

Parametric analysis of the factors affecting the efficiency of ground heat exchangers and design application aspects in Cyprus



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ABSTRACT

The objective of this paper is to examine the factors affecting the sizing and positioning of Ground Heat Exchangers (GHEs) in Cyprus. This is achieved through the investigation of the influence of the temperature, thermal conductivity, specific heat and density of the ground as well as pipe diameter on the performance of GHEs using computer software modelling in conjunction with test data. Also, the long term temperature variation of the ground around the boreholes is examined since this affects the positioning of the GHEs. Because of the large number of parameters involved in the design the desired result can be achieved in various ways by considering the specific parameters. The results of the simulations have shown that, generally speaking, the island of Cyprus is suitable for geothermal heat pumps.

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1. Introduction

A typical vertical Ground Heat Exchanger (GHE) consists of a plastic pipe (tube) (usually of polyethylene type) with a descending and an ascending leg connected at their ends with a U-joint. The pipe is placed in the ground within a 100 m deep borehole of a diameter of 0.1–0.2 m filled with grout – usually thermally enhanced bentonitic clay or silica sand. Due to the good contact of the pipe and the ground, the heat transfer fluid – usually water – that circulates in the pipe can be either cooled or heated depending on its temperature difference with the ground.

To predict the long- and short-term performance of GHEs various mathematical models – analytical, numerical and hybrid – have been developed. These can be used to estimate the heat transfer in and around boreholes and compute the required borehole depth. The long- and short-term responses of GHEs can be determined using different approaches and simplifications. Regarding the long-term responses of a GHE, the borehole is modelled either as a line or as a cylindrical source with finite or

infinite lengths with the borehole thermal details being ignored. The g-function approach of Elkinson [1] is considered as the state of the art in this field. On the other hand regarding the short-term responses, the actual geometry of the borehole is retained with the short-term g-functions developed by Yavuzturk et al. [2] being the state of the art. Both long- and short-term response g-functions have been implemented in various building simulation and ground loop design software, including TRNSYS, Energy Plus and GLEHE-PRO as reported in Ref. [3].

The most adopted models for vertical GHEs, including the heat transfer processes outside and inside the boreholes, are summarized in detail in Ref. [4]. Moreover, exhaustive comparisons between analytical, numerical and hybrid modelling have been realised in a number of studies (see for example [5,6]).

Now, the classic analytical solutions used for dimensioning vertical GHEs are based on the line- and the cylindrical-source models, which have been presented, among others, by Refs. [7–11] and, more recently, by Refs. [12,13]. The advantage of analytical models, although less precise than numerical models, is their shorter computational time and flexibility for parameterized design.

Regarding numerical models, some indicative ones are presented in Refs. [14–17] and more recently in Refs. [18,19], which are

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based on finite-differences, finite-volumes, finite elements and Discrete Fourier transforms. Of course numerical models give accurate solutions and are good for theoretical analysis. The so-called hybrid models have been proposed so as to combine precision (see *numerics*) with computational speed (see *analytics*), and can provide a feasible alternative to numerical and analytical models as described by Refs. [1,2,20–22]. In such models special temperature response functions can be computed numerically and then be incorporated into some simulation software as databases.

The dramatic increase of computer power has led to the construction of a number of software packages that can simultaneously handle the finite element method and provide solutions to partial differential equations for a massive cell number. The packages may include a number of built-in modules that can facilitate the formulation of the problem. Examples of recent use of such packages can be found in Refs. [23–25], where COMSOL Multiphysics, TOUGHREACT and FEFLOW have respectively been used [26–28].

In particular, for the design of GHEs a number of software tools have been developed [29–31]. GLD, the software tool, selected for use in this study is a modular program that provides the user with flexibility in the design process and customization based on designer preferences [31]. GLD allows users to assess the effect of various parameters and perform multiple design simulations to optimize geothermal systems. It can also be easily integrated with other commercial software programmes like AutoCAD, Carrier HAP, and so on, allowing data to be easily imported or exported. Finally, it enables designers to compare different types of systems such as vertical and horizontal GHEs.

The rest of the paper is organised as follows. Section 2 discusses the data required as input to the software, while in Section 3 the main parameters affecting the borehole thermal resistance and the computations are examined. Section 4 examines the effect of the weather conditions in the computations. We conclude with Section 5.

2. Ground heat exchanger design

In order to provide engineers with a useful guide for sizing and positioning GHEs in Cyprus, the heating and cooling load of a typical house along with the thermal characteristics of the ground in eight selected locations (Fig. 1), where boreholes were drilled and studied [32], were used as input data in the GLD software.

Fig. 2 shows the number of parameters affecting the design of geothermal systems.

