Experimental study of a domestic solar-assisted ground source heat pump with seasonal underground thermal energy storage through shallow boreholes

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Nomenclature

ΔT	temperature difference [°C]	PVT	photovoltaic thermal collector
η_o	maximal thermal efficiency	Q	heat [Wh]
A	surface [m ²]	SA	solar assisted GSHP
$ASHP$	air source heat pump	T	temperature [°C]
COP	coefficient of performance	c_p	specific heat [J/kg°C]
EEB	earth energy bank	k	thermal conductivity [W/mK]
GHE	ground heat exchanger	$\dot{m}$	mass flow rate [kg/s]
$GSHP$	ground source heat pump	t	time [s]

Subscripts

eva	evaporator	$loss$	losses
EEB	earth energy bank	$soil$	soil
ghe	ground heat exchanger	$solar$	solar
hp	heat pump	st	stored
in	inlet	out	outlet

Abstract

With the current need to reduce carbon emissions, new technologies have been developed in recent years to satisfy building thermal demands. Among others, ground-source heat pumps (GSHP) have been implemented, in both commercial and residential applications, to meet heating and cooling needs in a cleaner and more energy efficient way. Likewise, solar thermal systems have been integrated into conventional GSHP systems to reduce the size of the ground heat exchanger and provide seasonal heat storage. So far, this technology has been used in large commercial or residential buildings, mainly due to its high installation costs. This paper describes a study of an experimental Solar Assisted Ground Source Heat Pump (SAGSHP) system for domestic heating applications. The system uses an array of shallow (1.5-metre deep) vertical boreholes to store heat seasonally in an underground 'earth energy bank'. The results show that after 19 months of operation the system was able to show a good performance in order to cover the space heating requirements of the building in winter. Likewise, it was evidenced that the solar energy injected in the ground is useful not only to recover the soil from the thermal imbalance but also to store heat. Results also highlighted the need to improve the control strategy, mainly to avoid excessive inlet fluid temperatures at the evaporator.

Keywords

Solar assisted ground source heat pump, GSHP, photovoltaic-thermal collectors, shallow boreholes, seasonal storage, building.

Highlights

A shallow solar assisted ground source heat pump was experimentally studied.

The ground heat exchanger consists of 16 shallow boreholes of 1.5-metres deep.

Heat is seasonally stored in a volume of soil insulated on the top and sides.

The usable heat from the PVTs is limited by the size of the ground heat exchanger.

The heat stored helped to cover heating loads and to prevent soil thermal imbalance.

1. Introduction

Large scale combustion of fossil fuels has negatively impacted the global environment, especially in recent decades and one of the main challenges facing mankind is reducing carbon dioxide emissions in order to diminish the effects of global warming [1]. Policy makers in many countries have promoted the implementation of modern renewable energy systems in the energy matrix and most governments in developed countries offer incentives such as tax exemptions and subsidies to promote the use of environmentally friendly technologies [2]. Besides, a reduction in the growth of global energy consumption is encouraged as well as the implementation of energy efficiency measures, particularly in the highest energy consumption sectors [3]. Within this, the built environment is a key sector that needs improvement, as it is responsible for 30% of the total end-use energy-related carbon emissions [4], of which more than half are from the residential sector. For this reason, there has been a significant increase in renewable energy systems, mainly photovoltaic and solar hot water systems, in both residential and non-residential buildings in Europe in recent years [5]. However, due to the intermittent nature of renewable energy resources, most renewable energy systems are unable to replace fossil-fuelled systems fully. Likewise, renewable energy sources are characterised by a mismatch between their peak power generation and the peak energy demand. This is especially true for solar thermal energy in cold climates, for which heat production in the summer months is highest when heating requirements are lower. This has led to the implementation of thermal storage systems or hybrid heating systems with multiple renewable energy sources [6]. Alternatively, the use of systems with more stable heat sources like ground source heat pumps (GSHP) has been proposed. In fact, according to Emmi et al. [1], GSHPs today represent the most promising technology for reducing carbon emissions in the building thermal sector, and many research efforts are being focused on this technology. The market for GSHP systems is predicted to expand at an annual rate of 13.1% between 2014 and 2020 [7].

A common configuration of heat pumps (HP) uses ambient air as the low-temperature energy source (or sink for cooling) in a device known as an air source heat pump (ASHP). An advantage of this configuration is the low cost, compared to systems using other heat sources. However, the ambient air has several seasonal and daily fluctuations, which leads to unstable HP operation and therefore its average COP is relatively low [8]. Additionally, defrost processes may be required at very low ambient temperatures to prevent ice build-up in the evaporator [9]. These drawbacks led to the development of the GSHP, a device in which the low-temperature energy source is the ground, as shown in Figure 1. This technology has a better average performance than ASHP. The ground is not only a stable heat source (or sink when the building is to be cooled) but also, its average temperature in winter is higher

and the daily and seasonal temperature variation is much lower than those of the air [10]. Indeed, the ground temperature is affected by the seasonal variations only in the first few metres from the surface [11]. Hence, GSHP systems show advantages compared to ASHP which include: no need for a supplemental heat source in times of extreme cold temperature, , no need for a defrost cycle, greater thermal stability of the heat source and lower energy consumption [12]. The main disadvantage of GSHP is the initial cost (mainly for borehole drilling) which is 20% to 30% higher than ASHP systems [13].

