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RENEWABLE ENERGY COMBINED WITH SUSTAINABLE DRAINAGE: GROUND SOURCE HEAT AND PERVIOUS PAVING.

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ABSTRACT

Taken individually, Ground Source Heat (GSH) pervious paving systems (PPS) and rainwater harvesting are not new, but in combination, this energy-water blend is relatively recent. Sealed with impermeable geomembrane, PPS becomes a water harvesting tank and by installing GSH collectors in the base, there is the potential to sustainably heat and cool buildings, provide flood resilience and improve water quality.

A review of the literature found that Coefficients of Performance suggest that such systems could be considered viable, reaching the value of 2.875 required by the EU Renewable Energy Directive, 2009. Small-scale laboratory-based test rigs of the combined system were able to reduce pollutants by up to 99% for biological oxygen demand and 95% for ammonia-nitrogen, with rare occurrences of potentially pathogenic bacteria e.g. *Legionella*, and low survival rates of *E.coli*.

Whilst test rigs provide valuable information, field monitoring at the building scale is the only way to validate the technology. Thus, this paper presents previously unpublished results of monitoring a combined system at the building scale which found that there is clear potential to use a clean, renewable and sustainable source of heat at the same time as providing flood resilience, water quality improvements and some amenity in a domestic setting. However, it was also found that seasonal changes and building use affected levels of comfort achievable. Lessons were learnt, such as construction strategies to optimise design, including depth of the heat collectors and the optimal surface area of the PPS available to infiltrate water.

Keywords: Ground Source Heat Pumps; Pervious Paving Systems; rainwater harvesting; water quality; Coefficient of Performance; sustainability; resilience.

Abbreviations used:

GHG: Greenhouse Gas

GSH: Ground Source Heat

GSHP: Ground Source Heat Pump

PPS: Pervious Paving System

SuDS: Sustainable Drainage System

WWTW: Waste Water Treatment Works

1. Introduction

In order to provide resilience to the effects of change and for it to be sustainable in the long term, interventions need to have multiple benefits and be flexible. Simply addressing individual or relatively few outcomes is inefficient and restrictive in terms of the impacts. This paper has two principle foci: the provision of a renewable, sustainable source of energy coupled with resilience to flooding at the building scale.

Global demands for energy, a large proportion of which is used for electricity [1], are increasing and are likely to continue to do so. Factor in such concerns as the likely depletion of fossil fuels, upon which much of the world depends for its' energy, associated pollutant emissions such as the increase in Greenhouse Gas (GHG) emissions which Li and Lin [2] estimated to have increased by 80% between 1970 and 2004 and De Boeck et al., [3] predict will rise by a further 52% between 2005 and 2050, as well as the far-reaching impacts of global climate change, and a scenario is created whereby seeking alternative sources of energy becomes urgent [4, 5]. Many governments are encouraging the use of renewable energy, and in February 2014, the European Parliament voted to increase the percentage of Member States' energy to come from renewable sources from 20% to 27% by 2020. Shafiei and Salim [5] suggest that investing in renewable sources of energy in general has the potential to reduce GHG emissions, CO_2 in particular. An abundant and constantly renewable source of energy is that from the ground, or Ground Source Heat (GSH), the extraction of which is said by Self et al., [1] to be relatively easy. In a review of the systems used for extracting and concentrating this heat (GSH Pumps, GSHP) Omer [4] states that it is: "highly efficient renewable energy technology" which can be used for both heating and cooling buildings. Whilst when extracted, the temperature of this heat is relatively low, once concentrated [1, 4] the heating it provides is "environmentally and economically advantageous" [1]. Omer [4] also suggests that GSHPs are suitable for any kind of building worldwide, and are particularly suited to underfloor heating. Furthermore, specifically extracting GSH has the potential to reduce CO_2 emissions and hence mitigate the impacts of climate change [6]. Whilst using this technology has been predicted by Bayer et al., [6] to save up to 30% of GHG emissions in comparison with conventional heating methods across Europe, this is dependent on the efficiency of the pump, the electrical mix and the substituted heat. These potential savings are country-specific and depend on a saturated market for the technology and the use of renewables (e.g. solar or wind) to provide power for the pump. A problem with their use in dense urban settlements may be a lack of space; thus the ability to integrate it with other technologies to provide multiple benefits and flexibility in application needs to be explored.

Extraction of GSH is particularly flexible in that it can be harvested from the soil and also surface waters, such as rivers, streams, lakes and wetlands [7]. It can also be installed vertically using boreholes, or horizontally in the form of slinky coils laid in the bottom of a trench. However, vertical boreholes are expensive, and horizontal slinky coils require a reasonably large area to be excavated [4], which might limit their use, particularly in dense urban areas. If integrated with Sustainable Drainage Systems, or SuDS [8], there are opportunities for horizontal slinky coils to occupy the space already provided by a variety of individual devices and management trains. SuDS mimic nature in order to address the impacts of urbanisation on the storm hydrograph of short reaction times and “flashy” catchment responses, leading to flooding and pollution. They achieve this by allowing water to infiltrate or be stored and then conveyed slowly to the receiving watercourse [8, 9] utilising hard infrastructure, such as Pervious Paving Systems (PPS) or vegetated devices, such as swales, filter strips, wetlands, green roofs and walls [10, 11]. PPS are hard infiltrating structures which provide running or parking surfaces for vehicles as well as pedestrian pavements [12]. They are particularly well suited to hosting a GSHP as they require a trench in which the pump can be installed, and furthermore, if the PPS is used as a parking space to the front of a property, they will not use any extra space.

Neither GSH nor SuDS are new approaches taken separately, however designing them together, making use of a renewable source of energy as well as finding a secondary use for excess surface water which would otherwise be directed to the storm sewer, is relatively new, and a timely development. In fact, Tota-Maharaj and Paul [13] call this infrastructure the “next generation” of PPS. Laboratory experiments with model test rigs have indicated the potential for this technology, but there has been very little information published at the building scale. Previously unpublished data from a combined GSHP and PPS system in a domestic setting are presented, which enables a thorough critique of these approaches to be achieved, with further recommendations made, based on their combined potential.

2. Pervious paving systems and ground source heat

PPS attenuate the storm peak by reducing water quantity and slowing water flow, but also improve water quality as well as providing some amenity benefits [14]. By reducing the volume of water needing to be managed by the storm sewer system and consequently passed through the Waste Water Treatment Works (WWTW) [8], there are positive changes in the hydraulics of the sewer; the frequencies of overflow and their durations are reduced, and ultimately the fraction of wet weather flow that arrives at the treatment plant [15]. Taken overall, these effects will reduce the energy required to treat this excess water and hence reduce GHG emissions [16].

The surface course of PPS can comprise permeable block pavers, porous asphalt, concrete or resin, generally with the underlying bedding layer divided from the coarse aggregates beneath by means of a geotextile (see Figure 1). Further details of the various PPS structures and their functions in terms of water quantity reduction, water quality improvements and amenity provision can be found in [9, 12, 14].

