

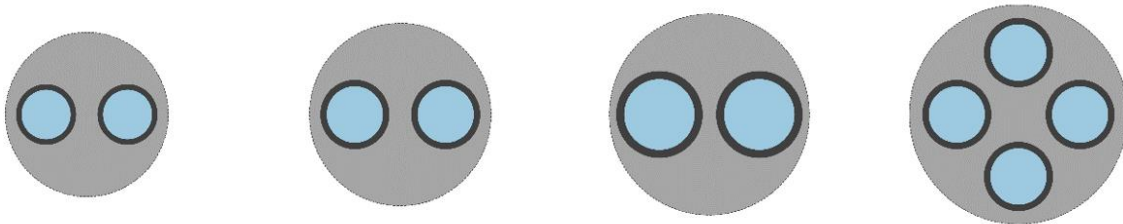


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Comparative analysis of the performance of typical geothermal heat exchangers



Prepared for Versaprofiles.

by Solutions Geolearn, with the collaboration of the Centre Eau Terre Environnement of
the Institut national de la recherche scientifique

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Nomenclature

\dot{m}	Mass flow rate of the heat carrier fluid in kg/s
C_p	Specific heat of the heat carrier fluid in J/kg/°C
k_g	Thermal conductivity of the ground in W/m/°C
q_b	Ground heat flux in W
q'_b	Ground heat flux per unit length in W/m
T_g	Mean undisturbed temperature of the ground
T_b	Borehole mean temperature in °C
T_{fi}	Temperature of the fluid entering the borehole in °C
T_{fo}	Temperature of the fluid leaving the borehole in °C
T_f	Mean fluid temperature in °C
$T_{g_{4m}}$	Mean undisturbed ground temperature at a depth of 4 m below the ground surface in °C
N_b	Number of boreholes
L_b	Borehole length in m
L_{tot}	Total borehole length in m
R_b	Thermal resistance of the borehole in °C·m/W
R_b^*	Effective fluid-to-ground thermal resistance of the borehole in °C·m/W
$G(F_0)$	G-function
Q_g	Mean deep terrestrial heat flow in W/m ²

1. Objectives

The length of heat exchangers to be installed in the ground with geothermal heat pump systems can be optimized to reduce installation cost. For vertical heat exchangers installed in boreholes, this can be done by selecting optimal materials, dimensions and configurations. One item to optimize is the pipe loop that can help reduce the borehole thermal resistance.

The objective of this study was to compare the performance of different configurations of ground loop heat exchangers (GLHE) made with large diameter pipes. This was done in two parts using analytical modelling and sizing calculations.

In the first part, heat extraction (heating) and injection (cooling) rates in the ground were calculated with an analytical method for four different configurations of GLHE and the results were compared with each other. The impact of the ground thermal conductivity and borehole length on the performance of the GLHEs was also assessed.

In the second part, the VersaGLD software was used to perform sizing calculations for a typical building, a high school located in a climate corresponding to that of Boston, USA. The sizing calculations were carried out for each of the four GLHE configurations considered in part 1.

Overall, the study allowed to evaluate the performance of single and twin GLHE having pipe with a nominal diameter varying from 1.25 to 2 inches. The conventional pipe diameter used by the geothermal industry is 1.25 inches and novelty of this work relied in the performance assessment of GLHE with a larger pipe diameter.

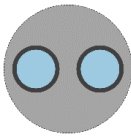
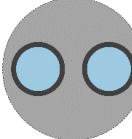

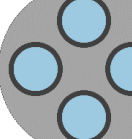
2. Borehole configurations and heat carrier fluid

The characteristics of the four different GLHE configurations compared in this study are presented in Table 1. The heat exchangers are composed of one or two loops of HDPE circular pipe. The dimensions of the pipes for each configuration were determined using the IPS DR-PR PE Plastic Pipe sizing system of the D3035-14a standard (ASTM Standard D3035 2014). The distance between the center of the pipes (shank spacing) was calculated for each configuration so as to represent an intermediate case between the case where the pipes are completely pressed against the wall of the borehole (when clips are used) and the case where the pipes are completely stuck together. The diameters of the boreholes were defined based on information collected by Versaprofiles from clients, mainly drillers in Ontario (J.F. Lavoie, personal communication, 2021).

The thermal conductivity of the pipe was assumed to be 0.4 W/m/°C for all the GLHE configurations and the borehole was assumed to be filled with a thermally enhanced grout with a thermal conductivity of 1.70 W/m/°C.

For the heat carrier, a fluid composed of a mixture of water and propylene glycol with a concentration of 30% was used for all the calculations carried out in this study. This heat carrier fluid type is commonly used in Ontario with concentration varying between 25% and 30%, according to information collected by Versaprofiles from driller clients in Ontario (J.F. Lavoie, personal communication, 2021). We chose a concentration of 30% in order to allow calculations for cold climate, even though the results for such calculations are not presented in this report.

Table 1 – Characteristics of the heat exchangers compared in this study.

		1	2	3	4
Feature	Units	Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth grout	W/m/°C	1.70	1.70	1.70	1.70

3. Part 1 – Heat extraction and injection rate calculations

3.1. Theory

3.1.1. Heat transfer in the heat pump

The heat transfer in the heat pump is defined as:

$$q'_b = \frac{\dot{m} \cdot C_p \cdot (T_{fo} - T_{fi})}{L_b} \quad \text{Equation 1}$$

where q'_b is the heat flux per unit length between the borehole and the heat pump in W/m, \dot{m} is the mass flow rate of the heat carrier fluid in kg/s, C_p is the specific heat of the fluid in J/kg/°C, T_{fo} and T_{fi} are, respectively, the temperature of the fluid leaving and entering the borehole in °C, and L_b is the length of the borehole in m.

The temperature of the fluid entering the borehole (T_{fi}) is controlled in this closed-loop system by the heat pump. It is thus a known value that we impose to the system.

3.1.2. Heat transfer in the fluid

The heat transfer in the fluid is defined as:

$$q'_b = \frac{T_b - T_f}{R_b^*} \quad \text{Equation 2}$$

where q'_b is the heat flux per unit length between the borehole and the fluid in W/m, R_b^* is the effective fluid-to-ground thermal resistance of the borehole in °C·m/W, T_b is the borehole mean temperature in °C and T_f is the mean fluid temperature in °C.

The value of R_b^* is calculated using the multipole method (Claesson and Hellström 2011) and the effect of varying fluid temperatures along the flow channels as well as the heat exchange between these channels are taken into account using equation 8.101 in Hellström (1991). The G-function is calculated using the finite line source solution (Lamarche and Beauchamp 2007).

3.1.3. Heat transfer in the ground

The heat transfer between the borehole and the ground is defined as:

$$T_b - T_g = -\frac{q'_b}{k_g} \cdot G(F_0) \quad \text{Equation 3}$$

where q'_b is the heat flux per unit length between the borehole and the ground in W/m, T_g is the mean undisturbed temperature of the ground in °C, T_b is the borehole mean temperature in °C, k_g is the thermal conductivity of the ground in W/m/°C, and $G(F_0)$ is the G-function.

The mean undisturbed ground temperature, T_g , is calculated using the following equation:

$$T_g = Q_g \frac{(0.5L_b - 4)}{k_g} + T_{g_4m} \quad \text{Equation 4}$$

where Q_g is the mean terrestrial heat flow in W/m^2 , L_b is the length of the borehole in m, k_g is the thermal conductivity of the ground in $\text{W/m/}^\circ\text{C}$, and T_{g_4m} is the average undisturbed ground temperature at a depth of 4 m below the ground surface. A value of 0.064 W/m^2 was used for the mean terrestrial heat flow, which is typical for Canada according to the work of Majorowicz et al. (2009).

3.1.4. Problem solving strategy

First, we rework the fluid heat transfer equation (Equation 2) to isolate T_b :

$$T_b = T_f + q'_b \cdot R_b^* \quad \text{Equation 5}$$

Then, we substitute Equation 5 in the ground heat transfer equation (Equation 3):

$$T_f + q'_b \cdot R_b^* - T_0 = -\frac{q'_b}{k_g} \cdot G(F_0) \quad \text{Equation 6}$$

Finally, we rework Equation 6 to isolate q'_b , which is the unknown that we want to calculate:

$$q'_b = -\frac{T_f - T_g}{R_b^* + \frac{G(F_0)}{k_g}} \quad \text{where} \quad T_f = (T_{fo} + T_{fi})/2 \quad \text{Equation 7}$$

Since the thermal properties of the ground and heat carrier fluid are known, it is possible to use Equation 1 and Equation 7 jointly to compute the values of q'_b and T_{fo} with an iterative approach. Briefly, the method consists in using Equation 7 to compute a first intermediate value for q'_b by assuming that $T_f = T_{fo} = T_{fi}$. This intermediate value for q'_b is then used in Equation 1 to calculate a new intermediate value for T_{fo} . This new intermediate value for T_{fo} is then used in Equation 7 to compute a new intermediate value for q'_b . This iterative process is then repeated until convergence is reached for both q'_b and T_{fo} .

The calculations were performed in this project with a Python script that was developed as part of this work. This script is available in the Electronic Appendix A that is distributed with this report.

3.2. Methodology

Using the problem solving strategy described in the previous section, heat extraction and injection rates in the ground were first calculated for 152.4 m (500 ft) long boreholes and a ground thermal conductivity of 2.5 W/m/°C.

In a subsequent step, the impact of the borehole length on the performance of the heat exchangers was assessed by calculating additional heat extraction and injection rates for boreholes of 205.7 m (675 ft) and 259.1 m (850 ft), while keeping the ground thermal conductivity at a value of 2.5 W/m/°C.

Finally, the impact of the ground thermal conductivity on the performance of the heat exchangers was assessed by carrying out the calculations for 152.4 m (500 ft) long boreholes using a ground thermal conductivity of 1.6 W/m/°C (typical of moist clay) and 3.4 W/m/°C (typical of granite bedrock), in addition to the calculations that were carried out previously with a thermal conductivity of 2.5 W/m/°C (typical of saturated sandstone).

The calculations were carried out using a volumetric flow of 1.07 L/s for all the GLHE configurations in both heating and cooling mode. This value was selected to ensure turbulent flow in the pipes of the GLHEs at all times. The use of an identical volumetric flow rate for all GLHE configurations makes the comparison of results easier in order to evaluate the impact of the borehole configuration on the performance of the GLHEs.

