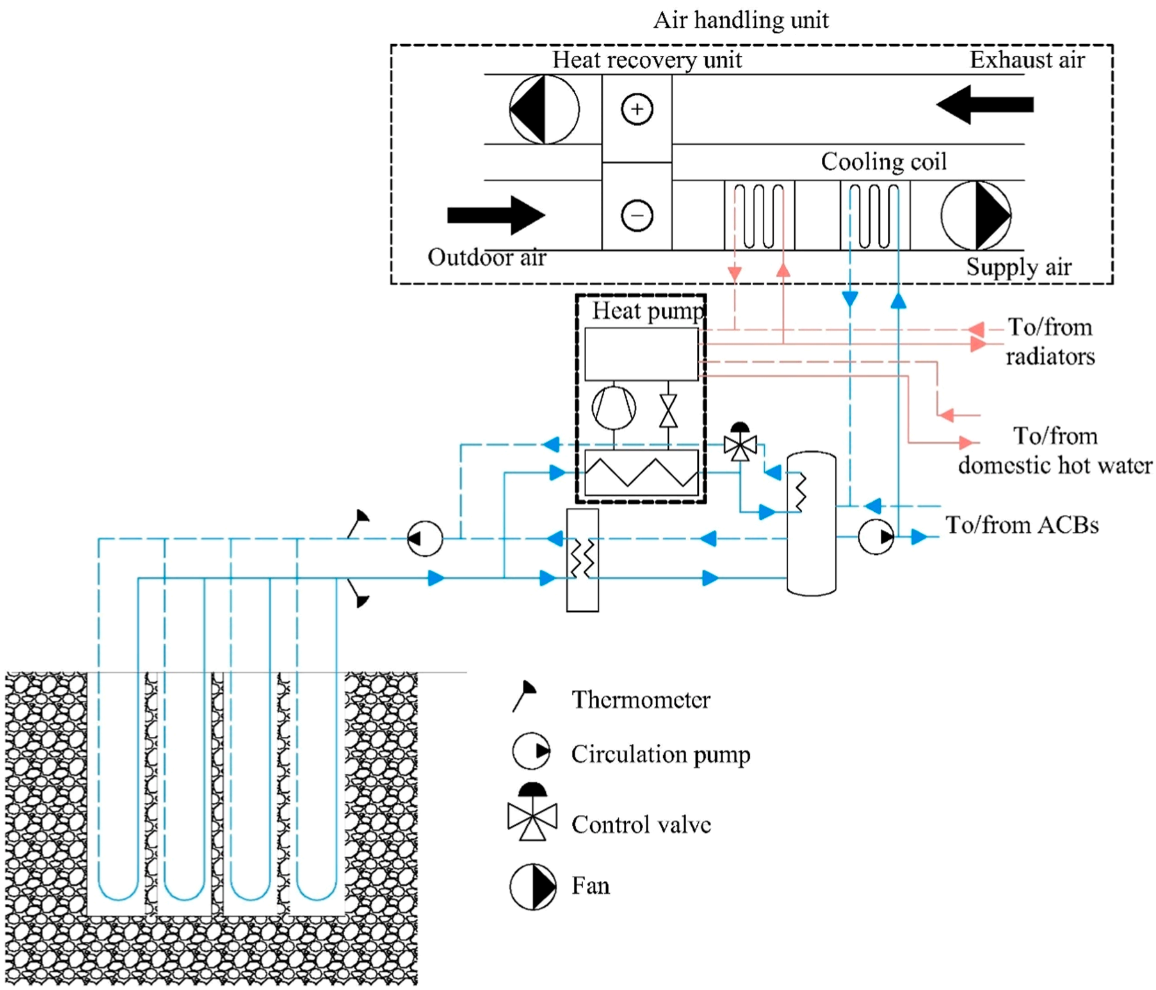


**Fig. 4.** Schematic of the DGC and GSHP plant consisting of a heat pump and direct cooling from the boreholes.

## 3. Results

The hourly heating and cooling demands and the borehole field design of the six cases are presented in Sections 3.1and 3.2. Results from the two borehole optimization methods are detailed in parts 3.3 and 3.4.

### 3.1. Building heating and cooling loads

Fig. 5 shows the effect of various U-values and G-values on the building's annual energy and daily peaks. The G-value has a significant influence on the annual energy and peak cooling loads, but its influence on building heating demand is insignificant. This is because the G-value determines the amount of solar heat gain in the zones and thus, strongly influences the cooling loads' intensity and duration.

