IGSHPA Research Track
Stockholm September 18-20, 2018

Are shallow boreholes a suitable option for inter-seasonal ground heat storage for the small housing sector?

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ABSTRACT

In recent years, various researchers have studied the performance of Solar Assisted Ground Source Heat Pump (SAGSHP) systems using borehole heat exchangers. However, the research conducted has been limited to conventional boreholes (30m to 150m depth), which are expensive and not suitable for the small housing sector. This paper reports an experimental analysis of a shallow SAGSHP system with inter-seasonal storage. The system, installed in Leicester UK, consists of seven photovoltaic-thermal (PVT) collectors connected in series with an array of 16 shallow boreholes (1.5 meters depth). Data regarding the energy fluxes involved in the soil-based thermal store have been monitored and analysed for one year. The results show that the shallow soil is able to serve as a storage medium to cover the heating demands of a near zero energy domestic building. However, it was noticed that in addition to the solar heat captured and stored in the soil, the system covers part of the heating demand from heat extracted from the soil surrounding the thermal store. During winter, the lowest temperature reached by the soil so far is 2 °C. Hence, no freezing problems have occurred in the soil. An analysis of the temperature variation of the ground storage under the system operation is also shown.

INTRODUCTION

Ground source heat pumps (GSHP) with vertical boreholes have been largely used as an alternative system to cover both cooling and heating thermal loads by using the ground as a renewable energy source or sink (Emmi et al. 2015). The main reason to use this technology is increasing the heat pump efficiency by having a more stable energy source or sink when compared to air source heat pumps (ASHP) (You et al. 2015). In fact, GSHP has been shown to be a very promising option when implemented in the early design of new buildings and in a climate where the thermal loads are balanced over the entire year (i.e. cooling and heating needs). However, in most climates the thermal loads are not balanced over the year and consequently GSHPs tend to lose efficiency in the long term (Wu et al. 2013). For instance, in heating dominated climates, the ground serves as a heat source, which mean that over the time the constant heat extraction from the ground will affect the natural ground temperature. Indeed, Zhu et al. (2015) show that the continued use of a GSHP decreased soil temperature by 0.185°C per year. This problem has been one of the main obstacles for the development of GSHP technologies (You et al. 2015). An option to deal with this problem might be to increase the borehole depth. However, this leads to an increase in the initial cost due to the need for large machinery for the drilling process (You et al. 2015). Therefore, storing heat in the ground from another heat source is an option that has been studied in recent years, solar energy being the most common of the external heat sources

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(Banjac 2015). This system is known as Solar Assisted Ground Source Heat Pump (SAGSHP) and it is claimed be a sustainable system that can maintain a highly efficient heat pump operation in the long term. The functioning principle of SAGSHP is that of inter-seasonal heat storage where heat collected in summer using a solar thermal collector is stored in the ground to be used by the GSHP during winter. The increase in the heat source temperature allow the system to have a higher efficiency and to compensate for the thermal imbalance of the ground (Zhai et al. 2011). Moreover, with the increase in the ground temperature, the required borehole length in the GSHP can be minimised as stated by Cao et al. (2014).

Regarding SAGSHP systems, both numerical (Emmi et al. 2015; Eslami-nejad and Bernier 2011; Chiasson and Yavuzturk 2003; Paiho et al. 2017) and experimental (Xi et al. 2011; Wang et al. 2010) studies are found in the literature. However, the application of this technology has been limited to large buildings due to the high cost of system installation, mainly related to drilling costs. Conventional boreholes in GSHP systems are installed at depths from 30m to 150m, which makes the technology unsuitable for domestic applications. On the other hand, shallow boreholes in GSHP have not been deeply studied, as the soil near to the surface is thermally disturbed so that a system installed at shallow depths will be inefficient. For a domestic application a shallow borehole system can be a potential alternative for conventional heating systems if the boreholes are installed at the foundation construction stage (Wright et al. 2014). Shallow boreholes at depths up to 5 meters installed at the same time as the building foundations might be an option for low energy housing in heating dominated climates.

