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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)
$T_{f_{outlet}}$	Temperature of coolant leaving the heat exchanger loop (°C or K)
$T_{f_{inlet}}$	Temperature of coolant entering the heat exchanger loop (°C or K)

1 **1. Introduction**

2 **1.1 Background**

3 The UK aims to reduce its greenhouse gas emissions by at least 80 % by 2050 against the 1990
4 baseline set in the 2008 Climate Change Act. Part of this reduction will include the use of low carbon
5 technologies at a residential level which is the highest end user of energy in the UK accounting for 32
6 % of total energy consumption IEA (2012). Ground Source Heat Pumps (GSHPs) are one of the four
7 technologies listed in the domestic Renewable Heat Incentive scheme opened on 9 April, 2014 to help
8 homeowners save money by contributing to the countries Greenhouse Gas emission goals. A feed in
9 tariff of 19.10 p/kWh is available from October 2015 (Ofgem, 2015) based on an expected cost of
10 renewable heat generation over 20 years and this aims to offset the current higher cost of electricity
11 compared to gas and encourage the uptake of this technology.

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

20 Studies on heat pump systems have centred along the traditional installation of a horizontal Ground
21 Heat Exchanger (GHE) such as series, parallel and slinky-coil loops (see for example, Esen et al.,
22 2005, Esen et al., 2007, Pulat et al., 2009, Wu et al., 2010 and Naili et al., 2013) or vertical ground
23 loop panel in the form of borehole U-tubes (see, Boait et al., 2011, Bakirci et al., 2011 and
24 Michopoulos et al., 2013). Ground loop systems are buried into the ground connected to the heat
25 pump system. Generated heat energy is then utilised using an internal heat distribution system of
26 either under floor heating panels or larger radiators. In general, the systems are set up to provide both
27 space heating and hot water. The choice of whether to use horizontal or vertical loops is site specific.
28 Vertical loops require less space but have high drilling costs and are advantageous where space is

1 limited whereas horizontal loops require more piping and space but utilise shallow trenches cost less
2 than drilling (see, Florides and Kalogirou, 2007, Omer, 2008 and Yang et al., 2010)

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

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

26 Pulat et al., (2009) experimented with a 20 m long heat exchanger pipe with a diameter of 16 mm
27 buried at 2 m below the ground in Turkey. Analysis was only done over 36 days of data and from a
28 heat pump COP range of 4.03 to 4.18, the system COP was only between 2.46 to 2.58. It should be
29 noted that the heat pump COP is the ratio of the heat delivered by the heat pump to the electricity

1 consumed by the heat pump compressor. Whereas, the System COP is the quotient of energy
2 delivered to energy used by the whole heat pump system. The winter in Turkey is mild compared to
3 UK and the length of the GHE is very short at 20 m only since most field heat exchangers have
4 lengths in hundreds of meters for this system.

5 Ozyurt and Ekinci (2011) experimented with a single U-tube polyethylene pipe borehole in the cold
6 climate of Turkey. 2 boreholes 52 m deep and a U-tube diameter of 105 mm were explored in the
7 warm climate of Turkey. A system COP range of 2.12 to 2.50 was achieved whilst the heat pump
8 COP ranged from 2.65 to 3.00. Other design parameters hadn't been carefully considered leading to
9 pressure losses in the pipes. Bakirci et al., (2011) investigated a hybrid system consisting of two 53 m
10 deep boreholes and a flat plate water cooled solar collector. The heat pump COP measured was only
11 3.00 and the mean system COP was found to be 2.60. Despite supplementing the heat source with
12 solar panel, the system COP did not improve compared to conventional borehole heat exchangers.