Figure 1 here

PPS are usually no more than 500mm deep, and can be “tanked”, or sealed, by means of an impermeable membrane, enabling them to harvest incident rainfall, roof or surface water runoff, hence providing a suitable environment for the installation of heat collectors. Below 3m depth in the ground, the temperature only varies between 6-13 °C throughout the year [17]; however, at approximately 500mm below the surface, within the aggregate sub-base of the PPS, the temperature is affected by seasonal temperature changes, as was found by Novo et al., [18]. It is still perfectly possible to harvest this shallow heat by means of a liquid, usually an ethylene glycol mix (anti-freeze) or sometimes brine, contained in pipes which circulate the heat into the building via a pump into a radiator system or underfloor heating (heating cycle) [4]. It is also possible to return heat to the ground store in times of excess in a building (cooling cycle). By keeping the buried heat exchanger apparatus wet, by means of harvesting rainwater, heat removal or return is more efficient since heat is transferred from water more effectively than from either air or soil. The finding that relatively wetter conditions have a positive effect on the performance of a GSHP has been supported by results obtained in other studies such as Tarnawski et al., [19].

The distribution of heat in PPS at the field-scale suggested that evaporation of water within the sub base, and the thermal properties of the surface course were the most important factors in designing a combined GSHP+PPS [18, 20, 21]. Application of these properties have resulted in the development of “cool” or “wet” pavements (e.g. [8, 22, 23]) achieved by designing the surface of the PPS so that it more efficiently transferred solar energy down into the structure, thus enabling evaporation to occur e.g. by making the surface a lighter colour. By applying cool pavement technology to GSHP+PPS the transfer of heat from the overlying atmosphere could be made more efficient, improving the performance of the combined system overall. Modelling of temperature and energy balances in these paving systems by Tota-Maharaj et al., [24], further developed the ability to optimise the design of the heat extracting PPS by determining slinky coil size, tank volume and energy efficiency.

3. Water quality at the laboratory scale

The main focus for laboratory-based experiments of the combined system were concerns regarding the impact on water quality of harvesting heat in the sub-base of a PPS [13]. Standard water quality determinands such as metals, nutrients and hydrocarbons have been assessed, but it was pathogenic bacteria such as *Salmonella* spp., *Escherichia coli*, faecal *Streptococci* and *Legionella* which were of most concern [18, 25, 26]. In order to address the latter, experiments were carried out by Scholz and Grabowiecki [27] where a mixture of gullypot liquor and dog faeces were applied to the surface of test models, attempting to mimic the most extreme conditions the combined system would face in the environment. These experiments found that it did not appear that the microorganisms of concern survived in the PPS environment, in spite of them being spiked with the dog faeces. Also, Coupe et al., [26] did not find *Legionella* in the test rig effluent, which, whilst not a faecal pathogen, could have been encouraged to grow by stored and heated water; there was similarly no growth of faecal *Streptococci* as well as small numbers of *E. coli*. Removal rates for other potential pollutants were also found to be high as shown in Table 1. Thus, concerns of whether combining GSHP with the harvesting of rainwater in a PPS would compromise the water treatment capability of the PPS and the survival of potentially toxic microorganisms associated with GSH extraction were largely addressed at the laboratory-scale. However, these experimental rigs were not installed into the ground and relied for their source of heat on aquarium heaters to simulate GSH. Whilst this enabled experimental control to be exerted, it did not mimic the real-life seasonal and operational variations which would be experienced.

Whilst the potential of the combined GSHP+PPS is obvious, the question of whether the combination would be able to transfer heat efficiently to where it was needed at the domestic building scale had not been answered. Thus, the following sections critically evaluate the efficiency of the system in a first of its kind monitoring of a domestic house fitted with the GSHP+PPS allowing recommendations to be made regarding real-world application of the technology.

Table 1. Percentage removal rates for chemical and biological pollutants in combined GSHP+PPS at the laboratory scale, test rigs located inside and outside where indicated.

Study	**Pollutant**	**% Removal Rate**
[28]	Biological Oxygen Demand	85-99
	Ammonia-nitrate	80-99
	Orthophosphate phosphorus	Outside: 58-95
		Inside: 79-96
	Suspended sediment	40-62
[29]	Turbidity	90-98
	Chemical Oxygen Demand	88-93
	Microorganisms	**% Removal Rate**
[26]	*E. coli*	Outside: 82-97.5
		Inside: 82-97.5
[30]	*E. coli*	97.6
	Faecal *Streptoccoci*	98.5
	Total Coliforms	99.1

4. Building-scale combined system

The first building to have a combined GSHP and PPS which would provide a means of heating was the Hanson Ecohouse built on the Innovation Park at the Building Research Establishment (BRE), Garston near Watford, UK (Figure 2). As was found by De Boeck et al., [31], solar systems and heat pumps were the leading renewable technologies according to literature focussed on the improvement in the energy efficiency of domestic buildings. Case study location was also found to be important, with the climatic context of the building monitored in the present study located in the temperate zone, UK. There are case studies, however, of utilising the technologies separately under different climatic regimes e.g. GSHP use worldwide [32] and PPS in the Mediterranean [20] which suggests that if they are designed correctly, the combined system should be applicable elsewhere other than temperate zones.

Figure 2 here

Finished in 2007, the Ecohouse is a detached two-storey, three-bedroomed, fully-furnished domestic dwelling, with a total internal floor area of 143m^2 (Figure 3). Whilst Figure 3 shows PPS to the north and west of the Ecohouse, Figure 4 shows that the combined system was some 30 metres to the SE of the house itself; Figure 1 shows its structure.

Figure 3 here

4.1 Details of the combined GSHP+PPS at the Ecohouse

Due to ground conditions at the site, including rubble from a previous construction, which may be encountered in many urban areas, the PPS could only be excavated to a depth of 350mm. Whilst this was not optimal, nonetheless it was predicted that up to 6 KW of heating or cooling energy could be produced from the 65 m^2 surface area of GSHP+PPS (a volume of 22.75m^3), which should have been sufficient to maintain a comfortable year round temperature. The heat exchanger used was a horizontal slinky pipe in which anti-freeze (a proprietary ethylene glycol/water mix of no more than 30 % ethylene glycol by weight) was circulated using an electric mains powered pump, with a low flow rate of 1.08 m^3 h^{-1}; the pipe was 50mm diameter, 150m long and installed into the sub-base of the PPS. Slinky coils or ground loops are space-efficient [4], and thus suitable for dwellings with limited open space in which to lay the overlapping pipe coils [33], for example a driveway to the front of the property. The GSHP+PPS was tanked by means of an impermeable 1mm thick geomembrane, but should the tank have become full, excess water was allowed to drain into an adjacent swale to avoid it overflowing.

Figure 4 here

The electric, closed loop water to water heat pump was located inside the EcoHouse; however, with a performance coefficient of 4:1, the use of electricity was justifiable and in future commercial applications, it could be replaced with solar, wind, or other renewable energy sources. Table 2 shows the specifications for the heat pump, which, at 8kW, was oversized and had many power outages during the study period. This led to the pump being unreliable at times as well as more energy being used than was actually required, leading to inefficiencies in heating. The heat distribution system was located in the Ecohouse, with the heat generated distributed by under-floor heating to the ground floor which [4] considered an "ideal partner" for GSHP due to the low water temperatures UK radiators and boilers usually run at.