This paper presents the preliminary results of an experimental study of a SAGSHP system, which has shallow vertical boreholes to cover the heating demands of a small dwelling. This research focuses on the energy flows to and from the shallow soil for a system that aims to store heat from solar energy in summer and use it in winter to cover heating demands. The system is evaluated under the climatic conditions of Leicester, UK during one year.

EXPERIMENTAL SET-UP

System configuration

The experimental project was conducted by the Institute of Energy and Sustainable Development (IESD), at De Montfort University (DMU) in Leicester, UK. The experiment was set-up to investigate whether shallow boreholes (1.5m deep and spaced 1.5m apart) can be a potential solution for SAGSHP systems in order to store enough energy in summer to cover heating demands in winter for the small domestic sector. The use of very shallow boreholes is the main innovation of this type of SAGSHP system. The reason for the choice of shallow boreholes is that they can be built very cheaply in the majority of locations without the need for expensive drilling equipment (Wright et al. 2014). In fact, the shallow boreholes of the experimental system were built using a simple fencepost auger mounted on a mini-excavator. The intention of this system is to be built during the construction stage of high efficiency buildings or buildings toward net zero energy as the footprint of the building above limits the number of boreholes and in consequence, the heat that can be stored. However, the SAGSHP of the present study was retrofitted to an unoccupied Victorian terrace owned by DMU. Although this building has been upgraded with loft insulation and double-glazing, it is draughty and has no solid wall insulation, hence it is a relatively inefficient building. Another difference between the intended application of the system and the current installation of this study is that the inter-seasonal ground thermal store (known as an 'earth energy bank', or EEB) could not be built within the foundations of the house. Instead, a thermal store of the same footprint was placed in an adjacent grass verge. The sides were reinforced with concrete (15cm) as if they were the footings for a new-build house and insulated at the edges and on top.

A system schematic is shown in Figure 1. As shown, the system consists mainly of three fluid loops. The solar loop, the ground loop and the heating loop (storage or radiant floor). In the solar loop, the fluid gains heat through seven solar-photovoltaic collectors (PVT) that transfer the heat to the fluid of the ground loop by means of a heat exchanger. Both, the solar loop and ground loop working fluids are a 30% glycol/water mix by volume. This concentration rate is the recommended by the PVT manufacturers to avoid freezing problems under the weather conditions in the UK. The thermal efficiency of the PVTs is 67% and the aperture area of the collector is 1.5m^2. If the temperature at the outlet of PVT collectors is greater than the EEB temperature by 7°C then the solar loop pump is activated. The ground fluid passes through a series of 16 shallow U-tube boreholes (1.5m deep) transferring heat into the EEB. If the heat pump is not calling for heat at this point, then the fluid circulates and recharges the thermal store until the temperature difference between the EEB and the outlet of the PVT falls below 4°C, at which point the solar loop pump switches off. If the heat pump is calling for heat during solar generation, the fluid releases some heat to the heat pump evaporator and any surplus recharges the thermal store. If there is any heat demand when the solar loop is inactive, then the heat pump will circulate fluid around the ground loop and through the evaporator, which therefore extracts heat from the EEB. In this way, the EEB will lose the stored heat, which must be recharged whenever solar energy is available again.

