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Design optimization of the borehole system for a plus-Energy kindergarten in Oslo, Norway

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ABSTRACT

This paper presents the case study of a newly constructed 1600 m^2 kindergarten building in Oslo, Norway. The building has been designed within the framework of the Norwegian Research Council Project LowEx, which aims at engineering solutions to achieve a seasonal coefficient of performance (SCOP) of 6–10 for heating, a seasonal energy efficiency ratio (SEER) of 80–100 for cooling, and an 80% reduction in the purchased electric energy for heating and cooling of the buildings. Several architectural and technical measures have been implemented in the case study building to meet these requirements. This paper first provides an account of the design measures implemented in the building to achieve the ambitious energy performance targets. It then focuses on the design of the ground source heating and cooling system for the building and presents the preliminary design of the borehole system to provide low-temperature heating and high-temperature cooling to the kindergarten. The possibility of improving the borehole system design by optimizing the solar heat gains through the building envelope to balance the ground thermal loads is explored next. Finally, the effect of uncertainties in the design input values of ground thermal conductivity, effective borehole thermal resistance, and undisturbed ground temperature on the final design of the borehole system is evaluated.

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Heating and cooling; design; building energy use; ground-source; energy efficiency; building envelope

Introduction

Ground-source heating and cooling systems are among the most environmentally clean heating and cooling technologies available today (Rees, 2016). In recent years, optimizing the design and sizing of the ground-source systems to further enhance their environmental and operational performance has been a topic of great interest and extensive research (Alavy, Nguyen, Leong, & Dworkin, 2013; Javed, 2012; Javed & Spitler, 2017; Kavanaugh & Rafferty, 2014; Ozbek, Yavuzturk, & Pinder, 2015; Rees, 2016). Attention has largely focused on more accurate estimation and calculation of design inputs (e.g. Claesson & Javed, 2018; Fujii et al., 2009), development of computationally efficient design methods (e.g. He, Rees, & Shao, 2011; Javed & Claesson, 2011), and determination of optimum ground loop lengths (e.g. Cui, Zhou, & Liu, 2015; Hackel & Pertzborn, 2011).

The design of the ground-source heating and cooling system for a building depends primarily on the thermal heating and cooling demands of the building, and the thermal properties of the ground and borehole heat exchanger. Thermal demands of a building include space heating, space cooling and domestic hot water (DHW). In general, higher building thermal demands lead to larger borehole

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system sizes. It is also desirable to have annually balanced ground heat injections and extractions as the size of the borehole system is negatively affected by imbalanced ground loads. The heat balance in the ground is often achieved through hybrid ground source heat pump systems using auxiliary heating or cooling sources. For cooling dominated systems, supplemental heat rejecters, such as cooling towers, dry coolers, cooling ponds, or pavement heating systems, are used to reduce the required size of the borehole system (Ramamoorthy, Jin, Chiasson, & Spitler, 2001). For heating dominated systems, supplemental heat sources, such as solar collectors, boilers, electric heaters, or waste heat sources, are used to reduce the required size of the borehole system (Kim, Lee, & Jeon, 2016). Another possible, but relatively unexplored, alternate is to optimally engineer the heat gains through building envelope elements, especially through the glazing, to redress the imbalance in ground thermal loads.

Among the ground and borehole thermal properties, ground thermal conductivity (λ), effective borehole thermal resistance (R_b*), and the undisturbed ground temperature (T_0) are the three key parameters for the design of borehole systems. The λ and T_0 are the intrinsic properties of the ground and cannot be modified. The R_b*, on the other hand, depends on the geometric arrangement and physical properties of the borehole elements and can thus be engineered, at least to some degree. High λ and low R_b* values are desired when sizing ground-source heating and cooling systems. For larger systems, λ, R_b*, and T_0 values are typically determined through in-situ thermal response tests (Spitler & Gehlin, 2015). For smaller systems, these parameters are generally estimated based on experience and educated guess work. The use of estimated design parameters can, however, introduce significant uncertainties in the design of borehole systems.

This paper presents a systematic and comprehensive study of sizing the ground-source heating and cooling system for a newly built kindergarten building in Oslo, Norway. Being a relatively small building of less than 1600 m^2, no thermal response test was performed for this project and the design parameters for sizing the system were guessed based upon available scientific information and geology of the area. One objective of this study was to explore the possibility of optimizing the borehole system design by changing the envelope characteristics of the building to balance the ground heating and cooling loads. Another objective was to study the degree of sensitivity guessed values of T_0, λ, and R_b* have on the design of the borehole system. In the next section, the case study building is described more fully. A detailed description of the methodology is then provided, followed by the presentation and discussion of the results and conclusions.

Case study building

Lia kindergarten is the first plus-energy kindergarten built in Oslo. It is designed to produce more electrical energy than consumed by it for its operations over the course of a year. The kindergarten is situated in the Ellingsrud district and was taken into use in January 2018. It has a total heated floor

Figure 1. Rendering of Lia kindergarten.

area of 1579 m^2. Figure 1 shows the rendering of the building. The kindergarten has been designed within the framework of the Norwegian Research Council project LowEx. In accordance with the project objectives, the design of Lia kindergarten aimed to achieve a seasonal coefficient of performance (SCOP) of 6–10 for heating, a seasonal energy efficiency ratio (SEER) of 80–100 for cooling, and a reduction of 80% or more in the purchased electric energy for heating and cooling of the building. Moreover, the kindergarten building was designed to achieve a 'Very Good' rating under BREEAM Norway (NGBC, 2012). To meet these objectives, the building has been incorporated with several sustainable features including ground source heating and free-cooling, and local renewable electricity production from photovoltaics (PV) panels, among others.

Energy simulations of the Lia kindergarten were performed using the Norwegian dynamic simulation tool SIMIEN version 6 (ProgramByggerne, 2016) with design inputs from ISO 11855–2 (2012). The simulation tool is based on European Standard EN ISO 13790 (CEN, 2008) and complies with the Norwegian Standard NS 3031 (Standard Norge, 2007) on the calculation of energy performance of the buildings. It has also been validated against EN 15265 (CEN, 2007). The kindergarten has a total simulated specific energy demand of 53.5 kWh/m^2/year, and a specific purchased energy demand of 21.7 kWh$_{el}$/m^2/year. The PV system has been designed to deliver 22.9 kWh$_{el}$/m^2/year, thus producing more energy over the course of a year than consumed by the kindergarten. The design capacities of heating and cooling systems at Lia kindergarten are 26 and 20 W/m^2, respectively.