In a GSHP, the evaporator is connected to the ground [14]. Within the configurations of the ground heat exchangers (GHE), there are two main groups: horizontal ground heat exchangers (HGHE) placed typically at depths of up to 2 m and vertical ground heat exchangers (VGHE) typically at depths from the surface to between 15 and 100 m. Of these two groups, the vertical configuration is mostly used since the temperature of the soil at greater depths is more stable, it requires less land area, will not affect the surface temperature (e.g. vegetation) and does not require excavation [15]. A GSHP can be used for heating only, cooling only or a seasonal mixture of both.

Despite the advantage of GSHP systems over ASHP systems, during prolonged operation of the former, the ground temperature is affected. In heating mode, the soil will lose heat, and thus its temperature will decrease. In cooling mode, the ground will serve as a heat sink, and its temperature will tend to increase [16]. This behaviour is less relevant when the thermal loads are balanced. However, there are very few cases where thermal loads are balanced throughout the year, so thermal imbalance of the soil, known as 'thermal drift', commonly occurs in the long-term. This results in the decrease in the HP efficiency in the long-term [1]. In climates dominated by heating loads, the use of GSHP will cause a decrease in the soil temperature after a few seasons. In fact, Zhu et al. [17] show that the continued use of a GSHP decreased soil temperature by 0.185°C per year. It is important to mention that after a few years, the ground temperature tends to reach a steady state condition [18]. However, depending on the amount of heat extracted from the ground, thermal imbalance might lead to a low steady state temperature. Increasing the length of the pipes in the borehole is an option to reduce the thermal imbalance, but the extra cost limits this practice [10]. In order to counter this problem, the idea of injecting heat into the ground from another energy source has been explored, the most common practice being the injection of heat from solar thermal energy [19], [20]. This stored solar heat counteracts the soil thermal imbalance. This technology, known as Solar Assisted GSHP (SAGSHP), can use solar energy as a heat source for space or DHW heating; as a heat source for increasing the evaporator temperature; as a heat source for recharging the soil or as combinations of all [21]. This is the principle of seasonal ground heat storage and has been proven to be economically feasible with a suitable design [22]. Seasonal heat storage in the ground, commonly known as underground thermal energy storage (UTES), is typically a low temperature storage in which the heat is mainly used to compensate the yearly thermal imbalance or increase the ground temperature in a few degrees K in order to increase the heat pump COP [20]. High temperature storage is another approach for seasonal heat storage. Nonetheless, this approach requires more efforts by the need of a higher input fluid temperature and insulation in the boundaries of the storage medium. Although there are few applications in which the ground is used as a high temperature storage medium [23], water has shown to be a more effective medium for seasonal heat storage. However, if a natural water reservoir is not available, such systems become more expensive than ground storage systems due to the need for a large tank, usually underground, to store water [24].

Figure 1. Ground Source Heat Pump

SAGSHP have been studied for many decades showing promising results. Researchers have studied SAGSHP with different system configurations [25], operation modes [26] and control strategies [27]. They have carried out numerical and experimental studies, as well as optimisation studies. However, it is hard to say that an optimal system configuration exists as several design configurations have been found to work properly. These configurations depend on many criteria including the ambient and operating conditions, the heating and (if any) cooling load, the size of the system among others.

Simulation studies (numerical modelling) have found evidence that the use of solar energy to recharge the ground can reduce the thermal imbalance of the ground [1], [28], [29], [30]. Other studies conclude that the most efficient way to use solar energy is to meet heat demands (domestic hot water or space heating) directly and then to use any excess solar energy for soil recharging [31]–[33]. Nevertheless, there is agreement that the use of solar energy allows the required length of the boreholes to be minimised so that the cost of the system installation is reduced through lower drilling costs [34]. On the other hand, experimental studies have shown that the main advantage of using solar energy to assist GSHP systems is to increase the heat pump efficiency [17], [35], [36]. The control system for heat injection has proved crucial in avoiding unnecessary fluid pumping in the system [37]. Most experimental studies of SAGSHP systems have been carried out using large buildings where deep (over 100 m) boreholes are required. Even though, boreholes have been installed in single house units at depths from 30 to 100 metres, this type of design is complex as a soil survey is usually required in addition to the complex drilling process. In this research, an alternative that reduces the borehole depth by using an array of shallow bores (of less than 2-metre deep) with solar assistance is proposed. This configuration reduces the drilling costs by avoiding the use of expensive machinery (instead, a simple fence-post auger is used). However, this can reduce the efficiency due to the higher influence of the ambient conditions on the shallow soil, which can increase heat loss to the environment. One solution is the creation of a soil-based thermal store, analogous to a water tank, by thermally insulating the top and sides of a volume of soil containing the boreholes. For cost reasons, the bottom of the thermal store remains uninsulated. The insulation reduces thermal losses but also reduces the natural recharge of the borehole array by the surrounding soil. On the other hand, by using an array of shallow boreholes, the fact of having boreholes interacting in a small storage volume increases the

storage efficiency (compared to a single deep borehole) due to the reduction of the surface in contact with the surrounding soil (outside the boundaries of the storage volume). Unlike conventional GSHP, this shallow configuration cannot be studied using the conventional analytical models, mainly because most available models are configured to study deeper ground which allows the ambient conditions above ground to be neglected, and the ground can be considered to be thermally undisturbed. If numerical modelling approach is used, the study of such systems can be very complex and computationally expensive (time and resources). Moreover, if any numerical study is conducted, experimental studies are needed for validation purposes. In this research, the authors had the opportunity to analyse, an empirical design of a shallow SAGSHP developed by a commercial company. This approach is very helpful in the initial stages of research in order to analyse the performance and potential applicability of such systems. This paper presents the results of the analysis of this experimental system which is applied for residential heating applications under the climatic conditions of Leicester, UK. The experimental system configuration and monitoring process is described, as well as an energy balance of the ground thermal store. The installers have constructed several houses using a similar type of system and one has been analysed [38]. However since the monitoring was quite limited, it was not practical to use this for a detailed scientific investigation.