13 Ally et al., (2012) simulated low energy consumption of a house for its cooling performance. Three
14 parallel circuits of slinky with 6 pipes and a total length of 559 m with an internal diameter of 19 mm
15 were used. System COPs between 3.44 and 4.90 were achieved in heating mode and 3.88 to 6.09
16 were obtained during cooling. The room temperatures were set to 21.67 °C during winter and 24.44
17 °C during summer. The performance of the system is impressive, the heat load on the heat pump was
18 simulated and actual heat load for an average house in the UK would be much higher. Naili et al.,
19 (2013) run in field experiments on a horizontal ground cooling system. The experimental length was
20 50 m whilst 25 m and 100 m loops were also explored. Simulation of longer pipes was done and the
21 heat pump COP was between 3.80 and 4.50 whilst the system COP ranged from 2.30 to 2.70. The
22 results of the simulations show that heat exchange rates were less variable at lengths more than a
23 100 m whilst the experiment only had 100 m as the longest exchanger.

24 **1.2 Carbon Emissions**

25 Carbon emission savings of a heat pump system compared to the gas boiler would depend on a
26 country's electricity grid fuel mix (see for example, Staffell et al., 2012 and Greening and Azapagic
27 2012). For example, the UK has a higher electricity emission factor at 4.46×10^{-1} KgCO_{2e}/kWh
28 (DEFRA, 2014) due to grid energy coming largely from coal and gas compared to France at 7.91×10^{-2}
29 KgCO_{2e}/kWh (see, Brander et al., 2011) where renewables are a big part of the energy mix.

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

14 **1.3 Scope of Work**

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

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

27

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/(m²K), 1.60 W/(m²K), 0.25 W/(m²K), 0.20 W/(m²K), 0.30 W/(m²K), 0.16 W/(m²K) 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.

1 2.2 Heat Pump Systems

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

10 Whilst all the three heat pump systems utilised a total pipe lengths of 350 m per system, the GHEs
11 were different. Custom heat exchanger loops were designed and installed to overcome the space
12 constraints in small house gardens. House 1 has got two 3.84 m by 5.50 m heat panels buried at
13 2.35m below the finished ground level at the house front and back gardens. Houses 2 and 3 have a
14 total of four panels installed in the front and back gardens and are located at 1.85 m and 2.35 m from
15 the finished ground level. A panel area of 2.72 m by 5.00 m was installed at the back of the house and
16 3.50 m by 4.00 m at the front of the house. All ground panels are made out of polyethylene pipes with
17 an outer diameter of 40 mm spaced at 0.12 m on House 1 and 0.16 m in houses 2 and 3. Glycol-
18 water mixture was circulated as the coolant in the pipe at a ratio of 2:1. Figure 2 (L) shows the
19 installation of ground heat exchanger in House 2.

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

27

28 Radiators were used as the heat delivery system for the houses at a constant temperature of 33 °C.
29 Occupants were briefed about the heat pump systems and were advised to contact the researchers

1 regarding comfort and issues relating to the heat pump system e.g. changing HP settings. The
2 thermostat setting has a significant effect on the energy consumption and it was set at the desirable
3 temperature for the comfort of occupants. It was thus in the interest of the study to keep the
4 thermostat setting of the houses monitored. Indoor temperature settings were varied between 18.00
5 and 19.50 °C while the DHW was set at around 52 °C in all three houses.

6

7 **2.3 Monitoring and Data Collection**

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

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

23

24 **2.4 Heat Pump System Performance**

25 The performance index of the heat pump systems is reflected by calculating a Coefficient of
26 Performance (COPs) for each system. The COP is calculated by getting the quotient of heat delivered
27 (\dot{Q}_{HD}) by the system to the electricity used by the heat pump (\dot{Q}_{HP}), see equation 1. Over specific

1 periods, this enables the determination of the Seasonal COP, the Heating COP and the Cooling COP
2 for each heat pump system.