Table 2. Manufacturer and model of the heat pump

Manufacturer:	Water Furnace Company
Performance standard	AHRI/ASHRAE/ISO 13256-2
Type:	Envision Series – NDW unit
Capacity:	8KW
Antifreeze	Ethylene Glycol

4.2 Measurement of Ecohouse and PPS temperature and water depth in the tank

In order to assess the performance of the GSHP+PPS, the temperature in the habitable spaces of the house, exterior and internal walls were monitored continuously for 3 years (March 2008 to November 2010), as were the air and subsurface temperatures above and below the surface of the pavement (15 sensors in total). Temperatures inside the house were monitored at 10 minute intervals using constantan (copper/nickel alloy) thermistor sensors (34970A Agilent data acquisition system) embedded into the walls in panels on all four sides of the house (North, South, East and West). The data generated (>1.5 million data points in total) were sent to a Tridium Java Application Control Engine (JACE) 200 logger system via an ultra-high bandwidth fibre connection to a Community Digital Management Centre based in the BRE Visitors Centre. The data were then downloaded to a PC DOS format.

Water depth in the PPS tank was measured in order to assess whether the levels were sufficient to completely cover the slinky coils via a vertical pipe well installed down to the base of the tank.

5. Results and Discussion

5.1 Measurement of temperature inside the Ecohouse

Over the monitoring period, the mean temperature inside the Ecohouse was 20.2°C, whilst the average outdoor temperature was 12.6°C. As a mean, the indoor temperature would be considered “comfortable” by CIBSE [34], which recommends a range of 19.5±0.5°C in winter and 21±1°C in summer. However, examination of the mean daily temperatures inside the house (Figure 4) shows how variable the temperatures were with more readings outside of CIBSE’s [34] “comfort” levels (ie either too warm or too cool) than were within them. Figure 5 also shows how closely indoor temperature followed that outside, although indoor temperature was as much as 15°C warmer than the outside temperature. However, winter 2008-2009 was one of the coldest in the UK for many years [35] and results indicated that the combined system was capable of functioning adequately under such cold conditions.

Figure 5 here

Results do show, however, that thermal stability was not established inside the house. Reasons for this included the fact that it was a demonstration house, part of a national sustainability exhibition, and thus visiting groups opened and closed the doors and windows during the daytime, disturbing the heat in the house. It was found on other occasions that the thermostat had been reset, the pump switched off or that there had been some kind of equipment failure.

5.2 Calculation of GSHP efficiency: Coefficient of Performance (CoP)

The efficiency of a GSHP is measured by calculating its CoP in the heating cycle or $CoP_{heating}$ (Formula 1) and its Energy Efficiency Rating, EER or $CoP_{cooling}$ in the cooling cycle (Formula 2).

Formula 1	Formula 2
$CoP_{heating} = \frac{T_{high}}{T_{high} - T_{low}}$	$CoP_{cooling} = \frac{T_{low}}{T_{high} - T_{low}}$

The focus for this paper is for the heating cycle, so any further reference to CoP will therefore be $CoP_{heating}$. The higher the value of CoP, the more efficient the system, thus a value of 5 would represent an output at the heat pump 5 times the electrical input, or an efficiency of 500%. Typical CoPs for geothermal systems are generally between 3 and 5 (Table 3), although values of up to 6 have been reported in the literature [e.g. 32, 36].

Table 3. Comparison of the efficiencies of a.) various heating systems with GSHP (after [1]) and b.) experimental test rig efficiencies of the combined system [25] measured using their CoP

A. Heating System	**CoP**
GSHP	3-5
Air Source Heat Pump	2.3-3.5
Electric baseboard heaters	1
Mid-efficiency natural gas furnaces	0.78-0.82
High-efficiency natural gas furnaces	0.88-0.97
B. GSHP+PPS test rigs	2.4-4.9

There were 351 days during the 3 years of monitoring when the house was heated by the combined system, of which complete datasets were available for 163 days across all 3 years and covering most of the 36 months. Analysis of these 163 days revealed that CoP varied according to season with the highest recorded for Autumn and the trend in values increasing as the ground temperature increased, thus the lowest CoPs were for Winter into Spring and highest in late Summer into Autumn (Figure 6). However, as is reflected in Figure 6, the mean CoP for the 3 years of monitoring was 1.8, lower than the 2.875 required to be classified as renewable under the EU Renewable Energy Directive; it was exceeded from late summer to early Autumn, but including the energy demand for the pump may account for the low CoP during the winter months where the ground was frozen (known from collected data and visual inspection). Calculating the CoP based on those days where heating to the house was only supplied by the combined system, i.e. ground temperatures were >1^{o}C, resulted in a CoP of 2.3, still lower than the EU requirement, but nonetheless the potential is clear.

Figure 6 here

There have been a few studies of the performance of just horizontal slinky coil GSHPs at the building- or room-scale and some of these are summarised in Table 4. At 350mm, the depth of the Ecohouse GSHP+PPS was very shallow in comparison with these other studies, but the CoP of 2.3 achieved when it was the sole source of heat to the house, whilst lower that these studies, is nonetheless comparable.

Table 4. Studies conducted on the heating performance of horizontal GSHPs

Author(s)	**Location**	**Application**	**Pipe depth**	**CoP$_{\text{heating}}$**
[36]	Long Island, New York	104m^2 house	1.2 m	2.46
[37]	Elaziğ, Turkey	16.24 m^2 room	1 m 2 m	2.66 2.81
[38]	Nottingham, UK	Eco-House: University of Nottingham	2m	approx. 2.7
			1 m^3 of tanked copper coil	approx. 3.0

[39]	Bursa city, Turkey	Room: Uludag University	2 m	2 - 2.5

5.3 Comparison of ambient air temperature with depth in the PPS tank

The ambient air temperature above the PPS and temperatures at 4 depths within it (60, 130, 200 and 350mm) revealed that even at 350mm, the temperature closely followed that of ambient air, confirming the findings of Novo et al., [18], i.e. it was not constant (Figure 7), although the trend with depth was that the difference became more marked. It was also found that the average temperature at 350mm during summer was 14.2^{o}C and during winter 4.5^{o}C; this compares with ambient air temperatures of 15.0^{o}C and 6.5^{o}C in summer and winter respectively. The temperature at the bottom of the tank was thus cooler both in summer and winter in contrast with studies by Song et al., [17], Ozgener and Hepbasli [41] and Nordell et al., [42] who found that ground temperatures were cooler in summer, but warmer in winter. Both the trends with depth and mean ground temperature compared with ambient suggest that the tank was not deep enough for optimum heating.

Figure 7 here

5.4 Measurement of water levels in the PPS tank

Water levels in the PPS tank were monitored, and at the beginning of the study were about 180mm, however, they declined over the following 4 months to 140mm because of a lack of rainfall for 30 days and temperatures reaching 27^{o}C during July 2009 [43]. This may have been too shallow to adequately cover the slinky coils completely, leading to inefficiencies.