2. System configuration

The experiment reported in this paper is based on a domestic building owned and used by De Montfort University in Leicester, UK. The project aims to improve the design of future SAGSHP systems by validating models to predict the performance of a shallow vertical SAGSHP system for heating domestic buildings.

2.1. Building description and location

The building in this study is a two-storey late 19th-century house of 70 m² floor area located in Leicester (52.63° N, 1.14° W), UK. It is a terrace (or row) house with shared walls to similar houses either side. Construction is solid brick with timber floors and a pitched timber roof covered in slate tiles. The house is unoccupied since the university uses it for crime scene mock-ups when teaching forensic science. The main heating system of the house features an underfloor system in the two main downstairs rooms (the timber floor here was replaced with a solid concrete floor for this purpose). This floor heating is controlled with a thermostat to maintain the room temperature at 18 °C. The existing heating system (using a gas boiler with radiators) remains available as a backup. Although the house has been retrofitted with loft insulation and modern double glazed windows, it has no insulation on the external solid walls; hence, the thermal loads are much higher than those of modern energy efficient houses. The SAGSHP heating system also includes a storage tank for domestic hot water (DHW). However, the hot water consumption is negligible due to the lack of occupants.

2.2. SAGSHP system

The SAGSHP system consists of eight photovoltaic panels (250 W_p each) of which seven are fluid-cooled PV-thermal (PVT) hybrid panels. The installed electric capacity of the system is therefore 2 kW_p. Table 1 shows the technical specifications of the PVT collectors as provided by the manufacturer. According to them, testing conditions were conducted at an insolation of 1000 W/m², fluid temperature difference of 2 K and wind speed of 0 m/s. From the thermal efficiency curve, to achieve the peak thermal output of 648 W, the temperature difference between the average fluid temperature in the collector and the ambient temperature must be lower than 1.2 K. The PVT collectors are installed in the roof of the house at 40° of inclination facing south-west (azimuth of 60°). The PVT collectors could not be installed facing south as their azimuth is constricted by the roof orientation. The solar thermal energy is transferred to the underground earth energy bank (EEB) via a

heat exchanger. This EEB serves as a low-temperature heat source for a GSHP, which delivers heat to the house to cover the thermal needs for DHW and space heating.

Table 1. PVT technical specifications

PV output (peak)	250 W
Electrical efficiency	15.6%
Thermal output (peak)	648 W
Gross collector area	1.6 m ²
Thermal efficiency	42%
Aperture area	1.5 m ²
Stagnation temperature	78.9 °C
Inclination/Azimuth	40°/60°

A schematic of the system is shown in Figure 2. There are three fluid loops: the solar loop, the low temperature source (ground) loop and the heating (storage tank or radiant floor) loop. Whenever the temperature at the outlet of PVT collectors is 7 °C higher than the soil temperature, the solar loop pump is activated. The heat gained through the PVT collectors is then transferred to the ground loop through a heat exchanger. The working fluid in the ground loop circulates through a series of 16 U-tube vertical boreholes (of 1.5-metre deep) transferring heat to the EEB (soil). If the heat pump is turned off, then the fluid recirculates and continues with the soil recharge from the solar system until the temperature difference between the ground and the output of the PVT is lower than 4 °C. Hence, the hysteresis for the control system is 3 °C.

If the outlet temperature of the PVT collectors is lower than the soil temperature, the solar loop pump is deactivated, and if heat is demanded, the ground loop pump will transfer heat from the EEB to the evaporator. By doing so, the soil will discharge the stored thermal energy, which would be replaced when solar energy becomes available again.

Figure 2. Schematic of the system configuration

2.3. Ground heat exchanger

The GHE consists of an array of 16 short boreholes which were connected in series (Figure 3). The distance between adjacent boreholes is 1.5 m except for distances between boreholes B1-B2, B10-B11 and B15-B16 (see Figure 3) which are spaced 1 m. The EEB, which is used as a thermal store, could not be built within the foundations of the house. Instead, it was installed in an adjacent grass verge under a surface of the same footprint as the house (10 m x 4 m). The EEB is insulated with polyisocyanurate on the top (20 cm) and sides (10 cm). The insulation has a thermal conductivity of 0.021 W/mK and a 0.3 mm polyethylene sheet is placed above the insulation to protect it from water. For a new build installation, the GHE would be located beneath the insulated solid ground floor, so it would lose very little heat loss from the top surface. The EEB has concrete sides (10 cm thick) between the insulation and the surrounding soil. The concrete represents the building foundations in a real situation. Additionally, the concrete will help to prevent groundwater flows which can be prejudicial for heat storage. The thermal properties of the soil were determined by a thermal response test conducted on site prior to building. The boreholes (15 cm diameter) are filled with thermal grout (bentonite). The working fluid for the solar and the ground loops is glycol (30% volume) and water is used for the heating loop. The thermal properties of the soil and the working fluid are shown in Table 2.