The heating and cooling system of Lia kindergarten is based on low-temperature heating and high-temperature cooling principles. Space heating and cooling are provided mainly through a radiant floor system. However, ventilation air is also used to cover some of the heating and cooling demands. The installed capacities of floor heating and cooling system are approximately 20 and 15 W/m^2, respectively, while, the installed air capacities of heating and cooling system are about 6 and 5 W/m^2, respectively.

The floor heating is served by a bivalent ground source heat pump system. The heat pump has a nominal heating capacity of 16–18 kW, whereas the integrated electric heater has an additional capacity of 9 kW for peak loads. On the load side, the heat pump has been designed to provide hot water at a maximum supply temperature of 28 °C for space heating. On the source side, the borehole system has been sized to provide a mean entering fluid temperature of over 5 °C to the heat pump. This results in a very energy-efficient heating system with low temperature-lifts and an ultra-high SCOP. The floor cooling is served by a direct ground cooling system. The boreholes provide cold water at less than 12 °C under peak cooling loads. The cooling system has a very high EER as the only energy input to the system is the work required to drive the circulation pumps.

Air heating and cooling are provided by a reversible extract air heat pump system integrated into the air handling unit (AHU). The DHW demands of the kindergarten have been taken to be 9 kWh/m^2/year based on measurements presented by Norwegian Water Resources and Energy Directorate (NVE, 2014). The DHW demand is also met mainly by the bivalent ground source heat pump system. The designed annual energy coverage of the floor heating and DHW demands from the ground source heat pump is approximately 99% and from and the electric resistance heater is about 1%. Table 1 provides more details of the construction and technical installations of Lia kindergarten.

Research design and methodology

The sizing of the borehole system for Lia kindergarten entailed a comprehensive design strategy. The design was aimed to deliver a mean borehole exit fluid temperature of over 5 °C for heating and a maximum borehole exit fluid temperature of 15 °C for cooling. First, the preliminary design of the borehole system was made using base case heating and cooling demands of the building. The preliminary design was specifically aimed at determining the number and depth of boreholes, the distance between holes, and the arrangement of the borehole elements. In the next step, the optimization of the design was performed to determine the optimal borehole depths by engineering the heating and cooling demands of the kindergarten building to improve the thermal balance of the

Table 1. Design details of the plus-energy Lia kindergarten.

System	Design Parameter	Value	Comment
	U-value external wall	0.17 W/m² K	250 mm insulation, prefabricated wall.
	U-value roof	0.10 W/m² K	450 mm insulation.
	U-value slab on ground	0.10 W/m² K	250–300 mm insulation.
	U-value windows and doors	0.79 W/m² K	Passivhouse standard windows.
	g-value windows and solar shading	0.18–0.50	Different for different facades.
	Normalized thermal bridge value	0.03 W/m² K	Optimized construction details.
	Infiltration at 50 Pa	0.50 ach	QA procedure in building phase.
	Normalized heat capacity	82 Wh/m² K	50-60% exposed ceiling.
	Average air flow rate Efficiency heat exchanger Specific fan power Supply temperature	4.0–7.0 m³/hm² 87% 0.70 kW/m³/s 18–20 °C	Demand-controlled. High-efficiency rotary exchanger. Low-pressure drops. Displacement ventilation.
	Cooling capacity, floor cooling Cooling capacity, air cooling	15 W/m² 5 W/m²	Free cooling from boreholes. DX cooling coil in AHU.
	Heating capacity, floor heating Heating capacity, air heating	20 W/m² 6 W/m²	GSHP and integrated electric heater. DX heating coil in AHU.
	Operating hours	2600 h	10 h x 5 days x 52 weeks.
	Occupational load	6.1 W/m²	Estimated load.
	Average load lighting Annual energy use lighting	2.35 W/m² 6.1 kWh/m²/year	LED fixtures. Presence and daylight control.
	Plug loads Annual electricity demand	2 W/m² 4 kWh/m²/year	Estimated load. Simulated demand.
	Annual demand DHW Annual coverage heat pump SCOP	4.5 kWh/m²/year 98% 3.0	Based on experience. Estimated coverage. Estimated performance.
	Energy supply room heating Annual coverage heat pump SCOP	18 kW + 9 kW 99% 6.3	Heat pump & electric heating. Estimated coverage. Estimated performance.
	PV-system Peak load Annual production	47.2 kW 36 600 kWh/year	178 modules (290 m²); 10° slope; EW orientation; 16.5% module efficiency.

borehole system. Values of all other design inputs were kept unchanged and equal to the preliminary design case. The number of boreholes and their layout and spacing was also kept the same as in the preliminary design case. The final step was to carry out a sensitivity analysis of the proposed design to assess the impact of uncertainty in the design parameters. All design simulations were made using the Superposition Borehole Model, SBM (Eskilson, 1986).

Preliminary design

Before performing the sizing of the borehole system, it was first necessary to decide upon the type and the configuration of the boreholes. In Norway, the most common application of GSHP systems is with groundwater-filled boreholes. Typically, a single U-tube heat exchanger of 32–50 mm outer diameter is installed in a 115–140 mm diameter borehole. The standard depth of a Norwegian borehole is between 200 and 300 m. In accordance with the Norwegian practices, it was decided to use groundwater-filled boreholes with a borehole diameter of 115 mm and single U-tube heat exchanger of 40 mm outer diameter. The preferred depth of boreholes was determined to be between 250 and 300 m from a combination of economic and space considerations.

The next step was to develop a preliminary design and layout of the borehole system. The preliminary design was made with specific constraints on fluid temperature exiting the borehole system. The design was based on the minimum and maximum temperatures of 3.5 and 15 °C, exiting the borehole at nominal flow rates, in heating and cooling modes, respectively. Another design constraint was that the average fluid temperature exiting the borehole system should be as high as possible but no less than 5 °C in heating mode.

