Ground heat exchangers in geothermal anomaly zones: a case study

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ABSTRACT

In this paper vertical ground heat exchangers in geothermal anomaly zone are investigated. Ground Coupled Heat Pumps (GCHP) have been increasingly used in the last years around Europe; therefore companies producing heat pumps, drilling wells and boreholes are paying more and more attention in this field.

Temperatures into the ground usually vary from 7°C to 20°C, depending on outdoor mean annual air temperature. An interesting and promising field of application is represented by geothermal areas, where the temperatures in the shallow underground can reach 30°C to 85°C, since the borehole ground heat exchangers can be reduced in terms of depth or number due to the favourable high temperatures. In these contexts the ground can be used only as a source for heating and not for injecting heating during summer due to the high temperatures which might be reached.

The aim of this paper is the evaluation of the possibility to use the direct coupling between the building heating system and the borehole heat exchangers. In North of Italy there are some places where thermal anomaly condition of the ground is present; the ground temperature is about 70-85°C, therefore the mean temperature over a depth of 100 m below the ground can be around 30-35°C instead of usual values which are about 13-15°C.

In the present study an energy analysis of a case study of a residential building has been carried out by means of the simulation tool TRNSYS, coupled with the CaRM model (acronym of “Capacity Resistance Model”), developed by authors, which is able to consider in detail the thermal behaviour of the ground heat exchangers. Several thermal plant solutions have been compared to evaluate the best solution in terms of energy consumption.

1. INTRODUCTION

GCHPs have been increasingly used in the last decade around Europe and companies producing heat pumps, drilling wells and boreholes are paying more and more attention in this field. A very interesting and promising field of application is represented by geothermal areas since the borehole ground heat exchangers can be reduced due to the favourable high temperatures.

Several regions in Europe are well known as low-temperature (i.e. liquid-dominated) geothermal sites. Many of these places are famous tourist locations. In many cases both the direct use of water for heating houses and the indirect use through water to water heat pumps with open circuit might be difficult, since local regulations and restrictions can be met. Nevertheless, even if temperatures of about 25°C to 30°C occur into the ground, the energy of this source can be exploited through the use of vertical closed loop heat exchangers in GCHP, which, if properly designed and installed, should not affect the environment nor damage the groundwater assessment.

For this reason a research activity has just started in the Euganean area, which extends over a plain covering about 23 km^2 immediately at East of the Euganean Hills (Figure 1). Such area comprises four towns (Abano Terme, Montegrotto Terme, Battaglia Terme and Galzignano Terme) close to Padua in Veneto region, North-East of Italy (Figure 1). The word “Terme” means “Spa”. More details on Euganean Basin can be found in (Antonelli et al. 1995) and (Fabbri and Trevisani 2005).

In areas where temperatures are higher than usual into the ground, some critical aspects have to be taken into account, like materials and drilling methods. Furthermore sealing by using properly grouting materials have to be chosen to obtain good thermal contact between the pipe and ground as well as good hydraulic isolation between different groundwater levels crossed by drilling. Last but not least attention has to be paid to the material of the pipes used in the BHE; due to high temperatures into the ground, the use of high strength PE-Xa (Peroxide Crosslinked Polyethylene) material is recommended and necessary: this material can resist at usual pressures inside the circuit and also at high temperatures. See Table 1, where a comparison between PE-Xa and PE-100 is shown. As it can be seen the life of the PE-Xa is longer of about 25 times then the PE-100 for the maximum temperature which normally find in places like the one in the study proposed.

Table 1: Properties of BHE pipes

	PE-Xa	PE-100
Temperature	Life/Pressure	
30 °C	100 Years/13.3 bar	50 Years/13.5 bar
40 °C	100 Years/11.8 bar	50 Years/11.6 bar
50 °C	100 Years/10.5 bar	15 Years/10.4 bar
60 °C	50 Years/9.5 bar	5 Years/7.7 bar
70 °C	50 Years/8.5 bar	2 Years/6.2 bar
80 °C	25 Years/7.6 bar	-
90 °C	15 Years/6.9 bar	-