As stated above, the heat pump satisfies demand for both space heating and domestic hot water (DHW) heating. Its heating capacity is 3 kW, which is approximately enough to cover the demand from a well-insulated small dwelling in the UK [39]. The heat pump stores the heat for DHW in a 200-litre water tank. Table 3 shows the technical specifications of the heat pump.

Figure 3. Vertical and horizontal cross-section view of the GHE with temperature sensor location

Table 2. Soil and working fluid thermal properties

Type of soil/fluid	Wet clay	Glycol (30%)
Thermal conductivity	1.5 W/mK	0.45 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	1.11 x10 ⁻⁷ m ² /s

Table 3. Heat Pump technical specifications

Manufacturer	Vaillant
Heating capacity	3 kW
Max. power input	1.1 kW
Source inlet temperature range	-10 to 20 °C
Source circuit fluid	Ethylene glycol 30%
Source flow rate	620 l/h

Heating circuit output temperature range	20 to 55 °C
Heating circuit flow rate	250 to 465 l/h
Refrigerant	R410A

2.4. Monitoring system

There are four different sources of experimental data. Each of these provides information about the main parameters that represent the behaviour of the whole system. This information is useful for the development of thermal models, energy balance analysis and determination of the efficiency of the system.

2.4.1. Earth energy bank temperature data

Temperatures of the EEB were measured at several locations using PT1000 resistance temperature detectors (RTD) sensors. PT1000 were used to minimise errors due to the length of the wires from the monitoring point to the data logger. A total of 48 RTD sensors were placed at different locations of interest around the EEB, as described in Table 4. These temperature data were logged with a NI cDAQ 9133 32-bit National Instruments data acquisition system via Labview [40]. PT1000 were connected through a NI9226 interface module. Signals were sampled every 15 minutes and were recorded from 10th February 2016 till 31st December 2017. Sensors were calibrated before installation and the margin of error in these measurements was calculated to be ± 0.3 °C. Figure 3 shows the location of the sensors (1 to 14) and Table 4 describes the depths of temperature monitoring of each sensor.

Table 4. Sensors location and depth of measurement for the cDAQ system

Sensors point	Location	Depth of measurement
1	9 m away from the EEB wall	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 (two measurement points)
13	Inlet flow temperature	0.75 m
14	Outlet flow temperature	0.75 m

2.4.2. Solar thermal system data

The RESOL VBus system was used to record temperature and flow rates of the thermal part of the SAGSHP. The data were monitored at a time step of 5 minutes and stored online. Real-time access to system monitoring can also be conducted. The system has nine temperature sensors (type K thermocouples) that record the temperature of the working fluids (solar loop, heat pump coolant circuit, EEB fluid temperature and solar output temperature). Likewise, flow rates of the solar loop and the heat exchanger loop were recorded. These variables (temperature and flowrates) were recorded from 4th June 2016 and been used to determine the heat fluxes of the system. Additionally, a half-hourly electricity sensor was used to monitor the electricity consumption of the heat pump. Figure 4 shows a schematic of the system as displayed on the *VBUS.net* portal showing the locations and typical readings of the installed sensors.

Figure 4. VBUS monitoring system and sensors location

2.4.3. Solar PV and PVT generation data

SMA's Sunny Portal application was used to record the electrical performance of the solar PVT collectors. Each panel has its own micro inverter, and Sunny Portal is capable of collecting data from each of these at 15-minute intervals and storing the data online. It can also display the electrical performance data in real time.

2.4.4. Weather data

Weather data are essential for this research, and are monitored from a weather station located on the roof of The Gateway House Building on De Montfort University campus (250 m from the experimental 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 5 shows the monthly solar insolation and ambient temperature from the actual data monitored from June 2016 to December 2017.

Figure 5. Monthly average ambient temperature and solar insolation from the monitored data

2.4.5. Uncertainty analysis

Before performing any analysis of the calculated heat fluxes involved in the EEB, an uncertainty analysis was conducted on the calculated parameters considering the errors in the measurement instrumentation. Firstly, the whole set of temperature and flow rate data was hourly averaged. Outliers were discarded and linear interpolation was used to fill in any missing data. The data acquisition systems for both the EEB temperature data (NI cDAQ unit) and the solar thermal system (RESOL unit) have a mathematical function for calibrating all channels, which compensates for any inaccuracy. For both systems, the temperature sensors, RTD and type K thermocouples, were calibrated in thermal baths at different temperatures and the readouts were matched with the bath temperatures. Pulse flow meters were connected to the RESOL unit verifying that every voltage pulse recorded matches with the display in the flow meters. The thermal conductivity of the soil was obtained through a thermal response test during a soil survey campaign of 54 samples of soil at different depths. The observed maximum deviations were used to estimate the uncertainty of the calculated parameters using Equation 1 [41], [42], where R is the calculated parameter, ω is the uncertainty, x is the measured value of the primary variable i , and a is the exponent of the primary variable in the function of the calculated parameter. More details on the process to conduct uncertainty analysis can be found in [42]. Table 5 shows the details of the uncertainty of the primary variables and the main calculated parameters.

