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Analysis of ground-source heat pumps in north-of-England homes

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ABSTRACT

The performance of Ground Source Heat Pumps (GSHPs) for domestic use is an increasing area of study in the UK. This paper examines the thermal performance of three bespoke shallow horizontal GSHP systems installed in newly built residential houses in the North of England against a control house which was fitted with a standard gas boiler. A total of 350 metres of High Density Polyethylene pipe with an external diameter of 40 mm was used for each house as a heat pump loop. The study investigated (i) the performance of a single loop horizontal Ground Heat Exchanger (GHE) against a double loop GHE and (ii) rainfall effects on heat extraction by comparing a system with an infiltration trench connected to roof drainage against a system without an infiltration trench above the ground loops. Parameters monitored for a full year from October 2013 to September 2014. Using the double GHE has shown an enhanced performance of up to 20% compared with single GHE. The infiltration trench is found to improve performance of the heat pumps; the double loop GHE system with an infiltration trench had a COP 5% higher than that of the double loop GHE system without a trench.

Keywords

Ground Source Heat Pump (GSHP), Coefficient of performance (COP), Ground Heat Exchanger (GHE), GSHP Field Data, Rainfall infiltration

Nomenclature

COP	Coefficient of performance of heat pump system
C_p	Coolant specific heat capacity (kJ/kg K)
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
$\dot{Q}_{HD}$	Heat delivered by the heat pump (kW)
$\dot{Q}_{HE}$	Heat Extracted rate from the ground (kW)
$\dot{Q}_{HP}$	Electricity Used by heat pump (kW)
$\dot{m}$	Coolant mass flow rate (kg/s)
Tf_{outlet}	Temperature of coolant leaving the heat exchanger loop (ºC or K)
Tf_{inlet}	Temperature of coolant entering the heat exchanger loop (ºC or K)

1. Introduction

1.1 Background

The UK aims to reduce its greenhouse gas emissions by at least 80 % by 2050 against the 1990 baseline set in the 2008 Climate Change Act. Part of this reduction will include the use of low carbon technologies at a residential level which is the highest end user of energy in the UK accounting for 32 % of total energy consumption IEA (2012). Ground Source Heat Pumps (GSHPs) are one of the four technologies listed in the domestic Renewable Heat Incentive scheme opened on 9 April, 2014 to help homeowners save money by contributing to the countries Greenhouse Gas emission goals. A feed in tariff of 19.10 p/kWh is available from October 2015 (Ofgem, 2015) based on an expected cost of renewable heat generation over 20 years and this aims to offset the current higher cost of electricity compared to gas and encourage the uptake of this technology.

The use of GSHPs for residential properties have been proved to provide clean heating and cooling energy at reasonably high efficiencies, see for example, Healy and Ugursal (1997) and Omer (2008). Heat pumps are often assessed using Coefficient of Performance (COP), which is ratio of energy rate produced by the heat pump to the input electricity. GSHPs have been shown to provide better COPs than Air Source Heat Pumps (ASHPs) even though 2012 installation figures by (Frontier Economics and Element Energy, 2013) in the UK showed air to water heat pumps dominated the market. Uptake has been high in European countries like Sweden, Switzerland and Austria whilst adoption in the UK remains low (see, Fawcett, 2011).

Studies on heat pump systems have centred along the traditional installation of a horizontal Ground Heat Exchanger (GHE) such as series, parallel and slinky-coil loops (see for example, Esen et al., 2005, Esen et al., 2007, Pulat et al., 2009, Wu et al., 2010 and Naili et al., 2013) or vertical ground loop panel in the form of borehole U-tubes (see, Boait et al., 2011, Bakirci et al., 2011 and Michopoulos et al., 2013). Ground loop systems are buried into the ground connected to the heat pump system. Generated heat energy is then utilised using an internal heat distribution system of either under floor heating panels or larger radiators. In general, the systems are set up to provide both space heating and hot water. The choice of whether to use horizontal or vertical loops is site specific. Vertical loops require less space but have high drilling costs and are advantageous where space is limited whereas horizontal loops require more piping and space but utilise shallow trenches cost less than drilling (see, Florides and Kalogirou, 2007, Omer, 2008 and Yang et al., 2010)

UK studies of heat pump systems have previously been conducted by the Energy Saving Trust (2010) and analysis of systems based on energy distribution types and energy splits was conducted in 2012 by the DECC (2012). Results from the study showed that the attained COPs of the systems are quite low compared to the European figures and EU Renewable Heat Incentive target. From 54 systems studied in the UK, a median COP of 2.20 was found and under EU rules, a COP of at least 2.50 (DECC, 2013) is required for each system to be classed as a renewable system that contributes to the goals of 15 % renewable energy generation and eligible for the Renewable Heat Incentive scheme. The low COP was attributed to a number of reasons; under-sizing of the heat pump, under-sizing of ground loop/borehole, insufficient insulation, too many circulation pumps, installation (radiator temperature and circulation pump cycles), over-sizing/control strategy leading to over-use of back-up heating. Other reasons attributed to underperformance include, a varied geology and/or unpredictable weather conditions; see for example; Sanner et al., (2003), Curtis et al., (2005), Busby et al., (2009), DECC (2012) and Underwood (2014).

Analysis of GSHP performances has been done by a lot of researchers in the past with focus on a specific system, occupancy conditions, field or laboratory set ups. These studies have led to different values of COP being found ranging from 2.09 to 6.09, see for example, Esen et al., (2007), Pulat et al., (2009), Ozyurt and Ekinci (2011), Bakirci et al., (2011), Ally et al., (2012) and Naili et al., (2013). Esen et al., (2007) carried out experiments on 2 horizontal GHEs buried at depths of 1 m and 2 m in the ground. The two GHEs were fabricated from high density polyethylene pipes with a diameter of 16 mm, a length of 50 m and were spaced at 0.3 m. The measured COP values were 2.50 for the GH exchanger installed at 1 m and 2.80 for the GH exchanger buried at 2 m below the ground. Low COPs were attributed to poor ground conditions in Turkey. The experiments showed some influence of outdoor temperature on the performance of the system closer to the ground surface.

Pulat et al., (2009) experimented with a 20 m long heat exchanger pipe with a diameter of 16 mm buried at 2 m below the ground in Turkey. Analysis was only done over 36 days of data and from a heat pump COP range of 4.03 to 4.18, the system COP was only between 2.46 to 2.58. It should be noted that the heat pump COP is the ratio of the heat delivered by the heat pump to the electricity consumed by the heat pump compressor. Whereas, the System COP is the quotient of energy delivered to energy used by the whole heat pump system. The winter in Turkey is mild compared to UK and the length of the GHE is very short at 20 m only since most field heat exchangers have lengths in hundreds of meters for this system.