The mean undisturbed ground temperature was calculated for each combination of borehole length and ground thermal conductivity with Equation 4 using a mean yearly temperature of 10.5°C estimated at a depth of 4 m below the ground surface from a typical meteorological year for the city of Boston, USA (Wilcox and Marion 2008). A 4 m deep mean yearly ground temperature estimated for the city of Boston was used because readily building thermal load profiles are available at that location (which was required for part 2 of this study)(National Renewable Energy Laboratory 2014) and because it is assumed that the weather and undisturbed ground temperature are somewhat similar to that of southern Ontario (where many Versaprofiles clients are located). According to Majorowicz and al. (2009), the average ground temperature in Ontario varies between 0°C and 10°C at a depth of 50 m and between 2°C and 12°C at a depth of 100 m. The mean undisturbed ground temperatures that were calculated with Equation 4 for the various combinations of borehole length and ground thermal conductivity considered in this study are presented in Table 2 below.

Independently of the mean ground temperature used in the calculation, the entering water temperature in the borehole (T_{fi}) was set to a value of -0.5°C in heating mode and to a value of 27.5°C in cooling mode. This was done in order to make the results easily comparable in order to evaluate the impact of the borehole length on the performance of the exchangers.

Finally, the calculations were carried out for a time period of 30 days. Calculations of heat extraction and injection fluxes between the borehole and the ground for time periods varying between 1 and 300 days showed that the rate of variation of the heat flux starts to stabilize around a value of 30 days both in heating and cooling mode for all the borehole configurations considered in this study (see Figure 2 and Figure 3 in Appendix A).

Table 2 – Mean undisturbed temperature calculated with Equation 4 for the various combinations of borehole length and ground thermal conductivity considered in this study. These values were calculated based on a mean yearly temperature of 10.5°C estimated at a depth of 4 m below the ground surface from a typical meteorological year for the city of Boston, USA.

Borehole length		Ground thermal conductivity (W/m/°C)	Ground mean undisturbed temperature (°C)
(m)	(ft)		
152.4	500	1.6	13.5
205.7	675	1.6	14.5
259.1	850	1.6	15.6
152.4	500	2.5	12.4
205.7	675	2.5	13.1
259.1	850	2.5	13.8
152.4	500	3.4	11.9
205.7	675	3.4	12.4
259.1	850	3.4	12.9

3.3. Results and Discussion

A summary of the results obtained for the 152.4 m (500 ft) long boreholes and a ground thermal conductivity of 2.5 W/m/°C are presented in Table 3 for the heating mode and in table Table 4 for the cooling mode. The detailed results are available in Table 19 and Table 20 of Appendix B.

These results highlight that the Twin loop 1.5 DR11 is by far the most efficient configuration, with heat extraction and injection rates per unit length that are 15.7% and 16.5% larger than those calculated for the Single loop 1.25 DR11 and 9.8% and 10.1% larger than those calculated for the Single loop 2 DR11. This is explained by the fact that the Twin loop 1.5 DR11 configuration offers a heat exchange surface between the fluid and the ground that is 2.28 greater than that of the Single loop 1.25 DR11 and 1.6 greater than that of the Single loop 2 DR11. These results also show that using larger pipes allow for interesting performance gains, with extraction and injection heat rates per unit length that are 5.4% and 5.8% larger for the Single loop 2 DR11 than those calculated for the Single loop 1.25 DR11.

Secondly, a comparison of the ground heat extraction (heating) and injection (cooling) rates that were calculated for three different borehole lengths and a constant ground thermal conductivity of 2.5 W/m/°C is presented in the Table 5 and Table 6. The detailed results for each case are available in Appendix B. The values presented in Table 5 and Table 6 correspond to the difference, in percent, between the heat extraction (heating) or injection (cooling) rates per unit length calculated for the GLHE configurations and borehole lengths on the lines of the table and those on the columns. So for example, the value on line 3 and column 6 of Table 5 reads like this: “the heat extraction rate per unit length calculated for a 152.4 m (500 ft) long Single loop 2 DR11 borehole is 0.3% larger than that calculated for a 205.7 m (675 ft) long Single loop 1.5 DR11 borehole.

First of all, the results presented in Table 5 and Table 6 show that the conclusions are the same when comparing the performance of heat exchangers of equal borehole length. For the three lengths considered, the Twin loop 1.5 DR11 is by far the most efficient configuration. Moreover, the performance of the single loop GLHE increases when using larger pipes. However, the difference between the heat

extraction and injection rates per unit length calculated between each configuration become less important as the length of the boreholes increase. For example, the difference between the heat extraction rates per unit length calculated for the Twin loop 1.5 DR11 and Single loop 1.25 DR11 configuration is 15.7% for 152.4 m (500 ft) long boreholes, 15.1% for 205.7 m (675 ft) long boreholes, and 14.4% for 259.1 m (850 ft) long boreholes.

These results also show that the impact of the length of the boreholes on the calculated heat extraction and injection rates is not insignificant. Depending on the configuration, increasing the length of the boreholes from 152.4 m (500 ft) to 205.7 m (675 ft) and from 152.4 m (500 ft) to 259.1 m (850 ft) resulted, respectively, in an increase of the heat extraction (heating) rates per unit length between 2.5% and 3.1% and 4.7% and 5.9%. Inversely, increasing the boreholes length from 152.4 m (500 ft) to 205.7 m (675 ft) and from 152.4 m (500 ft) to 259.1 m (850 ft) resulted, respectively, in a reduction of the heat injection (cooling) rates per unit length between 6.6% and 7.1% and 12.9 and 13.9% depending on the configuration. These results are explained by the fact that the mean undisturbed ground temperature increases for longer borehole, which results in greater heat extraction rates and lower injection rates when the conditions on the heat pump side are kept constant.

Finally, similarly to the results presented in Table 5 and Table 6, a comparison of the ground heat extraction (heating) and injection (cooling) rates per unit length calculated for 152.4 m (500 ft) long boreholes using three different values of ground thermal conductivity is presented in Table 7 and Table 8. The detailed results for each case are available in Appendix BS.

The results presented in Table 7 and Table 8 show that the conclusions are the same when comparing the performance of heat exchangers with the same ground thermal conductivity. For the three values of ground thermal conductivity considered, the Twin loop 1.5 DR11 is still by far the most efficient configuration and the performance of the single loop GLHE also increases when using larger pipes. However, the relative performance increase of the Twin loop 1.5 DR11 compared to the other configurations becomes larger when the thermal conductivity of the ground increases. For example, the difference between the heat extraction rates per unit length calculated for the Twin loop 1.5 DR11 and Single loop 1.25 DR11 configuration is 14.4% when the ground thermal conductivity is 1.6 W/m/°C, 15.7% when it is 2.5 W/m/°C, and 16.8% when it is 3.4 W/m/°C. Inversely, the size of the pipes has a smaller impact when the thermal conductivity of the ground increases. For example, the difference between the heat extraction (heating) rates per unit length calculated for the Single loop 1.25 DR11 and Single loop 2 DR11 are 5.7% when the ground thermal conductivity is 1.6 W/m/°C, 5.4% when it is 2.5 W/m/°C, and 5.1% when it is 3.4 W/m/°C.

These results also show that the impact of the ground thermal conductivity on the calculated heat extraction and injection rates is significant. Depending on the configuration, increasing the ground thermal conductivity from 1.6 W/m/°C to 2.5 W/m/°C resulted in an increase of the heat extraction (heating) rates per unit length between 21.9% and 23.6% and an increase of the heat injection (cooling) rates per unit length between 42.7% and 44.5%. In the same line, increasing the ground thermal conductivity from 1.6 W/m/°C to 3.4 W/m/°C resulted in an increase of the heat extraction (heating) rates per unit length between 40.2% and 43.1% and an increase of heat injection (cooling) rates per unit length between 76.1 % and 80.3%.

Table 3 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m. °C and 152.4 m (500 ft) long boreholes.

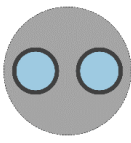
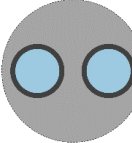

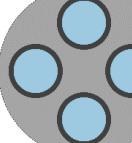
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
R_b	m.°C/W	0.09257	0.09234	0.0874	0.06231
R_b^*	m.°C/W	0.09381	0.09358	0.08871	0.06432
qb	kW	5.58	5.69	5.88	6.46
qb'	W/m	36.61	37.35	38.57	42.36
$\Delta qb'$	%	0	2.0	5.4	15.7

Table 4 – Ground heat injection rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m°C and 152.4 m (500 ft) long boreholes.

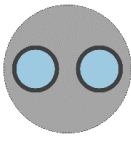
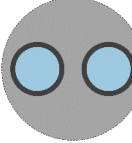
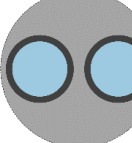
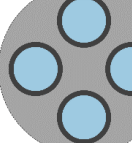
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
R_b	m.°C/W	0.0904	0.08977	0.08383	0.05829
R_b^*	m.°C/W	0.09164	0.09102	0.08517	0.06039
qb	kW	-6.58	-6.72	-6.96	-7.66
qb'	W/m	-43.15	-44.07	-45.65	-50.26
$\Delta qb'$	%	0	2.1	5.8	16.5

Table 5 – Comparison of ground heat extraction rates (heating) calculated for three different borehole lengths and a constant ground thermal conductivity of 2.5 W/m°C.