U-values affect both the cooling and heating demands. It is 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.

Fig. 5 also provides interesting features for designing the ground-coupled systems. The ground loads at a U-value of 0.2 W/m$^2$ k and G-value of 0.6 are highly imbalanced toward the heat rejection to the ground (Fig. 5). Using the same U- and G-value also results in the largest difference between the heating and cooling peaks (see Fig. 5). Thus, this combination most likely results in the longest required borehole length. One can also see that for a given G-value, an increase in the U-value shifts the reference building from a cooling-dominated to a heating-dominated condition.

Fig. 6 shows the annual ground loads for the DGC and DH, and the DGC and GSHP plants. The annual heat rejected to the ground by the DGC and GSHP plant is relatively lower than that of the DGC and DH plant. The difference is attributed to the recovered cold from the heat pump. The cold brine from the heat pump is circulated through a heat exchanger in the tank, which cools the water from the boreholes (Fig. 4). This cooling effect is sourced from electricity, as the heat pump is electric. Note that the annual heat rejection loads by the DGC and GSHP plant in cases 1, 2, and 3 are higher than the annual heat extraction loads. Therefore, cooling is the dominant mode for sizing the borehole in these cases. The highest imbalanced ratio between the heat extraction and rejection loads can be seen in cases 1 and 6. Due to the combination of U- and G-values, case 1 is highly cooling-dominated while case 6 is highly heating-dominated. The imbalanced loads will influence the sizing of the boreholes for the GSHPs with DGC but not for the DH and DGC. The ground heat rejection and extraction loads for the DGC and DH plant are nearly balanced as the injected heat to the ground is later utilized for preheating the ventilation air, which keeps the ground thermally balanced over time.

### 3.2. Borehole field design for the reference building

Fig. 7 and Table 4 present information regarding borehole dimensioning and design specifications. The required length for each case is calculated based on the inlet and outlet borehole fluid temperature constraints, available land area, and thermal interaction between the boreholes over 30 years, as mentioned in Section 2.4.