Ozyurt and Ekinci (2011) experimented with a single U-tube polyethylene pipe borehole in the cold climate of Turkey. 2 boreholes 52 m deep and a U-tube diameter of 105 mm were explored in the warm climate of Turkey. A system COP range of 2.12 to 2.50 was achieved whilst the heat pump COP ranged from 2.65 to 3.00. Other design parameters hadn't been carefully considered leading to pressure losses in the pipes. Bakirci et al., (2011) investigated a hybrid system consisting of two 53 m deep boreholes and a flat plate water cooled solar collector. The heat pump COP measured was only 3.00 and the mean system COP was found to be 2.60. Despite supplementing the heat source with solar panel, the system COP did not improve compared to conventional borehole heat exchangers.

Ally et al., (2012) simulated low energy consumption of a house for its cooling performance. Three parallel circuits of slinky with 6 pipes and a total length of 559 m with an internal diameter of 19 mm were used. System COPs between 3.44 and 4.90 were achieved in heating mode and 3.88 to 6.09 were obtained during cooling. The room temperatures were set to 21.67 °C during winter and 24.44 °C during summer. The performance of the system is impressive, the heat load on the heat pump was simulated and actual heat load for an average house in the UK would be much higher. Naili et al., (2013) run in field experiments on a horizontal ground cooling system. The experimental length was 50 m whilst 25 m and 100 m loops were also explored. Simulation of longer pipes was done and the heat pump COP was between 3.80 and 4.50 whilst the system COP ranged from 2.30 to 2.70. The results of the simulations show that heat exchange rates were less variable at lengths more than a 100 m whilst the experiment only had 100 m as the longest exchanger.

1.2 Carbon Emissions

Carbon emission savings of a heat pump system compared to the gas boiler would depend on a country's electricity grid fuel mix (see for example, Staffell et al., 2012 and Greening and Azapagic 2012). For example, the UK has a higher electricity emission factor at 4.46 x 10^{-1} KgCO2e/kWh (DEFRA, 2014) due to grid energy coming largely from coal and gas compared to France at 7.91x10^{-2} KgCO2e/kWh (see, Brander et al., 2011) where renewables are a big part of the energy mix.

Greening and Azapagic (2012) assessed UK domestic heat pumps and found the lifetime cycle emissions of the GSHPs to remain higher than a conventional gas boiler due to the electricity grid's fuel mix. Gupta and Irving (2014) investigated effects of future domestic heat pump installations on the UK energy supply by using the Building Research Establishment Domestic Energy Model (BREDEM) to estimate dwelling energy consumption up to 2020 and 2050.. Results showed that the application suitable for reducing emissions and electricity consumption was targeting dwellings where carbon emissions were highest. The results also showed that in a scenario of 15.60 million installations, reaching the UK's 2050 80 % emission reduction on 1990 levels is dependent on parallel decarbonisation of the UK electricity supply. Jenkins et al., (2009) formulated a GSHP model to estimate potential of the systems as a carbon savings technology. The results showed that the best performance was achieved when delivery temperature was set at 35 ºC compared to 45 ºC and 55 ºC, suggesting installations be aimed at new buildings due to reliance on low temperature distribution systems.

1.3 Scope of Work

In two of the houses utilised in this study, storm water was diverted into the ground from the house roof by connecting the roof drainage pipes to a gravel-filled infiltration trench in the ground. The novel system aims to i.) provide a sustainable mechanism for management of storm water by preventing roof run off going into the local sewer system via house drainage and ii.) aid the performance of the GHE loop by recharging the ground temperature and enhancing the heat transfer between the soil and ground HE loop.

Three heat pump systems are installed in 3 houses in Dewsbury, UK whereas a fourth house is heated using a conventional boiler and used as a control. The third house had a GSHP installed without a storm water infiltration trench. Analysis was performed on continuously monitored data for a year, from October, 2013 to September 2014 to provide performance of the systems. This paper presents results on the efficiencies of heat pump systems from experimental installations with and without storm water infiltration trenches conducted on two of the four houses.

2. Experimental Set Up and Monitoring

2.1 Description of Experimental houses and Occupancy

Four newly built houses were used for the demonstration project, three had bespoke heat pump systems and the fourth had a traditional gas boiler and was used as the control in the experiment. All houses have the same floor area of 150 m². Each house is East-facing, identical in terms of the size, has a roof area spanning 49.60 m² and extends to three floors. The four houses are made of the same building materials and fabrication. The heat transfer coefficients (U-value) of the building materials are 1.77 W/(m^{2}K), 1.60 W/(m^{2}K), 0.25 W/(m^{2}K), 0.20 W/(m^{2}K), 0.30 W/(m^{2}K), 0.16 W/(m^{2}K) for windows, doors, ground floor, upper floors, walls and roof respectively. A Standard Assessment Procedure (SAP) rating was carried out and all four houses received a SAP rating of 82%. The geotechnical report indicated that the subsurface soils are made ground for the top 2.70 m to 2.90 m comprising of brick, sandstone and ceramic in sandy clay matrix whilst a ground water table was found to be at 3.10 m below the finished ground surface. Thus, the made ground was replaced with silty sand to avoid damage to the ground heat loops and to enhance the heat exchange and interaction between the heat exchangers and adjacent soil.

The houses are thereby referred to as House 1, 2, 3 and 4. Table 1 provides a summary of experimental configurations for the four houses. Heat Pump systems were installed in houses 1, 2 and 3 whilst House 4 was utilised as the experimental control. The houses front gardens have an area of 30 m² each whilst the back gardens have an area of approximately 44 m². However, gabion walls were required at the back of the house due to level difference with neighbouring land resulting in a further reduction to the size of the back garden which could be employed for installation of the GHEs. The houses were built on a pile foundation in conjunction with ground beams. A clearance of at least 1 m was used for the ground loop trenches and 600 mm of top soil was used below the finished ground level as recommended by the Environment Agency as the site was previously contaminated. The heat extraction panel and connecting pipes in House 1’s back garden utilised an area of 24.80 m² whilst Houses 2 and 3 utilised 21.12 m² each. For House 1, the front garden utilised an area of 24.80 m² whilst Houses 2 and 3 occupied an area of 16.92 m². The habitation amongst the four houses is as follows: 5 occupants in House 1, 3 in House 2, 4 in House 3 and 2 occupants in the control house.