Thermal data for the eight representative locations, like undisturbed temperature of the ground, thermal conductivity, thermal diffusivity and thickness of each lithology of the borehole were

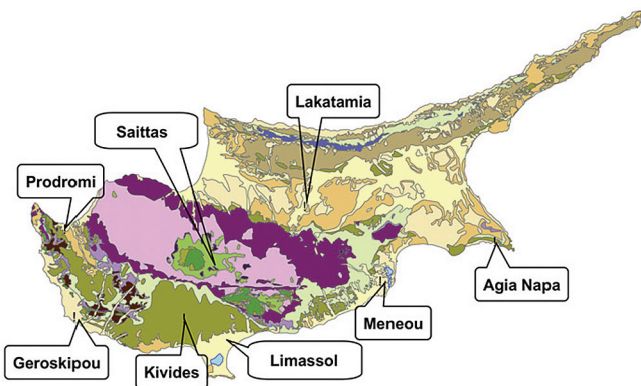


Fig. 1. Geological map of Cyprus with borehole locations [26].

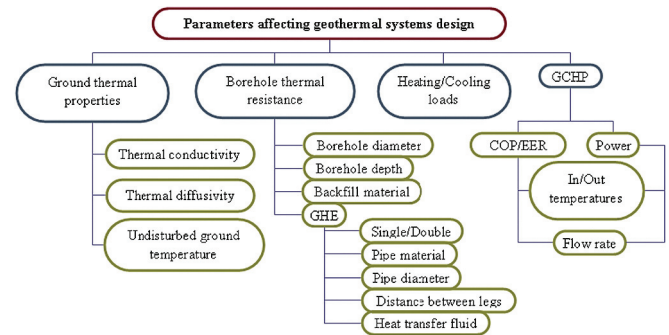


Fig. 2. Parameters affecting geothermal systems design.

collected and measured on site. The layer calculator in GLD that uses the line-source model technique was then used to produce a quick weighted-average computation for thermal conductivity, thermal diffusivity and borehole thermal resistance. This is necessary when the thermal response test is not carried out in situ but the above-mentioned properties are known. Table 1 shows these results in relation to the depth and the undisturbed ground temperature.

In the Borehole design module, designers have the option to decide if the design is to be based on a fixed borehole length or a fixed heat carrier fluid temperature. In the fixed temperature mode, the required length of the bores is calculated based on the desired temperatures of the heat carrier fluid. In the fixed length mode, the inlet temperature to the GHE is calculated when the length of the GHE is preset. In both cases GLD needs as input the borehole grid to be used.

The positioning of the boreholes forming the grid to satisfy a typical house load is very important taking into account the common way houses are built in Cyprus. Most are semi-detached, two houses built in the same plot and attached to each other on one side, or are linked-detached, with a short distance between them. In both cases, the only available space for drilling boreholes is a 3–4 m region at the edge of the plot. Rarely, houses are detached having enough land space free for drilling as many boreholes as needed and positioning them without any limitation.

For design purposes, the heating and cooling load of a typical house is needed. The selected typical house is a three bedroom, two storey house of a total useful floor area of 190 m². In one side the house is attached to another house, and there is available land space of at least 4 m in the other three sides. The house is made of reinforced concrete pillars and beams while the walls are made of red and sandy clay bricks. All parts of the house are thermally insulated, as stated by law. Extruded polystyrene is used for the thermal insulation while double glazed aluminium framed windows are used. Characteristic values of the elements of the house are tabulated in Table 2.

The possible available grids, their performance and the long term temperature variation of the ground in the 8 selected locations were examined based on the loads of the typical house as calculated according to the weather conditions of the city of Limassol.

For GLD monthly or hourly load data are necessary for the computation of monthly or hourly inlet temperatures for the GHEs and for the evaluation of heat pump performance. For the house under consideration, the monthly load data obtained from the Interface for Simplified Building Energy Model for Cyprus (iSBEM-CY) [33], shown in Table 3, were imported into the month-by-month load screen of GLD. For comparing the performance of the GHEs in the different locations without being affected by the load

Table 1

Thermal properties of the boreholes in each location as calculated by GLD.

Location	Actual Borehole depth (m)	Undisturbed ground temp. (°C)	Ground thermal conductivity (Wm ⁻¹ K ⁻¹)	Ground thermal diffusivity (m ² /day)
Agia Napa	100	23.4	0.97	0.056
Meneou	97	22.6	0.92	0.048
Geroskipou	100	22.4	1.1	0.057
Prodromi	100	21.3	1.32	0.073
Lakatamia	100	22.7	0.56	0.032
	160		0.73	0.047
Kivides	100	18.7	0.58	0.036
	196		0.58	0.036
Limassol	100	22.1	0.63	0.037
	120		0.61	0.036
Saittas	100	18.3	1.4	0.074
	178		1.42	0.076

Table 2

Characteristic values of the elements of the house.