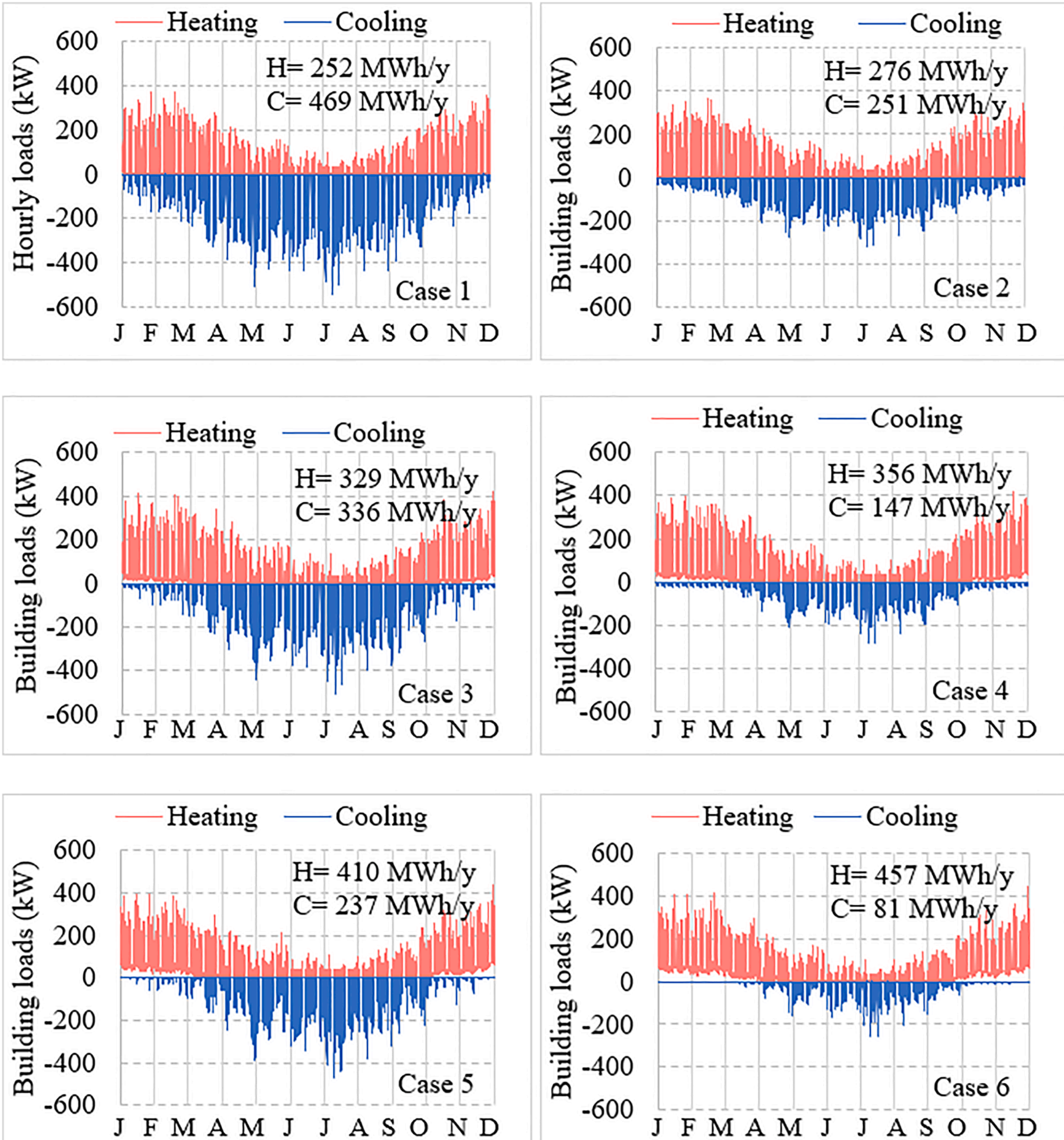


**Fig. 5.** Hourly heating and cooling loads for six cases summarized in Table 1. Domestic hot water demand constitutes approximately 20 MW h/y (53.8 kW h/day) of the annual heating demand.

Overall, cases with the DGC and DH require shorter boreholes compared to those with the DGC and GSHPs, two exceptions are cases 4 and 5. The ground loads are nearly balanced in case 4 and the peak heating loads are low, for which shorter boreholes can be designed for the DGC and GSHP. In case 5, the annual heating loads are higher than the cooling loads. But high peak cooling loads result in a longer borehole length for the DGC and DH plant.

Considering the cases with the DGC and GSHP, case 1 has the longest borehole length. This is partly due to the highly imbalanced annual ground loads (422 MW h rejection and 200 MW h extraction) and partly due to the intense peak cooling loads (543 kW). Case 3 has the second-longest borehole length. The ground loads are nearly balanced and lower than case 1, but the daily cooling peaks are still high because of the high G-value. Cases 1 and 3 cannot be implemented due to the land area limitation (see Fig. 7).

As the DGC and DH plant is designed as a thermally-balanced system, peaks play a major role in determining the borehole length. Therefore cases 1, 3, and 5, where G-value is high, have the longest total borehole length. The shortest borehole length is yielded for case 6 where both a high U-value and a low G-value contribute to reducing the annual and peak cooling loads.

### 3.3. Borehole sizing optimization based on cost

As explained in Section 2.4, the maximum borehole outlet temperature of 14 °C is considered in the borehole design to provide supply water at 16 °C to the ACBs. However, ACBs can be designed and operated for chilled water as warm as 18 °C to 20 °C (Spitler and Gehlin, 2019, Arghand et al., 2021, Maccarini et al., 2020). This section considers designing the boreholes for the maximum outlet temperature of

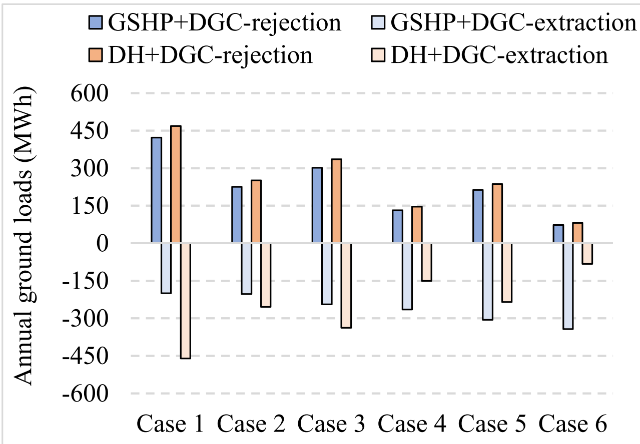


**Fig. 6.** The annual heat extraction from and rejection to the ground for each case with the GSHP and DGC plant, and DH and DGC plant.

