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ORIGINAL ARTICLE

Energy performance of Ground Source Heat Pump systems with flat-panel ground heat exchangers

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Abstract The important role of heat pump technology in the decarbonization challenge of Heating Ventilation and Air Conditioning systems is nowadays widely recognized by the scientific community and stakeholders. In this field, Ground Source Heat Pump systems represent one of the most promising solutions because of the much more favourable temperature of the ground if compared to ambient air, which is affected by weather conditions. Furthermore, air source heat pumps are further penalized by the defrosting cycles of the finned coil heat exchanger during the heating period. The continuous reduction of the building peak thermal loads and energy needs, thanks to the improvement of standards and European targets in the building sector, has revived the interest of operators in horizontal geothermal systems. In the past, this type of ground heat exchangers was normally not considered due to the large space needed for their installation. In the literature there is a lack of works and research of ground source heat pump systems coupled with shallow flat-panel ground heat exchangers. The present work improves the knowledge of this latter technology. The study analyses and compares the thermal behaviour of flat-panel and vertical 2U ground heat exchangers loops by means of using TRNSYS simulation tool. The simulations have been used to obtain the energy performance of the ground loops coupled with the heat pump. The comparison highlights the differences between different case studies and how the flat-panel ground heat exchangers field is a possible alternative to the current systems.

Keywords Ground Source Heat Pump · Flat-Panel · Borehole Heat Exchanger · COP · SCOP · Dynamic simulations

Abbreviations

Nomenclature

BHE	Borehole Heat Exchanger
C	Cooling
c	Specific heat, kJ kg^{-1} K^{-1}
COP	Coefficient Of Performance
D	Diameter, m
EE	Electric Energy, kWh
FP	Flat Panel
GHE	Ground Heat Exchanger
GHG	GreenHouse Gas
GSHP	Ground Source Heat Pump
H	Heating
HE	Heat Exchange
HGHE	Horizontal Ground Heat Exchanger
HP	Heat Pump

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HVAC	Heating Ventilation Air Conditioning
L	Length, m
R	Thermal resistance, $m^2\ K^1\ W^{-1}$
s	Thickness, cm
SCOP	Seasonal Coefficient of Performance
T	Temperature, K
t	Time, s
TRT	Thermal Response Test
U-value	Thermal trasmittance, $W\ m^{-2}\ K^{-1}$
x	Coordinate of the model
Greek symbols	
λ	Thermal conductivity, $W\ m^{-1}\ K^{-1}$
ρ	Density, $kg\ m^{-3}$
Subscripts	
c	Cooling
ext	External
h	Heating
int	Internal
tot	Total
wv	Water vapor

Introduction

The growing economic and social development, as well as the improvement of people quality of life have led to a constant evolution and increase in energy consumption to meet the growing needs. In recent years, the energy demand of buildings for Heating Ventilation and Air Conditioning (HVAC) has increased sharply. The European building sector is responsible for about 42% of the total energy consumption and the heating, cooling and domestic hot water production represent the 80% of this amount (European Commission, 2023a; Eurostat, 2023a). Similarly, about the 33% the European Union's energy related greenhouse gas (GHG) emissions come from buildings (European Commission, 2023a; Eurostat, 2023b). The improvement of the energy efficiency in the building sector is the key objective at worldwide level to lower energy needs, but also contributes to obtain better thermal comfort and quality of life (Santamouris & Vasilakopoulou, 2021). Many activities have been promoted at European and national level aimed at lowering the energy needs to reach the 20% of energy-saving, the 20% of renewable energy increase and the 20% of emission reduction by 2020. Recently, new environmental targes have been set to 55% and 100% GHG emissions reduction by 2030 and 2050 respectively (European Commission, 2023b).

About 160 million buildings there were in Europe in 2010, covering an overall floor space of about 24 billion m^2. More than 70% of the overall floor area is occupied by residential buildings and their energy consumption is much lower compared to non-residential buildings. Furthermore, a large amount of the building stock dates from before 1990 and about half of it predates the period of the energy crisis of the 1970s. The renovation of buildings could reduce the energy consumption up to 36% by 2030 and at the same time a reduction of the EU energy import dependency could be reached (Pavel & Blagoeva, 2018).

Ground Source Heat Pump (GSHP) systems are widely used in the last decade as sustainable solution to provide HVAC in residential and commercial building thanks to their well-known advantages, environmental friendliness, low energy consumption, high energy performance (high values of COP), flexible operation mode, and no pollution. A GSHP system operates by extracting and injecting heat from and to the ground through the use of a working fluid and ground heat exchangers (GHEs) (Lund & Boyd, 2016). In the past decades, the GSHP technology has increased with a growth rate of about 7% per year, despite some issues concerning the initial investment costs and the need of space in courtyard or near the building for the installation of the GHEs field (Yoon et al., 2015). Recently the heat pump market has seen a meaningful increase of about 35% and 39% in 2021 and 2022 respectively. Most of the plants installed are air to water heat pump (HP) systems (EHPA, 2023) and the GSHP applications represent a small part of the total installation. For this reason, GSHP applications still require further push and development to make them competitive in the market and attractive to the end user and stakeholders.

The energy performance of the GSHP system is significantly affected by the heat transfer of the GHEs field, which is influenced in turn by the thermal properties of the soil (Wang et al., 2023). Often the estimation of soil thermal properties has been obtained through the in situ so-called Thermal Response Test (TRT) (Eskilson, 1987; Spitler & Gehlin, 2015). In this test a constant heating/cooling load is exchanged by a borehole heat exchanger (BHE), and temperature trends of the supply and return working fluid are recorded and used in an inverse problem to calculate the equivalent thermal properties of the soil. The simplest algorithm is to only estimate the effective soil thermal conductivity using TRT data, in this case few parameters are assumed and used as known inputs (Li et al., 2019).

The vertical depth of the BHE installation usually involves different layers of the subsoil with different thermo-physical properties. These properties have a meaningful impact on the heat exchange performance of the GHEs field (Wang et al., 2023). However, in order to overcome the difficulty in analyzing in detail the heat exchange, many studies have been conducted using heat transfer models for the GHEs, which primarily rely on the assumption that soil is homogeneous and isotropic. In horizontal (linear pipes, slinky pipes, spiral coil) and flat-panel GHEs the depth of installation is limited to few meters, thus allowing a deep and precise knowledge of the thermal properties of the ground, also through direct measurements or visual investigations without the need to perform the TRT.

Vertical GHEs can be installed in drilling holes created by means of a drilling machine. In vertical GHEs, the pipes are installed vertically in the boreholes. They are inserted in helical shape, U or 2U layout, or in the coaxial configuration. After the installation of the pipes the borehole is filled with grout. In general, vertical GHEs need less installation courtyard space than horizontal GHEs. Furthermore, the heat exchange performance of vertical GHEs is better than that of common horizontal GHEs (Florides et al., 2013). Usually, vertical GHEs are characterized by a high ratio between their length and the diameter of the geothermal probe. This characteristic has allowed the development of simulation models based on the use of analytical solutions of systems to which vertical GHEs have been assimilated. In literature, many analytical models analyze the energy performance of these GHEs. Two of them are the finite- and infinite-line source model, which consider the vertical BHE as a line with uniform heat-flux. A similar approach is the cylindrical heat source, but in this case the model is more suitable for the energy piles. Other simulation models can be found in literature and in commercial software. All these models were created with the aim of having calculation tools capable of simulating in detail the behavior of geothermal systems (Carslaw & Jaeger, 1959; Ingersoll et al., 1954; Lamarche & Beauchamp, 2007).