Name of the elements of the house	Element description	U-value (Wm ⁻² K ⁻¹)	Thermal capacitance (kJ m ⁻² K ⁻¹)
External wall	10 cm brick	0.581	119
	3 cm extruded polystyrene		
External beams & pillars	10 cm brick	0.765	224
	20 cm reinforced concrete		
	3 cm extruded polystyrene		
Exposed roof	15 cm reinforced concrete	0.424	236
	5 cm concrete		
	5 cm extruded polystyrene		
Floor in contact with ground	5 cm loose lightweight rock	0.421	200
	15 cm reinforced concrete		
	10 cm lightweight concrete		
	3 cm extruded polystyrene		
Exposed floor	3 cm granite ceramic	0.546	132
	15 cm reinforced concrete		
	10 cm lightweight concrete		
	3 cm extruded polystyrene		
External door	3 cm granite ceramic	2.29	14
	5 cm Massif wood		
Openings: frame ≤ 25% opening area	Aluminium frame	2.6	N/A
Openings: frame > 25% opening area	4 mm glass	3.2	
	12 mm air gap		
	4 mm glass		

Table 3

Heating and cooling loads of the typical house used in the computations.

Month	Cooling load (kWh)	Cooling peak load (kW)	Heating load (kWh)	Heating peak load (kW)
January	0.00	0.00	1252.58	13.52
February	0.00	0.00	1622.21	15.87
March	137.43	0.185	555.19	12.54
April	99.32	0.138	108.57	11.33
May	482.86	4.67	0.00	0.00
June	1003.00	11.38	0.00	0.00
July	1508.43	14.83	0.00	0.00
August	1483.09	16.18	0.00	0.00
September	1048.94	11.07	0.00	0.00
October	214.93	0.29	12.18	8.46
November	0.00	0.00	731.30	12.24
December	0.00	0.00	1430.17	14.73

variations due to weather conditions, the same load data were assumed in all locations.

In order to proceed with the computations, a GCHP should be selected. Once the GCHP is coupled to the GHEs, the characteristics of the boreholes and the heat pump performance determine the desired number of GHEs required for the application. Table 4(a) shows the Capacity and Power of the selected GCHP in kW, based on the entering water temperature at a certain flow rate. The water flow rate in the GHEs in a geothermal system of about 5–7 GHEs should be between 52.5 and 84 L/min. Table 4(b) reports the factors

affecting the capacity and power required by the GCHP, when the water temperature entering the unit deviates from the design value. Similarly, Table 4(c) shows the factors affecting the capacity and power required by the GCHP, when the system flow rate deviates from the nominal value of 43.5 L/min. The above-mentioned factors are given by the GCHP manufacturers.

3. Parametric study of the design

The effect of some important parameters on the sizing and

Table 4

(a) Heat pump specifications. (b) Heat pump temperature corrections. (c) Heat pump flow corrections (nominal flow 43.5 L/min).

(a)						
Flow rate (L/min)	Cooling mode			Heating mode		
	Entering water temp. (°C)	Capacity (kW)	Power input (kW)	Entering water temp. (°C)	Capacity (kW)	Power input (kW)
30.3	21.1	18.2	3.17	−1.1	12.6	4.23
	32.2	16.5	4.04	10	15.8	4.3
	43.3	14.8	4.91	21.1	18.9	4.37
56.8	21.1	17.9	2.88	−1.1	13.1	4.27
	32.2	16.6	3.72	10	16.5	4.32
	43.3	15.2	4.57	21.1	19.9	4.38

(b)					
Cooling mode			Heating mode		
Entering water temp. (°C)	Capacity factor	Power factor	Entering water temp. (°C)	Capacity factor	Power factor
10	0.795	0.975	15.6	1.089	0.591
21.1	1	1	26.7	1.045	0.795
32.2	1.206	1.022	37.8	1	1
			48.9	0.955	1.205

(c)					
Cooling mode			Heating mode		
% of nominal flow	Capacity factor	Power factor	% of nominal flow	Capacity factor	Power factor
69.6	0.970	0.955	69.6	1.002	1.021
100	1	1	100	1	1
130	1.032	1.003	130	1	0.979

positioning of the boreholes are discussed in this section. Based on the selected heat pump and its specifications, and assuming a system flow rate of 11.4 L/min/3.5 kW of peak cooling load and a 100 m fixed borehole length, the minimum number of boreholes to be drilled in each of the locations in order to satisfy the heating and cooling loads of the house is calculated. The results are tabulated in Table 5. Increasing the system flow rate per peak load means that more heat will be exchanged with the ground, requiring measures to be taken to increase the borehole's capacity. Such measures can be i) larger distance between the boreholes, ii) an increased number of boreholes, iii) deeper boreholes, iv) installing 2 U-tube GHEs in a single borehole, v) larger pipe diameter or vi) a combination of the above.