		152.4 m (500 ft)				205.7 m (675 ft)				259.1 m (850 ft)			
152.4 m (500 ft)		0.0%	-2.0%	-5.1%	-13.6%	-3.0%	-4.8%	-7.8%	-15.7%	-5.6%	-7.4%	-10.1%	-17.5%
		2.0%	0.0%	-3.2%	-11.8%	-1.0%	-2.9%	-5.9%	-14.0%	-3.7%	-5.5%	-8.3%	-15.8%
		5.4%	3.3%	0.0%	-8.9%	2.2%	0.3%	-2.8%	-11.2%	-0.5%	-2.4%	-5.3%	-13.1%
		15.7%	13.4%	9.8%	0.0%	12.3%	10.1%	6.7%	-2.4%	9.2%	7.2%	4.0%	-4.5%
205.7 m (675 ft)		3.1%	1.0%	-2.2%	-10.9%	0.0%	-1.9%	-4.9%	-13.1%	-2.7%	-4.6%	-7.4%	-15.0%
		5.1%	3.0%	-0.3%	-9.2%	2.0%	0.0%	-3.1%	-11.4%	-0.8%	-2.7%	-5.6%	-13.3%
		8.4%	6.3%	2.9%	-6.3%	5.2%	3.2%	0.0%	-8.6%	2.3%	0.4%	-2.6%	-10.5%
		18.6%	16.3%	12.6%	2.5%	15.1%	12.9%	9.4%	0.0%	12.0%	9.8%	6.6%	-2.1%
259.1 m (850 ft)		5.9%	3.8%	0.5%	-8.5%	2.8%	0.8%	-2.3%	-10.7%	0.0%	-1.9%	-4.8%	-12.6%
		8.0%	5.8%	2.5%	-6.7%	4.8%	2.8%	-0.4%	-9.0%	1.9%	0.0%	-3.0%	-10.9%
		11.3%	9.1%	5.6%	-3.8%	8.0%	5.9%	2.6%	-6.2%	5.1%	3.1%	0.0%	-8.2%
		21.2%	18.8%	15.0%	4.7%	17.6%	15.3%	11.8%	2.2%	14.4%	12.2%	8.9%	0.0%

Table 6 – Comparison of ground heat injection rates (cooling) calculated for three different borehole lengths and a constant ground thermal conductivity of 2.5 W/m°C.

		152.4 m (500 ft)				205.7 m (675 ft)				259.1 m (850 ft)			
152.4 m (500 ft)		0.0%	-2.1%	-5.5%	-14.1%	7.0%	4.8%	1.3%	-7.6%	14.8%	12.5%	8.8%	-0.3%
		2.1%	0.0%	-3.5%	-12.3%	9.3%	7.1%	3.5%	-5.6%	17.2%	14.9%	11.1%	1.9%
		5.8%	3.6%	0.0%	-9.2%	13.2%	10.9%	7.2%	-2.2%	21.4%	19.0%	15.1%	5.5%
		16.5%	14.0%	10.1%	0.0%	24.7%	22.1%	18.0%	7.6%	33.7%	31.0%	26.7%	16.2%
205.7 m (675 ft)		-6.6%	-8.5%	-11.7%	-19.8%	0.0%	-2.0%	-5.4%	-13.6%	7.3%	5.1%	1.7%	-6.8%
		-4.6%	-6.6%	-9.8%	-18.1%	2.1%	0.0%	-3.4%	-11.8%	9.5%	7.3%	3.8%	-4.9%
		-1.3%	-3.3%	-6.7%	-15.2%	5.7%	3.5%	0.0%	-8.8%	13.3%	11.1%	7.4%	-1.5%
		8.2%	5.9%	2.3%	-7.1%	15.8%	13.4%	9.6%	0.0%	24.2%	21.7%	17.7%	7.9%
259.1 m (850 ft)		-12.9%	-14.7%	-17.7%	-25.2%	-6.8%	-8.7%	-11.8%	-19.5%	0.0%	-2.0%	-5.2%	-13.1%
		-11.1%	-13.0%	-16.0%	-23.7%	-4.9%	-6.8%	-10.0%	-17.8%	2.0%	0.0%	-3.3%	-11.3%
		-8.1%	-10.0%	-13.1%	-21.1%	-1.6%	-3.6%	-6.9%	-15.1%	5.5%	3.4%	0.0%	-8.3%
		0.3%	-1.8%	-5.2%	-13.9%	7.3%	5.1%	1.5%	-7.3%	15.1%	12.8%	9.1%	0.0%

Table 7 – Comparison of ground heat extraction rates (heating) calculated for three different values of ground thermal conductivity and a constant borehole length of 152.4 m (500 ft).

		1.6 W/m/°C				2.5 W/m/°C				3.4 W/m/°C			
1.6 W/m/°C		0.0%	-2.3%	-5.4%	-12.6%	-18.2%	-19.8%	-22.3%	-29.3%	-28.7%	-29.9%	-32.1%	-38.9%
		2.3%	0.0%	-3.2%	-10.6%	-16.3%	-17.9%	-20.5%	-27.6%	-27.0%	-28.3%	-30.6%	-37.5%
		5.7%	3.3%	0.0%	-7.6%	-13.5%	-15.3%	-17.9%	-25.3%	-24.6%	-25.9%	-28.3%	-35.4%
		14.4%	11.8%	8.3%	0.0%	-6.4%	-8.2%	-11.1%	-19.1%	-18.4%	-19.8%	-22.4%	-30.1%
2.5 W/m/°C		22.2%	19.4%	15.7%	6.8%	0.0%	-2.0%	-5.1%	-13.6%	-12.8%	-14.3%	-17.1%	-25.3%
		24.7%	21.9%	18.0%	9.0%	2.0%	0.0%	-3.2%	-11.8%	-11.0%	-12.6%	-15.4%	-23.8%
		28.8%	25.8%	21.9%	12.5%	5.4%	3.3%	0.0%	-8.9%	-8.1%	-9.7%	-12.6%	-21.3%
		41.4%	38.2%	33.8%	23.6%	15.7%	13.4%	9.8%	0.0%	0.9%	-0.8%	-4.0%	-13.6%
3.4 W/m/°C		40.2%	37.0%	32.6%	22.5%	14.7%	12.4%	8.8%	-0.9%	0.0%	-1.7%	-4.9%	-14.4%
		42.6%	39.4%	35.0%	24.7%	16.7%	14.4%	10.8%	0.8%	1.8%	0.0%	-3.2%	-12.9%
		47.4%	44.0%	39.5%	28.8%	20.6%	18.2%	14.4%	4.2%	5.1%	3.3%	0.0%	-10.0%
		63.7%	60.0%	54.9%	43.1%	33.9%	31.3%	27.1%	15.7%	16.8%	14.8%	11.1%	0.0%

Table 8 – Comparison of ground heat injection rates (cooling) calculated for three different values of ground thermal conductivity and a constant borehole length of 152.4 m (500 ft).

		1.6 W/m/°C				2.5 W/m/°C				3.4 W/m/°C			
1.6 W/m/°C		0.0%	-2.4%	-5.7%	-13.1%	-29.9%	-31.4%	-33.8%	-39.8%	-43.2%	-44.3%	-46.3%	-51.8%
		2.4%	0.0%	-3.4%	-10.9%	-28.2%	-29.7%	-32.1%	-38.4%	-41.8%	-42.9%	-45.0%	-50.6%
		6.0%	3.5%	0.0%	-7.8%	-25.7%	-27.3%	-29.8%	-36.2%	-39.8%	-40.9%	-43.1%	-48.9%
		15.0%	12.3%	8.5%	0.0%	-19.4%	-21.1%	-23.8%	-30.8%	-34.7%	-35.9%	-38.2%	-44.5%
2.5 W/m/°C		42.7%	39.3%	34.6%	24.1%	0.0%	-2.1%	-5.5%	-14.1%	-19.0%	-20.5%	-23.4%	-31.2%
		45.7%	42.3%	37.5%	26.7%	2.1%	0.0%	-3.5%	-12.3%	-17.3%	-18.8%	-21.7%	-29.7%
		51.0%	47.4%	42.4%	31.3%	5.8%	3.6%	0.0%	-9.2%	-14.3%	-15.9%	-18.9%	-27.2%
		66.2%	62.2%	56.8%	44.5%	16.5%	14.0%	10.1%	0.0%	-5.6%	-7.4%	-10.7%	-19.9%
3.4 W/m/°C		76.1%	71.9%	66.1%	53.1%	23.4%	20.9%	16.7%	6.0%	0.0%	-1.9%	-5.4%	-15.1%
		79.5%	75.2%	69.3%	56.1%	25.8%	23.2%	18.9%	8.0%	1.9%	0.0%	-3.6%	-13.5%
		86.2%	81.7%	75.6%	61.9%	30.5%	27.8%	23.3%	12.0%	5.7%	3.7%	0.0%	-10.2%
		107.4%	102.5%	95.6%	80.3%	45.4%	42.3%	37.4%	24.8%	17.8%	15.5%	11.4%	0.0%

4. Part 2 – GLHE sizing calculations

4.1. Methodology

In this second part of the study, the VersaGLD software (Gosselin and Lamarche 2018), that was developed by INRS with the collaboration of Versaprofiles, was used to do sizing calculations of the four GLHE configurations presented in Table 1 in order to compare their relative performance. For this exercise, the conductivity of the ground was assumed to be 2.5 W/m/°C and the properties of the heat carrier fluid were defined as described in section 2.

Figure 1 shows the thermal load profile of a typical high school-sized building for the climatic conditions of the city of Boston which was selected for this exercise (National Renewable Energy Laboratory 2014). As mentioned previously, it is assumed that the weather and the undisturbed ground temperature of Boston are similar to those of southern Ontario (where most Versaprofiles clients are located). The heating loads were clipped at a value corresponding to 25% of the peak heating load. This was done to flatten the heating load curve and to balance the heating and cooling yearly average loads. This assumes that 75% of the heating needs would be covered by the geothermal system and the remaining 25% would be covered by a secondary heating system.