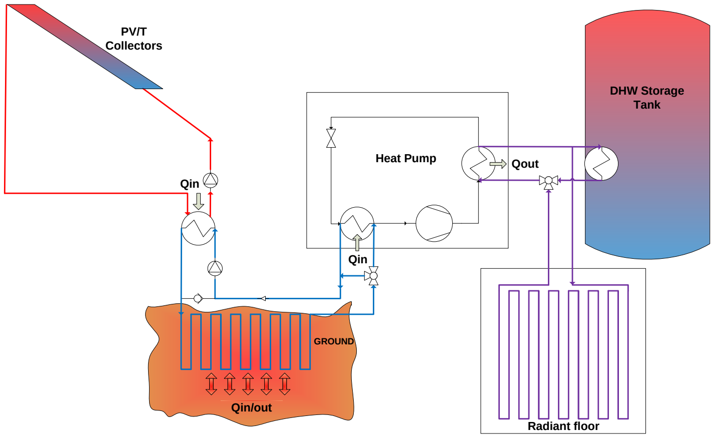

Figure 1 Schematic of the system configuration

The vertical ground heat exchanger (VGHE) consists of an array of 16 shallow boreholes in series (Figure 2). The EEB, which is used as a thermal store, has a dimension of 10m x 4m and is insulated on the top (20cm) and sides (10cm) as mentioned previously. The distance between each adjacent borehole is 1.5m except for distances between boreholes B1-B2, B10-B11 and B15-B16 (see Figure 2) which are separated 1m. The thermal properties of the soil were determined by a thermal response test conducted on site prior to construction of the EEB. The boreholes (15cm diameter) are filled with thermal grout (bentonite). The thermal properties of the soil and the working fluid are shown in Table 1. The heat pump heating capacity is 3kW, which is approximately enough to cover the heating needs of a well-insulated small dwelling in the UK. The heat pump stores the heat for DHW needs in a 200 litre cylinder.

Table 1. Soil and working fluid thermal properties

Type of soil/fluid	Wet clay	Glycol (30%)
Thermal conductivity	1.5 W/mK	---
Density	1800 kg/m^3	1070 kg/m^3
Specific Heat	1200 J/kgK	3768 J/kgK
Thermal diffusivity	6.94x10^{-7} m^2/s	---

Monitoring system

The National Instruments cDAQ system (2016) is used to monitor the EEB and using 48 temperature sensors (PT1000) that are distributed at distances and depths of interest around the EEB. Calibrated resistance temperature detectors (RTD) are used for the temperature monitoring to minimise errors in the data due to the length of the wires from the monitoring point to the data logger. The margin of error in these measurements is ±0.3 °C. Figure 2 shows the location of the sensors (1 to 14) and Table 2 describes the depths of temperature monitoring of each sensor. The time scale of the monitored data is 15 minutes and data have been recorded since 04/06/2016. The fluid flow rate for the ground loop is also monitored. This parameter is key for analysing the energy flows from/to the EEB.

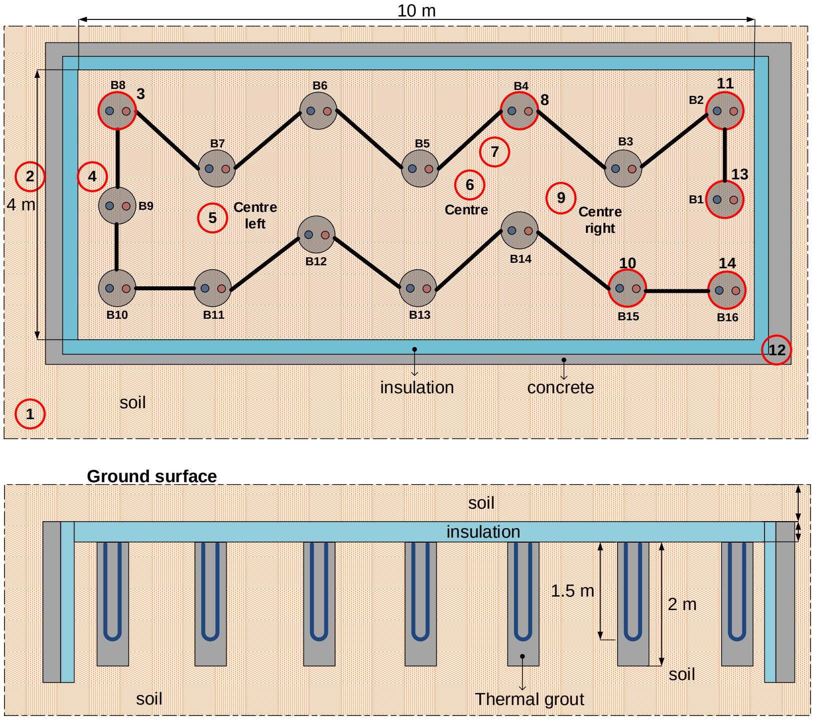

Figure 2 Vertical and horizontal cross-section view of the GHE with sensor location for the cDAQ system