Table 5 also shows that the increase in the temperature over a 50-year period is low, the maximum being 1.4 °C in Kivides when the distance between the boreholes is 3 m. As the distance between

the boreholes increases, the estimated ground temperature over the 50-year period decreases rapidly (with 70% thereof occurring between 3 m and 5 m) reaching 0 °C at a distance 10 m–11 m apart. But when increasing the distance between the boreholes the unit inlet temperature showed a slight decrease of about a 1 °C depending on the location. This resulted in an increase of up to 0.2 units in the system COP in the cooling mode and a decrease of up to 0.1 units in the respective one in the heating mode.

The modelling results also showed that in some cases the distance between the boreholes could be less than 3 m. Although a short distance between boreholes can save space, too short a distance is not desirable as drilling cannot be guaranteed to be entirely vertical. The greater the depth of the borehole, the larger the deviation from vertical could be and if boreholes are too close to each other, the effectiveness of the GHEs will be reduced. Therefore, it is desirable to keep the distance between boreholes as large as

Table 5

Calculated number of boreholes required for a single row grid.

Location	Total Length (m)	Boreholes	Minimum distance between the boreholes (m)	Estimated ground temp. change over 50 years (°C)	Cooling mode		Heating mode	
					System COP	Unit inlet/outlet temp. (°C)	System COP	Unit inlet/outlet temp. (°C)
Agia Napa	600	6	3	+0.9	4.5	42/47.7	3.7	14.4/11.2
			10	0	4.7	41/46.4	3.6	13.6/10.4
Meneou	600	6	3	+0.8	4.7	41.1/46.5	3.6	13.7/10.5
			10	0	4.9	40.1/45.5	3.6	12.9/9.7
Lakatamia	700	7	3	+1.1	4.6	41.1/46.5	3.7	14.5/11.3
			11	0	4.9	39.8/45.1	3.6	13.5/10.3
Limassol	600	6	3	+1.3	4.6	42.3/47.7	3.6	13.1/9.9
			11	0	4.8	41/46.3	3.5	11.9/8.7
Saittas	400	4	3	+1	5	41.6/46.9	3.3	7.2/4.2
			10	0	5.2	40.5/45.8	3.2	6.3/3.3
Kivides	600	6	3	+1.4	5.2	40/45.2	3.4	9.2/6.1
			11	0	5.5	38.5/43.7	3.3	8.1/5
Geroskipou	600	6	3	+0.8	4.8	39.8/45.2	3.6	13.8/10.6
			10	0	5	39.1/44.4	3.6	13/9.9
Prodromi	500	5	3	+0.7	4.8	41.9/47.3	3.5	10.9/7.8
			10	0	4.9	41.2/46.5	3.4	10.3/7.1

practically possible, particularly for deep boreholes. For 100 m deep boreholes and a 3 m distance between them the deviation from vertical should be less than 0.5°.

The backfill material assumed for filling the borehole is bentonitic clay with a thermal conductivity of $0.8 \text{ Wm}^{-1}\text{K}^{-1}$. Bentonitic clay was chosen because it has the ability to expand and completely fill the borehole and hold firmly the GHE in place. The thermal conductivity of the bentonitic clay though is lower than most of the soils or rocks forming the boreholes. This results in higher thermal resistance of the borehole when the pipes are placed close together in the middle of the borehole as opposed to the wall of the borehole. The modelling results in Table 6 show that when the pipes are moved towards the borehole wall the system efficiency increases, as expected. This is due to the reduction in the thermal resistance. The change in the unit inlet temperature, reduced in the cooling mode and increased in the heating mode, is the parameter affecting system COP in the degree shown in Table 4(a)–(c). Also, the balance between the heat injected and absorbed by the GHE strongly influence the long-term temperature variation of the ground. The movement of the pipes from the centre of the borehole to the borehole wall did not affect the change in the ground temperature over the 50-year period modelled. In all cases improved system efficiency in the cooling and heating mode was observed when the pipes are placed close to the borehole wall.

Bentonitic clay is the material most commonly used in Cyprus, because it is produced locally and is cheap. Available on the market are more expensive imported geothermal grouts with higher thermal conductivities that could lower the thermal resistance of the borehole. For the cases under consideration here, using a higher thermal conductivity grout, of $2 \text{ Wm}^{-1}\text{K}^{-1}$ say, an increase in the overall efficiency of the system of up to 5% was estimated when the pipes are moved towards the borehole wall, and up to 10% when the pipes are placed close together in the middle.

A way to minimise the number of boreholes in a system is to use GHEs with a larger pipe diameter. The effect on the borehole performance, when the 32-mm GHEs were replaced by 40-mm GHEs, can be seen through the simulation results in Table 7. A small

increase in the system COP in the cooling mode, between 0.2 and 0.5 units was determined. In the heating mode, if not unchanged, the system COP had a minor increase of 0.1 units.