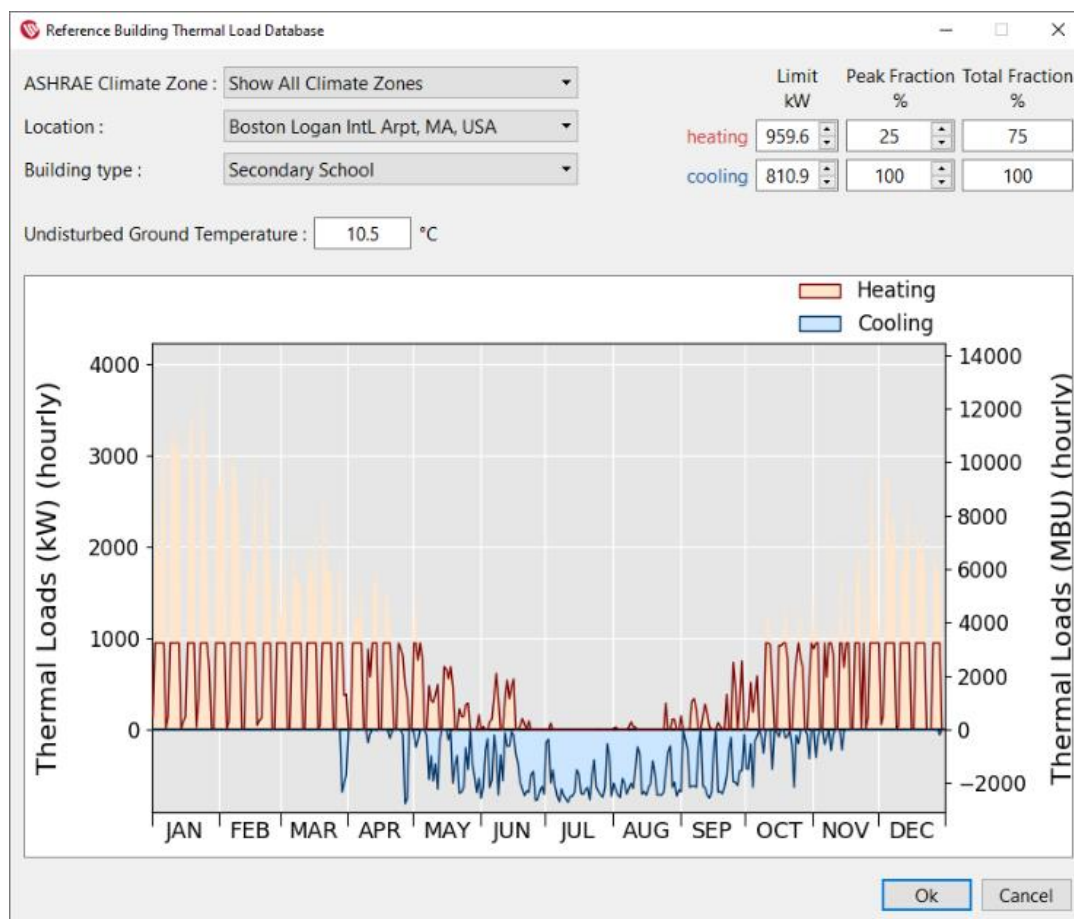


Figure 1 – Thermal load profile typical of a high school-sized building in a Boston area climate.

The mean yearly, maximum monthly, and peak hourly heating and cooling load calculated from the clipped hourly building load are presented in Table 9. The loads presented in Table 9 were used in VersaGLD to calculate the required length of vertical ground heat exchangers with the equation proposed in the ASHRAE handbook (ASHRAE, 2011). In the calculation, a period of 10 years was used for the mean yearly load, of 30.4375 days for the monthly load and of 6 hours for the peak hourly load. The borehole thermal resistance was calculated with the multipole method (Claesson and Hellström 2011) and the borehole wall temperature was calculated with the finite line source equation (Lamarche and Beauchamp 2007), similar to what was done in part 1.

Table 9 – Mean yearly, maximum monthly, and peak hourly loads of heating and cooling calculated from the clipped building thermal load profile presented in Figure 1..

Load	Units	Cooling	Heating
Mean yearly load	kW	-98.36	182.49
Max. monthly load	kW	-307.02	412.06
Peak hourly load	kW	-810.93	959.58

As mentioned previously, the yearly undisturbed ground temperature at a depth of 4 m calculated from a typical meteorological year for the city of Boston is 10.5°C (Wilcox and Marion 2008). Based on this value, the mean undisturbed subsurface temperature calculated with Equation 4 for a ground thermal conductivity of 2.5 W/m/°C and borehole length of 152.4 m (500 ft) is 12.40 °C. Based on this value for the mean undisturbed ground temperature, the entering water temperature in the heat pump was set to a value of -1.0 °C in heating mode and 28°C in cooling mode, which is in agreement with the recommendations in ASHRAE (2011).

With the conditions described above, a first comparative analysis was conducted by fixing the conditions on the heat pump side. More specifically, the total flow rate of the heat carrier fluid and the COP were set to the same values for the four different borehole configurations considered. First, the total flow rate of the heat carrier fluid was set to a value so that turbulent flow was ensured both in heating and cooling mode in all of the four exchanger scenarios. Second, the COP in heating and cooling mode were set, respectively, to a value of 3.1 and 4.7, based on the energy efficiency requirement for geothermal heat pump of the Energy Star program (see Table 10).

A second comparative analysis was conducted by using more realistic conditions on the heat pump side. First, the COP values in heating and cooling were calculated in VersaGLD from performance data of a real high efficiency and high capacity commercial water-to-water heat pump (ClimateMaster 2016, model TMW840). Second, the total flow rate of the heat carrier fluid was optimized in order to minimize the total length of each GLHE, while respecting the minimum and maximum flow requirements of the heat pump. Though this case is more realistic, the results are, however, more difficult to compare with each other because multiple factors are then causing changes in the calculated size of the GLHE. It is then impossible to know precisely the sole impact that the borehole configuration on the global results.

The strategy used for the sizing calculation for both analysis consisted in adding boreholes to the borehole field until the length of each individual borehole were as close as possible to 152.4 m (500 ft).

Table 10 – Energy efficiency requirements for geothermal heat pumps according to the Energy Star program. Models must meet or exceed the energy efficiency ratio (EER) and coefficient of performance (COP) values in the table below.

Requirements (Effective January 1, 2012)		
Product Type	EER	COP
Water-to-Air		
Closed Loop Water-to-Air	17.1	3.6
Open Loop Water-to-Air	21.1	4.1
Water-to-Water		
Closed Loop Water-to-Water	16.1	3.1
Open Loop Water-to-Water	20.1	3.5
DGX		
DGX	16.0	3.6

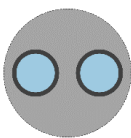
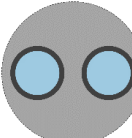
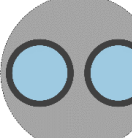
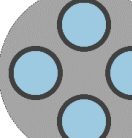
Note that $EER = COP \times 3.41$

source : https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal/key_product_criteria

4.2. Results and Discussion

First, a summary of the results obtained for the comparative analysis with fixed heat pump conditions is presented in Table 11 while the detailed results are available in Table 31 of Appendix C. These results are coherent with those obtained in the first part of this study. The Twin loop 1.5 DR11 remains by far the most efficient configuration with a total borehole length that is 22.3% lower than that calculated for the Single loop 1.25 DR11. The results additionally clearly show the performance gained by using larger pipes with a calculated total borehole length for the Single loop 2 DR11 that is 9% lower than that of the Single loop 1.25 DR11 and 5.5% lower than that of the Single loop 1.5 DR11.

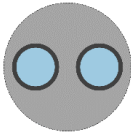
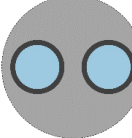

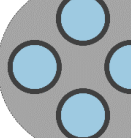
Table 11 – Comparative analysis results with fixed conditions on the heat pump size.

Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	–				
R_b^*	$m \cdot ^\circ C/W$	0.09094	0.08953	0.08388	0.05782
ΔR_b^*	%	0	-1.6	-7.8	-36.4
N_b	–	85	82	77	67
L_b	m	152.2	151.9	152.8	149.9
Ltot	m	12937	12459	11768	10046
ΔL_{tot}	%	0	-3.7	-9	-22.3

Secondly, a summary of the results obtained for the comparative analysis with variable heat pump conditions is presented in Table 12 while the detailed results are available in Table 32 of Appendix C. Comparing these results with those of Table 11 clearly illustrate the impact of the heat pump conditions on the total borehole length of each GLHE. The main conclusions remain, however, the same. The Twin loop 1.5 DR11 is the most efficient configuration and larger pipes for single loop configurations results in a reduction of total borehole length.

The difference between the total borehole lengths calculated in Table 11 and Table 12 can be attributed mainly to two factors. First, substantially larger COP values were used in the second comparative analysis compared to the first one (between 4.35 and 4.46 in heating and between 5.25 and 5.79 in cooling for the second analysis compared to 3.10 in heating and 4.7 in cooling for the first analysis). More efficient heat pump results in longer borehole lengths when the required total borehole length is determined by the heating load, which is the case in our case study. This is because the heat losses produced by inefficient heat pumps (due to friction and pumping losses) are larger than that of efficient heat pumps in order to extract the same amount of heat from the ground. The heat losses of the heat pump is added to the heat extracted from the ground and transferred to the building to meet the heat load requirements, thus resulting in lower borehole lengths, but with larger operation cost. Secondly, the optimization of the flow rates in the second analysis resulted in substantially lower volumetric flow rates in the Single loop 1.25 DR11 and Single loop 1.5 DR11 compared to the Twin loop 1.5 DR11 and Single loop 2 DR11 configurations. Larger flow rates result in a heat pump that is more efficient. For example, the heating COP for the Twin loop 1.5 DR11 and the Single loop 2 DR11 was 4.46 and 4.40. On the other hand, the COP of heating for the Single loop 1.5 DR11 and the Single loop 1.25 DR11 was 4.35 and 4.34. As we explained above, more efficient heat pump results in longer borehole lengths when the building thermal load profile is dominated by heating. Moreover, as per Equation 1, larger flow rates imply that the heat pump needs to provide less work to extract or inject a given amount of heat in the fluid. This translates into a smaller temperature difference between the fluid entering and leaving the heat pump. This reduced work load of the heat pump and smaller temperature difference of the fluid passing through the heat pump must be compensated by an increased length of the GLHE.

Table 12 – Comparative analysis results with variable conditions on the heat pump size.

Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	–				
R_b^*	$m \cdot ^\circ C/W$	0.09957	0.09805	0.09234	0.06193
ΔR_b^*	%	0	-1.5	-7.3	-37.8
N_b	–	98	97	96	88
L_b	m	153.3	152.3	152.4	152.8
Ltot	m	15022	14771	14635	13444
ΔL_{tot}	%	0	-1.7	-2.6	-10.5

5. Conclusions

The performance of four different configurations of GLHE was compared in this study under various conditions. Those are single GLHE having a nominal pipe diameter of 1.25, 1.5 and 2 inches as well as twin GLHE have a nominal pipe diameter of 1.5 inches. Overall, the Twin loop 1.5 DR11 is by far the most efficient solution for all situations. For the single loop configurations, the use of larger pipe size always resulted in better performances, but the gain is not as important as when using a twin versus single loop configuration. Calculations made in this report rigorously demonstrated the impact of increasing the GLHE pipe diameter.