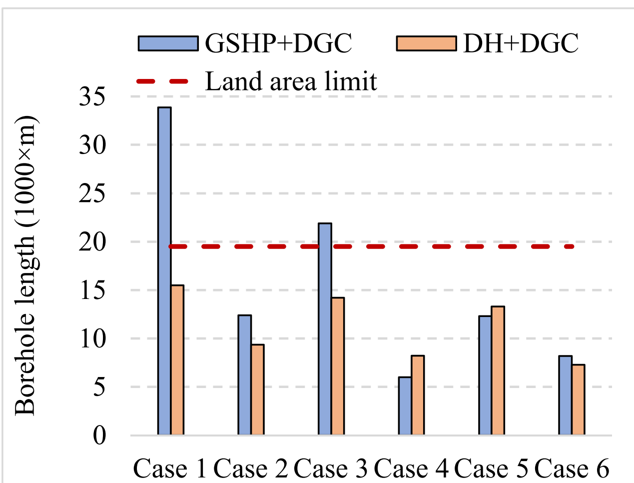


**Fig. 7.** Required borehole length.

**Table 4**
Specifications of borehole design and configuration.

| Plant type | Case study | Sizing mode | Configuration | Spacing (m) | Borehole length (m) |
|---|---|---|---|---|---|
| DGC + GSHP | Case 1 | Cooling | 4×29×295 | 7 | 34,220 |
| | Case 2 | Cooling | 3×14×295 | 7 | 12,390 |
| | Case 3 | Cooling | 4×19×290 | 6 | 22,040 |
| | Case 4 | Heating | 4×6×260 | 6 | 6,240 |
| | Case 5 | Heating | 4×11×295 | 6 | 12,980 |
| | Case 6 | Heating | 4×14×295 | 7 | 8,260 |
| DGC + DH | Case 1 | Cooling | 4×14×280 | 6 | 15,680 |
| | Case 2 | Cooling | 4×8×295 | 6 | 9,440 |
| | Case 3 | Cooling | 4×12×300 | 6 | 14,400 |
| | Case 4 | Cooling | 4×7×295 | 6 | 8,260 |
| | Case 5 | Cooling | 3×15×300 | 6 | 13,500 |
| | Case 6 | Cooling | 2×13×280 | 7 | 7,280 |

18 °C and the supply ACB water temperature at 20 °C. In the next step, the results for the previous and the redesigned systems are compared and discussed. The room cooling and heating setpoint temperatures are still 24 °C and 21 °C, respectively.

It is worth noting that increasing the borehole outlet temperature is only effective for cases where the sizing mode is cooling. This is because the outlet temperature determines the borehole depth only in the cooling mode. In the heating mode, the lowest temperature of the fluid entering the borehole is the decisive parameter. The design mode of each case is listed in Table 4. The design procedure for sizing the boreholes follows the criteria outlined in Section 2.4.

Fig. 8 plots the total length of the ACBs against the design supply water temperature to the beams. The borehole outlet temperatures are 2 K below the ACBs' supply temperature and therefore have the same increase rate.

For all cases, a steady increase can be seen in the coil length with the increase in the supply temperature. This is obviously because a larger heat exchange area for the ACBs is required to make up for the increased supply water temperature and to keep the overall heat extraction rate constant for all supply temperatures. In other words, to maintain the intended room temperature, longer ACBs and/or more ACBs are needed when the supply temperature increases.

For all cases with the DGC and DH plant, the required borehole length decreases with the increase of the ACBs' supply temperature. For instance, the borehole length for case 3, with the DGC and DH plant, decreases by 44% when the supply temperature is increased from 16 °C to 20 °C (see Fig. 8), this is because cooling is the sizing mode for all cases (see Table 4).

For cases with the DGC and GSHP plant, borehole land area optimization can only be applied to cases where cooling is the sizing mode for the boreholes, i.e., cases 1, 2, and 3. Case 1 has the relatively largest reduction (~ 47%) in the borehole length compared to the other two cases.

Fig. 9 shows a trade-off between the borehole installation and ACB costs for the investigated supply water temperature range. The most cost-effective ACB supply water temperature, and also borehole outlet temperature, is the intersection point between the borehole installation and ACB costs. For example, in case 3 with the GSHP and DGC plant, supply temperature between 18 °C and 19 °C yields the cheapest cost, at around 10.2 MSEK (Fig. 9). This is approximately 13% lower than the cost of the original design for a supply temperature of 16 °C. The optimized design supply temperature for the DH and DGC in Fig. 9 is 17 °C. Further increase in the supply temperature unreasonably increases the ACB investment cost. The same cost analysis can be made for case 4 in Fig. 9.