$$\frac{\omega_R}{R} = \left[\sum_i \left(\frac{a_i \omega_{xi}}{x_i} \right)^2 \right]^{1/2} \quad (1)$$

Table 5. Uncertainty in measured and calculated data

Parameter	Range	Max. Uncertainty
Fluid inlet and outlet temperature	-3 to 45 °C	0.23°C
Soil temperatures	0 to 20 °C	0.2°C
Volumetric flow rate	100 to 500 l/h	7.5 l/h
Thermal conductivity	1.44 to 1.64 W/mK	0.04 W/mK
Heat flow in the ground heat exchanger	-2000 to 2000 W	30 W
Heat flow by conduction in the ground	-100 to 180 W	4.93 W

3. System analysis

3.1. Control System and Energy Fluxes

The earth energy bank (EEB) is viewed as a sub-system that interacts with the solar sub-system and the heating sub-system (HP evaporator side). Consequently, the whole system's performance can be assessed through the EEB sub-system. Figure 6 shows the EEB boundaries and the energy fluxes involved in it. The system is insulated at the top and sides and the heat fluxes from these surfaces were found to be negligible (average of -0.17 ± 0.22 W/m² for the top and -0.24 ± 0.18 W/m² for the sides), hence they were assumed to be adiabatic. However, at the bottom of the EEB, heat can be exchanged by conduction with the surroundings. Hence, heat gains or losses occur. Equation 2 shows the general energy balance equation of the EEB.

$$Q_{solar} + Q_{geo} - Q_{eva} - Q_{loss} = Q_{EEB} \quad (2)$$

Heat from the PVT (Q_{solar}) is injected to the EEB while heat demanded by the HP (Q_{eva}) is extracted from the EEB. When solar heat is injected, the ground temperature in the EEB increases and consequently heat may be lost through the bottom of the EEB (Q_{loss}) if EEB temperature rises sufficiently. On the other hand, when heat is extracted from the EEB and the ground temperature decreases, heat may be gained from the surrounding ground through the bottom of the EEB (Q_{geo}). The remaining heat (Q_{EEB}) is the net heat stored (positive)/ extracted (negative) in/from the EEB.

Figure 6. Earth Energy Bank system's boundaries (vertical section); hatched areas insulated assumed adiabatic

Solar heat gains (Q_{solar}) and the heat extracted from the evaporator (Q_{eva}) are calculated using Equation 3 and 4 respectively.

$$Q_{solar} = \dot{m}_{ghe} \times c_p \times (T_{in_{solar}} - T_{out_{solar}}) \quad (3)$$

$$Q_{eva} = \dot{m}_{ghe} \times c_p \times (T_{in_{eva}} - T_{out_{eva}}) \quad (4)$$

In Equations 3 and 4, $\dot{m}_{ghe}$ is the mass flow rate of the glycol in the ground heat exchanger and c_p is its specific heat. The mass flow rate is determined from the measured volumetric flow rate data multiplied by the density of glycol. While it is true that the physical properties of fluids vary with temperature, from a practical point of view this variation can be neglected since it is less than 1.8% in the temperature ranges from 5 to 50 °C [43]. Thermal properties corresponding to a glycol average temperature of 26.7 °C were used in this study. Similarly, inlet and outlet fluid temperatures are the ones from experimental data monitored by the RESOL unit.

A numerical model developed in a previous study [44] was used to compare the temperature profile below the earth energy bank with the far field temperature, at similar depths. It was observed that the temperature profile was similar in both cases at 3.75 m depth. This implies the heat transfer from the borehole heat exchanger had no effect at 1.5 m from the bottom boundary of the earth energy bank (which is 2.25 m deep) and that below 3.75 m the soil temperature is that of the natural soil.

In order to quantify the heat loss from the bottom of the EEB (Q_{surr}), heat conduction analysis was carried out on the volume of soil in the 1.5 m region (i.e. between 2.25 m and 3.75 m) below the EEB. For the boundary conditions, the temperature at 2.25 m (the bottom boundary of the EEB) was

obtained from experimental measurements, while temperatures at 3.75 m were determined from the numerical model in [44]. Fourier's law (Equation 5) was then used to calculate the heat transfer between bottom of the earth energy bank and the natural soil temperature at 3.75 m ($Q_{EEB-Nat}$)

Due to the temperature gradient in the natural soil, heat transfer usually occurs in the vertical direction (Q_{Nat}). This was estimated using Equation 6 and temperatures from the far field soil. The temperature at 2.25 m (in the natural soil) was obtained from experimental measurements. Finally, in order to determine the actual heat transfer at the bottom of the EEB (Q_{surr}), solely resulting from the system, the natural heat transfer Q_{Nat} was subtracted from the total heat transfer ($Q_{EEB-Nat}$) as illustrated in Equation 7.

$$Q_{EEB-Nat} = k_{soil} \cdot \frac{A_{EEB}(T_{EEB_{2.25}} - T_{Nat_{3.75}})}{1.5 \text{ m}} \quad (5)$$

$$Q_{Nat} = k_{soil} \cdot \frac{A_{EEB}(T_{Nat_{2.25}} - T_{Nat_{3.75}})}{1.5 \text{ m}} \quad (6)$$

$$Q_{surr} = Q_{EEB-Nat} - Q_{Nat} \quad (7)$$

From the heat exchanged with the surroundings (Q_{surr}), negative values represent heating losses (Q_{loss}) while positive values represent heating gains (Q_{geo}) as shown in Equation 8.

$$Q_{surr} \begin{cases} < 0 = Q_{loss} \\ > 0 = Q_{geo} \end{cases} \quad (8)$$

3.2. Modes of operation

Using the data monitored, four possible operating modes of the system can be analysed. These are identified and summarised in Table 6. Note that the heat pump is turned on whenever there is a requirement for heating or domestic hot water.