This study further demonstrated the importance of borehole length, ground thermal conductivity and heat pump conditions on the calculated performance of heat exchangers. In all cases, the conclusions, however, remained the same. Even with deep boreholes, high thermal conductivity of the ground or favorable flow conditions of the heat pump, the Twin Loop 1.5 DR11 configuration is the one that best performed. When possible to install, twin loops are recommended for GLHE of geothermal heat pump systems. The Single loop 2 DR11 is the second-best solution and can be an alternative option when a Twin Loop is difficult to install due to field constraints. Indeed, Twin loop GLHEs require larger boreholes, specialized equipment and workforce, and they are substantially harder to handle than single loop GLHEs. Under the light of this study, geothermal designers can choose the best pipe loop dimension and configuration that will result in borehole length savings considering efforts that will be required upon installation.

6. References

- ASHRAE. 2011. *2011 ASHRAE Handbook - HVAC Applications*. SI edition. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- ASTM Standard D3035. 2014. "Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter." Barr Harbor Drive, West Conshohocken, USA: ASTM International.
- Claesson, Johan, and Göran Hellström. 2011. "Multipole Method to Calculate Borehole Thermal Resistances in a Borehole Heat Exchanger." *HVAC&R Research* 17 (6): 895–911. <https://doi.org/10.1080/10789669.2011.609927>.
- ClimateMaster. 2016. "Submittal Data - Tranquility Large Water-To-Water (TMW) Series." LC975. Oklahoma City, OK, USA: ClimateMaster. <http://www.climatemaster.com>.
- Gosselin, Jean-Sébastien, and Louis Lamarche. 2018. *VersaGLD: A Cross-Platform Software for Doing Quick Comparison Analysis of Ground Coupled Heat Pump (GCHP) Exchanger System* (version 0.3.13). Quebec City, Quebec, Canada: INRS, Centre Eau Terre Environnement. <https://github.com/cgq-qgc/versagld/releases/tag/v0.3.13>.
- Hellström, Göran. 1991. "Ground Heat Storage - Thermal Analyses of Duct Storage Systems." Department of mathematical physics, Lund, Sweden: University of Lund.
- Lamarche, Louis, and Benoit Beauchamp. 2007. "A New Contribution to the Finite Line-Source Model for Geothermal Boreholes." *Energy and Buildings* 39 (2): 188–98. <https://doi.org/10.1016/j.enbuild.2006.06.003>.
- Majorowicz, Jacek, Stephen E. Grasby, and Walter R. Skinner. 2009. "Estimation of Shallow Geothermal Energy Resource in Canada: Heat Gain and Heat Sink." *Natural Resources Research* 2 (18): 95–108. <https://doi.org/10.1007/s11053-009-9090-4>.
- National Renewable Energy Laboratory. 2014. "Commercial and Residential Hourly Load Profiles for All TMY3 Locations in the United States [Data Set]." <https://dx.doi.org/10.25984/1788456>.
- Wilcox, S, and W Marion. 2008. "Users Manual for TMY3 Data Sets." *Technical Report*, 58.

Appendix A: Variation of the ground heat extraction/injection rate with time

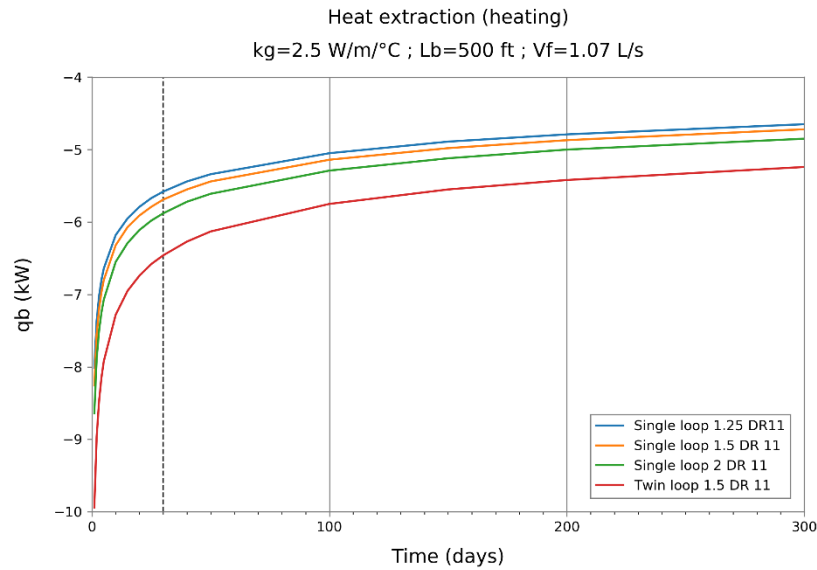


Figure 2 – Ground heat extraction rate as a function of time for the four GLHE configurations compared in this study (see Table 1).

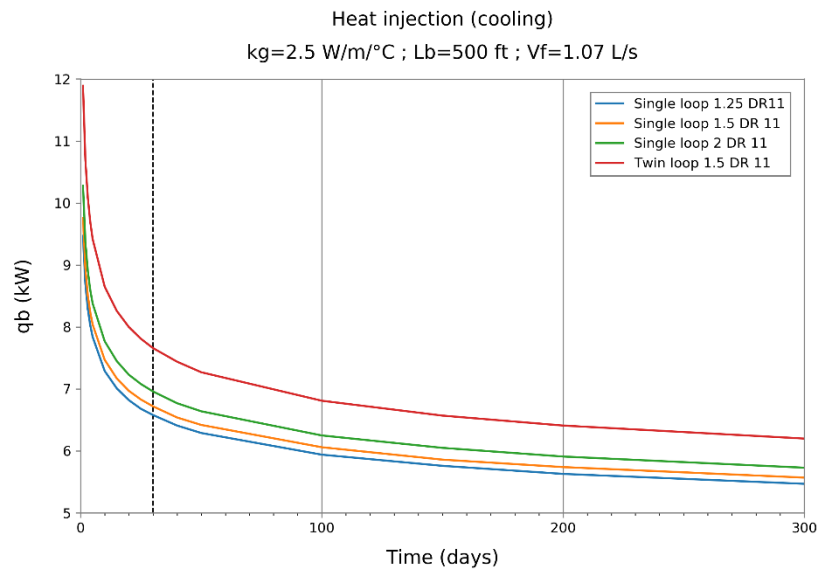


Figure 3 – . Ground heat injection rate as a function of time for the four GLHE configurations compared in this study (see Table 1).

Appendix B: Detailed Results for Part 1

Table 13 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 1.6 W/m°C and 152.4 m (500 ft) long boreholes.

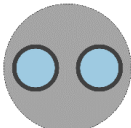
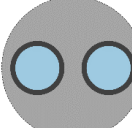
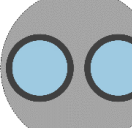
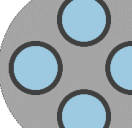
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09328	0.09304	0.08812	0.06236
Rbore 3D	m.°C/W	0.09445	0.09421	0.08936	0.06425
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.47	13.47	13.47	13.47
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	0.59	0.61	0.65	0.74
Tfluid avg	°C	0.04	0.06	0.07	0.12
Duration	days	30	30	30	30
qb	kW	4.56	4.67	4.82	5.22
qb'	W/m	29.95	30.65	31.65	34.27
Δqb'	%	0	2.34	5.68	14.42

Table 14 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 1.6 W/m°C and 152.4 m (500 ft) long boreholes.

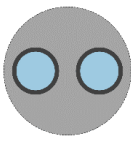
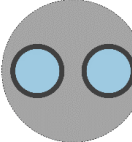
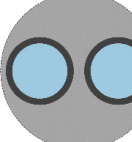
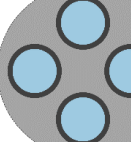
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.09112	0.09049	0.08458	0.05835
Rbore 3D	m.°C/W	0.09229	0.09167	0.08585	0.06032
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.47	13.47	13.47	13.47
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	26.41	26.39	26.35	26.25
Tfluid avg	°C	26.96	26.94	26.92	26.88
Duration	days	30	30	30	30
qb	kW	-4.61	-4.72	-4.89	-5.3
qb'	W/m	-30.24	-30.98	-32.06	-34.78
Δqb'	%	0	2.45	6.02	15.01

Table 15 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 1.6 W/m°C and 205.7 m (675 ft) long boreholes.

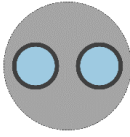
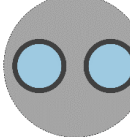
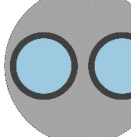
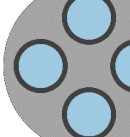
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09328	0.09304	0.08812	0.06236
Rbore 3D	m.°C/W	0.0954	0.09517	0.09037	0.0658
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	14.53	14.53	14.53	14.53
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.05	1.09	1.14	1.27
Tfluid avg	°C	0.28	0.29	0.32	0.38
Duration	days	30	30	30	30
qb	kW	6.53	6.68	6.89	7.44
qb'	W/m	31.72	32.45	33.48	36.15
Δqb'	%	0	2.3	5.55	13.97

Table 16 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 1.6 W/m°C and 205.7 m (675 ft) long boreholes.

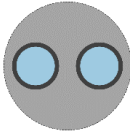
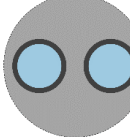
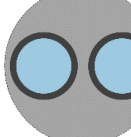
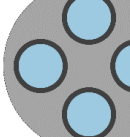
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.09112	0.09049	0.08458	0.05835
Rbore 3D	m.°C/W	0.09325	0.09264	0.08689	0.06194
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	14.53	14.53	14.53	14.53
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	26.17	26.13	26.09	25.97
Tfluid avg	°C	26.83	26.82	26.79	26.74
Duration	days	30	30	30	30
qb	kW	-5.66	-5.79	-5.99	-6.48
qb'	W/m	-27.49	-28.15	-29.11	-31.49
Δqb'	%	0	2.4	5.89	14.55

Table 17 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 1.6 W/m°C and 259.1 m (850 ft) long boreholes.