Table 2. Sensors location and depth of measurement for the EEB

Sensors point	Location	Depth of measurement
1	Distant from EEB	0.75 m, 1.25 m, 1.75 m, 2.75 m
2	Just Outside EEB	0.75 m, 1.25 m, 1.75 m, 2.75 m
4	Just Inside EEB	0.75 m, 1.25 m, 1.75 m, 2.75 m
3, 8, 10, 11	Borehole wall (B8, B4, B15, B2)	0.75 m, 1.25 m, 1.75 m, 2.75 m
5, 6, 7, 9	Centre of the EEB	0.75 m, 1.25 m, 1.75 m, 2.75 m
12	Inside and outside the insulation	1.75 m
13	Inlet flow temperature	0.75 m
14	Outlet flow temperature	0.75 m

Weather data have also been monitored from a weather station located on the roof of the Gateway House Building on DMU campus (250m from the experimental SAGSHP installation). These data can be downloaded from the station itself in one-hour time steps. The measured variables include ambient temperature, relative humidity, wind speed, solar radiation (global and diffuse), precipitation, etc. Figure 3 shows the monthly solar insolation and ambient temperature from the actual data monitored from March 2016 to February 2017. These data provide a useful context for the study but were not necessary to analyse the performance of the EEB.

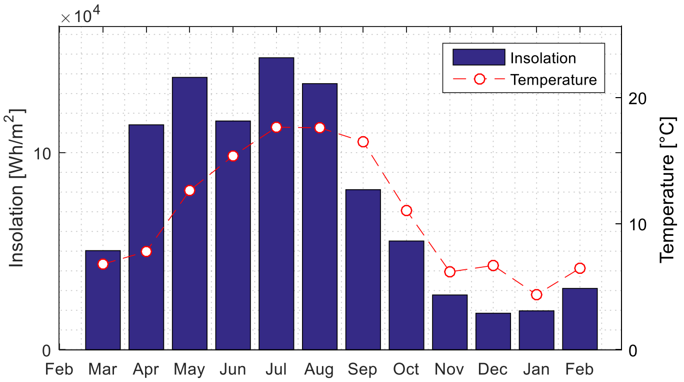

Figure 3 Monthly average ambient temperature and solar insolation from the monitored data

Earth Energy Bank heat flux

Using the data monitored, it is possible to determine the heat fluxes going to (heat stored) or taken from (heat removed) the EEB. Heat is stored mainly in summer when there is little heat demand from the building. During heat storage, the average soil temperature in the EEB is lower than the solar PVT outlet temperature. On the other hand, heat is removed from the EEB mainly in winter when there are large heating loads from the building and solar energy is not available. During the transition periods (Spring and Autumn) a combination of heat extraction and injection can be observed. The heat flux during storage or extraction can be calculated as follows (Equation 1):

$$Q_{gr} = \dot{m}_{ghe} \times c_p \times \left(T_{out_{EEB}} - T_{in_{EEB}}\right) \tag{1}$$

where, Q_{gr} (W) is the heat flux during storage (negative) or extraction (positive) from the EEB; $\dot{m}_{ghe}$ (kg/s) is the mass flow rate; c_p (kJ/kg°C) is the specific heat of the working fluid in the VGHE; $T_{out_{EEB}}$ (°C) is the VGHE outlet fluid temperature and $T_{in_{EEB}}$ (°C) is the VGHE inlet fluid temperature. The mass flow rate is determined from the monitored volumetric flow rate data multiplied by the glycol density. While it is true that the physical properties of fluids vary with temperature, from a practical point of view this variation can be ignored since it is less than 1.8% in the temperature ranges from 5°C to 50°C (Lemmon at al. 2005). Average values, corresponding to a fluid temperature of 26.7°C, have been used as thermal properties for the glycol.