In Mode 1, the PVT-Ground system is operating, but the heat pump is turned off. Hence, in this mode, the heat gained from the sun through the PVT collectors is stored in the EEB, and no heat is demanded by the HP; high heat losses through the bottom are expected in this operation mode. In Mode 2, the heat pump and the pumps of the PVT-Ground system are turned on and the solar heat gained is higher than the heat demand on the evaporator $Q_{solar} > Q_{eva}$. Therefore, the heat gained in the PVT can satisfy the heat demanded by the evaporator (Q_{eva}) and the remaining heat is injected into the EEB. In Mode 3, the heat pump and the pumps of the PVT-Ground system are turned on and the solar heat gained is lower than the heat demand on the evaporator $Q_{solar} < Q_{eva}$. Hence, the heat gained by the PVT cannot satisfy the heat demanded by the evaporator, therefore the remaining heat demand is extracted from the EEB. Finally, in Mode 4, the heat pump is operating and the PVT-Ground system is not operating. As a result, the heat demanded by the evaporator is satisfied by the heat stored in the EEB and by the natural heat gains from the surrounding soil.

Table 6. System operation modes

	Solar thermal pump	Heat Pump	Condition	Consequence
Mode 1	ON	OFF	N/A	Solar energy flows into the EEB

Mode 2	ON	ON	Solar energy > evaporator demand	Solar energy covers evaporator demand, and the surplus flows into the EEB
Mode 3	ON	ON	Solar energy < evaporator demand	Solar energy partially covers evaporator demand, and the EEB supplies the rest
Mode 4	OFF	ON	N/A	EEB supplies all the evaporator demand

4. Results and discussions

4.1. Energy balances of the whole system

The data used for the analysis of the energy balance is the RESOL VBUS data corresponding to the period from 04/06/2016 to 31/12/2017.

Figure 7 shows the hourly values of the EEB inlet and outlet temperature. As expected, the figure clearly shows that in summer (June to September), the heat injection process into the EEB takes place, whereas in winter (November to February), heat is mostly extracted. The difference between the inlet and outlet fluid temperature for summer (heat injection) and winter (heat extraction) is variable, but reaches a value of 3 K at optimal operation.

Figure 7. Inlet and Outlet fluid temperatures in the EEB

Before analysing the energy balances in each system operating mode, it is important to have an idea of the amount of useful heat collected by the PVT collectors relative to the incident solar radiation. For this, the usable solar heat gain was determined from the temperature difference between the inlet and outlet of the PVT and the flow rate of fluid in the solar station loop. The incident solar radiation on the tilted PVT surface (40°) was determined from the global horizontal radiation and the diffuse horizontal radiation by applying Perez's model [45] in TRNSYS software [46]. The results were summed on a monthly basis and are shown in Figure 8. It can be observed the average solar thermal efficiency is around 20%. However, it is important to mention that the usable solar heat gained is limited by the GHE size, which is undersized for the solar PVT system. Normally, at standard test

conditions (insolation of 1000 W/m^2), PVT collectors have a maximal thermal efficiency (η_0) between 40% to 60% [47], [48]. Hence there is much more solar thermal potential that cannot be captured. This problem needs further investigation.

Figure 8. Incident solar radiation on the PVT and actual heat gain

The analysed data corresponds to a total of 13820 hourly observations during which the ground loop pump (either for heat injection or extraction) was operating for 8605 hours. From the whole period of monitored data analysis, the system operated mainly in mode 4 and mode 1 (Table 7). That is, the system operates mainly in just heat injection mode or just heat extraction mode to/from EEB. This behaviour is the most desirable and is the principle of seasonal heat storage. On the other hand, it is observed that the system has a considerable number of hours in mode 2. This mode can be problematic as the fluid temperature entering the heat pump evaporator may be higher than the maximum tolerated fluid temperature, which can trigger an alarm and shut off the heat pump. The operation modes depend only on the actual system status as mentioned in Section 3.2.

Table 7. Hours of operation of the system in each mode

Operation mode	Hours of operation
Mode 1	2246 (26%)
Mode 2	915 (11%)
Mode 3	455 (5%)
Mode 4	4989 (58%)

4.1.1. Mode 1

Figure 9 shows the experimental results of the energy balance on a monthly basis for mode 1 operation. As shown in the figure, mode 1 occurs mainly in the summer period when the usable solar gain is high, and the heat pump load is low, with heat injection to the EEB. A mirroring trend (between the solar heat and stored heat) can be observed in the figure. The solar thermal potential might be higher however the size of the GHE limits the solar heat that can be actually stored. Minor heat losses can be observed in the summer months, while in the transition period (March-April), there are some heat gains from the bottom of the EEB. In June to August, between 230 and 280 kWh of thermal energy is stored in the EEB.