2.2 Heat Pump Systems

Figure 1 shows a schematic diagram of the GSHP system in a house which includes double GHE and an infiltration trench. A 6 kW rated heat pump type IVT Greenline HT Plus was installed for each of the three systems to deliver space heating and domestic hot water. Exhaust air recovery units (VBX) were installed in top floor to provide summer cooling, however, the choice was left to the occupants to have them either on or off. The VBX units are connected in series with the heat pump. When the heat pump is off, the VBX units circulate the coolant back to the GHE through the heat pump and back into the VBX units. Furthermore, when the heat pump comes on, coolant is circulated through a bypass valve.

Whilst all the three heat pump systems utilised a total pipe lengths of 350 m per system, the GHEs were different. Custom heat exchanger loops were designed and installed to overcome the space constraints in small house gardens. House 1 has got two 3.84 m by 5.50 m heat panels buried at 2.35m below the finished ground level at the house front and back gardens. Houses 2 and 3 have a total of four panels installed in the front and back gardens and are located at 1.85 m and 2.35 m from the finished ground level. A panel area of 2.72 m by 5.00 m was installed at the back of the house and 3.50 m by 4.00 m at the front of the house. All ground panels are made out of polyethylene pipes with an outer diameter of 40 mm spaced at 0.12 m on House 1 and 0.16 m in houses 2 and 3. Glycol-water mixture was circulated as the coolant in the pipe at a ratio of 2:1. Figure 2 (L) shows the installation of ground heat exchanger in House 2.

The GHEs in Houses 2 and 3 have configurations of 26 pipes at the front and 18 pipes at the back whereas House 1 has a configuration of 33 pipes for each heat panel. All heat panels are constructed to provide parallel flow of coolant through the pipes. The top panels in all houses are covered by 0.50 m of silty sand. In addition, the first two houses, rain water infiltration trenches designed for a 1 in 100 years rainstorm were backfilled with gravel at a height of 750 mm installed at the back as can be seen in Figure 2 (R). Clean top soil with a height of 600 mm is used to finish the ground level separated by a polyethylene membrane from the infiltration trench.

Radiators were used as the heat delivery system for the houses at a constant temperature of 33 ^{o}C. Occupants were briefed about the heat pump systems and were advised to contact the researchers regarding comfort and issues relating to the heat pump system e.g. changing HP settings. The thermostat setting has a significant effect on the energy consumption and it was set at the desirable temperature for the comfort of occupants. It was thus in the interest of the study to keep the thermostat setting of the houses monitored. Indoor temperature settings were varied between 18.00 and 19.50 ^{o}C while the DHW was set at around 52 ^{o}C in all three houses.

2.3 Monitoring and Data Collection

House room temperatures as well as local outdoor temperatures were monitored through wireless sensors and logged every 20 minutes by data loggers located in the garage of the house next to the heat pump unit. Other heat pump related parameters such as ground temperatures and glycol mixture flow rate were measured by wired sensors and logged every 20 minutes using the same data logger. Temperature sensors were installed for a range of 0 to 70 ºC with an accuracy of 0.10 ºC. Two temperature sensors were installed to monitor the temperature of the coolant flowing from the GHE to the heat pump, and the temperature of the coolant flowing from the heat pump to the GHE. The coolant flow rate was measured using a water flow meter whilst heat pump electricity was measured using a pulse meter. Other sensors were installed to monitor other parameters which will be used in future research.

Rainfall was logged via an external tipping bucket rain gauge installed at a school within 500 m from the four houses. A smart meter was used to monitor electricity usage of each house. Energy usage readings were collected at the end of each month together while logged data is collected remotely. The electricity used by the heat pump $(\dot{Q}_{HP})$ measured in pulses where 1000 pulses equals 1 kWh and this was logged at 20 minute intervals similar to all the other logged parameters

2.4 Heat Pump System Performance

The performance index of the heat pump systems is reflected by calculating a Coefficient of Performance (COPs) for each system. The COP is calculated by getting the quotient of heat delivered $(\dot{Q}_{HD})$ by the system to the electricity used by the heat pump $(\dot{Q}_{HP})$, see equation 1. Over specific periods, this enables the determination of the Seasonal COP, the Heating COP and the Cooling COP for each heat pump system.

$$COP\ (system) = \frac{\sum \dot{Q}_{HD}}{\sum \dot{Q}_{HP}} \qquad (1)$$

Based on the principles of conversation of energy, Goldschmidt (1984) deduced the heat delivered as a sum of the rate of heat extracted and the power input to the heat pump, see equation 2.

$$\dot{Q}_{HD} = \dot{Q}_{HE} + \dot{Q}_{HP} \qquad (2)$$

The rate of heat extracted $\dot{Q}_{HE}$ in kW, is determined as a function of the product of mass flow rate, specific heat of circulating fluid and the difference in temperature between the outlet and inlet of the GHE loop as explained in Pulat et al., (2009), see equation 3. Heat extracted was calculated on a monthly basis where a Seasonal Performance Factor (SPF) can be calculated over the whole year. Henceforth, for heating mode:

$$\dot{Q}_{HE} = \dot{m}\, C_p\ (Tf_{outlet} - Tf_{inlet}) \qquad (3)$$

where; $\dot{m}$ refers to the mass flow rate of the circulating fluid and C_p denotes its specific heat capacity. Tf_{outlet} is the circulating fluid temperature at the GHE outlet (leaving the GHE) while Tf_{inlet} is the circulating fluid temperature at the GHE inlet (flowing from the HP to the GHE) respectively.

3.0 Results and Discussion

Monitored data were analysed to identify annual weather pattern and house energy usage for the year to better understand the heating performance. The conventional system energy usage has been compared to that of the heat pump systems.

3.1 Temperatures and precipitation

Cumulative precipitation and outdoor temperature are shown in Figure 3 and Table 2. Rainfall in Dewsbury reached a total of 856 mm which is comparable to recent years in the UK. The heaviest precipitation encountered during winter at 256 mm which was higher than 2012 winter. Summer’s 174 mm of precipitation was however lower than that of 2012 which reached a record level of 350 mm. For the heat pump systems that had the roof drainage connected to an infiltration trench (houses 1 and 2), prevents a total of 43 m³ runoff from draining into the local sewer network. Figure 3 also shows that the average outdoor temperature dropped from around 10 ºC to around 2 ºC in January 2014. Sub-zero outdoor temperatures were rarely recorded during the year, representing a mild UK winter. Highest temperatures were recorded in the last week of July when outdoor temperature surpassed 25 ºC. Of note, due to the huge amount of data points, daily averages were presented.