The increase in the pipe diameter reduced the thermal resistance of the borehole since the heat exchange surface increased (approximately 5 m^2 in each borehole). But the most significant observation is that the number of boreholes could be reduced by 1 except from the cases of Limassol, Saittas and Prodromi. The changes in pipe diameter in combination with the thermal properties of the ground in these three locations were not sufficient for the further reduction in the number of boreholes. The reduction of the number of boreholes had almost negligible impact on the system COP and the temperature change over a 50-year period.

A combination of the results shown in the Tables mentioned above is graphically presented below. In Fig. 3 the correlation between the thermal properties of the ground and the borehole thermal resistance at each location is plotted against the total length required to satisfy the load of the house. Similarly, in Fig. 4 the parameters affecting the thermal resistance of a borehole, like pipe and borehole diameter, the distance between the GHE legs and the number of GHEs in the borehole were plotted against the borehole resistance.

For the positioning of the boreholes, since the single row grid is not always feasible to be used, because of the limitation in the length of the plot, the reverse 'L' shape is often utilized. Comparing the reverse 'L' grid shape system to the single row grid, it is estimated that the reverse 'L' shape grid does not offer any significant advantages apart from the flexibility in the installation that gives to engineers by increasing the available space and, therefore, the number of boreholes or the distance between them. The change in the system COP is insignificant, while in none of the locations the number of boreholes could be reduced.

Engineers should also be aware of the possibility that installing two independent geothermal systems close to each other could affect their performance. This may happen in the case when an engineer who designs a geothermal system for a newly-built house has not been informed of the presence of a geothermal system in

Table 6
Spacing between the legs of the GHE.

Location	Total length (m)	Leg spacing	Cooling mode		Heating mode	
			Unit inlet/outlet temp. (°C)	System COP	Unit inlet/outlet temp. (°C)	System COP
Agia Napa	600	CT*	41.9/47.3	4.5	14.4/11.2	3.7
		A*	37.2/42.5	4.9	17/13.7	3.8
		BW*	33.7/39	5.3	18.9/15.6	3.9
Meneou	600	CT*	41.1/46.5	4.7	13.7/10.5	3.6
		A*	36.4/41.7	5.1	16.1/12.9	3.8
		BW*	32.7/38	5.5	18.2/14.9	3.9
Lakatamia	700	CT*	41.1/46.5	4.6	14.5/11.3	3.7
		A*	37/42.3	5	16.6/13.4	3.8
		BW*	33.9/39.2	5.3	18.4/15.1	3.9
Limassol	600	CT*	42.3/47.7	4.6	13.1/9.9	3.6
		A*	39.3/44.6	4.8	14.7/11.4	3.7
		BW*	36.4/41.7	5.1	16.1/12.9	3.8
Saittas	400	CT*	41.6/46.7	5	7.2/4.2	3.3
		A*	36.9/42.1	5.7	9.3/6.2	3.4
		BW*	32.8/37.9	6.1	11.4/8.2	3.5
Kivides	600	CT*	40/45.2	5.2	9.4/6.3	3.4
		A*	35.2/40.4	5.7	11.5/8.4	3.5
		BW*	31.8/36.9	6.1	13.6/10.4	3.6
Geroskipou	600	CT*	39.8/45.2	4.8	13.8/10.6	3.6
		A*	35.2/40.5	5.3	16.2/13	3.8
		BW*	31.8/37	5.6	18.2/14.9	3.9
Prodromi	500	CT*	41.9/47.3	4.8	10.9/7.8	3.5
		A*	36.5/41.8	5.3	13.8/10.6	3.6
		BW*	32.3/37.5	5.7	18/15.9	3.8

*CT = Close Together in the middle of the borehole, A = Average, BW = Next to the Borehole Wall.

Table 7
Comparison of the 100 m borehole capacity in relation to pipe diameter.

Location	Pipe Diam. (mm)	Boreholes/total length (m)	Distance between the boreholes (m)	Ground temp. change over 50 years (°C)	System COP cooling mode	System COP heating mode
Agia Napa	32	6/600	3	+0.9	4.5	3.7
	40	6/600	3	+0.9	4.7	3.7
	40	5/500	4	+0.5	4.5	3.6
Meneou	32	6/600	3	+0.8	4.7	3.6
	40	6/600	3	+0.9	4.9	3.7
	40	5/500	3	+1.1	4.5	3.6
Lakatamia	32	7/700	3	+1.1	4.6	3.7
	40	7/700	3	+1.2	4.8	3.7
	40	6/600	3	+1.4	4.5	3.7
Limassol	32	6/600	3	+1.3	4.6	3.6
	40	6/600	3	+1.2	4.8	3.6
Saittas	32	4/400	3	+1	5	3.3
	40	4/400	3	+0.9	5.5	3.3
Kivides	32	6/600	3	+1.4	5.2	3.4
	40	6/600	3	+1.3	5.5	3.5
	40	5/500	3	+1.6	4.9	3.4
Geroskipou	32	6/600	3	+0.8	4.8	3.6
	40	6/600	3	+0.8	5.1	3.7
	40	5/500	3	+0.9	4.7	3.6
Prodromi	32	5/500	3	+0.7	4.8	3.5
	40	5/500	3	+0.8	5.1	3.6