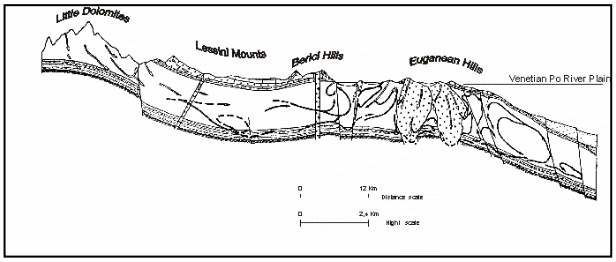


Figure 1: Euganean geothermal circuit sketch (from Piccoli et al.(1973) modified)

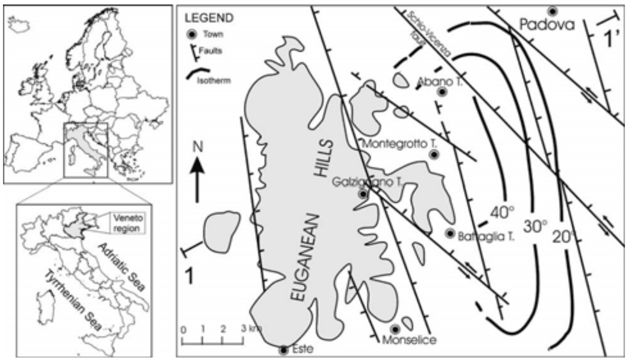


Figure 2: Faults and isotherms at 150m depth in the Euganean geothermal area (from Antonelli et al., 1995).“T.” stands for “Terme” (i.e. “Abano Terme”).

2. CASE STUDY

In this paper energy evaluation of different heating systems coupled with Borehole Heat Exchangers (BHE) into ground with anomalous gradient of temperature has been carried out.

The work has been divided in two steps. The first part regards the definition of a building model and the subsequent calculation of heating loads during the year. Afterword ground and BHE properties have been investigated to evaluate the thermal exchange capacity. For the ground properties evaluation, a Thermal Response Test (TRT) (Austin WA. 1998) (Gehlin S. 1998) (Kavanaugh S.P. 2000) (Gehlin S. 2002) has been performed in the study area through one BHE with a depth of 125 m long.

2.1 Building properties and climatic data

The simulated building is a two storeys residential home: the first one adjacent to the ground and the second one adjacent to an unheated attic.

Each level has a useful area of 60 m^2 with height of 2.7 m and the insulation level of the external walls respects the minimum requirements in force in Italy according to the EPBD (Energy Performance Building Directive). The emission system used for heating is a radiant floor with a supply water temperature of about 29°C. The internal loads have been deduced from the UNI EN ISO 13790 (2008) both for the living (ground floor) and sleeping zone (first floor). The set point temperature for the radiant floor control system has been kept equal to 20°C with a dead band of ±0.5°C.

In order to evaluate the heating loads a typical Test Reference Year (TRY) of Venice has been used (http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm), which is the official reference weather for places close to the study area. A graphical trend of the external temperature together with the resulting operative temperature of the simulated building and heating loads are reported in Figure 3.

In Table 2 the mean thermal properties of the building envelope and the boundary conditions used for the computer simulations are reported. Energy simulation of the building provides an overall heating power of 7 kW (58 W/m^2) and an overall energy need of 10 MWh (83 $kWh/(m^2y)$).

The calculated heating loads of the building have been used for each type of possible heating system as described hereafter.

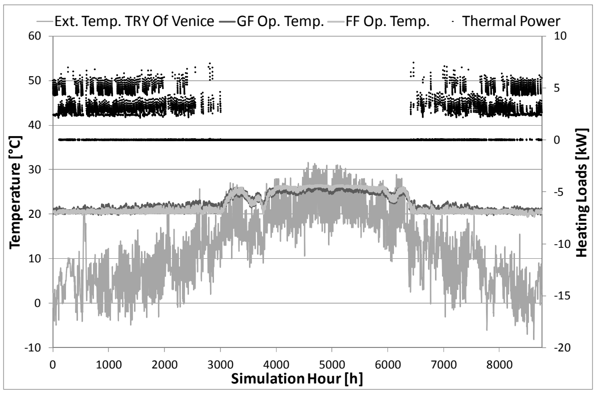


Figure 3: Zones Operative Temperature vs External Temperature (GF: Ground Floor, FF: First Floor) and Heating Loads