In horizontal GHEs the pipes are installed in trenches of about 2-3m depth. The best-performing installations are those with higher pipe length and therefore more heat exchange surface. Obviously, in this context the space required for the installation becomes very significant. It is for this reason that with the same length of the trench, a slinky pipe is more performing than a linear pipe (Zhou et al., 2022). In this context, the flat-panel GHE has a considerable advantage because its heat exchange surface is significantly higher than that of the pipes and its installation is easier.

The present study has been carried out using a comprehensive simulation model specially developed to analyse the thermal behaviour of flat-panel GHEs. Afterwards, the model has been modified to investigate the energy performance of the same system by replacing the flat-panels with the 2U BHEs. The model evaluates the thermal behaviour of the building and GHEs field affected by the climate and thermal load profile and the energy performances of the water-to-water HP. In this context, many studies have been published on the use of horizontal GHEs (HGHEs) in GSHP applications but there is a lack of works in the literature which involve the use of flat-panel HGHEs. The shallow flat-panel HGHE is normally installed vertically inside trenches and looks like a simple flat plate in which a sheet of working fluid flows inside. The top and bottom of the GHE are approximately 1.5 m and 2.5 m deep in the ground respectively as it will show in the following section in the text. More details about flat-panel HGHEs used as reference in the simulations can be found in Ciriello et al., (2015a, 2015b), Bottarelli et al. (2019), Emmi and Bottarelli (2023) and n. The present work aims at improving the knowledge of this type of HGHEs adding to the more common spiral-type, slinky-type and linear-type HGHEs. The study's main objective is to compare the flat-panel GHE with the more common 2U BHEs used in a GSHP system, highlighting how the proposed system could be a valid alternative in contexts where drilling is difficult or not allowed by local legislation. The energy analysis has been carried out considering a building as a case study in three different climates.

Method

The energy analysis presented in this paper has been carried out by using TRNSYS simulation tool (Klein et al., 2017). This software is commonly used in research and design fields for the study and optimization of energy systems to investigate their transient operation. The software is divided into two main programs, one of them dedicated to the definition of the buildings and their properties (named TRNBuild). If the energy system does not include the building and its behaviour, only the second main program of the package tools can be used. The latter, named Simulation Studio, is used to describe in detail the energy systems and the connections between the devices which are part of the plant using an extensive program library available to the users. The program and the models are based on the "Black Box" approach for the construction and definition of the dynamic energy models of the systems. Each device (i.e. each black box of the model) is called "Type". Furthermore, the users have the possibility to add personal devices to use in the simulation models by developing new Types, through the writing of new simulation codes. In the present work a new Type has been developed for the simulation of the flat-plate GHEs.

Flat-panel GHE model

The first part of the present work concerns the implementation of a novel TRNSYS Type by writing an improved model based on the code described in (Ciriello et al., 2015a, 2015b). The model has been written in the programming language used in the TRNSYS environment. The simulation model implemented in the TRNSYS type was already tested and calibrated with regard of real installation data as it can been seen in Ciriello et al., 2015a, 2015b. One of the main novelties of this TRNSYS type was the possibility of coupling Phase Change Materials with the flat-panels as mixed into backfilling materials of trenches. Even if this last feature is present, it has not been used for the purposes of this work, the latter being aimed at demonstrating the validity of flat-plate GHEs compared widely used 2U BHEs. Furthermore, other data about the flat-panels GHEs was collected from recent installations carried out in the last years in some experimental plants devoted to different objectives beyond the technology of these swallow GHE solution. In fact, they have been used to investigate the behaviour of multi-source heat pump system (Emmi et al., 2022) and of the coupling with phase change materials (Bottarelli et al., 2022), as referable to so-called the H2020 project IDEAS and ERDF (European Regional Development Fund) project CLIWAX.

In order to clearly understand the discussed technology, an example of a real flat-panel GHEs line before the installation in the trench is represented in Fig. 1. The flat-panel GHEs are usually connected in series in each line of the ground loop as it can be seen on the left side of the picture. Then, they are vertically installed in the trench, as it can be seen on the right side of the picture. Figure 2 shows a scheme of the section with the main dimensions of the system.

Fig. 1 Flat-panel GHE and trench for the installation

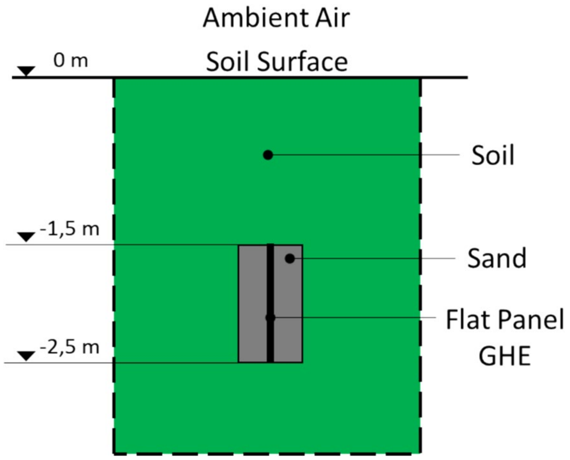


Fig. 2 Scheme of the flat-panel GHE installation

As it can be seen in the figure, the trench in which the flat-panel GHE is buried is filled with sand to allow an easy installation and the rest of the trench is filled with the backfill material from the trench itself.

The subsoil is considered in the development of the model as semi-infinite domain in which the flat-panel GHE is installed and generates a heat flux exchanged with the ground. The heat flux affects the temperature of the domain around GHE. A similar effect is due to the climate, to take into account this boundary condition the model requires as input data the surface soil temperature. The mathematical approach for the definition of the model starts from the well-known heat conduction equation that can be used for the evaluation of the temperature of the semi-infinite volume of the model, at each point and at each time (Ciriello et al., 2015a, 2015b), including the effect due to the heat exchange by the GHE. The general conduction equation for a three-dimensional space is reported in (1), this equation can be used for the study of the temperature T in the ground.

$$\rho c \frac{\partial T}{\partial t} = \nabla \bullet (\lambda \nabla T) + g \tag{1}$$

In the Eq. (1) ρ, c and λ represent density, specific heat capacity and thermal conductivity of the ground material, respectively. The term g in the equation evaluates the heat flux due to the GHE and it is equal to zero in the region of the medium where the GHE is not present. The heat flux due to the GHE affects the results in terms of temperature in the soil. The simulation model has been developed considering some assumptions and simplifications, some of them involve the ground properties considered constant over the time like thermal conductivity and diffusivity. Other properties of the problem like the thermal gradient in the medium are sufficiently smooth in space and time to allow simplifications by the lumped of these values in mean ones for the evaluation of integro-differential quantities.

For the development of the model the Green's functions have been used. These functions evaluate the general three-dimensional solution of the problem in which the arbitrary source (due to the GHEs) has a two-dimensional characteristic.