### 3.4. Borehole sizing optimization based on an available land area

Although a cost-effective design is desired, the land area sometimes can impose a major constraint in what concerns the application of the ground-coupled systems. This is a common situation in densely-built urban neighbourhoods where land area is strictly limited. Under this condition, increasing the ACB's supply temperature, and thus the borehole outlet temperature, can result in a smaller borehole field if the sizing mode of the boreholes is cooling.

The land area constraint is investigated here by adding extra floors to the simulated building. The building's cooling system and the boreholes are sized for low- and high-temperature cooling fluid. Sizing for the ACBs is done considering the maximum and minimum possible supply water temperature at 20 °C and 16 °C, respectively. Corresponding maximum borehole outlet temperatures are 18 °C and 14 °C. Other design assumptions are the same as those explained in Section 2.

Fig. 10 shows the required borehole length for the case studies with 20 °C and 16 °C supply water temperature to the ACBs. The most significant reduction in the borehole length can be seen for the DGC and GSHP system in case 3, by 50%, and in case 1, by 48%. In these cases, the ground loads are highly imbalanced for which an additional borehole length is required to meet the desired outlet temperature. Increasing the supply water temperature to the ACBs allows for a reduction in the borehole length if the borehole sizing mode is cooling. Therefore, there is no change in the required borehole length in cases 4, 5, and 6 with the DGC and GSHP system. In these cases, the borehole design mode is heating.