Figure 4 presents measured indoor temperatures at each floor of House 1. The temperature in the rooms was fairly constant throughout the year at around 20 ºC with the exception of late July where indoor temperatures reached just above 30 ºC in the hottest week of the year, showing that the cooling systems were not engaged. Indoor temperature in the hall way of the ground floor showed the highest temperature variation. Similar indoor temperature patterns in other houses were observed. The constant temperature over the year shows that the thermostat setting for indoor temperature was not changed and this is a similar pattern with houses 3 and 4. House 2 was the exception; it had a higher thermostat temperature of 22 ºC in October 2013 which was subsequently dropped back to 20 ºC in January 2014.

3.2 House Energy Usage

Table 3 represents the energy usage of each house over the year, it can be seen that the houses with heat pump systems had the highest electricity demand during winter in the months between January and March and the least demand during summer. The control (House 4), with an occupancy of 2 has a total annual electricity usage of 1890 kWh which is almost half the UK average electricity usage of 4,170 kWh (DECC, 2015). In terms of gas usage, the conventional system used 14010 kWh of gas, across the year, bringing its total annual energy usage to 15,895 kWh which is close to the average UK annual energy consumption figure of 14,829 kWh (DECC, 2015). The heat pump systems had similar electricity usage despite the variation in occupancy of the houses and ground systems. The gas usage in houses with heat pump systems was very minimal, only House 1 used significant amounts of gas at 1220 kWh over the year. This is likely to be attributed to some technical issues with the HP which caused it to stop working for around 20 days (from 28 December 2013 till 17 January 2014). Therefore, the backup system of the boiler covered the heat demands during this period and hence, the increase in gas consumption.

Overall, the total energy consumption of the conventional heating system was almost twice that of the heat pump systems, 15,895 kWh versus and average of 7,833 kWh respectively. However, operating the heat pumps resulted in higher electricity consumption than the equivalent UK average (4,192kWh).

From Table 3 it is evident that the total electricity usages doesn't have a strong correlation with the number of occupants, for example House 1 has the most number of occupants (5) but used less electricity than houses 2 and 3. Their lower electricity usage however seems to be offset by a use of gas consumed by the conventional boiler system compared to the other two houses.

3.3 Heating Performance

The performance index of the heat pump systems is reflected by calculating a Coefficient of Performance (COPs) for each system. Figures 5 to 7 show the difference in the temperature of the circulating fluid entering and leaving the heat exchanger loop over a 12 month period. Heat extraction is represented by a gain in temperature at the heat exchanger outlet to heat pump and it can be seen that heating mode started in the month of October in all three houses and continued to the months of April and May. Of note, data was smoothened using a moving average of 21 points to show variations every 7 hours. Less heat extraction is evident over the summer period between June and Oct 2014. The GHE outlet and inlet differential was around 1.80 ºC during winter. For House 1, the backup system (conventional boiler) seems to be switched on for 20 days at end of December 2013 till mid-January 2014 leading to a high gas usage. Careful inspection of the data of all three houses indicates that the system was not constantly in a heating mode during the month of March. A rise in outdoor temperature meant that demand for heating was varying at that period. Figure 7 shows a temperature gain of close to zero ºC from May to August for House 3 which suggests that the cooling system for the house was disengaged for that period.

Figure 8 represents the monthly COP values in heating mode. House 2 yields the highest COP on average at 4.79 followed by House 3 at 4.61 and House 1 at 4.04. It should be noted however, that the heat pump in House 1 was not working for 20 days as can be inferred from its circulating fluid temperature differential between outlet and inlet presented in Figure 5. Electricity usage of this heat pump increased in the months of December 2013 and January 2014 whilst the amount of heat extracted decreased significantly rendering COP heating for the 2 months 3.49 and 2.62 respectively. The three systems had yearly COPs higher than 2.88 which would place them in the renewable technologies contributing to EU's energy targets (REF, 2010). It should be noted that equation 2 does not account for energy losses in the connecting pipes. Although all connecting pipes have been carefully insulated, there might be some energy losses within the heat pump which have not been considered. Luo et al., (2015) examined the effect of energy loss in the horizontal connecting pipes without insulation in South of Germany and found that when taking energy losses in consideration maximum achieved COP is only 75% of the calculated value.

From Figure 8 there is a drop in the performance of houses 1 and 2 with their COP's reaching the lowest values for each house over the year. For House 2 however, the low COP was a direct result of the temperature thermostat being set higher at 22 ºC, a setting much higher than the 19.50 ºC in the other two houses. The heat pump had to do more work (consuming more energy) to extract more heat from a lower ground temperature to maintain the higher thermostat temperature and hence a reduction in COP. This setting was subsequently reset back in January and the COP rose to 4.7 in February 2014.

A closer look at the overall performance of the three systems shows the double loop system was considerably more effective at extracting heat than the single loop heat exchanger. The single loop heat exchanger (House 1) has the lowest Seasonal Performance factor of the three houses at 4.04 over the whole year and 4.24 excluding December 2013 and January 2014. These COP values are considerably lower than 4.79 and 4.61 for Houses 2 and 3 with double GHE loops respectively. The higher COP in houses 2 and 3 could be attributed to the fact that the spacing between the pipes is wider. As a result, thermal resistivity and interaction between pipes would be less. Furthermore, the top loop heat exchanger of House 2 is close to the infiltration trench which means that the surrounding soils would have higher degree of saturation leading to enhanced thermal conductivity. The double loop system with an infiltration trench system therefore performed better than single loop system with an infiltration trench and the double loop system without an infiltration trench by 17% and 4% respectively. The single loop system with an infiltration trench however, performs below the double loop system without infiltration trench by a factor of 14% and thus further analysis would have to be done to confirm the efficacy of the infiltration trenches. Mohamed et al., (2015) conducted preliminary laboratory investigations into the effects of groundwater table fluctuations and infiltration of rainwater on the amount of thermal energy that can be extracted from near surface soil layers and showed that heat recovery could be enhanced by a factor of 4 when the soil was wetted to 200 mm above the loop panel compared with that of dry conditions. There was a fivefold increase in thermal conductivity of the soil between residual and saturated conditions. The study also found that rainstorms caused temporary enhancement of heat recovery though the degree of enhancement was dependent on the intensity of the rain event. The concept of directing rainwater into the ground is therefore expected to have a positive impact on the recovery of thermal energy from ground at an average UK house scale. The outcomes are therefore consistent with previous study. Further monitoring of the systems and analysis of data are underway.