The Green's function G that analytically solves the problem has the following expression:

$$G\left(x, x', t - t'\right) = \prod_{i=1}^{3} G_{x_i}(x_i, x_i{}', t - t') \tag{2}$$

The function is obtained through the product of the corresponding three one-dimensional Green's function (with i from 1 to 3) as described more in detail in Ciriello et al., (2015a, 2015b).

The case study

The flat-panel GHE has been used to investigate a virtual case study of a GSHP system. The heating and cooling demands of a building are globally supplied by the plant. In particular, the study regards a building whose characteristics comply with the nowadays Italian building stock in case of existing buildings that have undergone deep renovation in the last years.

The building model

A dynamic model of two-storey building, 120 m^2 each floor, has been described in TRNbld. At each floor, a 4-person family was considered to live in. Several assumptions have been done for the definition of input parameters and schedules used in the simulations to evaluate the internal gains (sensible and latent heat). A 3D picture of the building is shown in Fig. 3. The main dimensions are reported in the same picture. The total area of the glazed elements of the building is equal to the 15% of the total floor area of the two dwellings.

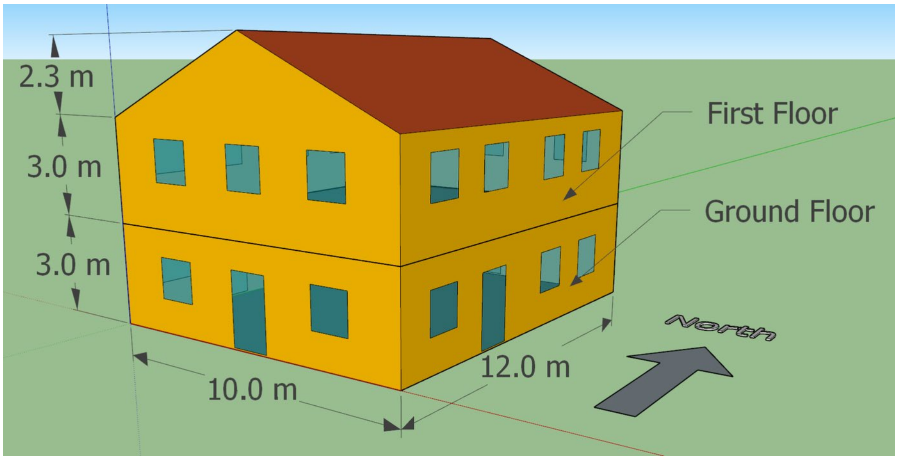


Fig. 3 3D render of the building used in the simulations

The properties of the external building structures are summarized in Table 1. As it can be seen the U-value are lower than 0.3 $Wm^{-2}K^{-1}$, this value should be considered as the reference upper limit of the new and deep renovated buildings in Italy. The U-value of all the glazed elements (glazed panel + frame) is equal to 1.06 $Wm^{-2}K^{-1}$.

Constant air infiltration rate has been considered equal to 0.3 air change per hour (ach), while the internal sensible loads are constant and equal to 120 W due to electric appliances and devices. A maximum of 4 people for each dwelling has been considered. Each person produces and release a water vapor flow rate equal to 66 g_{wv}/h in the indoor environment and exchanges a sensible heat equal to 70 W. The schedules in Fig. 4 have been used in the simulations to evaluate the presence of the people in the dwellings during the days of the week.

Thermal load profile of the building

In GSHP systems the thermal load profile is one of the main input data required for the design of the GHEs field. A single thermal power plant was considered for the whole building and therefore the reference thermal load profile includes the energy demands of the two floors. The energy demand of the domestic hot water was not considered in this analysis.

Different locations have been taken into consideration in the energy analysis of the case study. The climate of Bologna, Roma and Palermo have been considered because they represent three different climates that can be found in Italy. The TRY (Test Reference Year) of each location has been gathered from Energyplus weather database (https://energyplus.net/weather). The TRY data is the reference climate normally used in the simulations and it consists of a set of 8760 hourly values e.g. dry temperature, relative humidity and solar irradiation.

The air conditioning system was considered activated 24h/24h. This assumption is a stretch that deviates from the common real use of residential buildings, but it still leads to a result that overestimates the thermal load profile. As a consequence, the GHEs field will be oversized, keeping at the same time a safety in the results to compensate all the assumptions used in the simulations.

The indoor set point temperature was 20 °C during the heating period and 26 °C for cooling, with a control of the relative humidity set at 55% in the latter case. The results of the simulations on the building side are summarized in Fig. 5, Fig. 6 and Fig. 7 for the climate of Bologna, Roma and Palermo respectively. In Table 2 the annual heating and cooling demands of the building and their ratio are reported. As it can be seen the ratios between heating and cooling demand are quite different for the three case studies. For the climate of Bologna, the thermal load profile is almost balanced while for the other two cities the profiles are cooling-dominated, especially for Palermo in which the heating demand represents the 12% of the cooling demand.

Table 1 Properties of the building structures

Material	s	λ	c	ρ	R
	[cm]	[W/(m K)]	[kJ/(kg K)]	[kg/m^3]	[m^{2}K/W]
EXTERNAL WALL					
R_{int}	-	-	-	-	0.13
Int. Plaster	1.5	1.000	0.84	1800	0.02
Hollow Brick	38	0.200	0.84	750	1.90
Th. Insulation	8	0.035	1.4	45	2.29
Ext. Plaster	1.5	0.900	0.84	2000	0.02
R_{ext}	-	-	-	-	0.04
				R_{tot}	4.39
U-value [W/(m^{2}K)]					0.228
EXTERNAL ROOF					
R_{int}	-	-	-	-	0.13
Wood	3	0.186	2	600	0.16
Th. Insulation	15	0.035	1.4	45	4.29
Air	5	-	-	-	0.18
Roof Tiles	2	0.700	0.84	1700	0.03
R_{ext}	-	-	-	-	0.04
				R_{tot}	4.83
U-value [W/(m^{2}K)]					0.207
GROUND FLOOR					
R_{int}	-	-	-	-	0.13
Floor tiles	1.5	1.000	0.84	2300	0.02
Concrete	8	0.900	0.84	1800	0.09
Th. Insulation	10	0.035	1.4	45	2.86
Concrete	15	2.056	0.84	2400	0.07
Gravel	30	1.200	0.84	1700	0.25
				R_{tot}	3.41
U-value [W/(m^{2}K)]					0.293

The GSHP system

The layout of the flat-panel GHEs installation used in the energy analysis corresponds to the soil cross section reported in the Fig. 2. Once the dimensional characteristics of the GHEs installation are known, the thermal properties of the subsoil remain to be defined since these parameters affect the total heat exchange of the ground loop in the GSHP system. The thermal properties of the soil used in the simulations are summarized in Table 3 (Capozza et al., 2012). These thermophysical properties have been chosen because they represent typical values of different wet soils like mixtures of gravel, clay, silt, and sand; all these materials can be found easily in the shallow layers of the ground. The maintenance of wet conditions in the soil is not a big issue because the trench is wetted by rainwater or it can be filled directly with underground water or tap water, when necessary, by using buried drainage pipes installed close to the flat-panels. On the other hand, the soil is usually not completely dried at shallow depth e therefore this heals the maintenance of the thermophysical properties. Other soil materials could be better in geothermal applications if compared to the ones here discussed. Indeed, rock or rocky material can easily reach 3.0–4.0 W/(m K) of thermal conductivity, but the installation of flat-plate GHEs turns out to be particularly complex and certainly expensive if not even unfeasible.

