Renewable Energy 103 (2017) 721–728

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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

Panayiotis D. Pouloupatis [a], Savvas A. Tassou [b], Paul Christodoulides [c], Georgios A. Florides [a,*]

[a] Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, 31 Arch. Kyprianou, P. O. Box 50329, 3603, Limassol, Cyprus
[b] School of Engineering and Design, Brunel University Uxbridge, Middlesex, UB8 3PH, United Kingdom
[c] Faculty of Engineering and Technology, Cyprus University of Technology, Limassol, Cyprus

ARTICLE INFO

*Article history:*
Received 29 March 2016
Received in revised form
10 June 2016
Accepted 2 November 2016
Available online 4 November 2016

*Keywords:*
Ground heat exchangers
Ground parameters
Borehole
GLD software

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.


## 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

* Corresponding author.
*E-mail address:* georgios.florides@cut.ac.cy (G.A. Florides).

http://dx.doi.org/10.1016/j.renene.2016.11.006
0960-1481/

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 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.

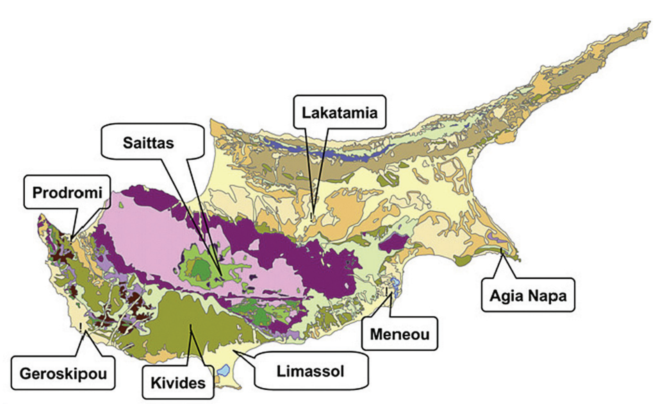

**Fig. 1.** Geological map of Cyprus with borehole locations [26].

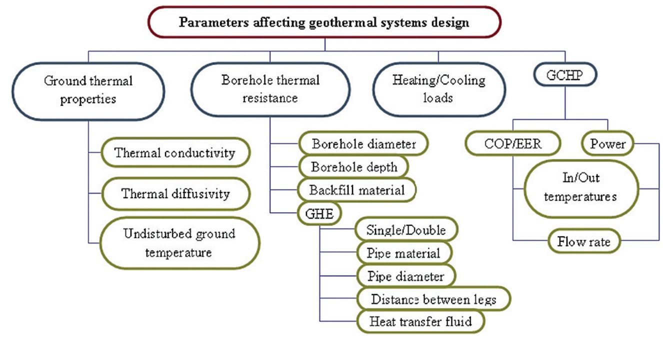

**Fig. 2.** Parameters affecting geothermal systems design.

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 $m^2$. 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<br>3 cm extruded polystyrene<br>10 cm brick | 0.581 | 119 |
| External beams & pillars | 20 cm reinforced concrete<br>3 cm extruded polystyrene | 0.765 | 224 |
| Exposed roof | 15 cm reinforced concrete<br>5 cm concrete<br>5 cm extruded polystyrene<br>5 cm loose lightweight rock | 0.424 | 236 |
| Floor in contact with ground | 15 cm reinforced concrete<br>10 cm lightweight concrete<br>3 cm extruded polystyrene<br>3 cm granite ceramic | 0.421 | 200 |
| Exposed floor | 15 cm reinforced concrete<br>10 cm lightweight concrete<br>3 cm extruded polystyrene<br>3 cm granite ceramic | 0.546 | 132 |
| External door | 5 cm Massif wood | 2.29 | 14 |
| Openings: frame ≤ 25% opening area | Aluminium frame | 2.6 | N/A |
| Openings: frame > 25% opening area | 4 mm glass<br>12 mm air gap<br>4 mm glass | 3.2 | |

**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 $Wm^{-1}K^{-1}$. 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 $Wm^{-1}K^{-1}$ 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 |

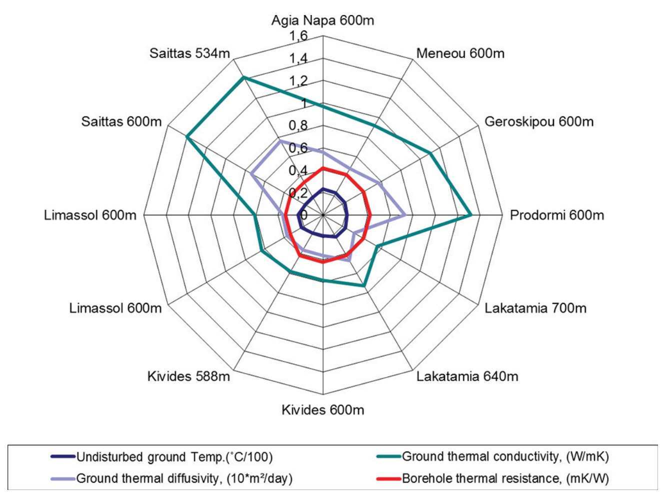


**Fig. 3.** Graphical representation of the ground thermal properties and borehole thermal resistance against the total length required in each location for the heating and cooling load of the typical house.

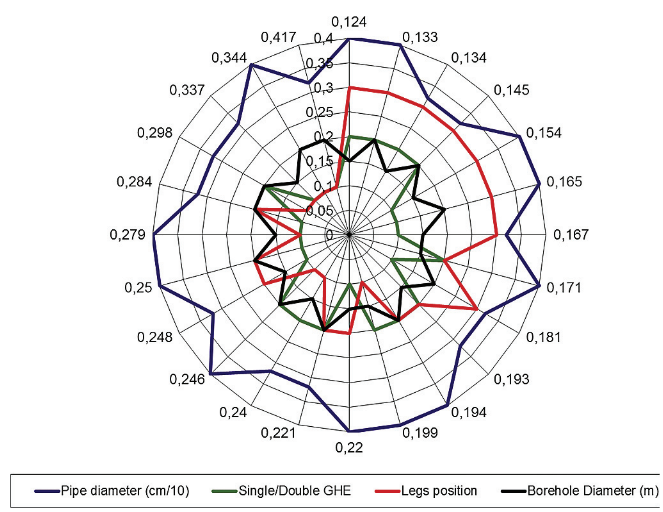


**Fig. 4.** Parameters affecting the borehole resistance.

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.

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

*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.

## Acknowledgements

This work was carried out as part of a research project cofunded by the Research Promotion Foundation (RPF) of Cyprus under contract ΤΕΧΝΟΛΟΓΙΑ/ΕΝΕΡΓ/0311(ΒΙΕ)/01 and the European Regional Development Fund (ERDF) of the EU.

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