Figure 9. Monthly heat fluxes: Mode 1

4.1.2. Mode 2

Figure 10 shows the experimental results of the energy balance on a monthly basis for mode 2. This indicates that the system rarely operates in mode 2. However, in certain cases, while heat is being transferred from the PVT to the EEB, there may be small requirements for domestic hot water or space heating. For example, taking a shower on a sunny day, and in such conditions, the demand for heat at the evaporator is met by the solar energy obtained directly from the PVT. To prevent damage to the heat pump, this mode should be avoided if the solar output temperature is higher than 20°C. The heat pump is designed to trip out when a fluid with excessive temperature is supplied to the evaporator, but this prevents the required heat from being delivered, and the pump does not reset when the evaporator inlet temperature reduce. To solve this problem, a three-way valve could be used in order to continue circulating the fluid in the PVT loop while heat is being extracted from the EEB to cover the heat demand. As seen in the figure, the majority of mode 2 heat transfer occurs during the transition period (i.e. from summer to winter or vice versa) and the average amount of heat going into the EEB per month is 50 kWh. It can be observed that in April and May, for mode 2, the solar output delivered to the evaporator is higher than the summer months because, there are still heat requirements in the building.

Figure 10. Monthly heat fluxes: Mode 2

4.1.3. Mode 3

Figure 11 shows the experimental results of the energy balance for mode 3 operation, which is an unusual mode of operation, similar to mode 2. There are very specific cases where the system

operates in this way, mainly in the transition periods. This can occur when heating demand exists during a period of low solar input, in which case some of the heat demand is met by heat stored in the EEB. It can be observed that in mode 3 there are minimal heat losses as in this mode the EEB is expected to be colder than the surrounding soils. Consequently, there are heat gains from the surrounding soil.

Figure 11. Monthly heat fluxes: Mode 3

4.1.4. Mode 4

Figure 12 shows the experimental results of the energy balance on a monthly basis for mode 4 operation. The figure shows that mode 4 is very common and occurs mostly in winter. In this mode, the system extracts heat from the EEB, most of which has been stored during the summer months in mode 1. Similar to mode 3, some amount of heat is gained from the surroundings in winter months. During winter months, from 150 to 340 kWh of heat are extracted from the EEB per month.

Figure 12. Monthly heat fluxes: Mode 4

4.1.5. Total data

Figure 13 shows the system performance under all the operating modes. During summer, the system mostly stores heat in the EEB and during winter the heat is mostly extracted from the EEB. It is also observed that during summer (June, July and August) there is occasional heat demand in the evaporator, (related to domestic hot water) that is supplied mainly by the solar panels. During the months where the thermal load from the evaporator is higher and solar energy availability is low (October to January), most of the heat is supplied by the EEB (seasonal stored heat). During the

months were the evaporator demand is high and there is solar energy availability (February to May), Most of the heat demand is directly supplied by the solar energy gained through the PVT collectors. An unusually low heat demand from the evaporator can be seen between December 2016 and March 2017. This is because the backup heating system (boiler and radiator) was enabled and the total heating load was partially covered by this system. This certainly has an impact to the total amount of heat extracted from the EEB during that period. However, it is also important to mention that the heating system was enabled 24 hours during the whole period for research purposes. In a real operation of the system, a standard control strategy will be used in which the heating system is limited by the building occupation schedule. Thus, the amount of heat that would be really extracted will be lower than in this experimental research project. Regarding the total energy balance during the whole period of analysis, it is worth mentioning that about 18% (0.87 MWh) of the input energy comes from geothermal energy and 82% (3.97 MWh) from solar energy. Likewise, the HP directly uses about 54% (2.6 MWh) of the input energy while 46% (2.24 MWh) is stored in the EEB. The total heat lost during the whole period of analysis is 6% (0.29 MWh). Figure 14 shows the Sankey diagram of the total energy use.

Figure 13. Monthly heat fluxes: All modes

Figure 14. Sankey diagram of the total data analysed

Regarding the performance of the heat pump unit, the seasonal performance factor (SPF), which is the ratio of the energy output and the electricity input, was determined. For this calculation, only the electricity demanded by the heat pump was considered. An average monthly SPF of 2.51 was determined during the whole period of analysis. The monthly SPF reached the lowest value (2.01) in December 2016. This is mainly related to the low temperature of the EEB due to the accumulated

heating extraction. Figure 15 shows the monthly values of the SPF of the heat pump. The heat pump only works in heating mode, so the SPF shown in summer months are mainly related to cold nights during summer. This SPF is higher compared to the winter SPF mainly due to the average temperature in the EEB. The higher the source temperature, the higher the heat pump COP.

Figure 15. Monthly Seasonal Performance Factor (SPF) of the heat pump unit

4.2. Earth energy bank thermal performance

In this section, an analysis of the thermal behaviour of the ground store (EEB) is conducted. Figure 16 shows the temperature variation of the soil outside the EEB (sensor 1) at different depths (0.75 m, 1.25 m, 1.75 m and 2.75 m), i.e. the natural temperature variation of the soil. According to the data measured, the natural heat recharging of the soil occurs from mid-March to mid-September, where the maximal temperature of the soil at 2.75 m is slightly higher than 15 °C. On the other hand, the natural discharging of the soil occurs from mid-September to mid-March and the minimum 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 natural annual temperature oscillation is around 5 K, which is small enough to not seriously reduce the performance of the heat pump.