Having to subsequently carry out a comparison with a GSHP system coupled with 2U BHEs, it was necessary to operate in a similar way for this purpose, avoiding the effects of further variables to the study. Given that the final objective of the work is the operational comparison between the two types of GHEs, the same thermal properties of the soil for both cases were considered. Normally, the subsoil layers could have different thermal properties and the reference values of these properties can be obtained from literature, geological documents of the locations or experimentally by the TRT (Eskilson, 1987). This test methodology provides the average thermal conductivity along the depth of the borehole heat exchanger. As reported before in the text the average thermal conductivity, specific heat capacity and density for the 2U probes installation have been considered equal to the thermal properties used in flat-panel GHEs case. This assumption leads to highlight how much the different technologies of GHEs affects the behavior of the ground loops and the final result in terms of energy performance of the whole GSHP system.

The number and length of the vertical BHEs have been designed by using the approach of the ASHRAE method (Kavanaugh & Rafferty, 1997). The properties of the BHEs field and boundary conditions used for designing the ground loop and the results are summarized in Table 4. This sizing method requires the data about building energy characteristics (monthly heating/cooling needs and peak loads), the thermal properties of the ground and some assumptions regarding the design boundary conditions. More detail about the results of this part of the work are reported in the following sections of the text. The study of the BHEs field and its behavior has been carried with the type 557a available in the library of TRNSYS program.

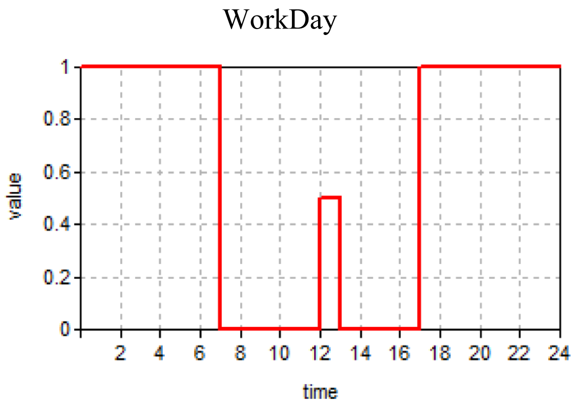
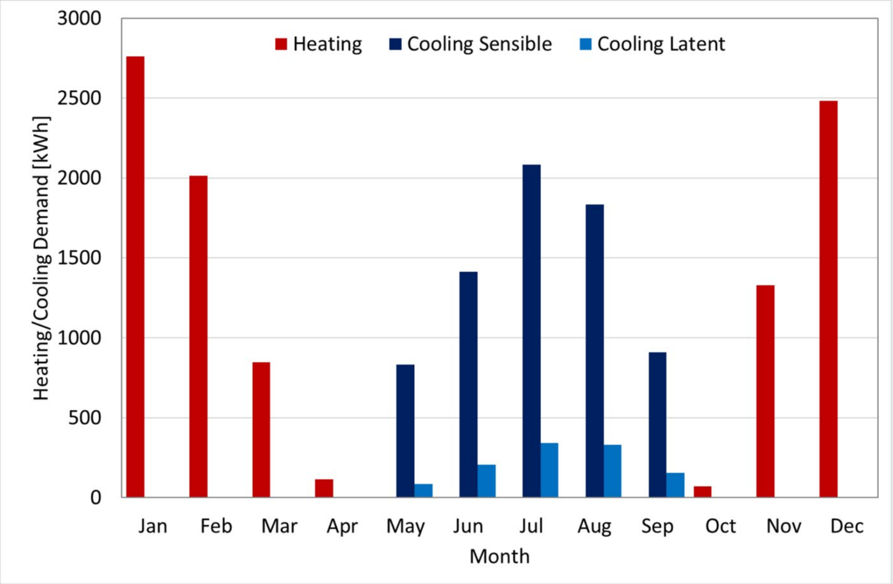


Fig. 4 Scheduling of the occupancy

Fig. 5 Thermal load profile – Bologna



For the case studies of the flat-panel GHEs field two different sizes of the ground loop were simulated: a small size with trenches of total length of 80 m and a larger one with a total length of 200 m, similar to the total length obtained with the ASHRAE method for the case study of Bologna and Roma.

In GSHP systems the core of the thermal power plant is the HP, which operates between the GHEs field and the terminal units of the building. Usually, two heat storage tanks are installed to increase the inertia of the plant and to hydraulically disconnect the primary loops of the HP from the geothermal and air-conditioned secondary loops. This choice allows to avoid any hydraulic balancing issues during the operation of the system. Similarly, the storage tanks must be designed according to the size of the heat pump. A sketch of the system is shown in Fig. 8. As it can be seen from the figure the plant is composed of two primary loops that hydraulically connect the HP with two tanks, 1000 L each, at the source and user side. Each tank operates with the secondary loops, the ground loop, and the terminal unit loop respectively.

The layout of the system and the devices of the thermal power plant are the same in all the