It is noted that the same amount of heat is rejected to the ground in

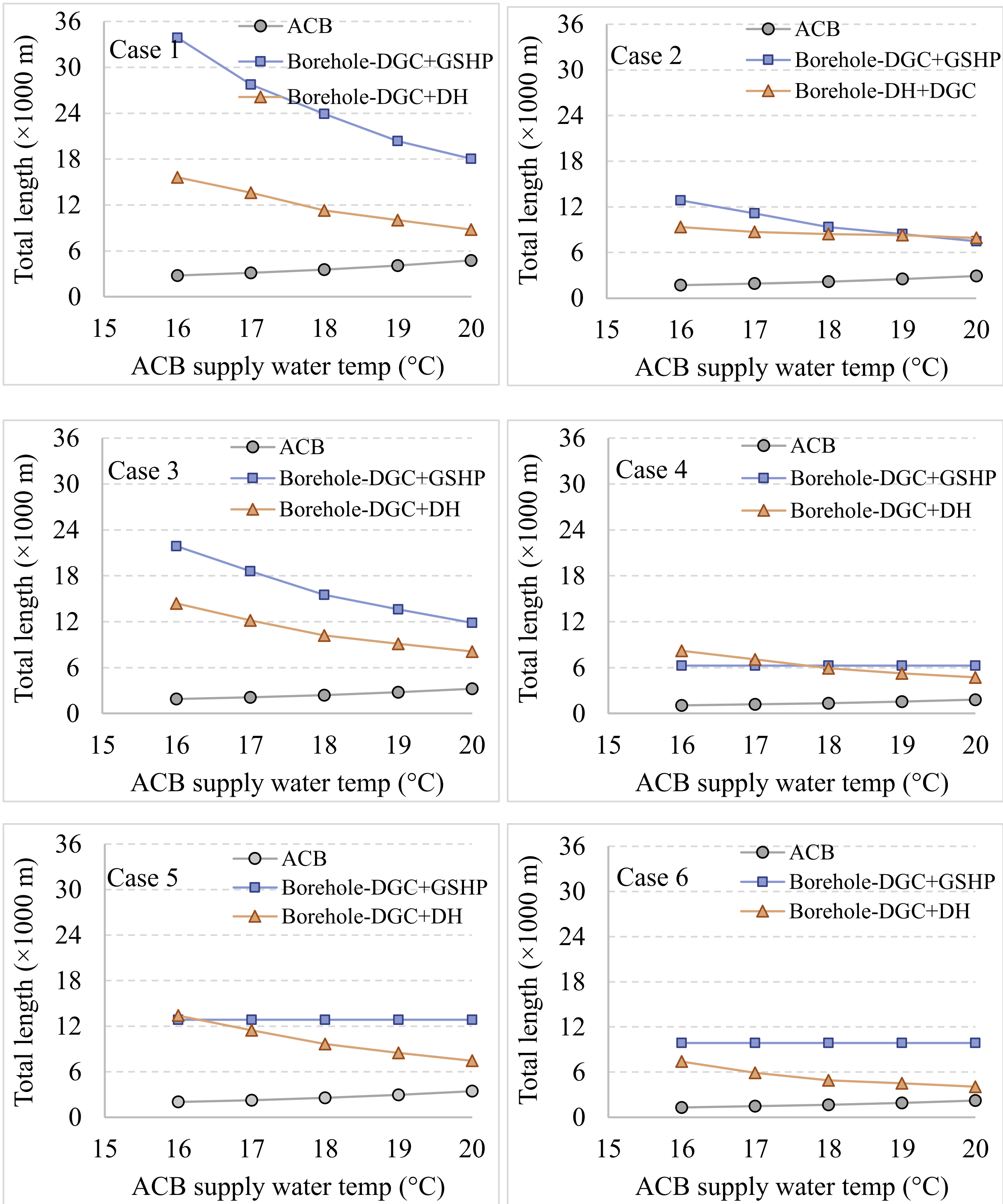


**Fig. 8.** The total length for the ACB length and the total required borehole length designed for studied cases (1-6) and various supply water temperatures for the ACBs.

both 16 °C and 20 °C supply water temperature design conditions. However, the heat rejection rate per borehole length increases. For example, in case 3, the heat rejection rate increases from 23 W/m to 45 W/m when the supply temperatures are 16 °C and 20 °C, respectively.

Fig. 11 shows the required borehole length as a function of the number of floors for the simulated building for cases 3 and 4 with the GSHP and DGC plant. These cases are chosen to exemplify two approaches to sizing the boreholes for tall buildings. However, the argument is valid for other cases. The required borehole length is designed for the supply temperature at 16 °C and 20 °C to the ACB systems. The corresponding borehole outlet fluid temperatures are 14 °C and 18 °C, respectively. “Case 3-ACB supply=16 °C” cannot be implemented even for a building of six floors. Increasing the supply water temperature to 20 °C allows for the design of a smaller borehole field and to use of the system for a building of nine floors. This is possible because cooling is the dominant mode for sizing the boreholes. Conversely, designing case 4 using either 16 °C or 20 °C supply temperatures results in no change in the required borehole length, as the sizing mode is heating.