To make the preliminary design of the borehole system, knowledge of building's thermal demands, and ground and borehole thermal properties was needed. Thermal demands, including hourly heating, cooling, and DHW loads of the Lia kindergarten, were modeled in the Norwegian simulation tool SIMIEN. Figure 2 presents the annual hourly ground heating and cooling loads used for the preliminary borehole system design of the Lia kindergarten. Ground and borehole thermal properties needed for designing the borehole system had to be estimated based on expert judgment and informed guesswork. This was because no thermal response test was performed for Lia kindergarten. The λ value was estimated based on the geology of the area. For Oslo region, λ values obtained from thermal diffusivity measurements of rock samples have been reported to have a median value of 2.6 W/m K, with lower and upper quartiles values of 2.1 and 3.9 W/m-K, respectively (Ramstad, Midttømme, Liebel, Frengstad, & Willemoes-Wissing, 2015). Similarly, λ values obtained from in-situ thermal response tests in the Oslo region have been reported to be between 2.6 and 3.7 W/m K (Liebel, Huber, Frengstad, Kalskin Ramstad, & Brattli, 2010).

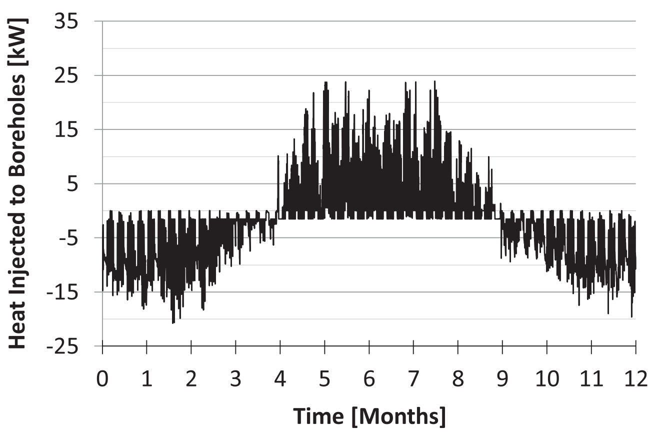

Figure 2. Base case ground thermal loads used for the preliminary design of the borehole system.

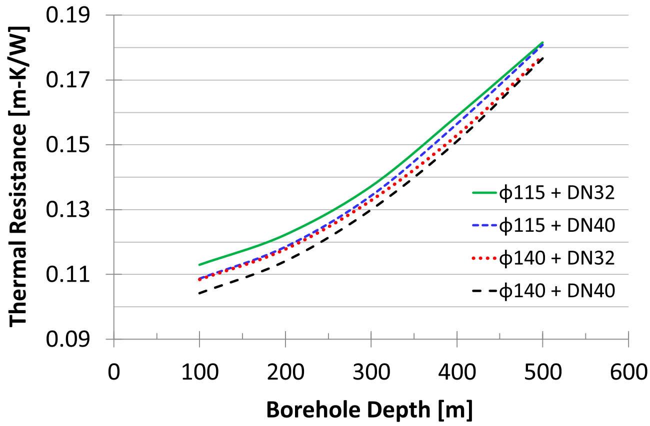

Figure 3. Effective borehole thermal resistance values for different geometries of single U-tube groundwater-filled boreholes.

The R_b* was estimated from the empirical model of Spitler et al. (2016) for waterfilled boreholes. Figure 3 presents R_b* estimations of single U-tube boreholes of different depths for different combinations of the standard borehole and U-tube diameters. Borehole diameters of 115 and 140 mm and U-tube outer-diameters of 32 and 40 mm were used. It can be seen from the figure that, for all combinations of the borehole and U-tube diameters, the estimated values of the R_b* increase with the borehole depth. This is due to the increasing thermal short-circuiting between the U-tube legs. The short-circuiting is caused by the heat exchange between the upward-flowing and downward-flowing pipes, which have circulating fluid at different temperatures at different borehole depths. Detailed explanation of this aspect can be found in Javed and Spitler (2017). On the other hand, as seen from the figure, the difference between different borehole and U-tube diameter combinations diminish with increasing borehole depths.

The T_0 was estimated with Equation 1, using the mean ground surface temperature (T_s) imposed with the ground thermal gradient. The geothermal gradient was obtained by dividing the geothermal heat flux (G) by the ground thermal conductivity (λ). This approach could be effectively used for estimating ground temperatures for depths more than a few tens of meters (Gehlin & Nordell, 2003; Xing & Spitler, 2017). Figure 4 presents the estimated T_0 values for boreholes of various depths using mean ground surface temperature of 5.7 °C, geothermal heat flux of 0.05 W/m^2, and λ range of 2.5–3.5 W/m K

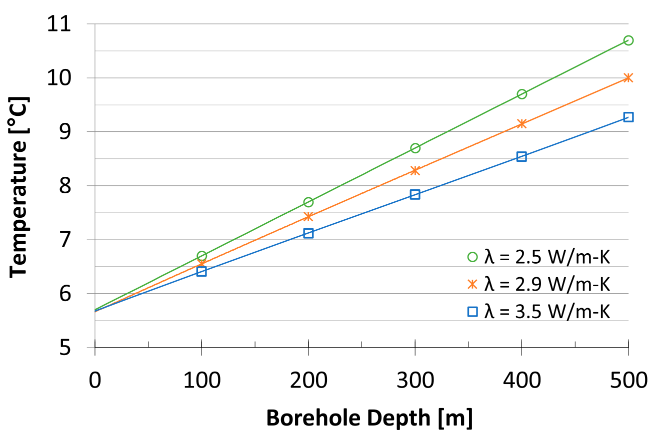

Figure 4. Undisturbed ground temperature estimates for the Oslo region.

typical for the Oslo region.

$$T_0 = T_s + \frac{H\dot{q}}{2\lambda} \tag{1}$$

Design optimization

After the preliminary design, the next step was to optimize the borehole system design to make it more cost effective and energy efficient. The optimization was studied by adjusting the heating and cooling demands of Lia kindergarten. Ideally, it is advantageous to have balanced ground heat injections and extractions over time as imbalanced ground thermal loads negatively affect the size of the borehole system, resulting in significantly larger systems. Ground thermal loads are a function of the building's heating, cooling and DHW demands, which, in turn, depend mainly upon occupants' behavior, envelope design, and climate conditions. Among these, building envelope design is the only parameter that could be engineered during the design phase of the project to achieve balanced ground heating and cooling loads.