Fig. 6 Thermal load profile – Roma

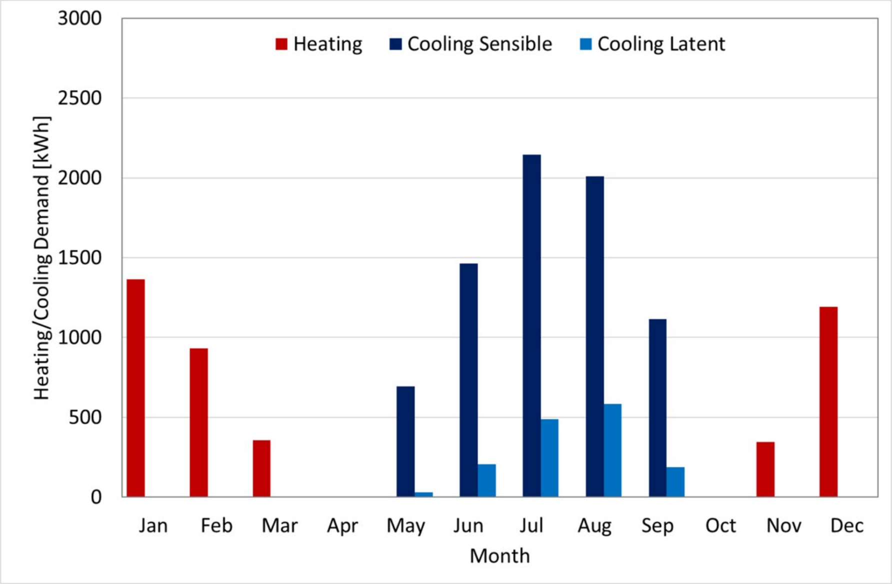


Fig. 7 Thermal load profile – Palermo

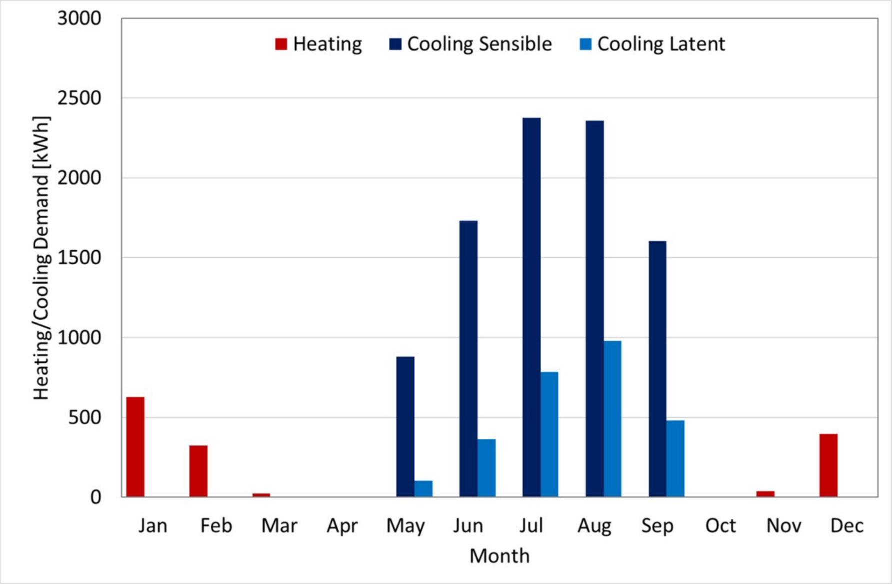


Table 2 Ratio between heating and cooling demand

	Bologna	Roma	Palermo
Annual Heating Demand [kWh]	9613	4188	1401
Annual Cooling Demand [kWh]	8188	8917	11669
Ratio Heating Demand/Cooling Demand [-]	1.17	0.47	0.12

Table 3 Thermal properties of the soil

λ	c	ρ
[W/(m K)]	[kJ/(kg K)]	[kg/m^3]
1.8	1.4	2100

Table 4 Properties of the BHEs field

	Bologna	Roma	Palermo
Undisturbed Tg [°C]	13.98	15.22	18.59
Type of BHE	2U		
D_{int}/D_{est} [mm/mm]	26/32		
λ_{pipe} [W m^{-1} K^{-1}]	0.4		
D_{BHE} [mm]	140		
λ_{grout} [W m^{-1} K^{-1}]	1.83		
Spacing [m]	7		
Total Length [m]	216	236	351
# of BHEs [-]	2	2	3
BHE depth [m]	108	118	117
Total HE Area of the pipes [m^2]	86.8	94.9	141.1
ΔT_g (@10 years) [°C]*	0.08	0.17	0.28

*estimated thermal drift of the ground (Kavanaugh & Rafferty, 1997)

simulations. The main characteristics of the HP and pumps are summarized in Table 5.

Results of the simulations

Thermal behaviour of the systems

The simulations have been conducted with a timestep of 15 min for one year period. Usually, the behaviour of GSHP systems with vertical BHEs is investigated by means of simulations for longer periods of around 10–20 years. The main objective of this extended time is to check and avoid the issue of thermal drift of the soil (Zarrella et al., 2020) that could happen when the thermal load profile on the ground side is extremely unbalanced. In the present case study, the design of the BHEs field has been done by means of the ASHRAE method and therefore this issue should be avoided or at least limited as shown in Table 4 before in the text where the estimate of the ten-year thermal drift of the ground is reported (ΔT_g). In the case of horizontal GHEs field the heat exchange with the external ambient and the weather agents offsets any similar issues (Bortoloni et al., 2017).

The first part of the simulation activities has involved the study of the GSHP systems with the flat-panel GHEs. The trends of inlet temperature at the source and user side and the COP values of the reversible HP in heating and cooling operation mode (distinguished by means of the letter *h* and *c* respectively) are reported in Fig. 9, Fig. 10 and Fig. 11. The source data are the results of the simulations for the different climates. The COP_h is the ratio between the thermal load at the condenser side and the electric energy consumption of the HP, while the COP_c is the ratio of the thermal load at the evaporator side and the electric energy consumption of the HP at each time step. The previous charts show the results for both the case studies with 80 m and 200 m length of flat-panel GHEs fields. The length of the GHEs field corresponds to trench needed for the installation of the flat-panel GHEs. In detail, the fields of the case studies have been divided in 8 and 20 lines 10 m each for the 80 m and 200 m case study respectively.

As it can be seen in all mentioned charts, the working fluid temperature in the geothermal loop has a shape similar to the trend of the soil temperatures

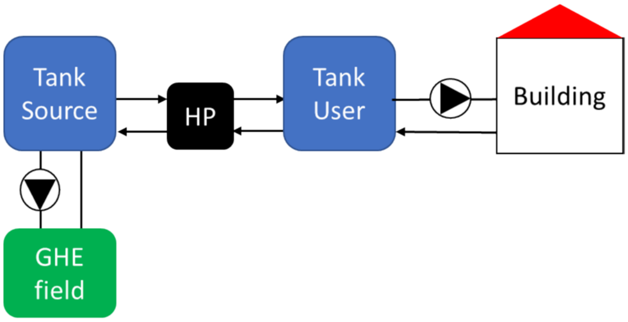


Fig. 8 Layout of the GSHP system

Table 5 Properties of the plant

HP	
Nom. Heating Load [kW] *	8.9
COP_h [-] *	3.4
Nom. Cooling Load [kW] **	9.9
COP_c [-] **	4.9
Source Side Mass Flow Rate [l/h]	2000
User Side Mass Flow Rate [l/h]	2000
GHEs field	
Total Mass Flow Rate [l/h]	2000
Building	
User Tank Setpoint Temperature H/C [°C]	35/10
Terminal Unit Mass Flow Rate [kg/h]	1150

*: $T_{insource} = 3$ °C, $T_{inuser} = 35$°C

**: $T_{insource} = 23$ °C, $T_{inuser} = 12$°C

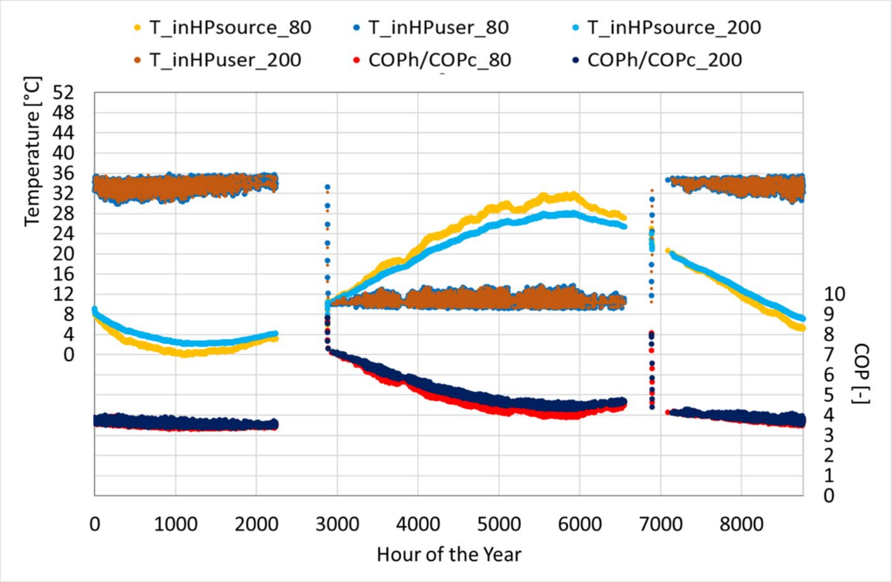
during the year at shallow depth. By way of example the undisturbed ground temperature at 2 m deep in the soil is shown in Fig. 12 for the all the locations. The reference point of the temperature represents the position of the flat-panel's midpoint along the vertical extension. As widely known the ground temperature in the first meters from the surface is affected by the environmental conditions. As expected, the charts depict favourable temperatures at the source side for the case study with the longer trench, while still maintaining a similar trend.