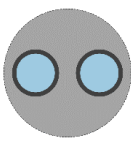
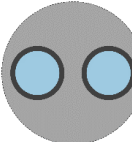
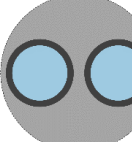
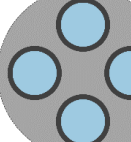
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09328	0.09304	0.08812	0.06236
Rbore 3D	m.°C/W	0.09665	0.09642	0.09169	0.06781
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	15.6	15.6	15.6	15.6
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.56	1.61	1.67	1.84
Tfluid avg	°C	0.53	0.55	0.59	0.67
Duration	days	30	30	30	30
qb	kW	8.66	8.85	9.13	9.83
qb'	W/m	33.42	34.18	35.24	37.94
Δqb'	%	0	2.27	5.45	13.52

Table 18 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 1.6 W/m°C and 259.1 m (850 ft) long boreholes.

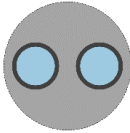
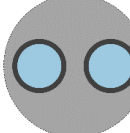
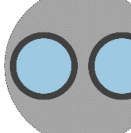
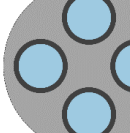
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	1.60	1.60	1.60	1.60
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.09112	0.09049	0.08458	0.05835
Rbore 3D	m.°C/W	0.09451	0.0939	0.08823	0.06405
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	15.6	15.6	15.6	15.6
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.98	25.95	25.9	25.77
Tfluid avg	°C	26.74	26.72	26.7	26.64
Duration	days	30	30	30	30
qb	kW	-6.43	-6.58	-6.8	-7.33
qb'	W/m	-24.82	-25.4	-26.25	-28.3
Δqb'	%	0	2.34	5.76	14.02

Table 19 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m°C and 152.4 m (500 ft) long boreholes.

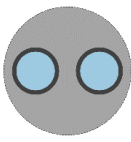
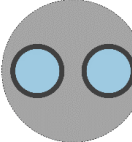
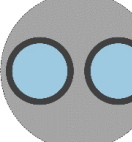
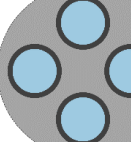
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09257	0.09234	0.0874	0.06231
Rbore 3D	m.°C/W	0.09381	0.09358	0.08871	0.06432
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.4	12.4	12.4	12.4
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	0.83	0.85	0.9	1.04
Tfluid avg	°C	0.16	0.18	0.2	0.27
Duration	days	30	30	30	30
qb	kW	5.58	5.69	5.88	6.46
qb'	W/m	36.61	37.35	38.57	42.36
Δqb'	%	0	2.02	5.35	15.71

Table 20 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m°C and 152.4 m (500 ft) long boreholes.

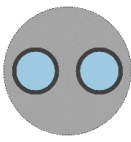
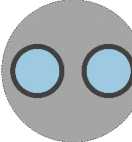
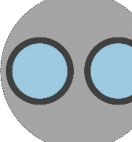
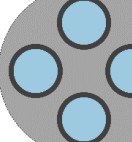
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.0904	0.08977	0.08383	0.05829
Rbore 3D	m.°C/W	0.09164	0.09102	0.08517	0.06039
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.4	12.4	12.4	12.4
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.95	25.92	25.86	25.69
Tfluid avg	°C	26.73	26.71	26.68	26.6
Duration	days	30	30	30	30
qb	kW	-6.58	-6.72	-6.96	-7.66
qb'	W/m	-43.15	-44.07	-45.65	-50.26
Δqb'	%	0	2.13	5.79	16.48

Table 21 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m°C and 205.7 m (675 ft) long boreholes.

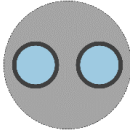
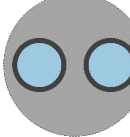
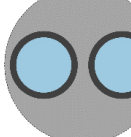
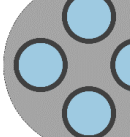
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09257	0.09234	0.0874	0.06231
Rbore 3D	m.°C/W	0.09482	0.0946	0.08979	0.06598
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.08	13.08	13.08	13.08
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.35	1.38	1.44	1.62
Tfluid avg	°C	0.42	0.44	0.47	0.56
Duration	days	30	30	30	30
qb	kW	7.76	7.92	8.17	8.93
qb'	W/m	37.73	38.47	39.69	43.42
Δqb'	%	0	1.96	5.19	15.08

Table 22 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m°C and 205.7 m (675 ft) long boreholes.

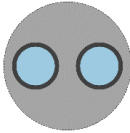
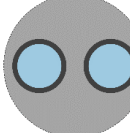
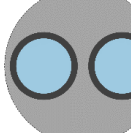
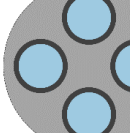
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.0904	0.08977	0.08383	0.05829
Rbore 3D	m.°C/W	0.09266	0.09205	0.08628	0.06213
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.08	13.08	13.08	13.08
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.54	25.5	25.43	25.24
Tfluid avg	°C	26.52	26.5	26.47	26.37
Duration	days	30	30	30	30
qb	kW	-8.3	-8.47	-8.76	-9.61
qb'	W/m	-40.32	-41.16	-42.6	-46.69
Δqb'	%	0	2.08	5.65	15.8

Table 23 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m°C and 259.1 m (850 ft) long boreholes.

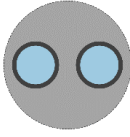
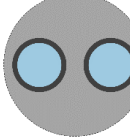
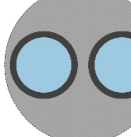
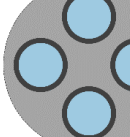
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09257	0.09234	0.0874	0.06231
Rbore 3D	m.°C/W	0.09614	0.09592	0.09119	0.06812
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.77	13.77	13.77	13.77
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.89	1.94	2.01	2.23
Tfluid avg	°C	0.69	0.72	0.76	0.87
Duration	days	30	30	30	30
qb	kW	10.05	10.24	10.56	11.5
qb'	W/m	38.78	39.53	40.74	44.37
Δqb'	%	0	1.93	5.05	14.41

Table 24 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m°C and 259.1 m (850 ft) long boreholes.

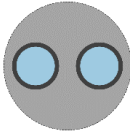
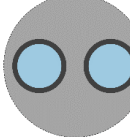
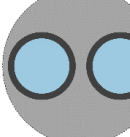
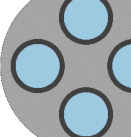
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.0904	0.08977	0.08383	0.05829
Rbore 3D	m.°C/W	0.09399	0.09339	0.08772	0.06438
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	13.77	13.77	13.77	13.77
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.2	25.16	25.08	24.86
Tfluid avg	°C	26.35	26.33	26.29	26.18
Duration	days	30	30	30	30
qb	kW	-9.74	-9.94	-10.27	-11.21
qb'	W/m	-37.59	-38.36	-39.66	-43.26
Δqb'	%	0	2.05	5.51	15.08

Table 25 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 3.4 W/m°C and 152.4 m (500 ft) long boreholes.

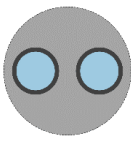
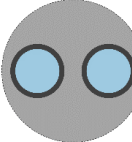
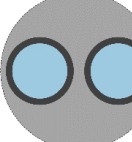
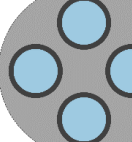
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09212	0.09189	0.08694	0.06228
Rbore 3D	m.°C/W	0.0934	0.09318	0.08831	0.06438
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	11.9	11.9	11.9	11.9
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.02	1.05	1.1	1.28
Tfluid avg	°C	0.26	0.27	0.3	0.39
Duration	days	30	30	30	30
qb	kW	6.4	6.51	6.73	7.47
qb'	W/m	41.98	42.72	44.14	49.03
Δqb'	%	0	1.76	5.15	16.79

Table 26 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 3.4 W/m°C and 152.4 m (500 ft) long boreholes.

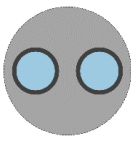
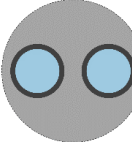
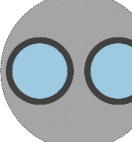
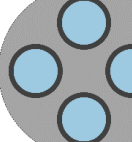
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	152.4 (500)	152.4 (500)	152.4 (500)	152.4 (500)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.08993	0.0893	0.08335	0.05825
Rbore 3D	m.°C/W	0.09122	0.09061	0.08475	0.06045
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	11.9	11.9	11.9	11.9
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.59	25.55	25.48	25.25
Tfluid avg	°C	26.54	26.53	26.49	26.37
Duration	days	30	30	30	30
qb	kW	-8.12	-8.27	-8.58	-9.56
qb'	W/m	-53.26	-54.28	-56.3	-62.72
Δqb'	%	0	1.92	5.71	17.76

Table 27 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 3.4 W/m°C and 205.7 m (675 ft) long boreholes.

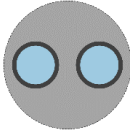
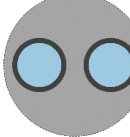
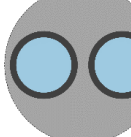
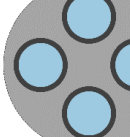
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C /W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C /W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C /W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C /W	0.09212	0.09189	0.08694	0.06228
Rbore 3D	m.°C /W	0.09446	0.09424	0.08943	0.06611
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.4	12.4	12.4	12.4
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.58	1.62	1.69	1.92
Tfluid avg	°C	0.54	0.56	0.59	0.71
Duration	days	30	30	30	30
qb	kW	8.76	8.91	9.2	10.16
qb'	W/m	42.57	43.31	44.7	49.39
Δqb'	%	0	1.74	5	16.02

Table 28 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 3.4 W/m°C and 205.7 m (675 ft) long boreholes.

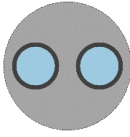
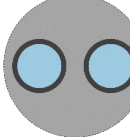
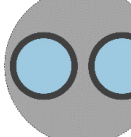
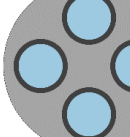
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	205.7 (675)	205.7 (675)	205.7 (675)	205.7 (675)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.08993	0.0893	0.08335	0.05825
Rbore 3D	m.°C/W	0.09229	0.09168	0.08591	0.06226
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.4	12.4	12.4	12.4
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.06	25.02	24.93	24.65
Tfluid avg	°C	26.28	26.26	26.21	26.08
Duration	days	30	30	30	30
qb	kW	-10.34	-10.53	-10.91	-12.08
qb'	W/m	-50.24	-51.18	-53.02	-58.73
Δqb'	%	0	1.87	5.53	16.9

Table 29 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 3.4 W/m°C and 259.1 m (850 ft) long boreholes.