The ground heating and cooling loads used for the preliminary design of the borehole system of Lia kindergarten were shown previously in Figure 2. The ground thermal loads were quite imbalanced, with ground heat extraction exceeding the ground heat injection by approximately 16,000 kWh/year. In the design optimization phase, the cooling demand of the building was increased to improve the balance in the ground thermal loads. This was done by adjusting the solar heat gains through windows. The base case thermal loads of Figure 2 were determined using g-values (solar factor) of 0.26 for windows facing south and 0.48 for windows facing north, east, and west. For the design optimization phase, three additional simulation cases (A, B and C) with increased cooling demands were studied. In Case A, the ground thermal loads used for sizing the borehole system were determined using a g-value of 0.45 for all windows. In Case B, the ground thermal loads were instead based on a g-value of 0.50 for all windows. In Case C, ventilation cooling loads were added to the ground loads on top of the thermal loads of Case B. In all other cases, the ventilation cooling loads were designed to be met by the extract-air heat pump integrated into the air handling system, and were, therefore, not included in the ground thermal loads. Figure 5 shows the ground heating and cooling loads for Cases A, B, and C.

The heat balance for all design cases is presented in Figure 6. It can be readily observed that the ground cooling loads increased incrementally between the base case and Cases A, B and C. The imbalance between the ground heat extractions and injections in Case A was approximately 19% lower than the base case. In Case B, the imbalance was reduced by over 37%. In Case C, in which the ventilation cooling loads were also met by the ground system, the imbalance between ground heat extractions and injections was reduced by approximately 54% compared to the base case.

Based on the results of the optimization cases, the final design of the borehole system was completed, considering potential reductions in borehole depths, energy use of the building, and technical constraints.

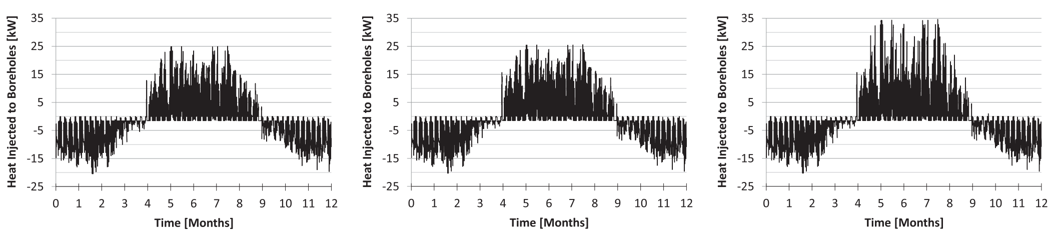

Figure 5. Ground heating and cooling loads for Cases A, B, and C.

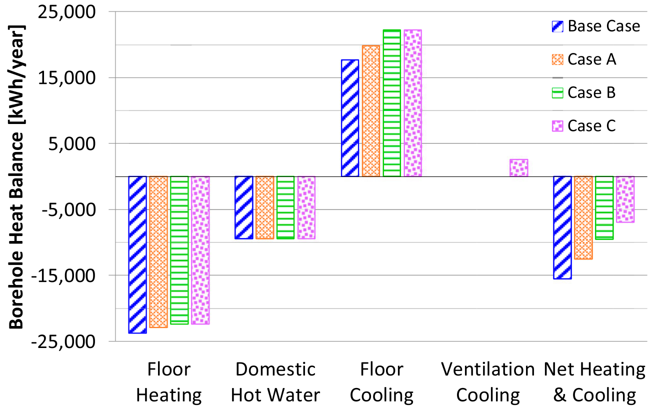

Figure 6. Heat balance of the borehole system for all design cases.

Sensitivity of final design

As mentioned earlier, the sizing of the borehole system of Lia kindergarten was performed using estimated values of design parameters. The estimated values were subjected to uncertainties due to incomplete knowledge of true ground and borehole thermal properties. The uncertainties in the estimated values of λ, R_b*, and T_0 introduced a corresponding uncertainty in the proposed design of the borehole system. Therefore, it was necessary to analyze the consequences of using estimated design parameters on the proposed design of the borehole system. This was done by performing a sensitivity analysis of the proposed design to uncertainties in the borehole design parameters. The uncertainties considered in the sensitivity analysis were ± 0.5 W/m K, ±0.02 m K/W and ± 1 °C in the estimated values of λ, R_b*, and T_0. The sensitivity of the borehole system design was first assessed in relation to each of the aforementioned parameters separately. In the end, a worst-case imputation analysis was performed, where the sensitivity of the borehole system was established for an absolute extreme scenario of all design parameters with their worst values occurring simultaneously.

Results and discussion

The first step in sizing the borehole system for Lia kindergarten was to estimate the values of the required design inputs and to make a suitable preliminary design based on the estimated parameters. The next step was to attempt to improve the design by engineering the heating and cooling demands of the kindergarten to balance the thermal demands on the borehole system, and to propose the final design. The final step was to investigate the effects of uncertainties in the estimated design inputs on the proposed design of the borehole system.

Preliminary design

The values of design input parameters, including λ, R_b* and T_0 were estimated based on expert judgment and informed guesswork. The values of λ, R_b* and T_0 were estimated to be 2.9 W/m K, 0.14 m K/W, and 8.1 °C, respectively. The estimated value of λ corresponded to the bedrock type in the area. The estimated values of R_b* and T_0 lied within the theoretically calculated range of 0.12–0.14 m K/W and 7.9–8.3 °C, respectively, for 250- to 300-meter-deep groundwater-filled boreholes drilled in the ground with λ of 2.9 W/m K. The estimated values of λ, R_b* and T_0 all compared well to the measured values in and around the Oslo region (Liebel, 2012).

Based on the base case thermal loads of Figure 2 and the above-mentioned estimates of the borehole and ground thermal properties, the size of the borehole system was determined. The results

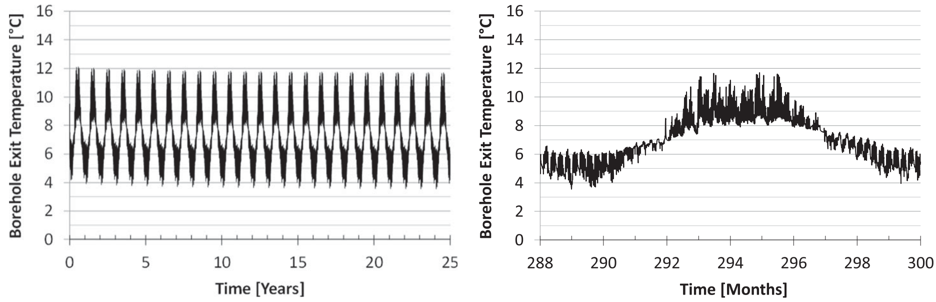

Figure 7. Extraction fluid temperatures for the base case with the ground thermal conductivity of 2.9 W/m-K, effective borehole thermal resistance of 0.14 m-K/W, and undisturbed ground temperature of 8.1 °C for (a) Twenty-five years and (b) Twenty-fifth year.