Table 2: Building properties

Element	Property	Value	Unit
External Walls	U-value	0.288	W/(m^{2}K)
Internal Floor	U-value	1.793	W/(m^{2}K)
No-Heating Floor	U-value	0.225	W/(m^{2}K)
Ground Floor	U-value	0.330	W/(m^{2}K)
Roofs	U-value	0.236	W/(m^{2}K)
Windows	U-value	1.24	W/(m^{2}K)
	Area	1.4	m^2
Air Change ratio	n	0.5	h^{-1}
Mean Internal Loads	-	5.83	W/m^2

2.2 Ground properties and CaRM model

The simulation tool used to simulate the behaviour of the ground and the BHEs is called CaRM (CApacity Resistance Model) (De Carli et al. 2010). This model considers the heat transfer within the ground by heat conduction. The BHE is described with a thermal resistance system and the ground around the BHE is modelled with thermal resistances and capacitances making use of the electrical analogy. The ground can be modelled into several regions (axial and radial), each of them characterized by different thermophysical properties (thermal conductivity, specific heat capacity, density), assumed independent of time, mainly determined by mineral composition, porosity content and degree of water saturation. Usually, the different thermal conductivity of vertical regions are considered together in the so-called equivalent thermal conductivity of the ground system, and which can be determined by a “Thermal Response Test” (TRT). The model allows to consider different compositions of the soil (defined sub-regions), each of them with a given undisturbed ground temperature; in this way it is possible to consider a vertical profile of temperature, which can be relevant for geothermal sites with anomalous gradient of temperature. These values of undisturbed ground temperatures are assumed independent of time. A graphical scheme of the model is represented in the Figure 4. The ground properties used as input of CaRM to simulate the thermal behaviour of BHE are reported in the Table 3. The thermal conductivity and the mean gradient of temperature are the results of a TRT which has been done in the place of the study. In Table 4 the BHE characteristics are reported. For the water a mean value of specific heat equal to 4366 J/(kg K) and density equal to 996 kg/m3 have been used in the simulations.

2.3 The heating systems

One of the aim of this study is the evaluation of energy efficiency of low temperature heating systems coupled with BHE installed in zones marked out by anomalous geothermal gradient of temperature. At the same time a comparison of four different heating generation systems have been investigated.

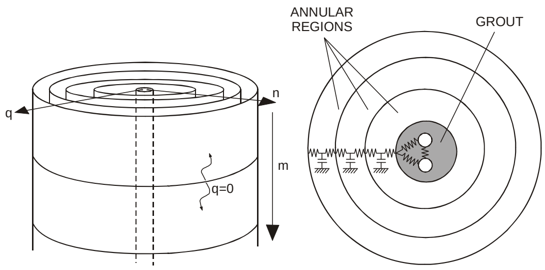


Figure 4: Scheme of CaRM model

Table 3: Ground properties used in the simulation tool CaRM

Thermal Conductivity	1.7	W/(m*K)
Density	1285	kg/m^3
Specific Heat	2614	J/(kg*K)
Mean Gradient of Temperature in Depth	0.5	°C/m
Mean Annual Surface Temperature	12	°C

Table 4: Ground properties used in the simulation tool CaRM

Type	2U	-
BHE Connection	Parallel	-
Borehole Length	120	m
Borehole diameter	0.14	m
Wheelbase Distance	0.07	m
Inside diameter of pipe	0.026	m
Outside diameter of pipe	0.032	m
Pipe Connection	Parallel	-
Th. conductivity of the pipe	0.35	W/(m*K)
Th. conductivity of the filling material	2	W/(m*K)
Total water flow rate	0.18	kg/s
Spacing between BHEs	10	m
RppA (reference to the model CaRM)	0.437	m*K/W
RppB (reference to the model CaRM)	0.589	m*K/W
Rp0 (reference to the model CaRM)	0.267	m*K/W

The first one is a field of ground heat exchangers directly coupled with the distribution heating plant of the building through a water-water heat exchanger (case 1), the latter with an efficiency of 95%. The second one has a reduced BHE field, with respect to the first one, connected in series with an air-water heat pump as back up device for heating load of the building (case 2); the third one has the smaller BHE field coupled with a water-water heat pump (WWHP) (case 3) and the last one has an air-water heat pump (AWHP) (case 4).