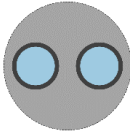
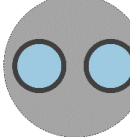
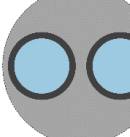
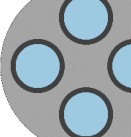
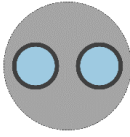
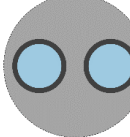
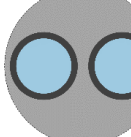
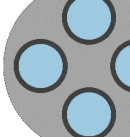
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m ³ /°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5020	4000	2510
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00752	0.00864	0.01114	0.02061
Rpipe	m.°C/W	0.09272	0.09482	0.0966	0.10678
Rbore	m.°C/W	0.09212	0.09189	0.08694	0.06228
Rbore 3D	m.°C/W	0.09583	0.09561	0.0909	0.06835
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.9	12.9	12.9	12.9
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	2.16	2.2	2.28	2.56
Tfluid avg	°C	0.83	0.85	0.89	1.03
Duration	days	30	30	30	30
qb	kW	11.17	11.36	11.71	12.86
qb'	W/m	43.11	43.83	45.19	49.65
Δqb'	%	0	1.67	4.82	15.17

Table 30 – Ground heat extraction rates (cooling) calculated with a ground thermal conductivity of 3.4 W/m°C and 259.1 m (850 ft) long boreholes.

Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Borehole length	m (ft)	259.1 (850)	259.1 (850)	259.1 (850)	259.1 (850)
Shank space	mm (in)	57.15 (2.25)	63.5 (2.50)	69.85 (2.75)	86.106 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	38.862 (1.53)	48.768 (1.92)	38.862 (1.53)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	3.40	3.40	3.40	3.40
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	15227	12134	7614
Rcond pipe	m.°C/W	0.08521	0.08618	0.08546	0.08618
Rconv pipe	m.°C/W	0.00349	0.00391	0.00474	0.00863
Rpipe	m.°C/W	0.0887	0.09009	0.09019	0.09481
Rbore	m.°C/W	0.08993	0.0893	0.08335	0.05825
Rbore 3D	m.°C/W	0.09367	0.09307	0.0874	0.06462
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.9	12.9	12.9	12.9
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	24.61	24.56	24.45	24.15
Tfluid avg	°C	26.05	26.03	25.98	25.82
Duration	days	30	30	30	30
qb	kW	-12.26	-12.49	-12.92	-14.22
qb'	W/m	-47.34	-48.2	-49.87	-54.9
Δqb'	%	0	1.82	5.34	15.97

Appendix C: Detailed Results for Part 2

Table 31 –Detailed results of the comparative analysis carried out with fixed conditions on the heat pump size.

Properties	Units	Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Building thermal load and soil temperature					
Annual cooling load	kW	98.36	98.36	98.36	98.36
Monthly cooling load	kW	307.02	307.02	307.02	307.02
Peak cooling load	kW	810.93	810.93	810.93	810.93
Peak cooling load duration	h	6	6	6	6
Annual heating load	kW	182.49	182.49	182.49	182.49
Monthly heating load	kW	412.06	412.06	412.06	412.06
Peak heating load	kW	959.58	959.58	959.58	959.58
Peak heating load duration	h	6	6	6	6
Tg	°C	12.40	12.39	12.39	12.39
Fluid Properties					
Fluid		prop_glycol	prop_glycol	prop_glycol	prop_glycol
Antigel	%vol	0.30	0.30	0.30	0.30
Thermal Properties					
conductivity :					
ground	W/m.°C	2.50	2.50	2.50	2.50
grout	W/m.°C	1.70	1.70	1.70	1.70
u-pipe	W/m.°C	0.40	0.40	0.40	0.40
inner pipe	W/m.°C	-	-	-	-
outer pipe	W/m.°C	-	-	-	-
capacity :					
ground	kJ/m ³ .°C	2500.0	2500.0	2500.0	2500.0
grout	kJ/m ³ .°C	3400.0	3400.0	3400.0	3400.0
u-pipe	kJ/m ³ .°C	1500.0	1500.0	1500.0	1500.0
inner pipe	kJ/m ³ .°C	-	-	-	-
outer pipe	kJ/m ³ .°C	-	-	-	-
Flow Conditions					
Total cooling flowrate	L/s	76.70	76.70	76.70	76.70
Re pipe (cooling)		15607	14120	12025	8641
Re annulus (cooling)		-	-	-	-
Total heating flowrate	L/s	76.70	76.70	76.70	76.70
Re pipe (heating)		4517	4087	3480	2501
Re annulus (heating)		-	-	-	-
Loop pressure drop	kPa	128.4	71.5	27.8	29.9
Borefield					
Borehole number		85	82	77	67
Borehole drilling length	m	152.2	151.9	152.8	149.9
Borefield total drilling length	m	12937.0	12459.0	11768.0	10046.0

Borehole spacing	m	6.00	6.00	6.00	6.00
Borefield area	m ²	3060.00	2952.00	2772.00	2412.00
Borehole Geometry					
Configuration		1U-Pipe	1U-Pipe	1U-Pipe	2U-Pipe
Borehole diameter	mm	114.30	127.00	139.70	152.40
u-pipe OD	mm	42.16	48.26	60.33	48.26
u-pipe ID	mm	33.99	38.94	48.69	38.94
inner pipe OD	mm	-	-	-	-
inner pipe ID	mm	-	-	-	-
outpipe pipe OD	mm	-	-	-	-
outpipe pipe ID	mm	-	-	-	-
shank spacing	mm	57.15	63.50	69.85	86.11
Borehole Thermal Resistance					
2D thermal resistance (Rb)	m·°C/W	0.09094	0.08953	0.08388	0.05782
Internal resistance (Ra)	m·°C/W	0.34824	0.34262	0.32009	0.20220
3D thermal resistance (Rb*)	m·°C/W	0.09267	0.09116	0.08543	0.05962
Heat Pump					
HP name		-	-	-	-
number of HP		1	1	1	1
COP cooling		4.70	4.70	4.70	4.70
COP heating		3.10	3.10	3.10	3.10
Total cooling capacity	kW	810.93	810.93	810.93	810.93
Total heating capacity	kW	959.58	959.58	959.58	959.58
TinHP cooling	°C	28.0	28.0	28.0	28.0
ToutHP cooling	°C	31.2	31.2	31.2	31.2
TinHP heating	°C	-1.0	-1.0	-1.0	-1.0
ToutHP heating	°C	-3.2	-3.2	-3.2	-3.2
Advanced Settings					
multipole order		4	4	4	4
Gf		FLS	FLS	FLS	FLS
G1		FLS	FLS	FLS	FLS
G2		STS	STS	STS	STS

Table 32 – Detailed results of the comparative analysis carried out with variable conditions on the heat pump size.

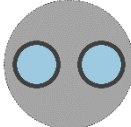
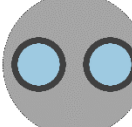

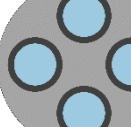
Properties	Units	Single loop 1.25 DR11	Single loop 1.5 DR11	Single loop 2 DR11	Twin loop 1.5 DR11
Building thermal load and soil temperature					
Annual cooling load	kW	98.36	98.36	98.36	98.36
Monthly cooling load	kW	307.02	307.02	307.02	307.02
Peak cooling load	kW	810.93	810.93	810.93	810.93
Peak cooling load duration	h	6	6	6	6
Annual heating load	kW	182.49	182.49	182.49	182.49
Monthly heating load	kW	412.06	412.06	412.06	412.06
Peak heating load	kW	959.58	959.58	959.58	959.58
Peak heating load duration	h	6	6	6	6
Tg	°C	12.40	12.39	12.39	12.39
Fluid Properties					
Fluid		prop_glycol	prop_glycol	prop_glycol	prop_glycol
Antigel	%vol	0.30	0.30	0.30	0.30
Thermal Properties					
conductivity :					
ground	W/m.°C	2.50	2.50	2.50	2.50
grout	W/m.°C	1.70	1.70	1.70	1.70
u-pipe	W/m.°C	0.40	0.40	0.40	0.40
inner pipe	W/m.°C	-	-	-	-
outer pipe	W/m.°C	-	-	-	-
capacity :					
ground	kJ/m ³ .°C	2500.0	2500.0	2500.0	2500.0
grout	kJ/m ³ .°C	3400.0	3400.0	3400.0	3400.0
u-pipe	kJ/m ³ .°C	1500.0	1500.0	1500.0	1500.0
inner pipe	kJ/m ³ .°C	-	-	-	-
outer pipe	kJ/m ³ .°C	-	-	-	-
Flow Conditions					
Total cooling flowrate	L/s	50.47	56.78	69.40	100.94
Re pipe (cooling)		9143	8991	8764	8541
Re annulus (cooling)		-	-	-	-
Total heating flowrate	L/s	50.47	56.78	69.40	100.94
Re pipe (heating)		2505	2505	2501	2518
Re annulus (heating)		-	-	-	-
Loop pressure drop	kPa	67.4	43.8	21.9	42.2
Borefield					
Borehole number		98	97	96	88
Borehole drilling length	m	153.3	152.3	152.4	152.8
Borefield total drilling length	m	15022.0	14771.0	14635.0	13444.0
Borehole spacing	m	6.00	6.00	6.00	6.00
Borefield area	m ²	3528.00	3492.00	3456.00	3168.00