RESULTS AND DISCUSSIONS

Heat flux throughout the Earth Energy Bank

The data used for the analysis of the energy balance correspond to the period from 04/06/2016 to 30/06/2017. As shown in Equation 1, the measured values of the EEB (vertical ground heat exchanger) inlet and outlet fluid temperature were combined with the measured mass flow rate of the fluid in the ground loop ($\dot{m}_{ghe}$) to calculate the amount of heat injected or extracted into or from the soil. Thus, Figure 4 shows the hourly values of the EEB inlet and outlet temperature. The figure shows that from June to September (summer), the heat injection process into the EEB takes place, whereas from November to February (winter) heat is mostly extracted. It is worth mentioning that the old heating system remained operative throughout test period, but in frost protection mode only. However, during January/February somebody tampered with the thermostat for the original system so that it provided space heating and the heat pump was not operating in the expected manner and the house was overheating. This explains why the fluid temperature in the EEB during this period did not go negative.

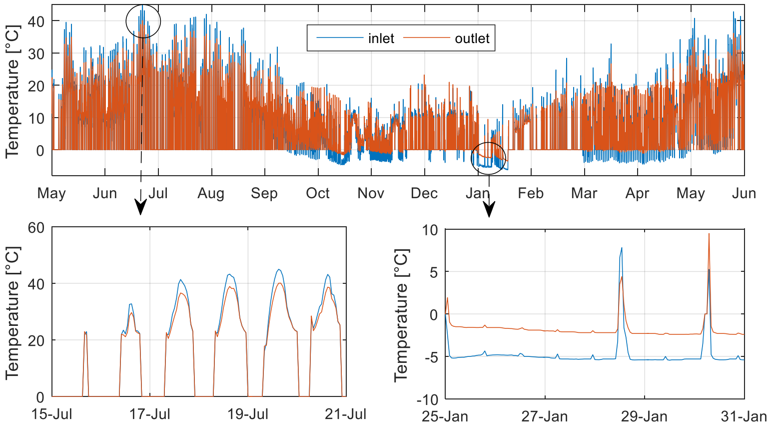

Figure 4 Inlet and Outlet fluid temperatures in the EEB

The analysed data correspond to a total of 9404 hours during which the ground loop pump was operating for 5964 hours (for either heat injection or extraction). Hence, to avoid erroneous heat flux readings, only the data in which the system was operating were analysed. In this context, Figure 5a shows the hourly heat flux (W) throughout the EEB. The heat injection rate (negative), predominant in summer, reaches peak values up to 5 kW, while the peak heat extraction rate (positive) is around 3 kW. This figure also shows that the heat injection is much more variable as it is governed by the solar energy availability. In addition, as seen in Figure 5a, heat extraction and heat injection can each occur in both summer and winter. Heat extraction in summer occurs when heating for domestic hot water (DHW) is required, while heat injection in winter occurs when there is solar energy available, typically on a mild, sunny day.

Figure 5b shows the total energy stored (negative) or extracted (positive) to/from the EEB. As can be seen, in the total balance there is more energy extracted than stored. This is logical due to the heating dominated climate in Leicester, UK. However, it is also important to mention that the extracted energy from the EEB is not only recovered by the solar energy injected by the system but also by the natural soil recovery. Since the bottom of the EEB is not insulated, in wintertime the EEB is partially replenished by the heat in the soil below. Hence, the heat extracted is both solar and geothermally sourced. Further research is needed in order to determine the amount of heat that the surrounding soil can transfer to the EEB during the whole year cycle. At present the cost-benefits of the side insulation are the subject of discussion and future analysis, and it may be that under some circumstances the benefits of heat retention in summer are outweighed by the reduction of heat gains from the surrounding soil in winter.