Figure 16. Natural soil temperature variation, sensor 1

The heat stored in the EEB, and the temperature variation of the soil in the EEB and the thermal grout (bentonite) are both directly related to the PVT output temperature. Figure 17 shows the temperature variation of the soil in the centre of the EEB at 1.25-metre deep, the temperature of the 16th borehole wall and the PVT output temperature. As seen in the figure, from March to the beginning of July the temperature of the EEB mainly increases. From September to December the EEB mainly discharges heat and the temperature falls. A transition occurs in the periods July-September and December-March. These transitional periods might vary from one year to another, as they will depend on the seasonal conditions as well as the thermal loads of the building.

Likewise, Figure 18 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 seen. For example, at a depth of 1.25 m, the EEB reaches a maximum temperature of 19 °C which is about 4 K 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 K lower than the natural soil at the same depth. At higher heating extraction rates, the ground in the centre of the EEB might reach temperatures below 0°C. This phenomenon can cause volume expansion due to the water freezing. However, the foundations will not be compromised as long as the boreholes are not placed very close to them. On the other hand, experimental 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.

Figure 17. Main temperature variations of the SAGSHP system

Figure 18. EEB and natural soil temperature variation

Figure 19 compares the temperature measurements at either side of the EEB insulation with the distant soil temperature (sensor 1) as a reference. The insulation reduces the heat exchange with the soil surroundings. In summer 2016, there was about 1 K temperature difference across the insulation (higher inside the EEB), while in summer 2017, the temperature inside the insulation remains very close to the temperature outside the insulation. In contrast, in winter months the inside temperature is lower (up to 3 K) than the outside temperature. This implies that the insulation prevents EEB from gaining heat from the surrounding soil on the sides in the colder months. As the EEB is not insulated at the bottom, most of the heat exchange with the surrounding soil occurs at the bottom. For this reason, it is important to analyse, in greater depth, the advantages and disadvantages of the insulation in the EEB as future research work.

Figure 19. Soil temperature variation inside and outside the insulation

Finally, it is important to highlight some points regarding the performance of the thermal energy store with shallow boreholes. The thermal storage capacity of the EEB depends on the volumetric heat capacity of the soil, the volume of the EEB and the temperature difference between the beginning and the end of heat injection/extraction. The volumetric heat capacity has a value of 2.16 MJ/m^3 , and the volume of the EEB is 80 m^3 . Considering that 57% of the heat demanded by the evaporator is covered directly by the heat gained through the solar collector (Figure 14), the EEB has to cover only the remaining heating demand. Furthermore, Figure 17 shows a very dynamic temperature profile in the borehole wall, therefore, the operation of the system is also dynamic with regards to the heat injection and extraction (i.e. significant heat can be injected and extracted on the same day or month). Consequently, the EEB acts like a buffer to balance the variable heating demand in short time periods and is not a volume to store all the heat required during the entire heating season.

5. Conclusions

In this paper, the performance of a shallow experimental SAGSHP for residential heating applications has been analysed. The system performance was studied from data collected over 19 months. The main innovation of this system is the use of a shallow (1.5-metre deep) ground heat exchanger, which is used as a seasonal thermal store known as an earth energy bank (EEB). During the time of operation, the system was able to inject 2.24 MWh from the solar energy into the ground to help not only in covering the evaporator demand in winter, but also to prevent/recover the ground from having a thermal imbalance all through the year. The experimental data also showed that the system exchanges heat with the surroundings. In the cold months, the soil in the EEB actually gains heat from the surrounding soil underneath it, while in summer, heat loss from the bottom was observed. During the transition periods (from summer to winter and vice versa) most of the evaporator demand was directly supplied from the usable solar energy gained through the PVT collectors. This operation mode must be analysed in detail, and a solution that avoids fluid with excessive temperature from entering the evaporator of the heat pump should be investigated. The EEB soil temperature, at a depth of 1.25 m , was observed to be up to 4 K higher than the natural soil temperature at the same depth. Likewise,

during the heat extraction period, the EEB soil temperature drops to only 2 °C. Without solar recharging, the temperature in the soil might reach temperatures below 0 °C, freezing the soil and affecting the overall system efficiency as well as causing volume expansion issues. This system configuration is worthy of further study because the use of shallow boreholes implies considerably reduced costs of installation of a SAGSHP system. The main results show that, despite the use of shallow boreholes, the system was able to operate at a SPF comparable to conventional GSHP systems. Indubitably, shallow boreholes would not be a good choice for large buildings, however, for the low-energy domestic sector, where the peak heating load are typically below 20 W/m², shallow boreholes seems to be an affordable and feasible solution to cover heating loads. The experimental data analysis has also indicated some key areas for further study. For example, it was evident that the rate of heat output from the PVT collectors is often much higher than the capacity of the GHE to absorb it into the ground, causing stagnation of the system. It is important to study other ways to match the storage capacity with the installed PVT as well as increase the rate of heat transfer to the EEB. As seen in the results, the actual solar output is not only limited by the efficiency of the PVT but also by the size of the GHE. Likewise, some improvements in the control strategy could be made to avoid high-temperature fluid entering the evaporator. The results indicated that the vertical insulation around the EEB helps in reducing heat losses during the charging period, but also prevents the natural recharging from the surrounding soil in winter months. Hence further research is needed in order to determine whether insulation around the EEB is actually beneficial. Overall, further numerical modelling and simulation of the entire system is needed to optimise its design and operation of individual sub-systems.

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