3.3 Carbon Emissions

Carbon dioxide accounts for most of the Greenhouse gas emission from the UK energy supply. From Table 4, carbon emission changes of 4.34 %, 2.38 % and 0.18 % for Houses 1, 2 and 3 respectively show similar carbon emissions compared with the traditional system in the control house (House 4) using carbon conversion factors stipulated by DEFRA (2014). The fuel mix of the UK electricity generation as of 2012 is comprised mainly of coal, gas and nuclear for electricity generation as reported by DECC (2015). This was due to an increase in coal by 32 % and reduction in gas by 30 % from 2011 mix and led to 5.90 % increase in emissions at power stations. Emissions at these coal and gas plants account for the carbon emission of the heat pump system and thus the systems have similar carbon emissions to the gas boiler in House 4 even though it is using twice the energy (7833 kWh average for heat pump equipped houses compared to 15,168 kWh for the control house).

When the same results are used with conversion factors of EU countries with a cleaner source of secondary energy for the heat pump, the carbon emission reductions are much larger. For example, France, which has electricity conversion factor of $7.91x10^{-2}$ as reported by Brander et al., (2011) would give carbon emission reductions of 70.01 %, 73.25 % and 76.95 % for the three houses with GSHPs respectively as well as the energy reductions.

The carbon emission tables show that even though the heat pump systems halve the KWh energy usage of the houses compared to the traditional systems, the carbon emission changes are essentially neutral. Hence, even though the heat pump itself produces zero carbon emissions, the emissions at the electricity supply in the UK which are dominated by the use of coal dictate the carbon emission levels. Therefore decarbonisation of the UK energy electricity supply would boost uptake of heat pump systems as it will lead to reduction in carbon emissions of up to 35 % (see Table 4).

Uptake of GSHPs would require the electricity grid to be closely reviewed as the UK's energy supply at the moment is gas dominant at 63 % in 2014 DECC (2015) with the average electricity consumption per household being 4,192 kWh whilst the average gas consumption per household was 15,462 kWh. An increase in GSHP installations could result in a subsequent increase in electricity consumption and thus increasing strain on the electricity grid. With a decrease in oil and gas production due to depletion of reserves, the role of renewables play a great role for the future of the UK energy market.

4.0 Conclusions

This paper aimed to present the heat performance of three bespoke heat pump systems as well as compare energy usage and carbon emissions between conventional gas boiler and GSHPs. The main findings are as follows:

(1) The heat pump system with a double heat exchanger loop panel with infiltration trench had the highest coefficient of performance at 4.79 followed by the double loop panel with no infiltration trench which had a COP of 4.61 and the single loop panel with infiltration trench that had the lowest coefficient of performance at 4.04 therefore loop design and soil moisture levels can impact on COP levels. All three systems had a COP higher than 2.88 and thus would be classed as renewable systems contributing positively to Renewable Heat Incentive targets

(2) The energy usage of the heat pump systems (7833 kWh) was almost half of that of the conventional system (15,895 kWh)

(3) The heat pump systems did not present a reduction in carbon emissions over the traditional system though this is largely attributed to the energy mix of the UK grid which comprises of mainly

coal and gas with very little renewables. It is anticipated that decarbonisation of the UK electricity supply would lead to carbon reductions of up to 35 % by 2022.

4) The coefficient of performance results suggest that the infiltration trench improved the performance of GSHP system though detailed analysis is required to determine the extent and mechanism.

To conclude, the results indicate that design of the ground loops has a significant impact on the performance. Monitoring of the systems performance is going on and further analysis will be made and published in due course.

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Table 1: Summary of Experimental configurations.

House	Ground Loops	Drainage System	Occupancy	Primary Heating Supply
1	Single	Infiltration trench	5	Heat Pump
2	Double	Infiltration trench	3	Heat Pump
3	Double	traditional	4	Heat Pump
4	None	traditional	2	Traditional (Gas Boiler)

Table 2: Rainfall and ambient temperature data.

Year	**Winter (Dec-Feb)**		**Summer (Jun-Aug)**		**Annual (Oct13 - Sep14)**	
2013-2014	Mean Temp. (°C)	Precipitation (mm)	Mean Temp. (°C)	Precipitation (mm)	Mean Temp. (°C)	Annual rainfall (mm)
	6.4	256	16.4	174	10.92	856

Table 3: Energy Consumption of each house. Elec. stands for electicity.

House	**Energy (kWh)**	**Oct. 2013- Dec. 2013**	**Jan. 2014- Mar. 2014**	**Apr. 2014- Jun. 2014**	**Jul. 2014- Sep. 2014**	**Total (kWh)**
1	Gas	620	460	100	40	1220
	HP Elec	1468	2014	752	410	4644
	House & HP Elec	2580	2500	1380	1050	7510
2	Gas	140	180	180	210	710
	HP Elec	2243	1945	807	425	5419
	House & HP Elec	3120	2260	1200	990	7570
3	Gas	40	30	30	40	140
	HP Elec	1477	1857	821	391	4546
	House & HP Elec	2480	2580	1440	1130	7630
4	Gas	5190	5160	2130	1530	14010
	Electricity	470	480	480	460	1890

Table 4: Carbon emissions of house with conventional boiler against houses with heat pump systems.

Parameter	House 4	House 1	House 2	House 3
Annual Electricity Usage (kWh)	1890	7510	7570	7630
Annual Electricity Carbon Equivalent (KgCO_2e)	812	3228	3254	3280
Annual Gas Usage (kWh)	14010	1220	710	140
Annual Gas Carbon Equivalent (KgCO_2e)	2580	230	130	30
Annual Gas & Electricity Usage (kWh)	15900	8730	8280	7770
Annual Gas & Electricity Carbon Equivalent (KgCO2e)	3390	3450	3378	3300
% Gas Used over Total Energy	88.14%	16.27%	8.65%	1.76%
Carbon Emission Change for System against control house (%)	Control	4.34%	2.38%	0.18%
Projected Emission Change using 2022-2024 factors (%)	Control	-32.97%	-35.57%	-38.53%