Considering the trench's length of 80 m in the case of Bologna the results are reported in Fig. 10. The COP_h is close 3.5 at the end of the heating period, i.e. from January to April while it is greater than 4 at the beginning of the heating period, just before the cooling period in which the ground has been thermally recharged by the cooling operation of the HP that exchanges the heat of the condenser with the ground. A similar behaviour has been obtained for thermal load profile for the climate of Roma (Fig. 11). For the case of Palermo (Fig. 12) this trend is less evident due to the lower heating demand of the building. Indeed, for Palermo, which has a cooling-dominant thermal load profile, the COP_h is always close to 4 during the whole heating period.

Although the good results in terms of COP_h for the last two cases in comparison with the case of Bologna, it must not be forgotten that the heating demand is lower than that of cooling, this leads to a low significant result in terms of electrical energy savings because of the most part of the electric energy demand is due to the cooling operation of the plant. In the cooling period the performance of the HP decreases quickly in the first part of the cooling period, stabilizing towards the middle of the season.

As expected, at the beginning of the season the system reaches high values of COP_c, close to 6–7 thank to the exploitation of low temperature of the ground near the GHEs. In the second half of the

Fig. 9 Flat-panel GHEs – Bologna



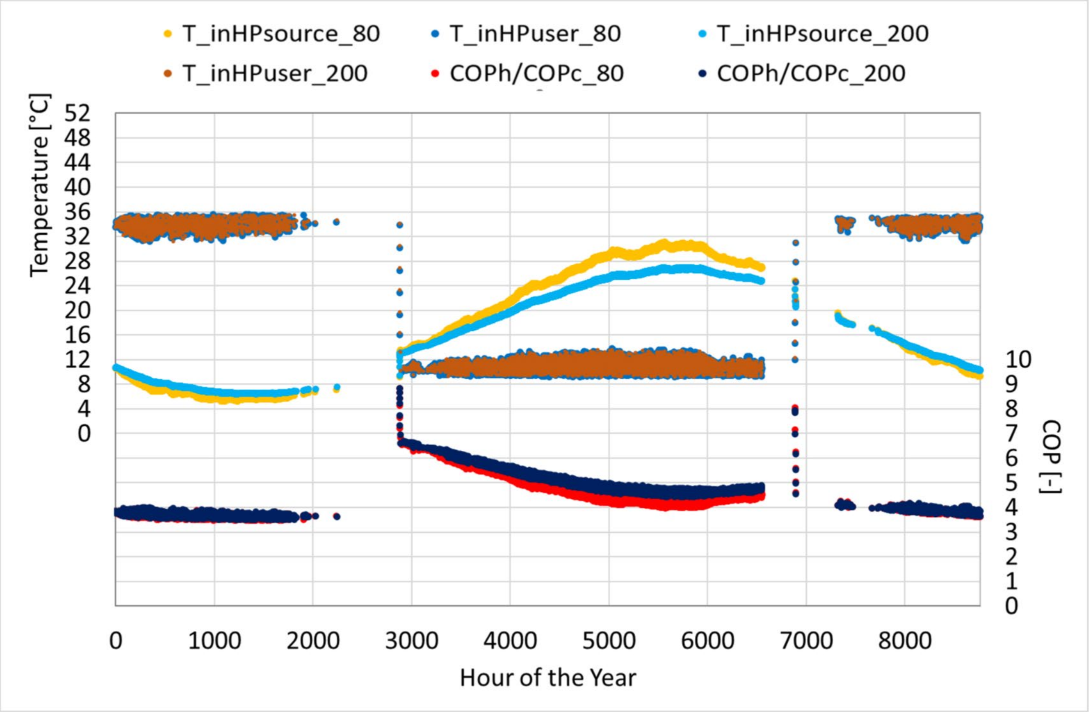


Fig. 10 Flat-panel GHEs – Roma

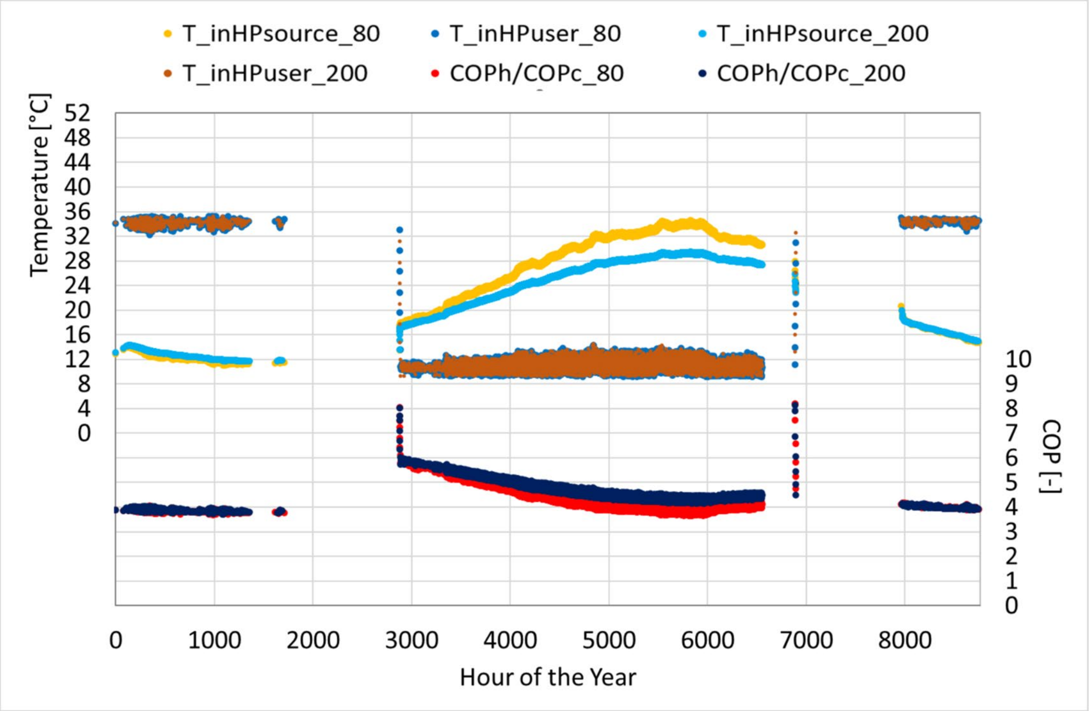


Fig. 11 Flat-panel GHEs – Palermo

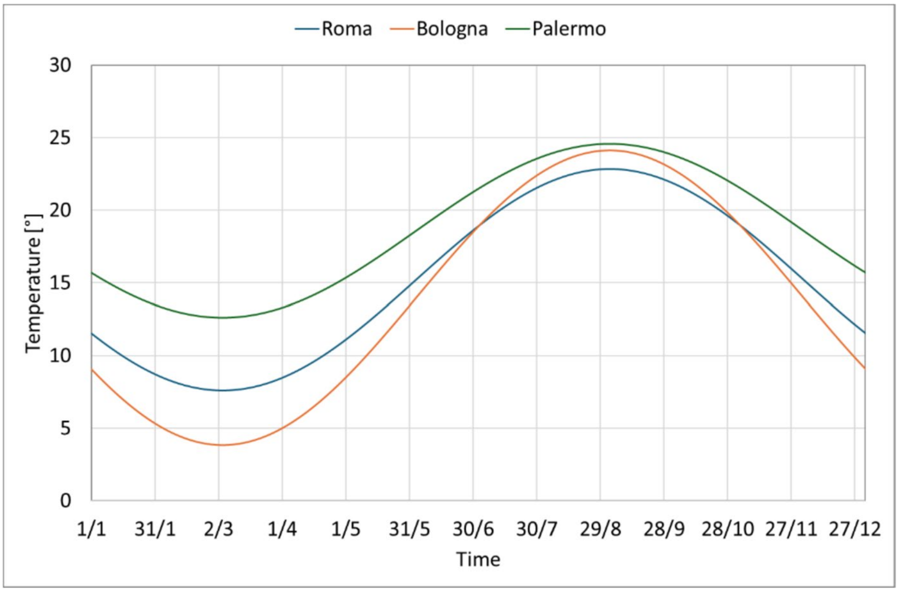


Fig. 12 Undisturbed ground temperature 2 m deep for the three locations

season the COP$_c$ keeps values of about 4 for all the case studies.

The same charts include the results of three additional simulations which have been carried out for a total length of the trenches equal to 200 m (20 lines 10 m each). In all cases, the size in term of length is close to the total length of the BHEs field reported in Table 3 for the case study of Bologna and Roma, and it is more than double the size used in the previous simulations.

The comparison of the behaviour of the systems with greater sizes of the GHEs field highlights minor differences in working fluid temperature despite the significant increase in the exchange surface with the ground. This highlights how in the comparison the dominant factor is the ground temperature rather than the already high heat exchange surface in the 80 m case. A cost-effective size of the system could be evaluated, but this analysis is not present in the work as this is beyond the scope of the present study. In heating, the minimum HP inlet temperature at the source side has increased of about 2 °C for Bologna and Rome, while in cooling the decrease is of about 5°C. For the climate of Palermo, the temperature deviations of the supply heat carrier fluid to the HP are not very significant in heating while during the cooling period it can be seen a reduction of about 4–5°C, similarly to the previous case studies of Bologna and Roma.

Energy performance of the GSHPs

The comparison in terms of energy demand has been carried out considering the seasonal COP in heating and cooling respectively (named SCOP$_h$ and SCOP$_c$ as defined before in the text). The global results are summarised in Table 6. The table highlights the inference in terms of COP and electric energy demand of the different case studies.

As it can be seen in the table, the reduction of the electric energy demand is close to 1–2% and it increases with the increase in the heating demand of the building from Palermo to Bologna case study. Differently happens in case of cooling, where the electric energy saving increases from Bologna to Palermo case study. For the cooling operation period the energy saving is between 7 and 9% for the case study of Bologna and Palermo respectively.