indicated that three single U-tube boreholes, each of 280 m active depth, with a borehole spacing of 15 m, would best meet the temporal, spatial and performance requirements. Figure 7 presents the extraction fluid temperature from this borehole configuration at nominal flows. The figure shows that the extraction fluid temperature exiting the borehole system and entering the heat pump would have a minimum value of 3.5 °C and an average value of 5.9 °C in winter. In summer, the maximum fluid temperature exiting the borehole system would be 11.7 °C. The resulting SCOP of the heat pump, calculated with the manufacturer's software for the entire heating season, would be 6.3 while the SCOP of the overall heating system, including the power consumptions of the backup heater and the circulation pumps, would be 5.2. The SEER for the cooling system would be 86. The reduction in the purchased electric power for heating and cooling of Lia kindergarten would be approximately 83% compared to traditional electrical heating and mechanical cooling systems with thermal efficiencies of 100 and 250%, respectively.

Design optimization

To improve and optimize the preliminary design of the borehole system, three additional design cases were studied using the same approach and constraints as the preliminary design case (base case). The optimization was carried out by only varying the heating and cooling demands of the kindergarten building. According to the results obtained from the Superposition Borehole Model, borehole depths of 272, 265 and 262 m, would be needed for Cases A, B, and C, respectively, to fulfill the temporal requirements of 3.5 and 15 °C as the minimum and maximum exit fluid temperatures from the borehole system in the heating and cooling modes, respectively. Figure 8 shows the extraction fluid temperatures simulated for Cases A, B, and C under nominal flow conditions. Due to subsequent balancing of ground thermal loads, the average values of extraction fluid temperature exiting the borehole system increased incrementally from Case A to Case C. In winter, the average values of fluid temperature exiting the borehole system and entering the heat pump were simulated to be approximately 5.9, 6.0 and 6.1 °C for cases A, B and C, respectively. The maximum fluid temperatures exiting the borehole system in summer were simulated to be 12.3, 12.8 and 14.6 °C, approximately, for cases A, B, and C, respectively.

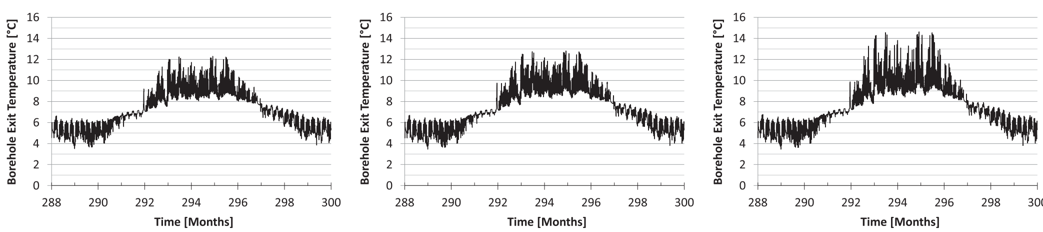

Figure 8. Twenty-fifth-year extraction fluid temperatures for Cases A, B, and C.

The above results clearly highlight the potential of optimizing the borehole system design by engineering heat gains through building envelope elements. For Lia kindergarten, the borehole system depth could be reduced from 3 × 280 m to 3 × 265 m by changing the g-value of windows, while still meeting the specified design constraints. The borehole system depth could even be shortened to 3 × 262 m by including ventilation cooling loads on the ground system. The reduction in required borehole depth would mean substantial cost savings in terms of drilling cost. Moreover, the use of windows with high g-values in Cases A, B and C would yield additional cost savings.

In the case of Lia kindergarten, however, factors other than potential savings in drilling cost were also considered when deciding upon the final depth of the borehole system. Among these were the thermal and electrical energy requirements for heating, cooling, and DHW of the kindergarten building. Figure 9 shows the predicted specific energy use of the kindergarten building for all design cases. The required borehole depth is also shown for each design case. It can be seen from the figure that the required borehole depth decreased successively between cases due to the improved balancing of ground thermal loads. However, this reduction in the borehole depth came at the expense of an increase in the specific thermal energy use of the building. The specific thermal energy use of the building increased from 38.1 kWh/m^2/year for the base case to 38.8 kWh/m^2/year for Case A. For Cases B and C, the specific thermal energy use of the building increased up to 39.9 and 41.5 kWh/m^2/year, respectively. The change in the specific electrical energy use of the building between different cases was marginal though.

As mentioned previously, the design of Lia kindergarten was made to achieve a 'Very Good' rating under BREEAM Norway (NGBC, 2012). There were 13 credits for energy efficiency in BREEAM Norway to recognize and encourage buildings to minimize their operational energy consumption through good design. The number of awarded BREEAM Norway credits was based upon the percentage improvement in the building's calculated delivered energy (kWh/m^2/year) in relation to the level required to achieve an energy label C within the Norwegian Energy Performance Certificate scheme. Hence, to obtain the maximum energy efficiency credits, the borehole system designed for the base case scenario was chosen as the final design option, despite having higher drilling length than required in other design cases.

Sensitivity of final design

The sensitivity of the final borehole design to the uncertainty in λ, R_b* and T_0 was studied over a wide range of values. Figure 10 shows the borehole leaving fluid temperature after 25 years for λ values of 2.5 and 3.5 W/m K. The proposed design was based on the λ value of 2.9 W/m K. The comparison of

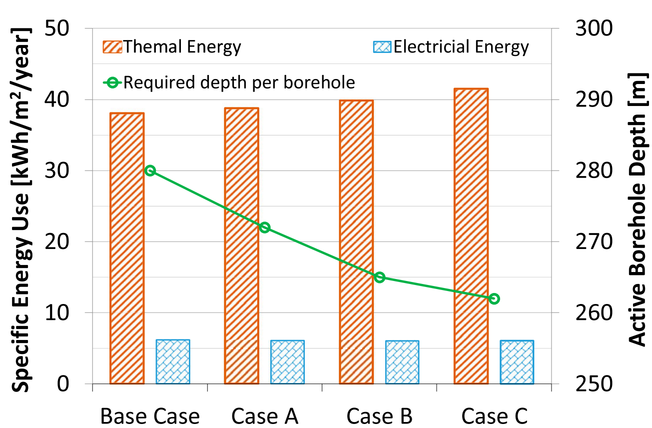

Figure 9. Energy use and required borehole depth for all design cases.