6. Costings, savings and maintenance

Detailed costings are outside the remit of this paper, and the installation of this technology is still very new, but there is information related to the two technologies separately, as well as an estimate for the Ecohouse combined system. For example, Joblin [44] states that schools in the USA spent in excess of $US6bn on energy per annum. If they had converted to GSHPs, they would have saved between 25 and 40% of their costs or $US1.5-2.4bn each year. For domestic properties Bose [45] argues they could save between 30-70% and 20-50% on their energy bills for heating and cooling respectively. In the UK, according to EST [46], GSHPs reduce running costs in comparison with oil (costing 6.02 pence/kWh), direct electricity (9.08 pence/kWh off peak, or 15.32 pence/kWh standard rate), LPG and solid fuel, saving between £300 (oil) and £685 (electric) per year based on an average performing GSHP (System Performance Factor of 2.82) installed in a detached, well-insulated house. In total, EST [46] makes an estimation of the potential savings and income for a home with GSHP of around £3,000 per annum at 2013-14 prices. Omer [4] states that up-front installation costs of the GSHP may be more than that incurred with conventional systems, with O’Brien et al., [47] suggesting 40% more than for oil or gas boilers and 50% more than electric storage heaters, but due to their low running and maintenance costs, in particular if some form of renewable is used to run the pump itself (e.g. solar, wind, hydropower), there would be considerable cost savings over their ca.20 year life span. In terms of return on installation costs, Kim et al., [48] typically assess this at between 5 and 10 years. All these are estimates based on what the fuel prices and running costs were at the time of the study, as well as the GSH extraction infrastructure used.

Figures for costs and maintenance of PPS is more complex, as there are many other, intangible benefits that it is difficult to assign a monetary value to, particularly those associated with societal and environmental factors [49]. However, according to the UK EA, Gordon-Walker [50], PPS can provide net financial and economic benefits for individual property owners. On a lifecycle basis PPS can cost less than conventional surfaces, since they have fewer costs for maintenance which outweighs the slightly more expensive capital costs. Extra excavation is needed to install PPS, but should the block pavers need to be replaced; it is less costly than having to renew an asphalt surface. In addition, where water companies charge to deal with surface water runoff from impermeable surfaces, since PPS will infiltrate this water, there is the potential for financial savings through not having to pay for its management or treatment at the WWTW. The volume of water passing through the WWTW would also be reduced and hence the incidence of Combined Sewer Overflows. The report goes on to estimate that replacing half of non-road hard surfacing nationwide with PPS when it reaches the end of its functional life would earn £1.7 billion in such discounted economic benefits, the majority of which would be passed on to site owners and operators.

In order to calculate operating costs specific to the Ecohouse, an average CoP of 2.3 was used (the days where the ground temperature was above 1°C: see section 5.2), or an efficiency of 230%. Table 5 compares the results with those of other heating fuels, which shows that the combined system at the Ecohouse is marginally better than oil, but costs more to run in comparison with gas. Quite obviously, increasing the efficiency of the combined system to 350% reduces the costs considerably; achieving better efficiency is discussed in section 8.

Table 5 A comparison of UK operating costs (pence/kWh) of different heating fuels (after [45]) with the GSHP+PPS at the Ecohouse

Heating Fuel	Average price [44]	Efficiency	Costs
Gas	4.29	78%	5.5
Oil	5.36	82%	6.5
Electricity/ GSHP	14.05	350%	4.0
Ecohouse		230%	6.0

7. Future prospects for GSHP+PPS

With the lessons learnt from the Hanson Ecohouse monitoring study, a combined system has been installed at an office scale. The offices at Stewartby, Bedford, UK, are a 3-floor open plan development with a total area of approximately 7000m^2. The GSHP+PPS was located in the 6500m^2 car park associated with the office block and were used as the only means of heating and cooling the offices [43]. There are five 130kW GSHPs working in series with each one working in turn until the desired temperature is achieved, and then they close down individually once this is reached. With an estimated pay back of about 5-6 years, cost savings of around 42% annually and CO_2 emissions savings of up to 26%, the system would appear to be providing the heat demands of the whole building efficiently; monitoring for this project is recent and on-going. Gang et al., [51] reviewed the application of cooling systems at the *district* scale, which included the harvesting of energy from surface water, such as the sea, rivers and lakes. There is no reason, therefore, why the combined GSHP+PPS should not be used for several buildings, for example a whole street, or block of houses; as shown by the offices at Stewartby, as long as sufficient area and depth of PPS is available, the harvested heat need only be distributed to each dwelling equally.

PPS are only one device in the SuDS arsenal [14]; the approach also includes such structures as wetlands and ponds constructed for the specific pupose of storm attenuation, water quality improvements, amenity provision and biodiversity enhancement. As was shown by Tota-Maharaj et al., [7], these devices can be used to house Surface Water Heat Pumps (SWHPs). Laboratory-based experiments of this technology immersed in a vertical flow constructed wetland test rig system which included *Phragmites australis* (common reed), treated added municipal wastewater which resulted in >75% suspended solids removal, reduction in chemical oxygen demand by 50%, ammonia-nitrogen and nitrate-nitrogen by 50-60% and orthophosphate-phosphorus by 40% [7]. Should a SuDS management train be designed to service the flood attenuation requirements of housing and industrial estates, it should be possible to incorporate GSHPs in suitable devices and harvest the energy available in the surrounding landscape cleanly and sustainably.

8. Conclusions

Combining GSHP, PPS and rainwater harvesting brings multiple benefits associated with each individual technique: a sustainable energy supply [1], flood resilience, water quality improvements, a use for harvested rain and excess surface water and therefore less water having to be treated through the WWTW [8, 9, 10]. These techniques were flexible in being able to be combined in one device which have been installed both at the domestic scale and in an office block to provide all its heating requirements [43].

Whilst there were concerns regarding possible negative impacts on the PPS's ability to treat water [13, 26], and the potential proliferation of harmful microorganisms due to harvesting heat [27], these would appear to have been addressed via laboratory experiments using small scale test rigs.

Once upscaled to a domestic building, whilst the potential of the combined system to be able to provide heat when needed was proven, thermal stability within the house was not always achieved, although the mean average temperature conformed to accepted "comfortable" levels as determined by CIBSE [34]. Lessons learnt from monitoring of the Ecohouse include:

- 350mm was not deep enough for the PPS tank. Ambient air temperatures had too much influence on the temperature within the tank as was also found by Novo et al., [18] and thus heat transfer was not efficient.
- The combined system was 30m away from the Ecohouse which may have lead to inefficiencies. The inefficiencies include the electrical energy needed to move the coolant

through 30 metres of ground source pipe and back again (60 extra metres in total) compared with the case if the ground collector was adjacent to the property.

- The Ecohouse was a demonstration building. It was therefore subject to doors and windows being opened constantly, and the GSHP equipment being interfered with upon occasion. Monitoring this kind of activity may have been beneficial, and locating the study in a domestic setting may have been more suitable. At 8kW, the pump was oversized and as a result had many power outages leading to inefficiencies
- The PPS tank may have leaked during the monitoring period since the water level reduced, but this may also have been a result of naturally occurring evaporation inside the tank, and also lack of rainfall.
- Over the 3 years of monitoring the mean CoP of 1.8 for the system was too low. A CoP of 2.875 is required for it to be “satisfactory” under the 2009 EU Renewable Energy Directive.
- A 65m^2 tanked PPS was, at times able to provide heat to a domestic building, however a larger area would probably have been more efficient since PPS is not normally installed deeper than 500mm and thus increasing the area is a more likely proposition.