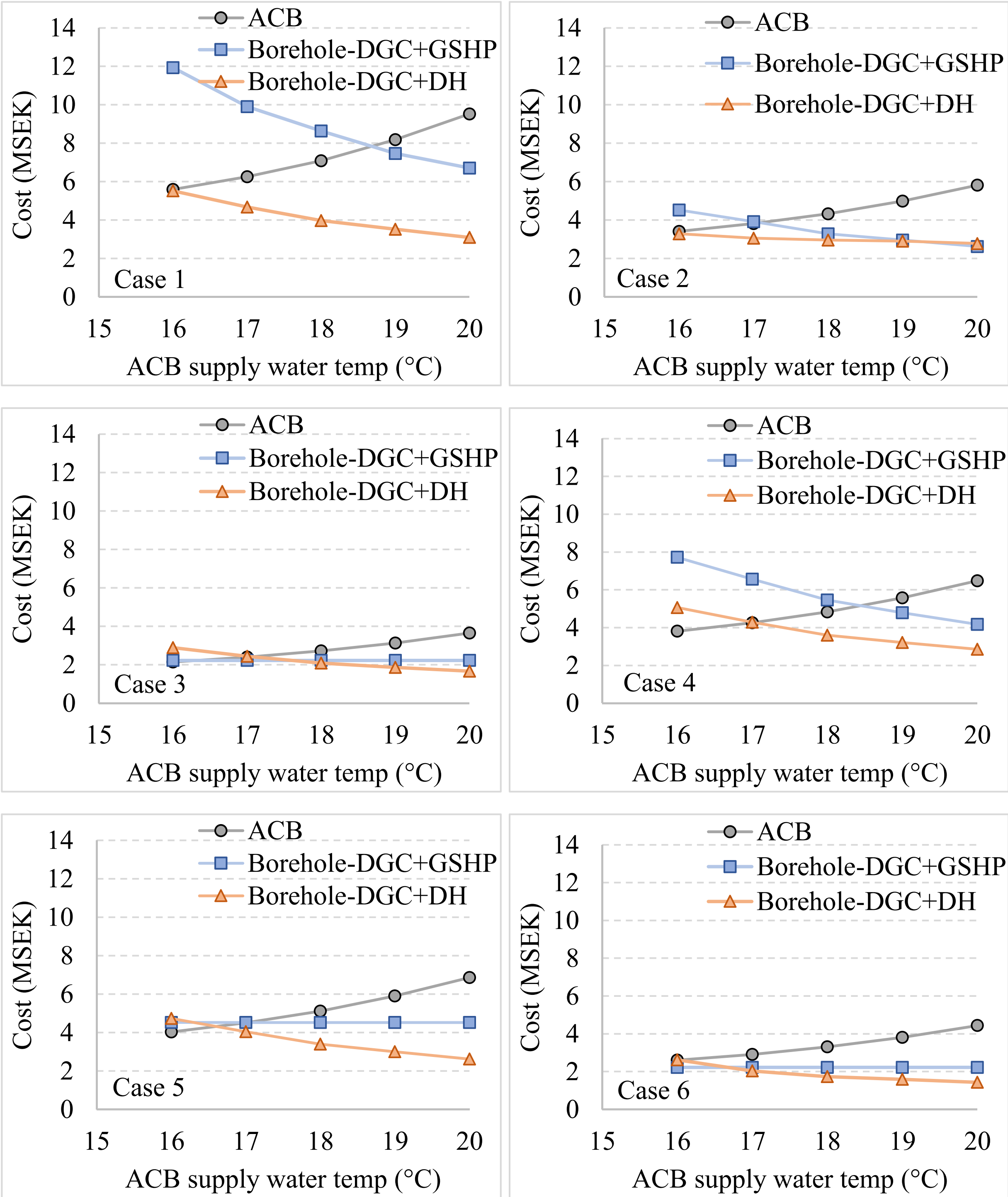


**Fig. 9.** Cost trade-off between ACB and borehole installation investments for studied cases (1-6) and various supply water temperatures to the ACBs.

Fig. 11 also shows the importance of considering buildings' thermal characteristics and building heating and cooling systems from the early stages of design. "Case 3" and "case 4" have the same building U-value but have different window G-values. A high G-value in case 3 upsets the balance between building heating and cooling loads, resulting in a large borehole system. Case 3 cannot be used for tall buildings, even when designed for the increased supply temperature. However, using windows with a low G-value can easily alleviate the imbalanced ground loads situation.

## 4. Discussion

Based on interviews with designers, our initial hypothesis was that the DGC and DH plants generally require a larger borehole field. However, results from the parametric study show that the required borehole length is generally shorter for DGC and DH plants. In most cases with DGC and GSHPs, additional borehole length was required to compensate for the imbalanced ground loads. In those cases, using the DGC and GSHP plant resulted in a smaller borehole field. The most relevant use case for the DGC and DH plant was for the buildings with low G-values and high U-values. This outcome confirms the previous finding of Javed

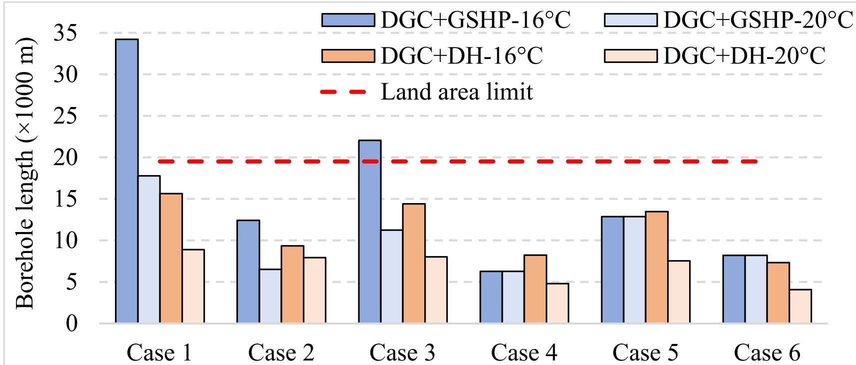


**Fig. 10.** Required borehole length designed for 16 °C and 20 °C supply temperature to the ACBs. The corresponding borehole outlet fluid temperatures are 14 °C and 18 °C, respectively.