$$3 \quad COP (system) = \frac{\sum \dot{Q}_{HD}}{\sum \dot{Q}_{HP}} \quad (1)$$

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

$$6 \quad \dot{Q}_{HD} = \dot{Q}_{HE} + \dot{Q}_{HP} \quad (2)$$

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

$$12 \quad \dot{Q}_{HE} = \dot{m} C_p (Tf_{outlet} - Tf_{inlet}) \quad (3)$$

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

16 **3.0 Results and Discussion**

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

20 **3.1 Temperatures and precipitation**

21 Cumulative precipitation and outdoor temperature are shown in Figure 3 and Table 2. Rainfall in
22 Dewsbury reached a total of 856 mm which is comparable to recent years in the UK. The heaviest
23 precipitation encountered during winter at 256 mm which was higher than 2012 winter. Summer's 174
24 mm of precipitation was however lower than that of 2012 which reached a record level of 350 mm. For
25 the heat pump systems that had the roof drainage connected to an infiltration trench (houses 1 and
26 2), prevents a total of 43 m³ runoff from draining into the local sewer network. Figure 3 also shows

1 that the average outdoor temperature dropped from around 10 °C to around 2 °C in January 2014.
2 Sub-zero outdoor temperatures were rarely recorded during the year, representing a mild UK winter.
3 Highest temperatures were recorded in the last week of July when outdoor temperature surpassed 25
4 °C. Of note, due to the huge amount of data points, daily averages were presented.

5

6 Figure 4 presents measured indoor temperatures at each floor of House 1. The temperature in the
7 rooms was fairly constant throughout the year at around 20 °C with the exception of late July where
8 indoor temperatures reached just above 30 °C in the hottest week of the year, showing that the
9 cooling systems were not engaged. Indoor temperature in the hall way of the ground floor showed the
10 highest temperature variation. Similar indoor temperature patterns in other houses were observed.
11 The constant temperature over the year shows that the thermostat setting for indoor temperature was
12 not changed and this is a similar pattern with houses 3 and 4. House 2 was the exception; it had a
13 higher thermostat temperature of 22 °C in October 2013 which was subsequently dropped back to 20
14 °C in January 2014.

15

16 **3.2 House Energy Usage**

17 Table 3 represents the energy usage of each house over the year, it can be seen that the houses with
18 heat pump systems had the highest electricity demand during winter in the months between January
19 and March and the least demand during summer. The control (House 4), with an occupancy of 2 has
20 a total annual electricity usage of 1890 kWh which is almost half the UK average electricity usage of
21 4,170 kWh (DECC, 2015). In terms of gas usage, the conventional system used 14010 kWh of gas,
22 across the year, bringing its total annual energy usage to 15,895 kWh which is close to the average
23 UK annual energy consumption figure of 14,829 kWh (DECC, 2015). The heat pump systems had
24 similar electricity usage despite the variation in occupancy of the houses and ground systems. The
25 gas usage in houses with heat pump systems was very minimal, only House 1 used significant
26 amounts of gas at 1220 kWh over the year. This is likely to be attributed to some technical issues with
27 the HP which caused it to stop working for around 20 days (from 28 December 2013 till 17 January
28 2014). Therefore, the backup system of the boiler covered the heat demands during this period and
29 hence, the increase in gas consumption.

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

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

9 **3.3 Heating Performance**

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

24
25 Figure 8 represents the monthly COP values in heating mode. House 2 yields the highest COP on
26 average at 4.79 followed by House 3 at 4.61 and House 1 at 4.04. It should be noted however, that
27 the heat pump in House 1 was not working for 20 days as can be inferred from its circulating fluid
28 temperature differential between outlet and inlet presented in Figure 5. Electricity usage of this heat
29 pump increased in the months of December 2013 and January 2014 whilst the amount of heat

1 extracted decreased significantly rendering COP heating for the 2 months 3.49 and 2.62 respectively.
2 The three systems had yearly COPs higher than 2.88 which would place them in the renewable
3 technologies contributing to EU's energy targets (REF, 2010). It should be noted that equation 2 does
4 not account for energy losses in the connecting pipes. Although all connecting pipes have been
5 carefully insulated, there might be some energy losses within the heat pump which have not been
6 considered. Luo et al., (2015) examined the effect of energy loss in the horizontal connecting pipes
7 without insulation in South of Germany and found that when taking energy losses in consideration
8 maximum achieved COP is only 75% of the calculated value.