The Ecohouse project was a “first of its kind”, a genuine pilot study and as such it was always likely that problems would occur. Its suboptimal performance was due to unavoidable site installation compromises such as tank depth, and also unforeseen visitor interference rather than the actual potential of the combined technology. Lessons have been learnt from the study, leading to the successful implementation of the technology at a larger, office scale [43], and the potential for combined GSHP+SuDS systems to harvest a clean and sustainable source of energy would appear to be substantial.

References

1. Self SJ, Reddy BV, Rosen MA. Geothermal heat pump systems: Status review and comparison with other heating options. Applied Energy, 2013; 101: 341–348.
2. Li K, Lin B. Impacts of urbanization and industrialization on energy consumption/CO2 emissions: Does the level of development matter? Renewable and Sustainable Energy Reviews, 2015; 52: 1107-1122.
3. De Boeck L, Verbeke S, Audenaert A, De Mesmaeker L. Improving the energy performance of residential buildings: A literature review. Renewable and Sustainable Energy Reviews. 2015; 52: 960-975.
4. Omer A. M. Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews. 2008; 12(2): 344-371.
5. Shafiei S, Salim RA. Non-renewable and renewable energy consumption and CO_2 emissions in OECD countries: A comparative analysis. Energy Policy. 2014; 66: 547-556.
6. Bayer P, Saner D, Bolay S, Rybach L, Blum P. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. Renewable and Sustainable Energy Reviews. 2012; 16(2): 1256-1267.
7. Tota-Mahara K, Grabowiecki P, Babatunde A, Devi Tumula P. Constructed wetlands incorporating surface water heat pumps (SWHPS) for concentrated urban stormwater runoff treatment and reuse. Sixteenth International Water Technology Conference, IWTC 16; 2012, Istanbul, Turkey. Available at: http://tinyurl.com/qb8jhod accessed 10 February 2016.
8. Charlesworth S. A review of the adaptation and mitigation of Global Climate Change using Sustainable Drainage in cities. J. Water and Climate Change. 2010; 1(3): 165-180.

9. Davies J, Charlesworth SM. Urbanisation and Stormwater. In: Water Resources in the Built Environment - Management Issues and Solutions. Booth, C. and Charlesworth S.M. (eds) Wiley Blackwell. 2014.
10. Charlesworth SM, Harker E, Rickard S. Sustainable Drainage Systems (SuDS): A soft option for hard drainage questions? Geography, 2003; 88(2): 99-107.
11. Watkins S, Charlesworth S. Sustainable Drainage Design. In: Water Resources in the Built Environment - Management Issues and Solutions. Booth, C. and Charlesworth S.M. (eds) Wiley Blackwell. 2014.
12. Scholz M, Charlesworth S, Coupe S. Drainage Benefits of Porous, Permeable and Pervious Paving. In: Water Resources in the Built Environment - Management Issues and Solutions. Booth, C. and Charlesworth S.M. (eds) Wiley Blackwell. 2014.
13. Tota-Maharaj K, Paul P. Sustainable Approaches for Stormwater Quality Improvements with Experimental Geothermal Paving Systems. Sustainability. 2015; 7(2): 1388-1410.
14. Charlesworth SM, Lashford C, Mbanaso F. Hard SUDS Infrastructure. Review of Current Knowledge, Foundation for Water Research ;2014 Available at: http://www.fwr.org/environw/hardsuds.pdf accessed 10 February 2016.
15. De Sousa MRC, Montalto FA, Spatari S. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. Journal of Industrial Ecology. 2012; 16(6): 901-913.
16. Wang R, Eckelman MJ, Zimmerman JB. Consequential environmental and economic life cycle assessment of green and grey stormwater infrastructures for combined sewer systems. Environ. Sci. Technol. 2013; 47: 11189−11198.
17. Song J, Lee, K, Jeong Y, Cheong S, Lee J, Hwang Y, Lee Y, Lee D. Heating performance of a ground source heat pump system installed in a school building. Science China, Technological Sciences 2009; 53(1): 80-84.

18. Novo AV, Bayon JB, Castro-Fresno D, Rodriguez-Hernandez J. Temperature performance of different pervious pavements: rainwater harvesting for energy recovery purposes. Water Resour. Manag., 2013; 27: 5003-5016.
19. Tarnawski, V.R., Leong, W.H., Momose, T., Hamada, Y. Analysis of ground source heat pumps with horizontal ground heat exchangers for northern Japan. Renewable Energy. 2009; 34(1): 127–134
20. Novo A, Gomez-Ullate E, Bayon JB, Castro-Fresno D, Rodriguez-Hernandez J. Monitoring and evaluation of thermal behaviour of permeable pavement under northern Spain climate. Proceedings: Sustainable Techniques and Strategies in Urban Water Management. 7th International Conference Novatech, Lyons, France, 2010. Available at: http://tinyurl.com/q68azxz accessed 10 February 2016.
21. del Castillo-Garcìa G, Borinaga-Treviño R, Sañudo-Fontaneda LA, Pascual-Muñoz P. Influence of pervious pavement systems on heat dissipation from a horizontal geothermal system. European Journal of Environmental and Civil Engineering. 2013; 17(10): 956-967.
22. Qin, Y. A review on the development of cool pavements to mitigate urban heat island effect. Renewable and Sustainable Energy Reviews. 2015; 52: 445-459.
23. Santamouris M. Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. Renewable and Sustainable Energy Reviews. 2013; 26: 224-240.
24. Tota-Maharaj K, Scholz M, Coupe SJ. Modelling Temperature and Energy Balances within Geothermal Paving Systems. Road Materials and Pavements Design. 2011; 12(2): 315-344.

25. Tota-Maharaj K, Scholz M. Permeable (pervious) pavements and geothermal heat pumps: addressing sustainable urban stormwater management and renewable energy. Int. J. Green Economics. 2009; 3(3/4): 447–461.
26. Coupe S, Tota-Maharaj K, Scholz M, Grabowiecki P. Water stored within permeable paving and the effect of ground source heat pump applications on water quality. Proceedings 9th. International Conference on Concrete Block Paving. Buenos Aires, Argentina, 2009/10/18-21. Available at: http://www.icpi.org/sites/default/files/techpapers/1423.pdf accessed 10 February 2016.
27. Scholz M, Grabowiecki P. Combined permeable pavement and ground source heat pump systems to treat urban runoff. J. Chem. Technol. Biotechnol. 2008; 84(3): 405–413.
28. Tota-Maharaj K, Grabowiecki P, Scholz M. Energy and temperature performance analysis of geothermal (ground source) heat pumps integrated with permeable pavement systems for urban run-off reuse. International Journal of Sustainable Engineering. 2009; 2(3): 201 – 213.
29. Tota-Maharaja K, Scholz M, Coupe SJ. Utilisation of Geothermal Heat Pumps within Permeable Pavements for Sustainable Energy and Water Practices. Zero Emission Buildings - Proceedings of Renewable Energy Conference 2010, Trondheim, Norway. Available at: http://tinyurl.com/p2tooxy accessed 10 February 2016.
30. Scholz M, Tota-Maharaj K, Grabowiecki P. Modelling of retrofitted combined permeable pavement and ground source heat pump systems. Retrofit Conference, University of Salford, Manchester, 2012. Available at: http://tinyurl.com/nmohxwj accessed 10 February 2016.
31. De Boeck L, Verbeke S, Audenaert A, De Mesmaeker L. Improving the energy performance of residential buildings: A literature review. Renewable and Sustainable Energy Reviews. 2015; 52: 960–975.