The comparison of the proposed technology with the more common 2U BHEs have been carried out using the same plant and boundary conditions in the simulations. The results of the simulations and the comparison with the smaller flat-panel GHEs fields (80 m) are summarized in Table 7.

As it can be seen in the table the energy performances of the system are almost the same. The flat-panel GHEs fields perform better than the 2U BHEs up to 3% in heating. In cooling, the behaviour is slightly different, for Bologna and Roma the

Table 6 Results of the simulations – Flat-panel GHEs

	Bologna		Roma		Palermo	
L_{tot} [m]	80	200	80	200	80	200
Total HE Area [m^2]	160	400	160	400	160	400
$SCOP_h$	3.67	3.73	3.77	3.80	3.94	3.95
ΔEE_h [%]	−1.7		−0.8		−0.7	
$SCOP_c$	4.64	4.99	4.60	4.99	4.20	4.63
ΔEE_c [%]	−7.1		−7.8		−9.4	

Table 7 Results of the simulations – Comparison between Flat-panel GHEs and 2U BHEs

	Bologna		Roma		Palermo	
	FP	2U	FP	2U	FP	2U
L_{tot} [m]	80	216	80	236	80	351
$SCOP_h$	3.67	3.58	3.77	3.64	3.94	3.86
ΔEE_h [%]	+ 2.5		+ 3.6		+ 1.8	
$SCOP_c$	4.64	4.15	4.60	4.14	4.20	4.33
ΔEE_c [%]	+ 11.8		+ 10.1		−3.0	

flat-panels have obtained a better results with a reduction up to 10% in electric energy demand while the case study of Palermo has obtained an increase of the about 3%. This result difference is attributable to the high thermal load in cooling required by the building in the climate of Palermo.

Conclusions

The present study has compared two different technologies of GHEs used in GSHP systems for the heating, ventilation and air conditioning of buildings. The research fills the lack of works and researches in literature which involve flat-panel GHEs technology and at the same time improves the knowledge of the behaviour of GSHP systems coupled with flat-panel GHEs fields. In fact, the results show how the installation of flat-panel GHEs in quite short length trench allows to obtain similar if not better results in terms of energy performance than the 2U GHEs field. The recent developments in the field of building efficiency and the revealed operators' interest in shallow horizontal GHEs have pushed the present work. The 2U BHEs, which are installed using drilling rigs in wells that reach depths up to 120 m, and flat-panel GHEs installed in trenches of 2–3 m deep have been compared. The analysis was conducted through dynamic simulations, which highlighted the different behaviour of the technologies investigated.

From the results of the simulations the following observations and conclusions were obtained:

- The growing improvement in the performance of building envelopes allows a re-evaluation of the horizontal GHEs systems thanks to the lowering of heating demand and thermal peak loads.
- In the case of balanced thermal load profiles, the proposed solution seems to have good behavior comparable to that of the traditional systems in the cases under study. This result is attributable to the large exchange surface which compensates for the negative effect due to the high and low temperature of the ground near the surface in cooling and heating period respectively.
- The case studies have demonstrated that flat-panel GHEs technology require an installation length that is less than half the total length of 2U BHEs, obtaining similar or better energy performances with the same boundary conditions. In fact, in most of the case studies reported in the results, the flat-panel GHEs have obtained a better result in electrical energy demand with a reduction up to 11.8% and 3.6% in cooling and heating respectively.
- The flat-panel GHEs is a valid alternative to traditional systems even though it requires a greater available surface area of the courtyard than traditional systems. However, this last requirement is less problematic than in the past.

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Data availability The authors cannot provide data as this work is partly related to activities currently in progress.