In Figure 5, a schematic diagrams of the different investigated systems are proposed.

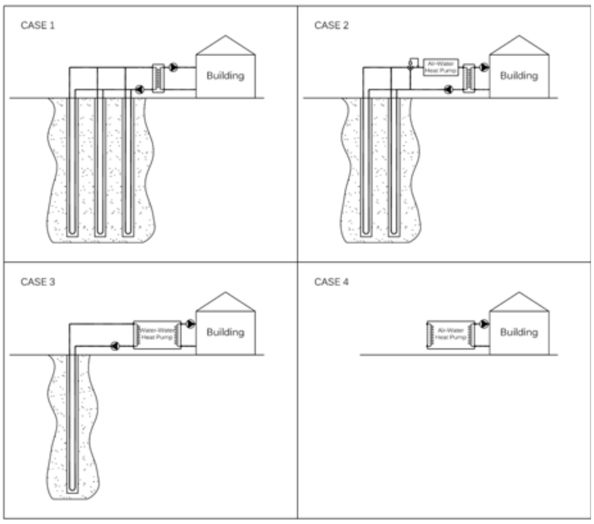


Figure 5: Schematic diagrams of different heating systems

Each simulation is based on the same internal building conditions calculated as first step of the work. The behavior of the building have been simulated with the dynamic code called TRNSYS. Using the energy required by the distribution system of the building, the different plant systems have been analyzed.

In all cases the radiant floor system is supplied with the same configuration composed by two circulators, each of them with a nominal power of 50 W and water supplied with a temperature of 29.5°C.

The first image in Figure 9 is the case of “free heating” with a direct connection between the hot carrier fluid inside the BHE and low temperature heating system. The BHE field has a bigger extension if compared with usual field. In GSHP (as in the case 3). In the first approach the minimum number of BHE has been investigated. To evaluate this choice, the maximum depth permitted by pipe materials has been considered with a distance of 10 m between the boreholes. Then, the number of BHE has been chosen in order to raise the minimum inlet radiant system water temperature used in the simulation of the behavior building and equal to 29,5°C. This analysis has been carried out with the simulation code CaRM, and 3 BHEs with 120 m of depth has been chosen. Through the simulations, electric energy use for the three circulation pumps of the system has been considered. The two circulators for the ground and first floor have a power of 50 W.

In the second case the BHE field has been reduced to two boreholes and an AWHP has been used to integrate the heating demand by the distribution pipes of the building heating plant. As for case 1 each BHE has the same depth of 120 m and spacing equal to 10 m. The performance of the machine has been calculated with a code developed in the Department of Applied Physics (Scarpa M. et al. 2012).

The third is the case with only one BHE coupled with a WWHP. The properties of the BHE are the same but in this case a borehole in free field has been considered.

In the last case an AWHP supplies the required heating loads.

The most relevant properties for the several analyzed cases are summarized in Table 5.

Table 5: System properties

Case number		1	2	3	4
Number of BHE	-	3	2	1	0
Total BHE fluid flow	kg/s	0.54	0.36	0.18	-
BHE pump power	W	170	160	150	-
Mean COP of AWHP/GCHP	-	-	2.8	4.1	3.3
Nominal Power of AWHP/GCHP	kW	-	8.5	10.9	8.5
Nominal COP of AWHP/GCHP	-	-	3.54	3.54	3.54

3. RESULTS AND DISCUSSION

3.1 Energy Evaluation

By means of the simulations the energy consumptions of the analyzed systems have been evaluated. In Table 6, the results are summarized as electrical and primary energy consumptions.. The primary energy has been evaluated considering an electric efficiency factor of 0.46, as suggested by the deliberation of the Italian Electrical Energy and Gas Authority.