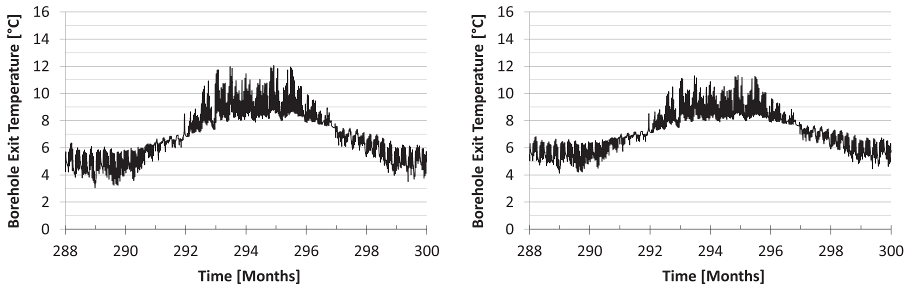

Figure 10. Twenty-fifth-year borehole exit fluid temperatures considering ground thermal conductivity values of (a) 2.5 W/m-K and (b) 3.5 W/m-K.

Figures 7 and 10 demonstrates the sensitivity of the borehole exit fluid temperatures to the uncertainty in the estimation of the λ value. The minimum fluid temperatures leaving the borehole system for λ values of 2.5, 2.9 and 3.5 W/m K were simulated to be 3.0, 3.6 and 4.1 °C, respectively. The average fluid temperatures exiting the borehole system in winter for the three λ estimations were simulated to be 5.6, 5.9 and 6.2 °C, respectively. The maximum fluid temperatures leaving the borehole system in summer were simulated to be 12.1, 11.7 and 11.3 °C for the λ values of 2.5, 2.9 and 3.5 W/m K, respectively.

Together, the simulation data implied that, as expected, the extraction fluid temperatures from the borehole system would be negatively affected by a λ value lower than the estimated value and vice versa. However, at least in the case of Lia kindergarten, the impact of a low λ on the extraction fluid temperatures would not be as severe as anticipated. An overestimation of 0.5 W/m K in the estimated λ value would mean that, in the proposed design scenario, the values of average and minimum extraction fluid temperatures in winter were being overestimated by approximately 0.3 and 0.5 K, respectively, while the value of maximum extraction fluid temperature in summer was being underestimated by 0.4 K. This means, the actual SCOP of the heat pump and the overall system, including the backup heater and the circulation pumps, would be approximately 1% lower than in the proposed design scenario. The actual SEER for cooling would be approximately 4% lower. Yet, the net reduction in the purchased electric power for heating and cooling would be roughly at the same level as in the proposed design scenario.

Figure 11 shows the borehole leaving fluid temperature after 25 years for R_b* values of 0.12 and 0.16 m-K/W. The proposed design was based on the R_b* value of 0.14 m-K/W. The comparison of Figures 7 and 11 demonstrates the sensitivity of the borehole exit fluid temperatures to the uncertainty in the estimation of the R_b* value. The minimum fluid temperatures leaving the borehole system for R_b* values of 0.12, 0.14 and 0.16 m K/W were simulated to be 4.0, 3.6 and 3.1 °C, respectively. The average fluid temperatures exiting the borehole system in winter for the three R_b* values

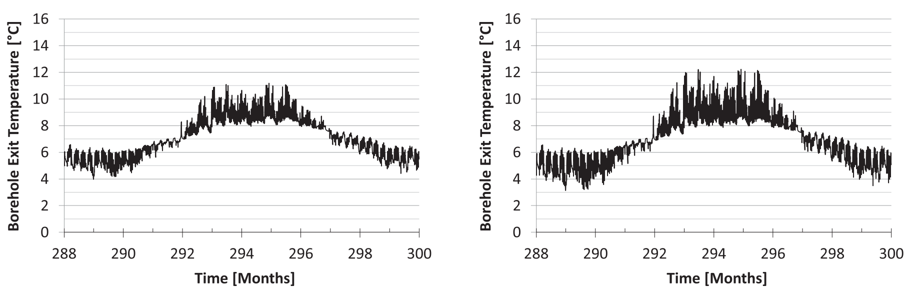

Figure 11. Twenty-fifth-year borehole exit fluid temperatures considering effective borehole thermal resistance values of (a) 0.12 m-K/W and (b) 0.16 m-K/W.

were simulated to be 6.0, 5.9 and 5.7 °C, respectively. The maximum fluid temperatures leaving the borehole system in summer were simulated to be 11.2, 11.7 and 12.2 °C for the R_b* estimates of 0.12, 0.14 and 0.16 m K/W, respectively.

The above results indicated that, as expected, the extraction fluid temperature from the borehole system would be adversely affected by an R_b* value higher than the anticipated value and vice versa. However, the impact of a high R_b* value on the extraction fluid temperatures would not be particularly large. An overestimation of 0.02 m-K/W in the estimated R_b* value would mean that, in the proposed design scenario, the average and minimum extraction fluid temperatures in winter were being overestimated by approximately 0.2 and 0.5 K, respectively, while the value of maximum extraction fluid temperature in summer was being underestimated by 0.5 K. This means, the actual SCOP of the heat pump and the overall system, including the backup heater and the circulation pumps, would be approximately 1% lower than in the proposed design scenario. The actual SEER for cooling would be approximately 5% lower. However, the net reduction in the purchased electric power for heating and cooling would be roughly at the same level as in the proposed design scenario.

Figure 12 shows the borehole leaving fluid temperature after 25 years for T_0 values of 7.1 and 9.0 °C. The proposed design was based on the T_0 value of 8.1 °C. The comparison of Figures 7 and 12 demonstrates the sensitivity of the borehole exit fluid temperatures to the uncertainty in the estimation of T_0 value. The minimum fluid temperatures leaving the borehole system for T_0 values of 7.1, 8.1 and 9.0 °C were simulated to be 2.6, 3.6 and 4.5 °C, respectively. The average fluid temperatures exiting the borehole system in winter for the three T_0 values were simulated to be 4.9, 5.9 and 6.8 °C, respectively. The maximum fluid temperatures leaving the borehole system in summer were simulated to be 10.7, 11.7 and 12.6 °C for the T_0 values of 7.1, 8.1 and 9.0 °C, respectively.