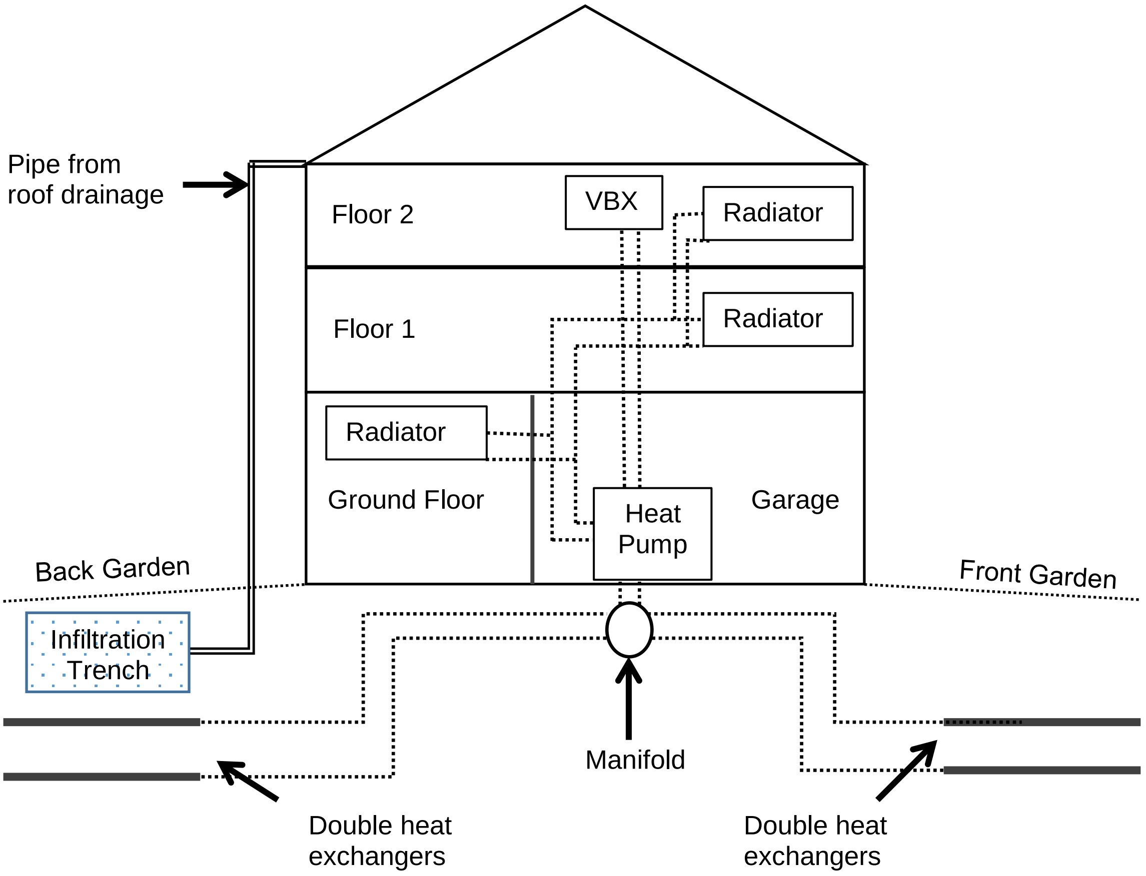

Figure 1: A schematic of the heat pump system of a double heat exchanger loop with infiltration trench.

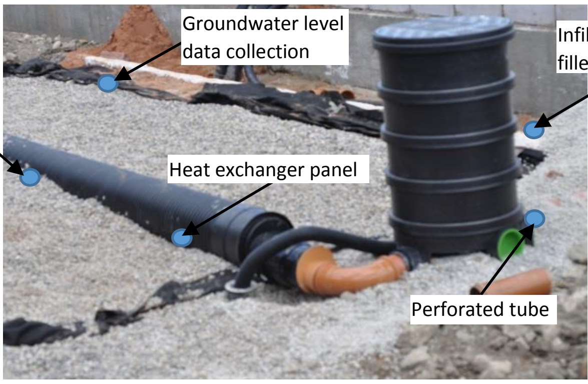

Figure 2: (L) Installation of ground heat exchanger and (R) Infiltration trench and drainage pipe.

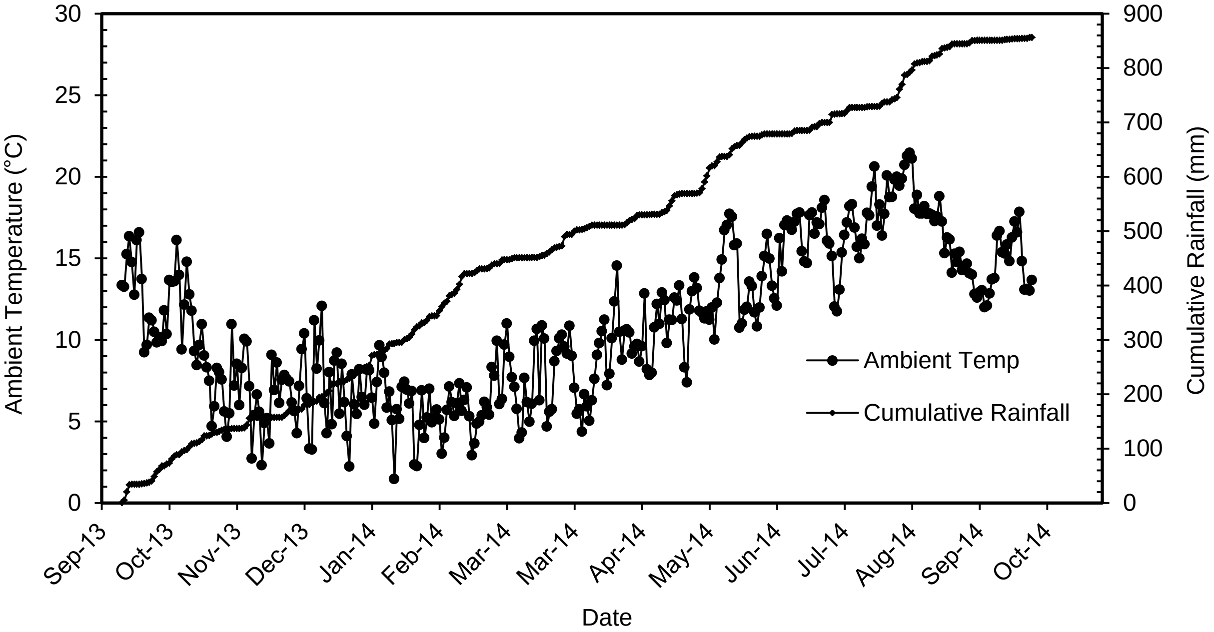

Figure 3: Cumulative rainfall and outdoor ambient temperature.