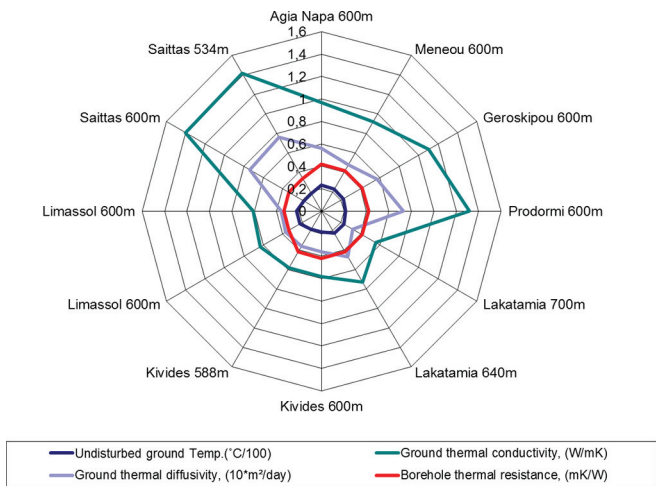


Fig. 3. Graphical representation of the ground thermal properties and borehole thermal resistance against the total length required in each location for the heating and cooling load of the typical house.

the adjacent house.

A determination of how this affects the performance of the systems and the possible ways to avoid it follows. Since it is not possible to simulate in GLD the operation of the geothermal system of two houses, it is assumed that a single grid is used to serve the loads of two typical houses entered in Zone Manager as two different zones. The same pump as before was assigned to each zone with both of them connected to a grid. The two most important borehole grids of interest are i) the 2 single row (2SR) grids with boreholes 3 m apart to each other, with one row placed on the left and the other on the right side of the plot, and ii) a similar grid but with a vertical offset (2SRO) of 1.5 m between the two rows. The results of the computations, along with a comparison with the single row case (SR), are tabulated in [Table 8](#).

According to the results, the effect on the system COP is minor as it is on the change in the temperature of the ground over a 50-year time. As mentioned before, it is desirable to keep the distance between boreholes as large as practically possible keeping the balance between heating and cooling system COP.

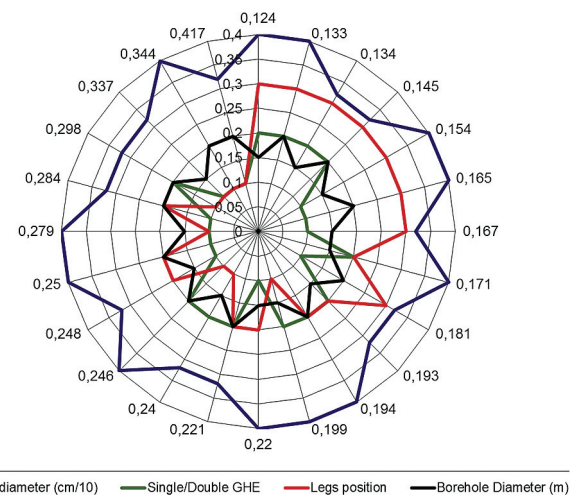


Fig. 4. Parameters affecting the borehole resistance.

4. Weather condition effects

Next, the effect of the weather conditions on the design of a geothermal system is also determined. This is done by computing the heating and cooling loads of the selected house based on the weather conditions. Cyprus is divided in four representative regions as per the prevailing climatic data. Zone 1 accounts for the sea-side locations like Agia Napa, Meneou, Limassol, Geroskipou and Prodromi, Zone 2 for the inland locations like Lakatamia, Zone 3 for the semi-mountainous locations like Kivides, and Zone 4, for the mountainous locations like Saittas. The results of the computation are shown in [Table 9](#).

According to the results shown in [Table 9](#) and, as it was expected, the heating load is higher and the cooling load is lower in the cooler zones. In all locations except from Limassol 5 boreholes, 500 m in total length, were needed to satisfy the new loads. The impact of the weather conditions caused significant increase in both the total and peak heating loads. Consequently, the system COP in the heating mode had a slight drop. The drop in the peak cooling load in the three locations resulted in an increase of the

Table 8

Effects on the operation of two independent geothermal systems when their single row grids are positioned close to each other.

Pattern	Boreholes per grid	Minimum distance between the boreholes	Ground temp. change over 50 years (°C)	System COP cooling	System COP heating
SR	6	3	+1.3	4.6	3.6
2SR	6	3	+0.7	4.7	3.5
2SRO	6	3	+0.7	4.7	3.5

Table 9

Comparison of the heating and cooling loads in the four different climatic zones and the geothermal system required to satisfy the loads.