9

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

17 A closer look at the overall performance of the three systems shows the double loop system was
18 considerably more effective at extracting heat than the single loop heat exchanger. The single loop
19 heat exchanger (House 1) has the lowest Seasonal Performance factor of the three houses at 4.04
20 over the whole year and 4.24 excluding December 2013 and January 2014. These COP values are
21 considerably lower than 4.79 and 4.61 for Houses 2 and 3 with double GHE loops respectively. The
22 higher COP in houses 2 and 3 could be attributed to the fact that the spacing between the pipes is
23 wider. As a result, thermal resistivity and interaction between pipes would be less. Furthermore, the
24 top loop heat exchanger of House 2 is close to the infiltration trench which means that the
25 surrounding soils would have higher degree of saturation leading to enhanced thermal conductivity.
26 The double loop system with an infiltration trench system therefore performed better than single loop
27 system with an infiltration trench and the double loop system without an infiltration trench by 17% and
28 4% respectively. The single loop system with an infiltration trench however, performs below the
29 double loop system without infiltration trench by a factor of 14% and thus further analysis would have

1 to be done to confirm the efficacy of the infiltration trenches. Mohamed et al., (2015) conducted
2 preliminary laboratory investigations into the effects of groundwater table fluctuations and infiltration of
3 rainwater on the amount of thermal energy that can be extracted from near surface soil layers and
4 showed that heat recovery could be enhanced by a factor of 4 when the soil was wetted to 200 mm
5 above the loop panel compared with that of dry conditions. There was a fivefold increase in thermal
6 conductivity of the soil between residual and saturated conditions. The study also found that
7 rainstorms caused temporary enhancement of heat recovery though the degree of enhancement was
8 dependent on the intensity of the rain event. The concept of directing rainwater into the ground is
9 therefore expected to have a positive impact on the recovery of thermal energy from ground at an
10 average UK house scale. The outcomes are therefore consistent with previous study. Further
11 monitoring of the systems and analysis of data are underway.

12

13 **3.3 Carbon Emissions**

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

24 When the same results are used with conversion factors of EU countries with a cleaner source of
25 secondary energy for the heat pump, the carbon emission reductions are much larger. For example,
26 France, which has electricity conversion factor of 7.91×10^{-2} as reported by Brander et al., (2011)
27 would give carbon emission reductions of 70.01 %, 73.25 % and 76.95 % for the three houses with
28 GSHPs respectively as well as the energy reductions.

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

7 Uptake of GSHPs would require the electricity grid to be closely reviewed as the UK's energy supply
8 at the moment is gas dominant at 63 % in 2014 DECC (2015) with the average electricity
9 consumption per household being 4,192 kWh whilst the average gas consumption per household was
10 15,462 kWh. An increase in GSHP installations could result in a subsequent increase in electricity
11 consumption and thus increasing strain on the electricity grid. With a decrease in oil and gas
12 production due to depletion of reserves, the role of renewables play a great role for the future of the
13 UK energy market.

14 **4.0 Conclusions**

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

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

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

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

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

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

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

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11 Recovery Strategies in the urban water cycle (INNERS, www.inners.eu).