32. Lund J, Sanner B, Rybach L, Curtis R, Hellström G. Geothermal (ground-source) heat pumps a world overview. Renewable Energy World. 2003; 6(4): 218-227.
33. Singh H, Muetze A, Eames PC. Factors influencing the uptake of heat pump technology by the UK domestic sector. Renewable Energy. 2010; 35(4): 873-878.
34. CIBSE. Guide A: environmental design, heating, air conditioning and refrigeration, 7th edition. Chartered Institute of Building Services Engineers, 2006. Available at: http://tinyurl.com/oll2w8a accessed 10 February 2016.
35. Coupe SJ, Charlesworth S, Faraj AS. Combining Permeable paving with renewable energy devices: installation, performance and future prospects. 9th International Conference on Concrete Block Paving, Buenos Aires, Argentina, 2009. Available at: http://tinyurl.com/pgozqry accessed 10 February 2016.
36. O'Connell S, Cassidy SF. Recent large scale ground source heat pump installations in Ireland. Proceedings: International Geothermal Conference, Reykjavik, Iceland, 2003. Available at: http://tinyurl.com/o6yxkj3 accessed 10 February 2016.
37. Metz P.D. Ground Coupled Heat Pump System Experimental Results. Brookhaven. National Laboratory, Uptona Report No. BNL-33540, 1983.
38. İnallı M, Esen, H. Experimental thermal performance evaluation of a horizontal ground-source heat pump system. Applied Thermal Engineering. 2004; 24(14-15): 2219-2232.
39. Doherty P S, Al-Huthaili S, Riffa, S B, Abodahab N. Ground source heat pump - description and preliminary results of the Eco House system. Applied Thermal Engineering 2004; 24(17-18): 2627-2641.
40. Coşkun S, Pulat E, Ünlü K, Yamankaradeniz R. Experimental performance investigation of a horizontal ground source compression refrigeration machine. International Journal of Energy Research 2008; 32(1): 44-56.

41. Ozgener O, Hepbasli A. Modeling and performance evaluation of ground source (geothermal) heat pump systems. Energy and Buildings 2007; 39(1): 66-75.
42. Nordell B, Grein M, Kharseh M. Large-scale utilization of renewable energy requires energy storage. International Conference for Renewable Energies and Sustainable Development, 2007. Université Abou Bekr BELKAID – TLEMCEN, Algeria.
43. Coupe SJ, Faraj AS, Nnadi EO, Charlesworth SM. Integrated Sustainable Urban Drainage Systems. In: Water Efficiency in Buildings: Theory and Practice. K. Adeyeye. Wiley Blackwell Chapter 9. 2014; 147-163.
44. Joblin N. Geothermal Heat Pumps: Environmental and Economic Benefits for Public Schools. 2004. Available at: http://tinyurl.com/hc7yxfy accessed 10 February 2016.
45. Bose JE. International GSHP Association, Space Conditioning: The Next Frontier. Air Innovations Conference August 24 – 26 2005. Chicago, IL, USA: US Environmental Protection Agency, Office of Air and radiation.
46. Energy Saving Trust (EST). The heat is on: heat pump field trials, Phase 2. 2013. Available at: http://tinyurl.com/pxgufc7 accessed 10 February 2016.
47. O'Brien M, McGovern C, Walsh M. Geothermal Energy Utilization in Cork City. Geothermal Association of Ireland Newsletter. 2000; 3: 4–6.
48. Kim S, Bae G, Lee K, Song Y. Field-scale evaluation of the design of borehole heat exchangers for the use of shallow geothermal energy. Energy. 2010; 35(2): 491–500.
49. CIRIA. Demonstrating the multiple benefits of SuDS – A business case (Phase 2); 2013.
50. Gordon-Walker S, Harle T, Naismith I. Cost-benefit of SUDS retrofit in urban areas. Science Report – SC060024; 2007. Environment Agency.
51. Gang W, Wang S, Xiao F. Gao D-c. District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. Renewable and Sustainable Energy Reviews. 2016; 53: 253-264.

Headings for Figures and Tables

Figures

Figure 1 Cross section through the combined GSHP+PPS at the Ecohouse, Building Research Establishment, including siting of the geotextile and geomembrane tank

Figure 2 Location of BRE, near Watford, UK (Google maps)

Figure 3 Hanson Ecohouse, BRE, Watford, UK

Figure 4 Orientation of the Ecohouse, the PPS and the combined system.

Figure 5 Difference between daily indoor and outdoor temperatures (^{o}C) (n =718)

Figure 6 Mean CoPs and ground temperatures (^{o}C) during the monitoring period (n=163)

Figure 7 Monthly mean temperature (^{o}C) with depth (mm) in the PPS in comparison with ambient overlying air.

Tables

Table 1. Percentage removal rates for chemical and biological pollutants in combined PPS/GSHP at the laboratory scale, test rigs located inside and outside where indicated.

Table 2. Manufacturer and model of the heat pump

Table 3. Comparison of the efficiencies of a.) various heating systems with GSHP (after [1]) and b.) experimental test rig efficiencies of the combined system [23] measured using their CoP

Table 4. Studies conducted on the heating performance of horizontal GSHPs

Table 5 A comparison of UK operating costs of different heating fuels (after [40]) with the GSHP+PPS at the Ecohouse