The above simulation results suggested that the extraction fluid temperatures from the borehole system would be directly influenced by the T_0 value. An overestimation of 1 K in the estimated T_0 value would mean that, in the proposed design scenario, the values of average and minimum extraction fluid temperatures in winter, and the maximum extraction fluid temperature in summer were all being overestimated by 1 K. Consequently, the actual SCOP of the heat pump and the overall system, including the backup heater and the circulation pumps, would be approximately 3% lower than in the proposed design scenario. Whereas, the actual SEER for cooling would be approximately 8% higher. Overall, the net reduction in the purchased electric power for heating and cooling would be roughly at the same level as in the proposed design scenario.

Figure 13 shows the borehole leaving fluid temperature after 25 years for the most unfavorable combination of design parameters estimates. The λ, R_b*, and T_0 values used in this scenario were 2.5 W/m K, 0.16 m K/W, and 7.1 °C, respectively. The proposed design was based on the estimated values of 2.9 W/m K, 0.14 m K/W, and 8.1 °C. The comparison of Figures 7 and 13 demonstrates the sensitivity of the borehole exit fluid temperatures to the overall uncertainties in the design parameters estimates. Compared to the minimum and maximum extraction fluid temperatures of 3.5

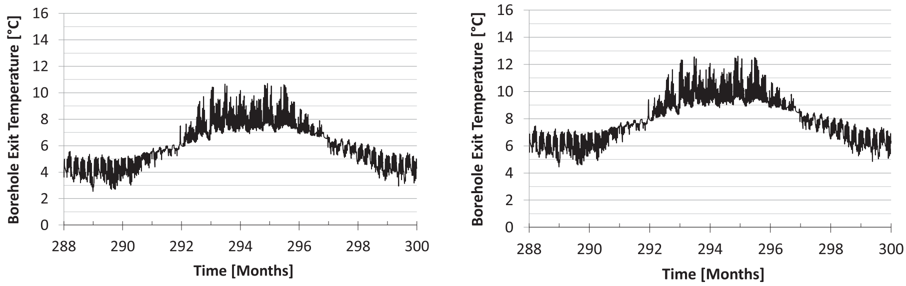

Figure 12. Twenty-fifth-year borehole exit fluid temperatures considering undisturbed ground temperatures of (a) 7.1 °C and (b) 9.0 °C.

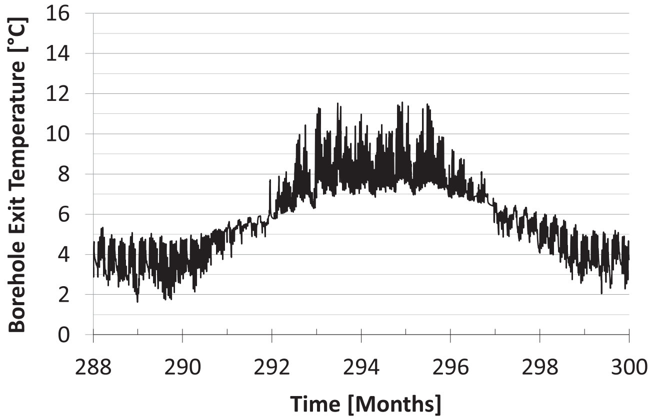

Figure 13. Twenty-fifth-year borehole exit fluid temperatures considering the most unfavorable combination of design parameters, i.e. ground thermal conductivity value of 2.5 W/m-K, effective borehole thermal resistance values of 0.16 m-K/W, and undisturbed ground temperature value of 7.1 °C.

and 11.7 °C in the proposed design scenario, the corresponding fluid temperatures exiting the borehole system under the most adverse combination of design parameters were simulated to be 1.6 and 11.6 °C, respectively. The average extraction fluid temperature was simulated to be 4.5 °C compared to 5.9 °C in the proposed design scenario. This suggests if the worst-case scenario would come to pass, the average and minimum extraction fluid temperatures in winter would be deteriorated approximately by 1.5 and 2.0 K, respectively. In contrast, the change in the maximum extraction fluid temperature in summer would be trivial. The resulting SCOP of the heat pump and the overall system, including the backup heater and the circulation pumps, would be approximately 4% worse than in the proposed design scenario. The change in the SEER for cooling would, however, be negligible. As a result, the net reduction in the purchased electric power for heating and cooling would be nearly at the same level as in the proposed design.

The results of the sensitivity analysis suggest that the proposed design of Lia kindergarten's borehole system is quite tolerant to uncertainties in design parameters. Under the assumed conditions, the individual uncertainties in the estimated values of λ, R_b* and T_0 would have an adverse effect of less than 5% on the SCOP and SEER of the heating and cooling systems, respectively. The cumulative effect of these uncertainties, as depicted in the worst-case scenario, would be even smaller. This is because of the counterbalancing effect of some of the design parameters on the performance of the system in heating and cooling modes. For example, a lower value of T_0 negatively affects the SCOP of the heating system but positively affects the SEER of the cooling system. Consequently, all together, the uncertainties in design parameters would have an insignificant effect on the total purchased electric power for heating and cooling of the kindergarten building. Hence, compared to traditional electrical heating and mechanical cooling systems, the percentage reduction in the purchased electric power for heating and cooling of Lia kindergarten would be at the same level as in the proposed design scenario.

Conclusions

This paper presented a detailed and illustrative study of using ground source heating and cooling systems for modern low energy-buildings. The potential and robustness of these systems to provide low-temperature heating and high-temperature cooling while achieving high levels of system performance was demonstrated. It was shown that through careful design and engineering, it is possible to achieve a seasonal coefficient of performance (SCOP) of over 6 for heat pump systems and a seasonal energy efficiency ratio (SEER) of over 80 for direct ground cooling systems.

The paper also addressed key design issues and considerations for sizing and optimizing the ground-source heating and cooling systems. It was demonstrated how the main design parameters, including undisturbed ground temperature, ground thermal conductivity, and borehole thermal resistance, can be estimated for small- to medium-sized systems without performing a thermal response test. The use of sensitivity analysis to quantify the effects of uncertainties in design parameters to aid the design decisions was illustrated. Moreover, a novel and relatively unexplored approach to optimize the borehole system design by balancing the ground heating and cooling demands of the building by changing its envelope characteristics was proposed and thoroughly investigated. The suggested approach offers an attractive alternate to the traditional use of supplemental heat sources (such as solar collectors, boilers, and electric heaters) or supplemental heat rejecters (such as cooling tower and dry coolers) for balancing annual ground thermal loads in heating or cooling dominated systems, respectively. It could result in significant cost savings in terms of borehole drillings and auxiliary equipment.