Borehole Geometry					
Configuration		1U-Pipe	1U-Pipe	1U-Pipe	2U-Pipe
Borehole diameter	mm	114.30	127.00	139.70	152.40
u-pipe OD	mm	42.16	48.26	60.33	48.26
u-pipe ID	mm	33.99	38.94	48.69	38.94
inner pipe OD	mm	-	-	-	-
inner pipe ID	mm	-	-	-	-
outpipe pipe OD	mm	-	-	-	-
outpipe pipe ID	mm	-	-	-	-
shank spacing	mm	57.15	63.50	69.85	86.11
Borehole Thermal Resistance					
2D thermal resistance (Rb)	m·°C/W	0.09957	0.09805	0.09234	0.06193
Internal resistance (Ra)	m·°C/W	0.38171	0.37559	0.35247	0.21633
3D thermal resistance (Rb*)	m·°C/W	0.10459	0.10194	0.09507	0.06370
Heat Pump					
HP name		TMW840 (70 tons, 246 kW)	TMW840 (70 tons, 246 kW)	TMW840 (70 tons, 246 kW)	TMW840 (70 tons, 246 kW)
number of HP		7	8	8	8
COP cooling		5.15	5.13	5.37	5.79
COP heating		4.35	4.34	4.40	4.46
Total cooling capacity	kW	2060.64	2351.56	2395.33	2460.83
Total heating capacity	kW	1318.91	1505.29	1529.39	1547.59
TinHP cooling	°C	28.0	28.0	28.0	28.0
ToutHP cooling	°C	32.8	32.3	31.5	30.4
TinHP heating	°C	-1.0	-1.0	-1.0	-1.0
ToutHP heating	°C	-4.7	-4.3	-3.7	-2.9
Advanced Settings					
multipole order		4	4	4	4
Gf		FLS	FLS	FLS	FLS
G1		FLS	FLS	FLS	FLS
G2		STS	STS	STS	STS

Appendix D: Comparative analysis with varied borehole length and pipe diameter ratio (DR)

This appendix presents the results of an exercise that was carried out using the same methodology as that presented in section 3.2 for Part 1, but with boreholes of different lengths and using pipes that have different diameter ratio (DR) (see Table 33). In practice, pipes with a lower DR (therefore thicker walls) are used in GLHEs with boreholes longer than 500 to 600 feet, offering sufficient mechanical resistance to compensate for the increase in pressure on the pipes with depth. Smaller pipes (1.25 inches nominal) are generally not used in deeper boreholes because of the resulting increase in pressure drop that translate into a significant increase in the required loop pumping power.

Table 33 – Properties of the heat exchangers considered in the comparative analysis with boreholes of varied length and pipe diameter ratio (DR).

Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR9	Single loop 2 DR9	Twin loop 1.5 DR9
Scale drawing	-				
Borehole diam.	mm (in)	114.3 (4.5)	127.0 (5.0)	139.7 (5.5)	152.4 (6.0)
Shank space	mm (in)	57.150 (2.25)	63.50 (2.5)	69.850 (2.75)	86.195 (3.39)
Pipes inner diam.	mm (in)	34.036 (1.34)	36.830 (1.45)	45.974 (1.81)	36.830 (1.45)
Pipes outer diam.	mm (in)	42.164 (1.66)	48.260 (1.90)	60.452 (2.38)	48.260 (1.90)
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Lb	m (ft)	182.88 (600)	243.84 (800)	243.84 (800)	243.84 (800)

The detailed results obtained for sizing calculations with the borehole configurations presented in Table 33 are given in Table 34 for the heating mode and in Table 35 for the cooling mode. First of all, it is interesting to note that the results obtained here for the heating mode (see Table 33) are similar to those presented in Table 7 of Part 1 of this study. Indeed, the Twin loop 1.5 DR9 800 ft is still by far the most efficient solution and reduces the total borehole length by 16.19% compared to the Single loop 1.25 DR11 600 ft configuration. Similarly, the Single loop 2 DR9 800 ft and Single loop 1.5 DR9 800 ft are both, respectively, 4.93% and 2.21% more efficient than the Single loop 1.25 DR11 600 ft. This is explained by the fact that the increase in performance gained by a deeper borehole and reaching a higher mean ground temperature is more or less counterbalanced by the decrease in performance caused by the greater thermal resistance of the thicker-wall pipes. In heating mode, even though the results obtained here do not suggest that drilling deeper provides significant

gains of the efficiency of the GLHE (when comparing the ground heat flux per unit length, qb' , in W/m), it does allow extracting more total heat per borehole (when looking at the ground heat flux, qb , in W). Using 800 ft boreholes instead of 500 ft allowed to increase the amount of heat extracted per boreholes by 65.8%, 70.3%, and 88.5% for, respectively, the Single loop 1.5 DR9 800 ft, Single loop 2 DR9 800 ft, and Twin loop 1.5 DR9 800 ft configurations. These results suggest that deeper boreholes could be a solution to reduce the area of a borehole field and save footprints on available real estate.

The results obtained in cooling mode are, however, very different. In that case, the Twin loop 1.5 DR9 800 ft is still the most efficient solution, but only by 4.44% when compared to the Single loop 1.25 DR11 600 ft configuration. The Single loop 2 DR9 800 ft and Single loop 1.5 DR9 800 ft are in this cooling case less performant than the Single loop 1.25 DR11 600 ft configuration by, respectively, 5.86% and 8.55%. These results are explained by the fact that, in cooling mode, both the higher mean ground temperature at greater depth and larger thermal resistance of the thicker-wall pipes are detrimental to the performance of the GLHE. This means that, under cooling dominant conditions, it is best to use 500-600 ft boreholes with DR 11 pipes when designing a GLHE. However, using longer boreholes resulted in an increase of the total amount of heat injected in the ground per borehole by 41.2%, 45.3%, and 61.2% for the Single loop 1.5 DR9 800 ft, Single loop 2 DR9 800 ft, and Twin loop 1.5 DR9 800 ft configurations, respectively. When saving footprints on available real estate is important, deeper boreholes is a valid option to consider even for a project with cooling-dominant loads.

Table 34 – Ground heat extraction rates (heating) calculated with a ground thermal conductivity of 2.5 W/m°C, variable borehole length, variable pipe diameter ratio (DR).

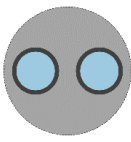
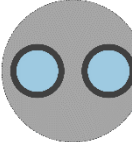

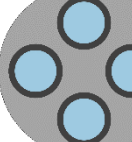
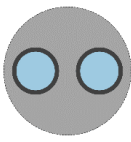
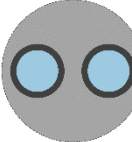

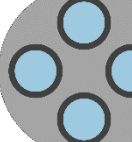
Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR9	Single loop 2 DR9	Twin loop 1.5 DR9
Scale drawing	-				
Mode	-	heating	heating	heating	heating
Borehole diam.	mm (in)	4.5	5	5.5	6
Borehole length	m (ft)	182.88 (600)	243.84 (800)	243.84 (800)	243.84 (800)
Shank space	mm (in)	2.25	2.5	2.75	3.39
Pipes inner diam.	mm (in)	1.34	1.45	1.81	1.45
Pipes outer diam.	mm (in)	1.66	1.9	2.38	1.9
kth pipes	W/m°C	0.4	0.4	0.4	0.4
kth ground	W/m°C	2.50	2.50	2.50	2.50
kth grout	W/m°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	5732	5297	4243	2648
Rcond pipe	m.°C/W	0.08521	0.10755	0.10893	0.10755
Rconv pipe	m.°C/W	0.00752	0.00816	0.01041	0.01902
Rpipe	m.°C/W	0.09272	0.11571	0.11934	0.12657
Rbore	m.°C/W	0.09257	0.10359	0.09993	0.06881
Rbore 3D	m.°C/W	0.09435	0.10641	0.10287	0.07348
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.74	13.52	13.52	13.52
Tfluid in	°C	-0.5	-0.5	-0.5	-0.5
Tfluid out	°C	1.11	1.7	1.76	2
Tfluid avg	°C	0.31	0.6	0.63	0.75
Duration	days	30	30	30	30
qb	kW	6.79	9.25	9.5	10.52
qb'	W/m	37.12	37.94	38.95	43.13
Δqb'	%	0	2.21	4.93	16.19

Table 35 – Ground heat injection rates (cooling) calculated with a ground thermal conductivity of 2.5 W/m°C, variable borehole length, variable pipe diameter ratio (DR).

Parameter	Units	1	2	3	4
		Single loop 1.25 DR11	Single loop 1.5 DR9	Single loop 2 DR9	Twin loop 1.5 DR9
Scale drawing	-				
Mode	-	cooling	cooling	cooling	cooling
Borehole diam.	mm (in)	4.5	5	5.5	6
Borehole length	m (ft)	600	800	800	800
Shank space	mm (in)	2.25	2.5	2.75	3.39
Pipes inner diam.	mm (in)	1.34	1.45	1.81	1.45
Pipes outer diam.	mm (in)	1.66	1.9	2.38	1.9
kth pipes	W/m/°C	0.4	0.4	0.4	0.4
kth ground	W/m/°C	2.50	2.50	2.50	2.50
kth grout	W/m/°C	1.70	1.70	1.70	1.70
Cp ground	J/m³/°C	2.26E+06	2.26E+06	2.26E+06	2.26E+06
Vol. flow rate	L/s	1.07	1.07	1.07	1.07
Re	-	17386	16067	12871	8034
Rcond pipe	m.°C/W	0.08521	0.10755	0.10893	0.10755
Rconv pipe	m.°C/W	0.00349	0.00374	0.00451	0.0082
Rpipe	m.°C/W	0.0887	0.11128	0.11344	0.11574
Rbore	m.°C/W	0.0904	0.10122	0.0967	0.06528
Rbore 3D	m.°C/W	0.09218	0.10406	0.09969	0.07011
Tground @ 4m	°C	10.5	10.5	10.5	10.5
Tground avg	°C	12.74	13.52	13.52	13.52
Tfluid in	°C	27.5	27.5	27.5	27.5
Tfluid out	°C	25.7	25.31	25.25	25
Tfluid avg	°C	26.6	26.4	26.37	26.25
Duration	days	30	30	30	30
qb	kW	-7.62	-9.29	-9.56	-10.61
qb'	W/m	-41.66	-38.1	-39.22	-43.51
Δqb'	%	0	-8.55	-5.86	4.44

Electronic Appendix A

This electronic appendix contains all the Python codes and results in Excel spreadsheet format that were produced as part of the work done in the Part 1 and the Appendix D of this study.

Electronic Appendix B

This electronic appendix contains the VersaGLD software and the results that were produced as part of the work done in the Part 2 of this study.