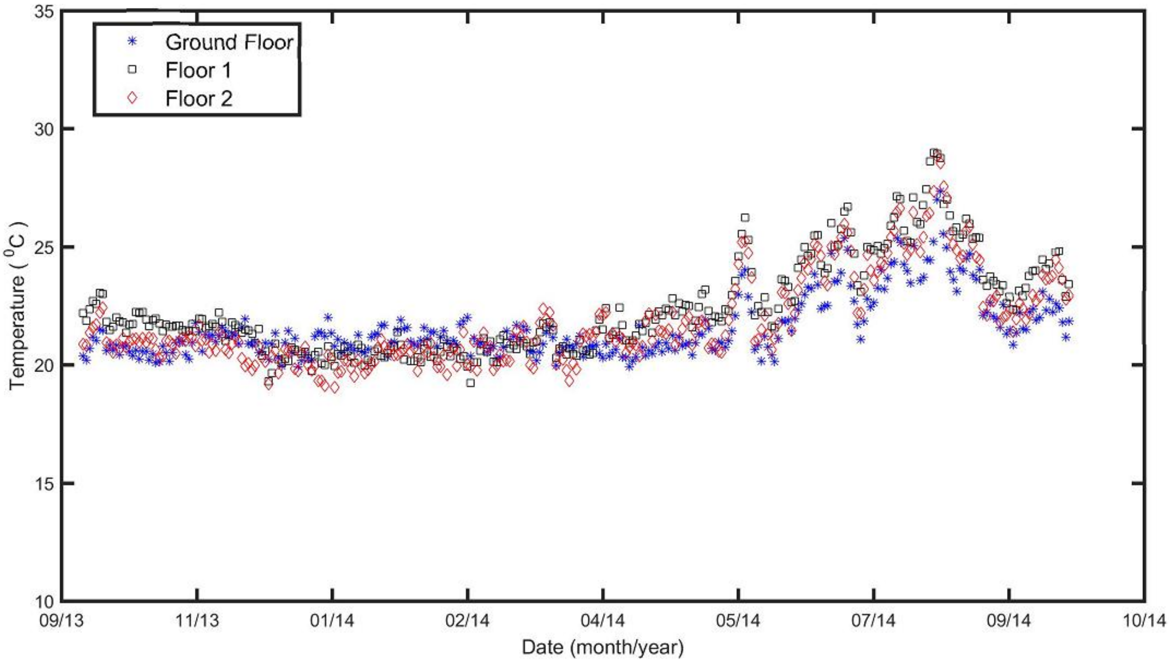

Figure 4: Ambient temperatures for House 1.

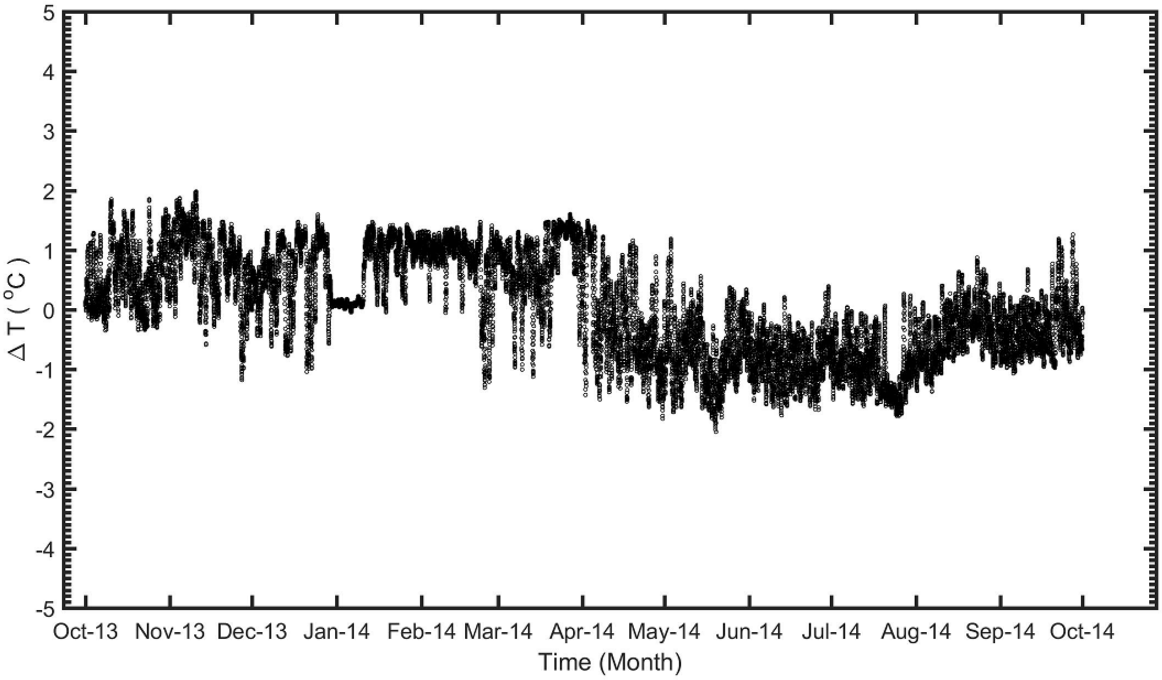

Figure 5: Temperature gain ($Tf_{outlet} - Tf_{inlet}$) for house 1. Data was smoothened using a moving average of 21 points to show variations every 7 hours.