The study was carried out as a case study of a plus-energy kindergarten building in Oslo. The ground and borehole thermal properties including the undisturbed ground temperature, ground thermal conductivity, and borehole thermal resistance, were estimated based on experience and educated guess work. The sizing of the borehole system was made to provide a mean entering fluid temperature of over 5 °C to the heat pump for space heating, and a maximum fluid temperature of less than 15 °C for direct ground cooling. The resulting SCOP of the heat pump was estimated to be 6.3, whereas the SEER of the cooling system was predicted to be 86. The design was shown to reduce the purchased electric power for heating and cooling of Lia kindergarten by 83% compared to traditional electrical heating and mechanical cooling systems with thermal efficiencies of 100 and 250%, respectively. It was shown that the required depth of the borehole system could be significantly reduced by engineering heat gains through the building envelope to balance the ground heating and cooling demands. It was also shown that the proposed design is quite robust and fairly insensitive to the probable uncertainties in the estimated design parameters.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Alavy, M., Nguyen, H. V., Leong, W. H., & Dworkin, S. B. (2013). A methodology and computerized approach for optimizing hybrid ground source heat pump system design. *Renewable Energy*, *57*, 404–412.

CEN. (2007). *EN 15265:2007: Energy performance of buildings – calculation of energy needs for space heating and cooling using dynamic methods – general criteria and validation procedures*. Brussels: CEN – European Committee for Standardization.

CEN. (2008). *EN ISO 13790:2008: Energy performance of buildings – calculation of energy use for space heating and cooling*. Brussels: CEN – European Committee for Standardization.

Claesson, J., & Javed, S. (2018). Explicit Multipole Formulas for Calculating thermal resistance of single U-tube ground heat Exchangers. *Energies*, *11*(1), 214.

Cui, W., Zhou, S., & Liu, X. (2015). Optimization of design and operation parameters for hybrid ground-source heat pump assisted with cooling tower. *Energy and Buildings*, *99*, 253–262.

Eskilson, P. (1986). Superposition Borehole Model. Manual for computer code.
Fujii, H., Okubo, H., Nishi, K., Itoi, R., Ohyama, K., & Shibata, K. (2009). An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers. *Geothermics*, *38*(4), 399–406.
Gehlin, S., & Nordell, B. (2003). Determining undisturbed ground temperature for thermal response test. *ASHRAE Transactions*, *109*(1), 151–156.
Hackel, S., & Pertzborn, A. (2011). Effective design and operation of hybrid ground-source heat pumps: Three case studies. *Energy and Buildings*, *43*(12), 3497–3504.
He, M., Rees, S., & Shao, L. (2011). Simulation of a domestic ground source heat pump system using a three-dimensional numerical borehole heat exchanger model. *Journal of Building Performance Simulation*, *4*(2), 141–155.
ISO. (2012). *11855-2:2012 (E): building environment design – design, dimensioning, installation and control of embedded radiant heating and cooling systems – Part 2 determination of the design heating and cooling capacity*. Geneva: International Organization for Standard.
Javed, S. (2012). Thermal modelling and evaluation of borehole heat transfer. *PhD Thesis*. Chalmers University of Technology, Gothenburg, Sweden.
Javed, S., & Claesson, J. (2011). New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. *ASHRAE Transactions*, *117*(1), 3–12.
Javed, S., & Spitler, J. (2017). Accuracy of borehole thermal resistance calculation methods for grouted single U-tube ground heat exchangers. *Applied Energy*, *187*, 790–806.
Kavanaugh, S. P., & Rafferty, K. D. (2014). *Geothermal heating and cooling: Design of ground-source heat pump systems*. Atlanta: ASHRAE.
Kim, Y., Lee, J. S., & Jeon, S. W. (2016). Hybrid ground-source heat pump systems. In S. J. Rees (Ed.), *Advances in ground-source heat pump systems* (pp. 331–357). Oxford: Woodhead Publishing.
Liebel, H. T. (2012). *Influence of groundwater on measurements of thermal properties in fractured aquifers* (*Doctoral thesis*). Norwegian University of Science and Technology, Norway.
Liebel, H. T., Huber, K., Frengstad, B. S., Kalskin Ramstad, R., & Brattli, B. (2010). *Rock core samples cannot replace thermal response tests – a statistical comparison based on thermal conductivity data from the Oslo region (Norway)*. Proceedings of renewable energy Conference. (pp. 145-154).
NGBC. (2012). *Technical Manual BREEAM-NOR ver. 1.1 New construction*. Oslo: Norwegian Green Building Council.
NVE. (2014). *Analyse av energibruk i undervisningsbygg (In English: Analysis of energy use in teaching buildings)*. Oslo: Norwegian Water Resources and Energy Directorate.
Ozbek, M., Yavuzturk, C., & Pinder, G. (2015). *Optimal ground source heat pump system design*. New Jersey: Environ.
ProgramByggerne. (2016). SIMIEN version 6.004.
Ramamoorthy, M., Jin, H., Chiasson, A. D., & Spitler, J. D. (2001). Optimal sizing of hybrid ground-source heat pump systems that use a cooling pond as a supplemental heat rejecter – A system simulation approach. *ASHRAE Transactions*, *107*(1), 26–38.
Ramstad, R. K., Midttømme, K., Liebel, H. T., Frengstad, B. S., & Willemoes-Wissing, B. (2015). Thermal conductivity map of the Oslo region based on thermal diffusivity measurements of rock core samples. *Bulletin of Engineering Geology and the Environment*, *74*(4), 1275–1286.
Rees, S. (ed.). (2016). *Advances in ground-source heat pump systems*. Oxford: Woodhead Publishing.
Spitler, J. D., & Gehlin, S. E. (2015). Thermal response testing for ground source heat pump systems—An historical review. *Renewable and Sustainable Energy Reviews*, *50*, 1125–1137.
Spitler, J. D., Javed, S., & Ramstad, R. K. (2016). Natural convection in groundwater-filled boreholes used as ground heat exchangers. *Applied Energy*, *164*, 352–365.
Standard Norge. (2007). *NS 3031: Calculation of energy performance of buildings, methods and data*. Oslo: Standard Norge.
Xing, L., & Spitler, J. D. (2017). Prediction of undisturbed ground temperature using analytical and numerical modeling. *Part I: Model Development and Experimental Validation. Science and Technology for the Built Environment*, *23*(5), 787–808.