Location	Load (kWh)		Number of Boreholes/total length (m)	System COP		Ground temp. change over 50 years (°C)
	Cooling	Heating		Cooling	Heating	
Limassol	6195.08	16.18	6/600	4.6	+1.3	
	5712.21	15.87		3.6		
Lakatamia	6129.76	11.56	5/500 (7/700)*	4.8 (4.6)*	+1.4 (+1.1)*	
	7382.32	20.78		3.1 (3.7)*		
Kivides	7053.50	10.97	5/500 (6/600)*	5.4 (5.2)*	+1.6 (+1.4)*	
	8294.65	21.51		2.9 (3.4)*		
Saittas	2136.39	10.82	5/500 (4/400)*	7.6 (5)*	−1.8 (+1)*	
	26885.40	23.94		2.7 (3.3)*		

*In the brackets are shown the results of the computations obtained considering the loads calculated based on the weather conditions in Limassol.

system COP in the cooling mode even if the total cooling load in Kivides increased. The change in loads due to weather conditions was sufficient to reduce the number of boreholes needed in Lakatamia and Kivides and increase them in Saittas. The change in the ground temperature over a 50-year time was considerably decreased in Saittas, where it dropped from +1 °C to −1.8 °C.

5. Conclusions

In determining the number of boreholes required as well as the heating and cooling performance of ground source heat pumps it is important that accurate data are used in simulations. It is preferable that data specific to the location and application are obtained from in-situ investigations and measurements.

Because of the large number of parameters affecting the design of geothermal systems, graphical presentations have been drawn to show the interaction between them. These show that one can arrive at a satisfactory result in various ways by considering the specific parameters.

Bentonitic clay as backfill material should be avoided since it acts as an insulator and reduces borehole efficiency. Enhanced bentonitic clay or even the drill chipping material taken out from the borehole during drilling improves borehole performance. This will enhance the efficiency of the system by 5–10%.

The efficiency of a geothermal system depends on the borehole thermal resistance, which should be as low as possible. Apart from the backfill material, the distance between the pipes of the GHE influences borehole efficiency. The thermal resistance of the borehole is at its minimum when the pipes touch the borehole wall. The heat exchange between the pipes and the borehole wall increases as the pipe diameter increases. The heat exchange process between the pipes and the ground also improves as the borehole depth is increased.

The degree that each of these factors alone or in combination affects the system efficiency is strongly dependant on the thermal properties of the ground. Thermal conductivity and diffusivity of the ground and the temperature of the undisturbed ground are the most important factors.

The selection of the GCHP should be made in accordance to the thermal properties of the ground. Its performance is also dependent on the borehole arrangement to be used. The number of boreholes in relation to the distance between them also affects the

temperature variation of the ground in the long term.

For the most of the 8 tested locations in Cyprus, about 6 boreholes of 3 m apart from each other are required to satisfy the 16.2 kW peak cooling load and the 15.87 kW peak heating load of a typical house. In all cases the ground temperature variation in a 50-year period is negligible. This is due to the fact that the load in the summer and winter balances out. When there is a large difference between the heating and cooling load (12.5 times greater, as in Saittas) the balance between the two periods is impossible and significant temperature change occurs (from +1 °C to −1.8 °C).

The results of the simulations have shown that geothermal systems are appropriate for installation in Cyprus, as they can lead to the efficient utilisation of the heat pumps. The performance of the GCHPs is not affected by the ambient conditions since the temperature of the ground remains unchanged.

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References

- [1] P. Eskilson, Thermal analysis of Heat Extraction Boreholes, PhD thesis, Department of Mathematical Physics, Lund University, Sweden, 1987.
- [2] C. Yavuzturk, Modeling of Vertical Ground Loop Heat Exchangers for Ground Source Heat Pump Systems, PhD thesis, Graduate College, Oklahoma State University, 1999.
- [3] S. Javed, P. Fahlén, J. Claesson, Vertical ground heat exchangers: a review of heat flow models, in: Proceedings of the 11th International Conference on Thermal Energy Storage, Effstock 2009, 2009.
- [4] H. Yang, P. Cui, Z. Fang, Vertical-borehole ground-coupled heat pumps: a review of models and systems, Appl. Energy 87 (1) (2010) 16–27.
- [5] P. Cui, H. Yang, Z. Fang, Numerical analysis and experimental validation of heat transfer in ground heat exchangers in alternative operation modes, Energy Build. 40 (6) (2008) 1060–1066.
- [6] D. Bauer, W. Heidemann, H.-G. Diersch, Transient 3D analysis of borehole heat exchanger modeling, Geothermics 40 (4) (2011) 250–260.
- [7] L.R. Ingersoll, H.J. Plass, Theory of the ground pipe heat source for the heat pump, Heat. Pip. Air Cond. 20 (7) (1948) 119–122.
- [8] J.H. Blackwell, A transient-flow method for determination of thermal constants of insulating materials in bulk part I - Theory, J. Appl. Phys. 25 (2) (1954) 137–144.
- [9] H.S. Carslaw, J.C. Jaeger, Conduction of heat in solids, in: Chapter A32: Geothermal Energy, CD-ROM, 2003 ASHRAE HVAC Applications, second ed.,