Figure 1

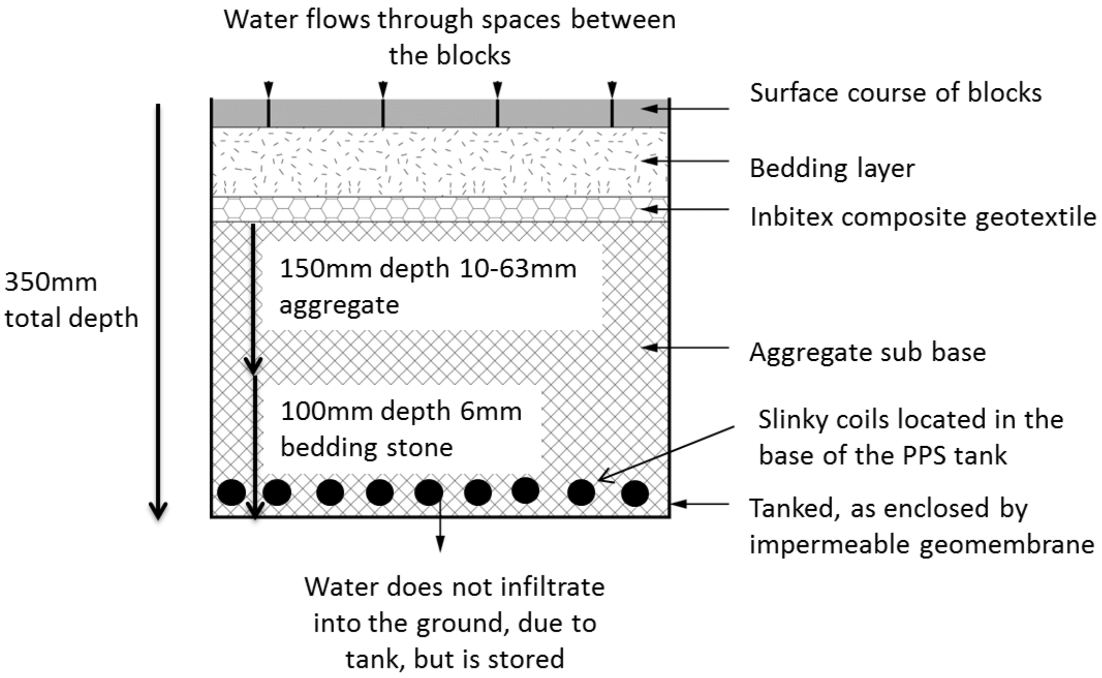
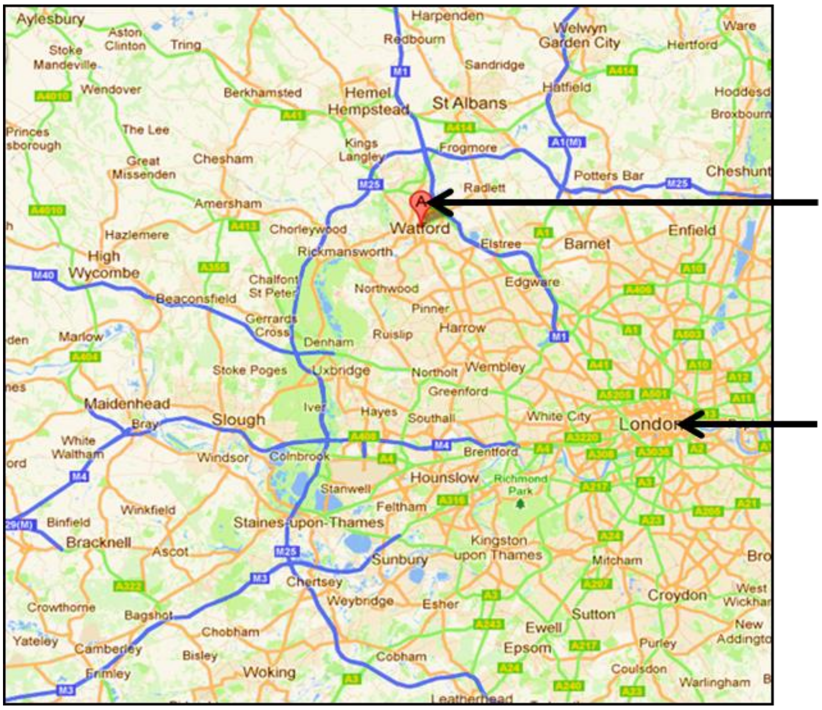