Table 6: Electrical and Primary Energy Consumptions after 20 years working (e: electrical, p: primary)

Case Study	[kWh_e/y] *([$kWh_e/(m^2y)$])*					kWh_p/y *$kWh_p/(m^2y)$*
	BHE Pump	Radiant System Pumps	Air-Water HP	Water-Water HP	Total	
1	*461 (3.8)*	181 (1.5)	- *(-)*	- *(-)*	643 (5.4)	*1397 (11.6)*
2	*434 (3.6)*	181 (1.5)	459 (3.8)	- *(-)*	1075 (9.0)	*2337 (19.5)*
3	*407 (3.5)*	181 (1.5)	- *(-)*	2061 (17.2)	2664 (22.2)	*5790 (48.3)*
4	- *(-)*	181 (1.5)	3201 (26.7)	- *(-)*	3382 (28.2)	*7353 (61.3)*

From a purely energy point of view the best solution among whose examined is the first one. In all other cases the energy consumption to ensure the temperature control inside the building more than the double compared to the case with the direct connection between the building plant system and the BHE field.

In terms of primary energy the results is the same because in these analysis the energy vector is always electrical energy.

3.2 Temperature of the ground after long time working

Through the code CaRM, the behavior of the ground near and far the BHE has been investigated. The ground around the boreholes has been divided into 20 annular regions (as shown schematically in Figure 5) till a maximum diameter of 10 m. For all the cases the profile temperature of the ground have been plotted for the end of the 1st, the 6th and the 10th year of operation of the plant. In the case 1 the field distribution of the BHEs is linear and the diagrams are related to the most disadvantaged BHE, the one in the center. On the other hand for the case 2 the temperature profile is the same for the two BHEs.

In the Figures 6 and 7 the temperature profile of the annular regions n.1, 5 and 10 compared to the depth of the ground are shown. Since the diagrams for the cases 1 and 2 are similar, only the case 1 has been plotted. In these diagrams the plotted values are for the 12.00 p.m. on 31th December of each year.

The previous diagrams prove how the temperature profile of the ground as function of the ground depth undergo changes from the 1st to the 6th year of operation while as for the subsequent years the behavior of the soil can be considered constant. The latter consideration is confirmed by the fact that temperatures of ground and water are not subject to significant changes going from sixth to twentieth year. In the case 3, the BHE subjecting the ground to a thermal stress greater than the other cases, since the inlet temperatures at the BHE are lower than the other cases, the outlet temperatures appear to be similar to case 1 (and 2). In the images, the temperature increase of the fluid through the passage inside the BHE is about 1.5-2.0 °C for the case 1 (and 2) and 5.5-6.0 °C for the case 3.

Analyzing the diagrams it appears that the ground in cases 1 (and 2) is more thermally stressed. In fact, looking for example the temperature profile corresponding to the radius R equal to 3,576 m, this turns out to have a slope greater for Case 1 and 2 which would result from a practical point of view an average temperature less than in the case 3. To justify