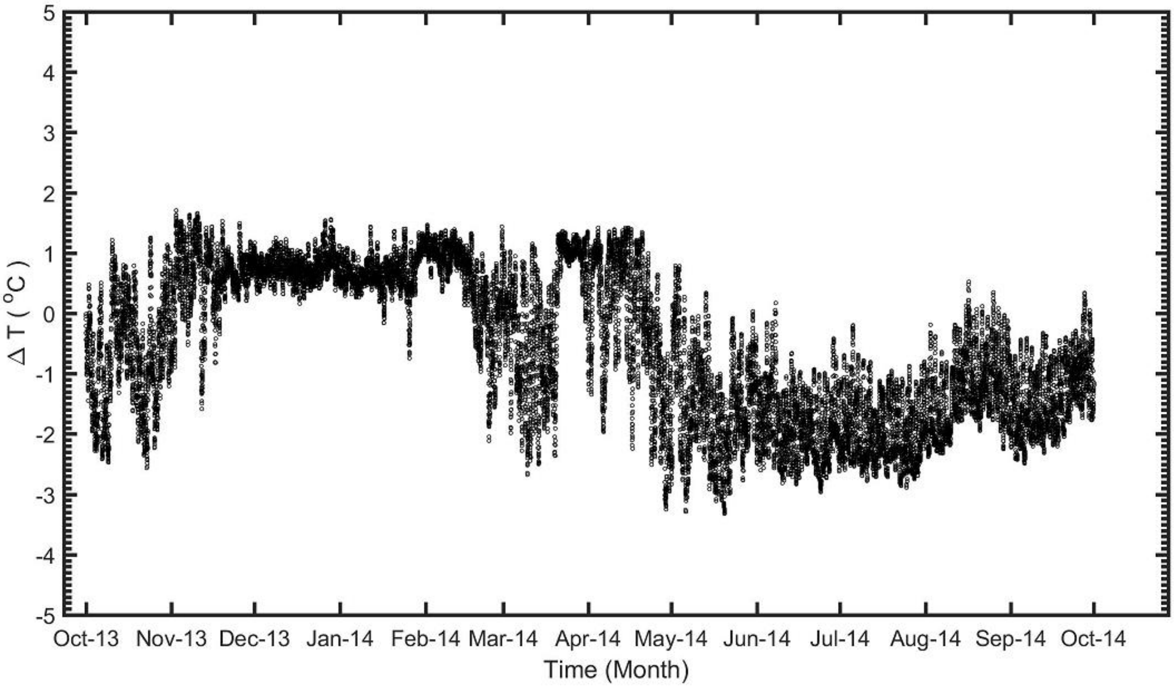

Figure 6: **Temperature gain** $(Tf_{outlet} - Tf_{inlet})$ for house 2. Data was smoothened using a moving average of 21 points to show variations every 7 hours.

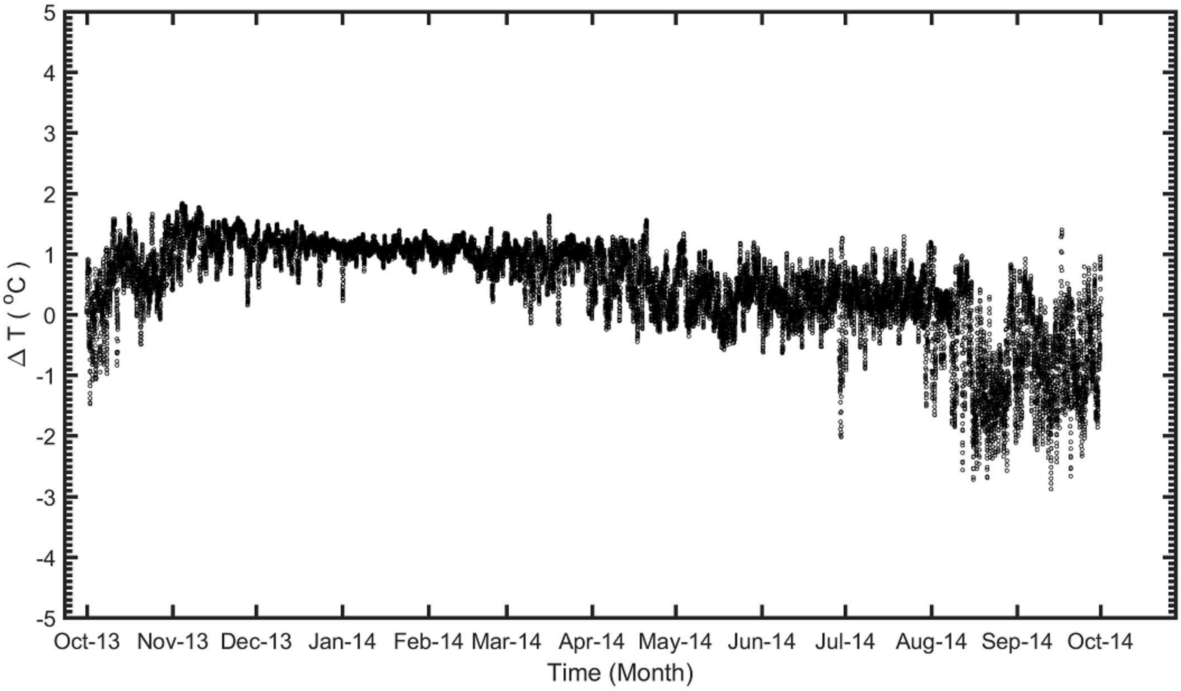

Figure 7: Temperature gain ($\boldsymbol{Tf_{outlet}} - \boldsymbol{Tf_{inlet}}$) for House 3. Data was smoothened using a moving average of 21 points to show variations every 7 hours.

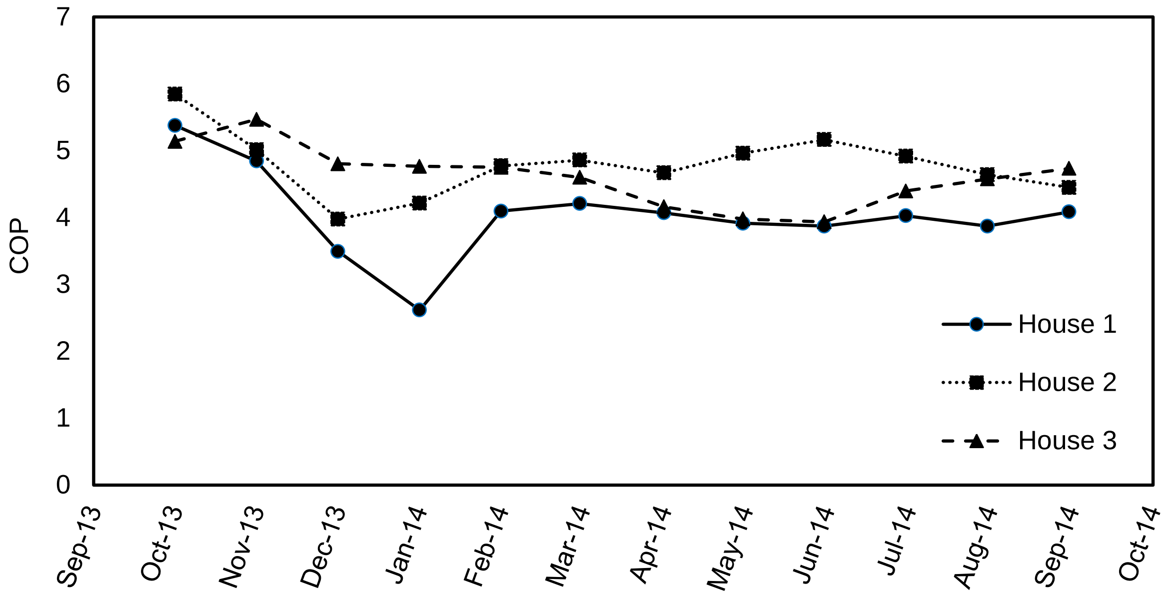

Figure 8: COP of the three heat pump systems.