1 **References**

- 2 Ally M R, Munk D J, Baxter V D and Gehl A C (2012) Energy analysis and operational efficiency of a
3 horizontal ground-source heat pump system operated in a low-energy test house and simulated
4 occupancy conditions. *International Journal of Refrigeration*, 35(4): 1092-1103.
- 5 Bakirci K, Ozyurt O, Comakli K and Comakli O (2011) Energy analysis of a solar-ground source heat
6 pump system with vertical closed loop for heating applications. *Energy*, 36(5): 3224-3232.
- 7 Boait P, Fan D and Stafford A (2011) Performance and control of domestic ground-source heat
8 pumps in retrofit installations. *Energy and Buildings*, 43(8): 1968–1976.
- 9 Brander M, Sood A, Wylie C, Houghton A and Lovell J (2011) Electricity-specific emission factors for
10 grid electricity. Ecometrica, London. Available from: [http://ecometrica.com/assets/Electricity-specific-](http://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf)
11 [emission-factors-for-grid-electricity.pdf](http://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf) (accessed on 02 July 2015).
- 12 Busby J, Lewis M, Reeves H and Lawley R (2009) Initial geological considerations before installing
13 ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*,
14 42(3): 295-306.
- 15 Curtis R, Lund J, Sanner B, Rybach L, and Hellstrom G (2005) Ground Source Heat Pumps -
16 Geothermal Energy for Anyone, Anywhere: Current Worldwide Activity. Proceedings World
17 Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005, 1-9.
- 18 DECC (Department for Energy and Climate Change) (2012) Detailed analysis from the first phase of
19 the Energy Saving Trust's heat pump field trial. London, UK. Available from:
20 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_second_phase_est_heat_pump_field_trials.pdf)
21 [second_phase_est_heat_pump_field_trials.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_second_phase_est_heat_pump_field_trials.pdf) (accessed on 02 July 2015).
- 22 DECC (Department for Energy and Climate Change) (2013) Domestic Renewable Heat Incentive.
23 London, UK. Available from:
24 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI_policy_statement.pdf)
25 [_policy_statement.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI_policy_statement.pdf) (accessed 02 July 2015).

- 1 DECC (Department for Energy and Climate Change) (2015) Energy Consumption in the UK:
2 Domestic energy consumption in the UK between 1970 and 2014. London, UK. Available from:
3 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/338662/ecuk_chapter_3_domestic_factsheet.pdf (accessed on 02 August 2015).
- 4
5 DEFRA (2014) Greenhouse Gas Conversion Factor Repository. London, UK. Available from:
6 <http://www.ukconversionfactorscarbonsmart.co.uk/Filter.aspx?year=38> (accessed on 02 July 2015).
- 7 Energy Saving Trust (2010) Getting warmer: a field trial of heat pumps. Energy Saving Trust, London,
8 UK.
- 9 Esen H, Inalli M and Esen M (2007) Numerical and experimental analysis of a horizontal ground-
10 coupled heat pump system. Building and Environment, 42(3):1126-1134.
- 11 Esen H, Inalli M, Esen M and Pihtili K (2007) Energy and exergy analysis of a ground-coupled heat
12 pump system with two horizontal ground heat exchangers. Building and Environment, 42(10): 3606-
13 3615.
- 14 Fawcett T (2011) The future role of heat pumps in the energy domestic sector. Environmental Energy
15 Institute, Oxford. Available from: <http://www.eci.ox.ac.uk/publications/downloads/fawcett11b.pdf>
16 (accessed on 02 July 2015).
- 17 Florides G and Kalagirou S (2007) Ground Heat Exchangers - A Review of Systems, Models and
18 Applications. Renewable Energy, 32(15): 2461-2478.
- 19 Frontier Economics and Element Energy (2013). Pathways to high penetration of heat pumps.
20 Frontier Economics Ltd., London, UK. Available from: <https://www.theccc.org.uk/wp-content/uploads/2013/12/Frontier-Economics-Element-Energy-Pathways-to-high-penetration-of-heat-pumps.pdf>
21 (accessed on 02 July 2015).
- 22
23 Goldschmidt V W (1984) HEAT PUMPS: Basics, Types, and Performance Characteristics. Ann. Rev.
24 Energy. 9: 447-72.
- 25 Greening B and Azapagic A (2012) Life cycle environmental impacts and potential implications for the
26 UK. Energy, 39(1): 205-217.