Figure 6: Temperature profiles of the ground and water for the Case 1

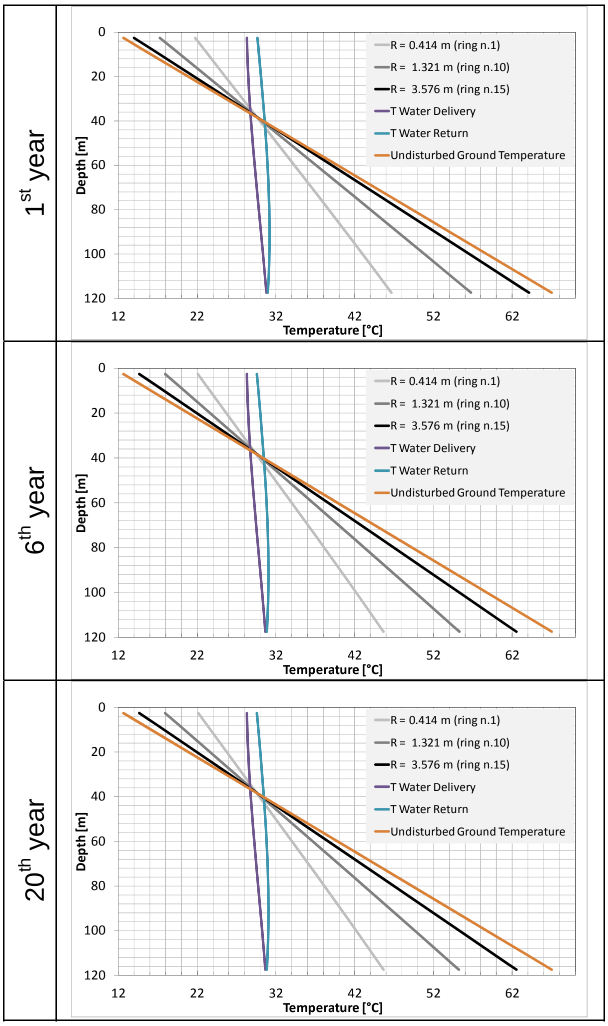
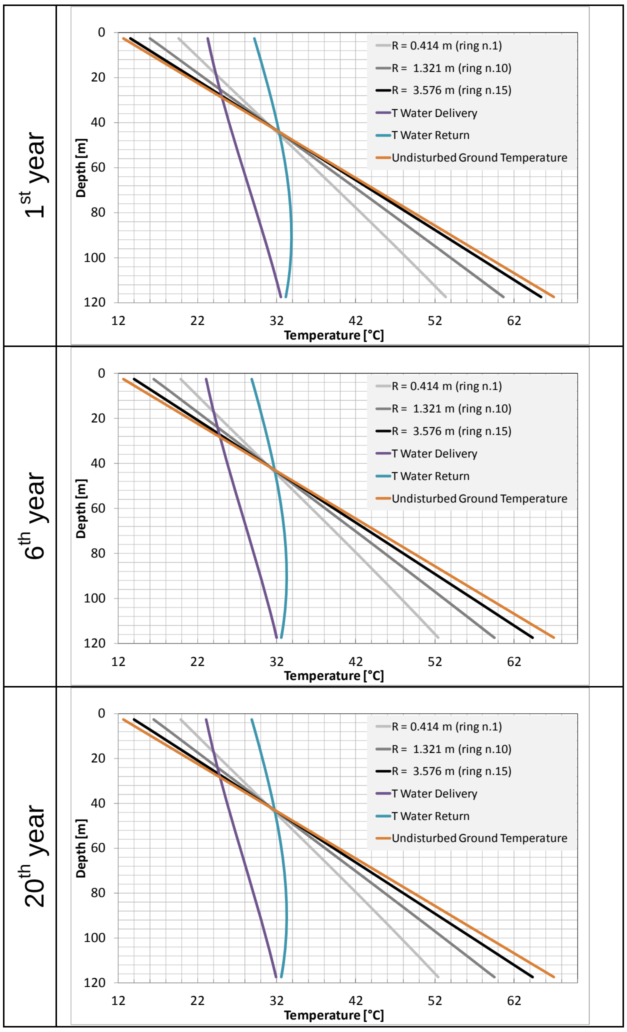


Figure 7: Temperature profiles of the ground and water for the Case 3



the reported should remember that the BHE case 3 is in open field while in the other two cases, the BHE is not free field but is positioned between or next to other BHEs that consequently make the exchange with the ground more penalized.

4. CONCLUSIONS

As shown in Tables 6 there are relevant differences in terms of energy requirements for the various systems under investigation, therefore consequent costs will change proportionally in the same way. From energy point of view from the case 4 to case 1 the energy requirements is reduced by a factor of six. In this context, a cost analysis has not been carried out, but it will be subject of future studies. In a qualitative way, it might be said that investment costs increase significantly from case 4 to case 1. In particular, results of case 1 show a very limit amount of primary energy which is usually below any type of heating system.

Form results of case 2, it might be assessed that this solution seems particularly interesting, when looking at a compromise between the energy point of view and practical aspects. This system is the only one that allows to heat the building with relatively reduced consumptions and, at the same time, it allows the cooling during summer bypassing the BHE field, without adding further equipment. To give an idea, the energy need for cooling in the case study is 0.9 MWh, i.e. 8 kWh/(m^{2}year), while the peak power is 2.4 kW (20 W/m^2).

From the ground analysis can be said that the investigated systems can guarantee a constant efficiency for a long time working. In the case with one BHE and a coupled heat pumps (case 3), the variation of the fluid temperature circulating inside the BHE is negligible for the global performance of the heat pump, because the difference, after 20 years, is about 1°C like the deviation of the ground temperature.

From the above it can be concluded that areas such as the one analyzed in this study can be well suitable for installation of systems for the direct exchange or GCHP for heating of buildings.

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