Earth Energy Bank thermal performance

In this section, we conduct an analysis of the thermal performance of the thermal store (EEB). Figure 6 shows the natural temperature variation of the soil (sensor 1) at different depths (0.75m, 1.25m, 1.75m and 2.75m). The natural recharging of the EEB from below occurs from late March to September, where the maximal temperature of the soil at 2.75m is slightly higher than 15°C. On the other hand, from late September to March the EEB soil is naturally discharging and the minimal soil temperature at 2.75 m is below 10°C. Hence, although the installation of the ground heat exchanger is at a maximum depth of 2.75 m, the annual temperature oscillation is around 5°C, which is small enough that it does not seriously reduce the performance of the heat pump.

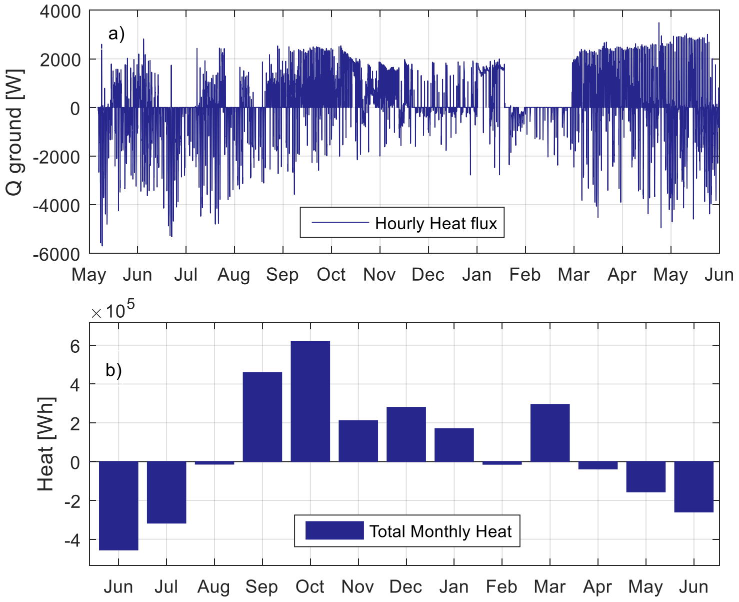

Figure 5 **a)** Hourly ground heat flux; **b)** Monthly ground heat

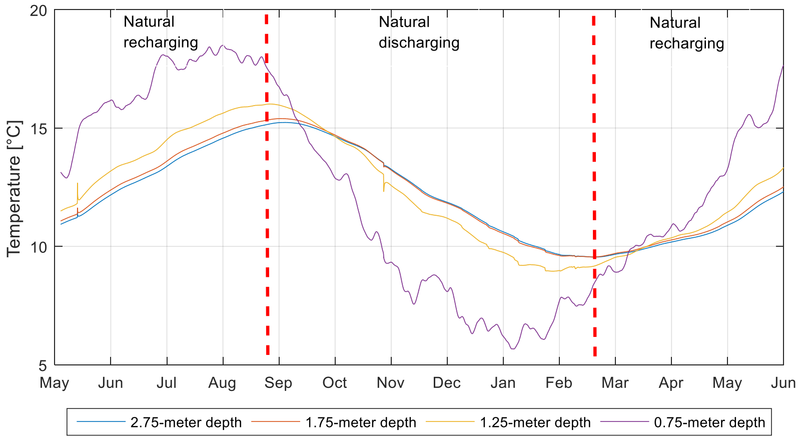

Figure 6 Natural soil temperature variation, sensor 1

Figure 7 shows the temperature variation of the EEB centre temperature (sensors 5, 6, 7 and 9) compared to the natural soil variation (sensor 1) at different depths. The regions of heat storage and extraction can be clearly seen. For example, at a depth of 1.25m, the EEB reaches a maximum temperature of 20°C which is about 5°C higher than the natural soil temperature at the same depth. In contrast, the lowest temperature of the EEB at the same depth is close to 2°C which is around 8°C lower than the natural soil at the same depth. These data show greater storage effects (ΔT) at mid-range depths, as expected. However, no conclusions about the long-term energy balance can be drawn yet, as this analysis must be performed using data collected over several years or through multi-year simulations.