- Great Britain: Oxford Science Publications, 1959. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- [10] J.D. Deerman, S.P. Kavanaugh, Simulation of vertical U-tube ground-coupled heat pump systems using the cylindrical heat source solution, *ASHRAE Trans.* 97 (1) (1991) 287–295.
- [11] S.P. Kavanaugh, K. Rafferty, *Ground-source Heat Pumps, Design of Geothermal Systems for Commercial and Institutional Buildings*, ASHRAE, Inc., 1997, pp. 72–113.
- [12] P. Eslami-Nejad, M. Bernier, Coupling of geothermal heat pumps with thermal solar collectors using double U-tube boreholes with two independent circuits, *Appl. Therm. Eng.* 31 (14–15) (2011) 3066–3077.
- [13] L. Lamarche, Short-term behaviour of classical analytic solutions for the design of ground-source heat pumps, *Renew. Energy* 57 (2013) 171–180.
- [14] P. Eskilson, J. Claesson, Simulation model for thermally interacting heat extraction boreholes, *Numer. Heat Transf.* 13 (2) (1988) 149–165.
- [15] N.K. Muraya, Numerical Modelling of the Transient Thermal Interface of Vertical U-tube Heat Exchangers, 1994. Numerical modelling of the transient thermal interference of vertical U-tube heat exchangers.
- [16] H. Zeng, N. Diao, Z. Fang, Heat transfer analysis of boreholes in vertical ground heat exchangers, *Int. J. Heat Mass Transf.* 46 (23) (2003) 4467–4481.
- [17] A. Michopoulos, N. Kyriakis, Predicting the fluid temperature at the exit of the vertical ground heat exchangers, *Appl. Energy* 86 (10) (2009) 2065–2070.
- [18] C.K. Lee, Effects of multiple ground layers on thermal response test analysis and ground-source heat pump simulation, *Appl. Energy* 88 (12) (2011) 4405–4410.
- [19] R. Baccoli, C. Mastino, G. Rodriguez, Energy and exergy analysis of a geothermal heat pump air conditioning system, *Appl. Therm. Eng.* 86 (2015) 333–347.
- [20] C. Yavuzturk, J.D. Spitler, S.J. Rees, A transient two-dimensional finite volume model for the simulation of vertical U-tube ground heat exchangers, *ASHRAE Trans.* 105 (2) (1999) 465–474.
- [21] M. Fossa, F. Minchio, The effect of borefield geometry and ground thermal load profile on hourly thermal response of geothermal heat pump systems, *Energy* 51 (2013) 323–329.
- [22] S. Koochi-Fayegh, M.A. Rosen, An analytical approach to evaluating the effect of thermal interaction of geothermal heat exchangers on ground heat pump efficiency, *Energy Convers. Manag.* 78 (2014) 323–329.
- [23] L. Schiavi, 3D Simulation of the thermal response test in a U-tube borehole heat exchanger, in: *Proc COMSOL Conference*, 2009.
- [24] S. Kim, G. Bae, K. Lee, Y. Song, Field-scale evaluation of the design of borehole heat exchangers for the use of shallow geothermal energy, *Energy* 35 (2) (2010) 491–500.
- [25] A. Casasso, R. Sethi, Efficiency of closed loop geothermal heat pumps: a sensitivity analysis, *Renew. Energy* 62 (2014) 737–746.
- [26] **Comsol Multiphysics**: <https://www.comsol.com/comsol-multiphysics>.
- [27] **TOUGHREACT**: <http://esd1.lbl.gov/research/projects/tough/software/>.
- [28] **FEFLOW**: <http://www.mikepoweredbydhi.com/products/feflow>.
- [29] **Right-Loop**: <http://www.wrightsoft.com/products/right-loop.aspx>.
- [30] **GLHEPRO**: <https://hvac.okstate.edu/glhepro/overview>.
- [31] **GLD - The Ground Loop Design™ Premier 2012**: <http://www.groundloopdesign.com/>.
- [32] G.A. Florides, P.D. Pouloupatis, S. Kalogirou, V. Messaritits, I. Panayides, Z. Zomeni, G. Partasides, A. Lizides, E. Sophocleous, K. Koutsoumpas, The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus, *Energy* 36 (8) (2011) 5027–5036.
- [33] **Interface for Simplified Building Energy Model for Cyprus (iSBEM-CY)**: <http://www.infotrendco.com/files/SBEM/>.