- 1 Gupta R and Irving R (2014) Possible effects of future domestic heat pump installations on the UK
2 energy supply. *Energy and Buildings*, 84: 94-110.
- 3 Healy P F and Ugursal V I (1997) Performance and Economic Feasibility of ground source heat
4 pumps in cold climate. *International Journal of Energy Research*, 21(10): 857-870.
- 5 IEA (International Energy Agency) (2012) Energy policies of IEA countries: United Kingdom 2012.
6 IEA, France. Available From: [http://www.oecd-ilibrary.org/energy/energy-policies-of-iea-countries-
7 united-kingdom-2012_9789264170988-en](http://www.oecd-ilibrary.org/energy/energy-policies-of-iea-countries-united-kingdom-2012_9789264170988-en) (accessed on 02 July 2015).
- 8 Jenkins D P, Tucker R and Rawlings R (2009) Modelling the carbon-saving performance of domestic
9 ground-source heat pumps. *Energy and Buildings*, 41(6): 587-595.
- 10 Luo J, Rohn J, Bayer M, Priess A, Wilkmann L and Xiang W (2015) Heating and cooling performance
11 analysis of a ground source heat pump system in Southern Germany. *Geothermics*, 53: 57–66.
- 12 Michopoulos A, Zachariadis T and Kyriakis N (2013) Operation characteristics and experience of a
13 ground source heat pump system with a vertical ground heat exchanger. *Energy*, 51: 349-357.
- 14 Mohamed M, El Kezza O, Abdel-Aal M, Schellart A and Tait S (2015) Effects of coolant flow rate,
15 groundwater table fluctuations and infiltration of rainwater on the efficiency of heat recovery from the
16 near surface layers. *Geothermics*, 53: 171-182.
- 17 Naili N, Hazami M, Attar I and Farhat A (2013) In-field performance analysis of ground source cooling
18 system with horizontal ground heat exchanger in Tunisia. *Energy*, 61: 319-331.
- 19 Ofgem (Office of Gas and Electricity Markets) (2015) Tariffs and payments for the Domestic RHI.
20 London, UK. Available from: [https://www.ofgem.gov.uk/environmental-programmes/domestic-
21 renewable-heat-incentive-domestic-rhi/about-domestic-rhi/tariffs-and-payments-domestic-rhi](https://www.ofgem.gov.uk/environmental-programmes/domestic-renewable-heat-incentive-domestic-rhi/about-domestic-rhi/tariffs-and-payments-domestic-rhi)
22 (accessed on 16 November 2015).
- 23 Omer A M (2008) Ground Source Heat Pump systems and Applications. *Renewable and Sustainable*
24 *Energy Reviews*, 12(2): 344–371.
- 25 Ozyurt O and Ekinci D A (2011) Experimental study of vertical ground-source heat pump performance
26 evaluation for cold climate in Turkey. *Applied Energy*, 88(4): 1257-1265.

- 1 Pulat E, Coskun S, Unlu K and Yamankaradeniz N (2009) Experimental study of horizontal ground
2 source heat pump performance for mild climate in Turkey. *Energy*, 34(9): 1284-1295.
- 3 Sanner B, Karytsas C, Mendrinou D and Rybach L (2003) Current Status of ground source heat
4 pumps and underground thermal energy storage in Europe. *Geothermics*, 32(4-6): 579-588.
- 5 Staffell I, Brett D, Brandon N and Hawkes A (2012) A review of domestic heat pumps. *Energy and
6 Environmental Science*, 5 (11): 9291-9306.
- 7 REF (The Renewable Energy Forum) (2010) *The Renewable Heat Incentive: Risks and Remedies*.
8 Renewable Energy Limited REF Ltd. London, UK. Available from:
9 <http://www.ref.org.uk/attachments/article/181/ref.on.rhi.16.09.10.low.res.pdf> (accessed on 02 July
10 2015).
- 11 Underwood C (2014) On the design and response of domestic ground-source heat pumps in the UK.
12 *Energies*, 7(7): 4532-4553.
- 13 Wu Y, Gan G, Verhoef A, Vidale P L and Gonzalez R G (2010) Experimental measurement and
14 numerical simulation of horizontal-coupled slinky ground source heat exchangers. *Applied Thermal
15 Engineering*, 30(16): 2574-2583.
- 16 Yang H, Cui P and Fang Z (2010) Vertical-borehole ground-coupled heat pumps: A review of models
17 and systems. *Applied Energy*, 87(1): 16-27.