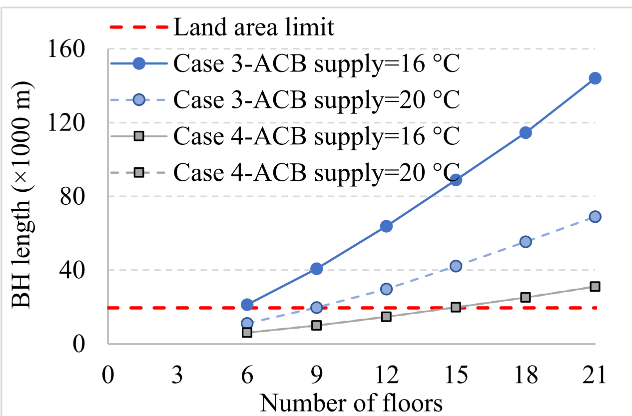


**Fig. 11.** Required borehole length in relation to the number of floors for the simulated building for cases 3 and 4 with the GSHP and DGC system. The corresponding borehole outlet fluid temperatures are 14 °C and 18 °C.

et al. (Javed et al., 2018) and Arghand et al. (Arghand et al., 2021) who suggested that adjusting the building envelope design parameters would balance the ground loads during the early stages of the system design.

Another important aspect of this study is utilizing the high-temperature cooling concept to reduce the required borehole length. The primary intention is to alleviate concerns about available land in densely built areas or places where land is too expensive. However, the main drawback of using this concept is the increased risk to design parameters that might not be fully understood, such as actual building cooling loads, heatwaves, and climate change. In both low- and high-temperature cooling approaches, the same building cooling load profile is used to size the boreholes. In the high-temperature approach, the borehole required length is sized shorter relative to the increased borehole outlet temperature. Since the daily peak cooling load is unchanged, the borehole heat exchange rates (described by W/m of boreholes) are higher compared to those with the low-temperature approach. Further studies are required to investigate this method from different aspects.

Some limitations need to be considered. First, the present study has investigated only one city. Studying other geographical conditions in Sweden would provide a more extensive assessment of the systems studied. Second, only radiators for heating and ACBs for cooling are used in this study. However, the use of other terminal units, especially those offering daily peak load shaving (such as pipe-embedded systems), favour the ground-coupled systems (Arghand et al., 2021, Arghand et al., 2021) and can influence the results. Third, in line with the previous point, other designs for the DGC and GSHP plants are expected to influence the results. Fourth, the choice of the energy plant not only influences the borehole design but can also profoundly impacts the energy and lifecycle costs of the system. This study has investigated the two energy plants from the perspectives of borehole sizing and land area requirements. The future work will investigate the energy performance, and the investment and lifecycle costs of the two energy plants.

## 5. Conclusions

This study describes some aspects of borehole design and land area optimization for DGCs combined with DH and GSHP for office buildings in Sweden. The following conclusions can be drawn:

1 Using DGC and GSHP plants does not necessarily result in a smaller borehole field. In this study, borehole fields are larger for DGC and GSHPs in most of the cases since the ground loads are imbalanced. The higher the imbalance level, the larger the borehole field, and the stronger the economic justification for using DGC and DH plants.
2 Increasing the borehole outlet temperature can considerably reduce the land area needed for ground-source cooling systems at the cost of an increased borehole heat exchange rate (W/m of the borehole). This method is always practical for DGC and DH systems and can be practical for DGC and GSHPs if cooling is the dominant sizing mode for boreholes.
3 From an investment perspective, the optimum borehole outlet temperature range can be defined by a trade-off analysis between borehole installation and the cost of terminal units. Higher outlet temperatures allow for shorter boreholes for which larger/more terminal units are required to compensate for the increased fluid temperature in the system.
4 Given the borehole installation costs, the DGC and DH plant can be regarded as inexpensive alternatives to the DGC and GSHP plant. Based on the assumptions made, borehole installation costs are lower in most cases when using the DGC and DH plants. Using DGC and DH instead of DGC and GSHPs is especially profitable when the ground loads are highly imbalanced towards heat extraction loads (heating the building).
5 This study demonstrates and quantifies the importance of harmonizing the building envelope design parameters (envelope U-value and windows G-value) to minimize the building peak loads and balance the annual loads. Such a comprehensive design can significantly reduce the required borehole length and thus, the borehole installation costs.

## CRediT authorship contribution statement

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

## Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence the authors' work.

## Data Availability

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

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