Declarations

Ethics approval We confirmed that this manuscript has not been published elsewhere and is not under consideration by another journal. Ethical approval and informed consent are not applicable for this study.

Consent None.

Data None.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Bortoloni, M., Bottarelli, M., & Su, Y. (2017). A study on the effect of ground surface boundary conditions in modelling shallow ground heat exchangers. *Applied Thermal Engineering, 111*, 1371–1377. https://doi.org/10.1016/j.applthermaleng.2016.05.063

Bottarelli, M., Baccega, E., Cesari, S., & Emmi, G. (2022). Role of phase change materials in backfilling of flat-panels ground heat exchanger. *Renewable Energy, 189*, 1324–1336. https://doi.org/10.1016/j.renene.2022.03.061

Bottarelli, M., Bortoloni, M., & Su, Y. (2019). On the sizing of a novel Flat-Panel ground heat exchanger in coupling with a dual-source heat pump. *Renewable Energy, 142*, 552–560. https://doi.org/10.1016/j.renene.2019.04.088

Capozza, A., De Carli, M., Galgaro, A., Zarrella, A. (2012). Linee Guida per la progettazione dei campi geotermici per pompe di calore, 2012 Ricerca sul Sistema Energetico – RSE S.p.A.

Carslaw, H. S., Jaeger, J. C. (1959). Conduction of Heat in Solids. Chapter X. Claremore Press, 1959.

Ciriello, V., Bottarelli, M., & Di Federico, V. (2015a). Uncertainty-based analysis of variations in subsurface thermal field due to horizontal flat-panel heat exchangers. *Procedia Environmental Sciences, 25*, 50–57. https://doi.org/10.1016/j.proenv.2015.04.008

Ciriello, V., Bottarelli, M., Di Federico, V., & Tartakovsky, D. M. (2015b). Temperature fields induced by geothermal devices. *Energy, 93*(2), 1896–1903. https://doi.org/10.1016/j.energy.2015.10.052

EHPA. (2023). EHPA Market Report 2023 | Version 1.1 https://www.ehpa.org/news-and-resources/publications/european-heat-pump-market-and-statistics-report-2023/. Access: 10/01/2024.

Emmi, G., & Bottarelli, M. (2023). Enhancement of shallow ground heat exchanger with phase change material. *Renewable Energy, 206*, 828–837. https://doi.org/10.1016/j.renene.2023.02.079

Emmi, G., Cavazzuti, M., & Bottarelli, M. (2022). A management strategy for multi-source heat pump systems. *International Journal of Heat and Technology, 40*(4), 879–887. https://doi.org/10.18280/ijht.400403

Eskilson, P. (1987) Thermal analysis of heat extraction boreholes. Doctoral Thesis, Department of Mathematical Physics and Building Technology. University of Lund, 1987.

European Commission. (2023a). https://climate.ec.europa.eu/eu-action/climate-strategies-targets_en. Access: 20/12/2023.

European Commission. (2023b). https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en#. Access: 20/12/2023.

Eurostat. (2023b). Environment and energy\Environment (env) https://ec.europa.eu/eurostat/databrowser/view/env_ac_aigg_q/default/bar?lang=en. Access: 10/01/2024.

Eurostat. (2023a). Section Environment and energy\Energy (t_nrg) https://ec.europa.eu/eurostat/databrowser/explore/all/cc?lang=en&subtheme=cli.cli_dri.cli_dri_nrg&displ

ay=list&sort=category&extractionId=ten00124. Access: 10/01/2024.

Florides, G., Theofanous, E., Iosif-Stylianou, I., Tassou, S., Christodoulides, P., Zomeni, Z., Tsiolakis, E., Kalogirou, S., Messaritis, V., Pouloupatis, P., & Panayiotou, G. (2013). Modeling and assessment of the efficiency of horizontal and vertical ground heat exchangers. *Energy, 58*, 655–663. https://doi.org/10.1016/j.energy.2013.05.053

Ingersoll, L. R., Zobel, O. J., & Ingersoll, A. C. (1954). *Heat conduction: With engineering and geological applications* (p. 1954). McGraw-Hill Book Co.

Kavanaugh, S. P., Rafferty, K. (1997). Ground source heat pumps. Design of geothermal systems for commercial and institutional buildings. ASHRAE; 1997.

Klein, S. A. et al. (2017). *TRNSYS 18: A transient system simulation program, Solar energy laboratory*. University of Wisconsin. http://sel.me.wisc.edu/trnsys

Lamarche, L., & Beauchamp, B. (2007). A new contribution to the finite line-source model for geothermal boreholes. *Energy and Buildings, 39*(2), 188–198. https://doi.org/10.1016/j.enbuild.2006.06.003

Li, M., Zhang, L., & Liu, G. (2019). Estimation of thermal properties of soil and backfilling material from thermal response tests (TRTs) for exploiting shallow geothermal energy: Sensitivity, identifiability, and uncertainty. *Renewable Energy, 132*, 1263–1270. https://doi.org/10.1016/j.renene.2018.09.022

Lund, J. W., & Boyd, T. L. (2016). Direct utilization of geothermal energy 2015 worldwide review. *Geothermics, 60*, 66–93. https://doi.org/10.1016/j.geothermics.2015.11.004

Pavel, C. C., Blagoeva, D. T. (2018). Competitive landscape of the EU's insulation for energy-efficient buildings, EUR 28816 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-96383-4, https://doi.org/10.2760/750646, PUBSY No. JRC108692.

Santamouris, M., & Vasilakopoulou, K. (2021). Present and future energy consumption of buildings: Challenges and opportunities towards decarbonization e-Prime. *Advances in Electrical Engineering, Electronics and Energy, 1*, 100002. https://doi.org/10.1016/j.prime.2021.100002

Spitler, J. D., & Gehlin, S. E. A. (2015). Thermal response testing for ground source heat pump systems - An historical review. *Renewable and Sustainable Energy Review, 50*, 1125–1137. https://doi.org/10.1016/j.rser.2015.05.061

Wang, S., Ji, Y., He, S., Gao, J., Wang, Y., & Cai, X. (2023). Analysis on influencing factors of heat transfer characteristics of vertical borehole heat exchanger under stratified soil conditions. *Case Studies in Thermal Engineering, 44*, 102840. https://doi.org/10.1016/j.csite.2023.102840

Yoon, S., Lee, S., & Go, G. (2015). Evaluation of thermal efficiency in different types of horizontal ground heat exchangers. *Energy and Buildings, 105*, 100–105. https://doi.org/10.1016/j.enbuild.2015.07.054

Zarrella, A., Zecchin, R., Pasquier, P., Guzzon, D., Prataviera, E., Vivian, J., De Carli, E., & Emmi, G. (2020). Analysis of retrofit solutions of a Ground Source Heat Pump system: An Italian case study. *Energies, 13*, 5680. https://doi.org/10.3390/en13215680

Zhou, K., Mao, J., Li, Y., Zhang, H., Chen, S., & Chen, F. (2022). Thermal and economic performance of horizontal ground source heat pump systems with different flowrate control methods. *Journal of Building Engineering, 53*, 104554. https://doi.org/10.1016/j.jobe.2022.104554