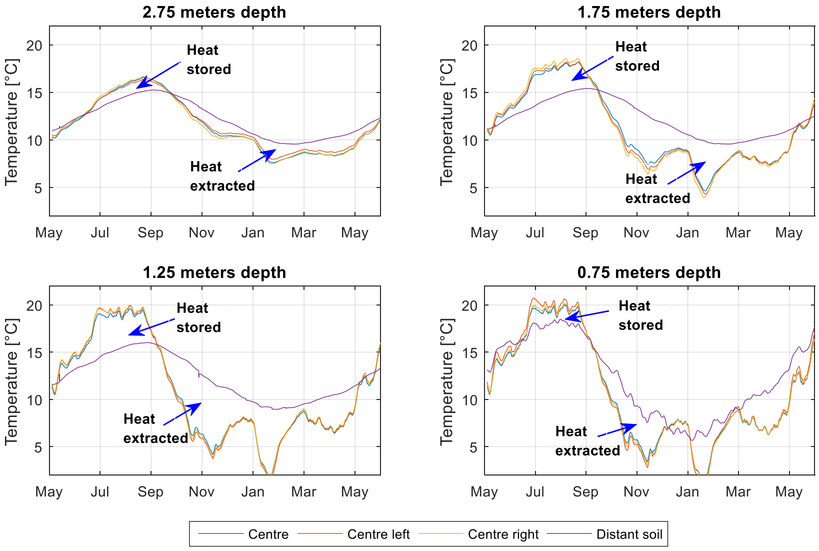

Figure 7 EEB and natural soil temperature variation

CONCLUSIONS

In this paper, the performance of an experimental SAGSHP with shallow boreholes for residential heating applications has been analysed. The system performance was studied from data collected over 13 months. The main innovation of this system is the use of a shallow (1.5 meter depth) vertical ground heat exchanger, which is used to seasonally store heat into a thermal store known as an earth energy bank (EEB). Although the system is small and it could not cover all the heating demands of the thermally inefficient test building, it is evident that the system can properly work to cover heating demands for a near net zero energy building. The use of long-term (inter-seasonal) heat storage as well as short-term (hot water tank) allow the system to cover heating loads during winter including peak heating loads. The total heat extracted during the whole period is higher than the total heat injected from solar energy. However, it was also evident that the soil in the EEB partially recovers heat from the surrounding soil below the EEB. Further research is needed to quantify this heat, which will help in the further optimisation of this shallow system. Regarding the performance of the EEB, during the heat extraction period, the EEB soil temperature drops to only 2°C. Without solar recharging, the temperature in the soil might easily reach temperatures below 0°C, freezing the soil and affecting the overall system efficiency.

ACKNOWLEDGMENTS

The authors of this publication gratefully acknowledge De Montfort University, Caplin Homes and Vaillant UK for their support in this research.

NOMENCLATURE

ΔT	temperature difference [°C]
$ASHP$	air source heat pump
COP	coefficient of performance
EEB	earth energy bank
GHE	ground heat exchanger
$GSHP$	ground source heat pump
PVT	photovoltaic thermal collector
Q	heat flux [W]
SA	solar assisted GSHP
T	temperature [°C]
c_p	specific heat [J/kg°C]
$\dot{m}$	mass flow rate [kg/s]

Subscripts

ghe	ground heat exchanger
in	inlet
out	outlet

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