Figure 2

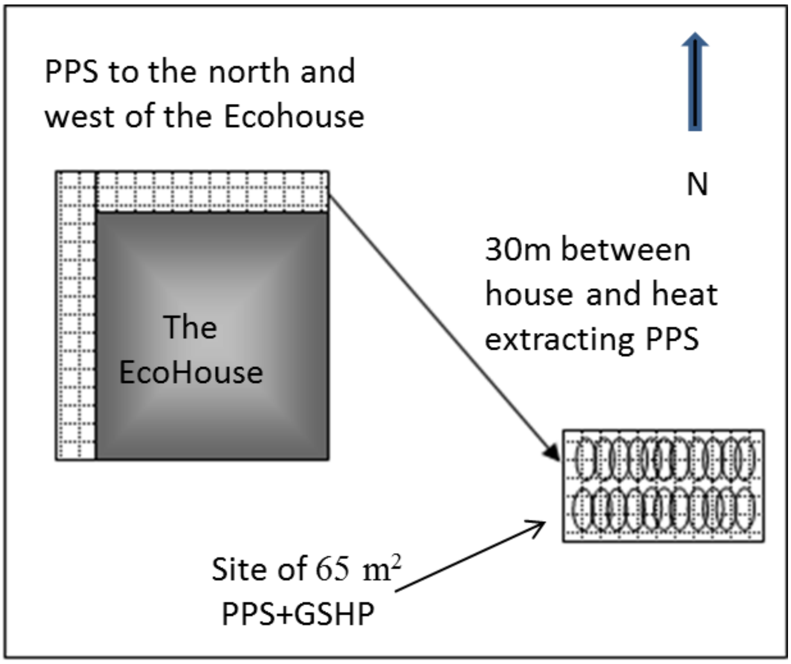


Location of Ecohouse

London

Figure 3

Fig 4



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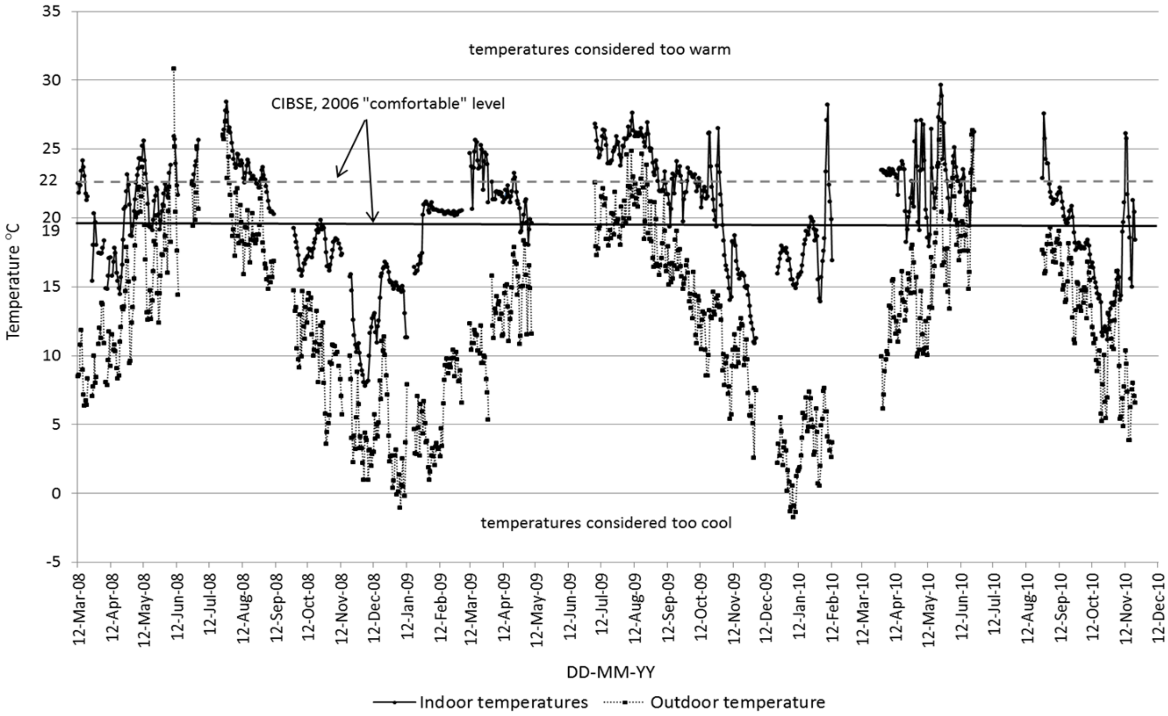
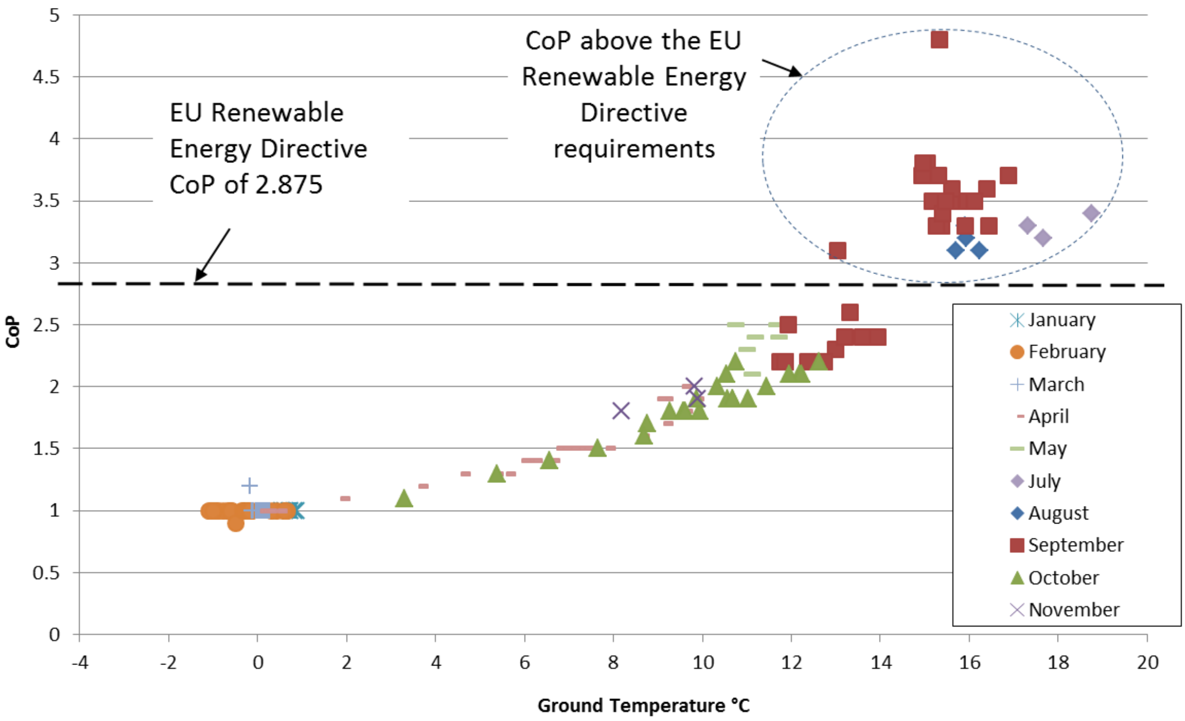


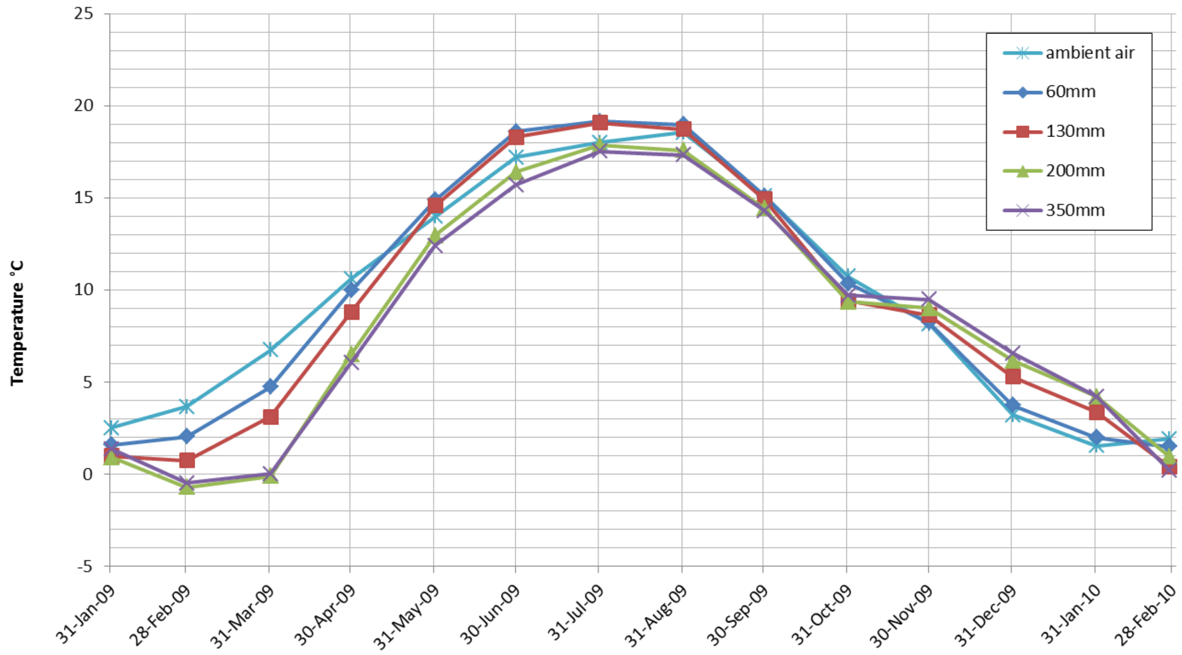
35
30
25
22
20
19
15
10
5
0
-5
Temperature °C
temperatures considered too warm
CIBSE, 2006 "comfortable" level
temperatures considered too cool
12-Mar-08
12-Apr-08
12-May-08
12-Jun-08
12-Jul-08
12-Aug-08
12-Sep-08
12-Oct-08
12-Nov-08
12-Dec-08
12-Jan-09
12-Feb-09
12-Mar-09
12-Apr-09
12-May-09
12-Jun-09
12-Jul-09
12-Aug-09
12-Sep-09
12-Oct-09
12-Nov-09
12-Dec-09
12-Jan-10
12-Feb-10
12-Mar-10
12-Apr-10
12-May-10
12-Jun-10
12-Jul-10
12-Aug-10
12-Sep-10
12-Oct-10
12-Nov-10
12-Dec-10
DD-MM-YY
Indoor temperatures
Outdoor temperature

Fig 6



5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
CoP
CoP above the EU Renewable Energy Directive requirements
EU Renewable Energy Directive CoP of 2.875
-4
-2
0
2
4
6
8
10
12
14
16
18
20
Ground Temperature °C
January
February
March
April
May
July
August
September
October
November

Fig 7


Temperature °C
25
20
15
10
5
0
-5
31-Jan-09
28-Feb-09
31-Mar-09
30-Apr-09
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30-Jun-09
31-Jul-09
31-Aug-09
30-Sep-09
31-Oct-09
30-Nov-09
31-Dec-09
31-Jan-10
28-Feb-10
ambient air
60mm
130mm
200mm
350mm