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 electricity.

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 ₂ e)	812	3228	3254	3280
Annual Gas Usage (kWh)	14010	1220	710	140
Annual Gas Carbon Equivalent (KgCO ₂ e)	2580	230	130	30
Annual Gas & Electricity Usage (kWh)	15900	8730	8280	7770
Annual Gas & Electricity Carbon Equivalent (KgCO ₂ e)	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%

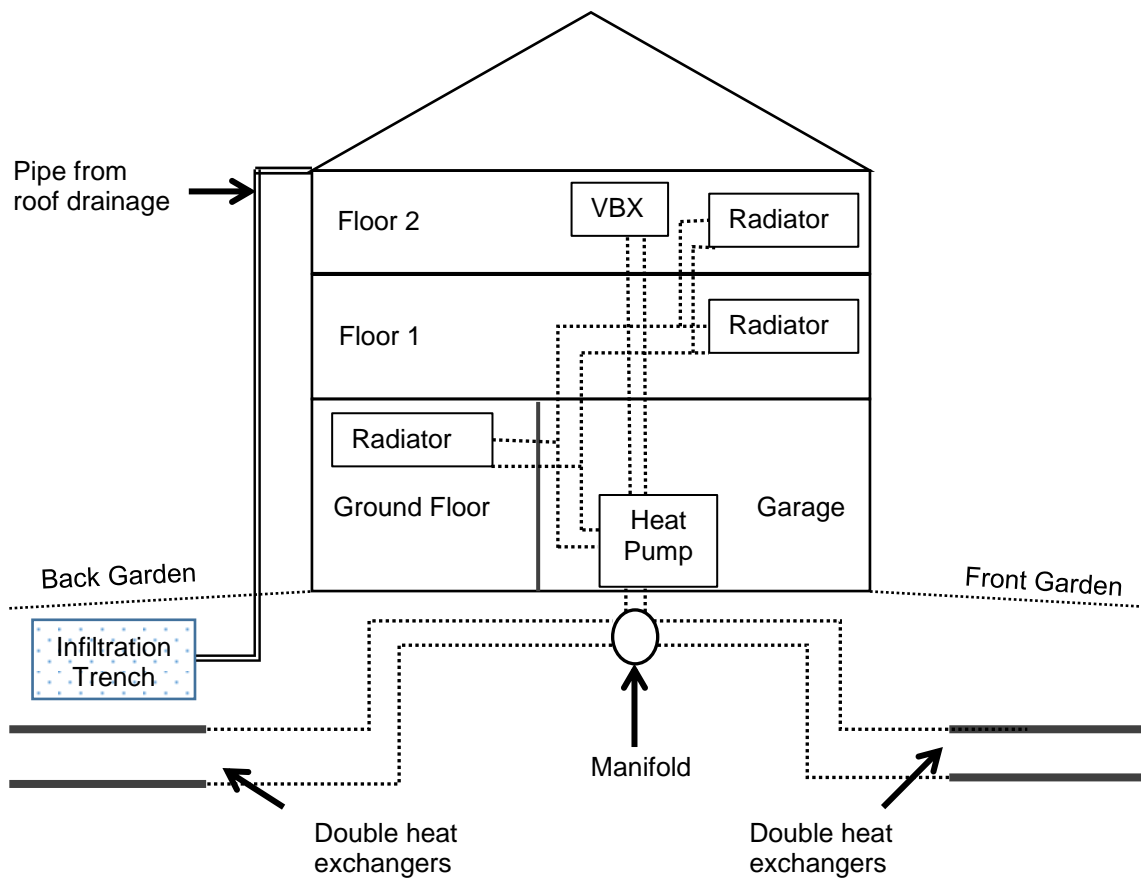
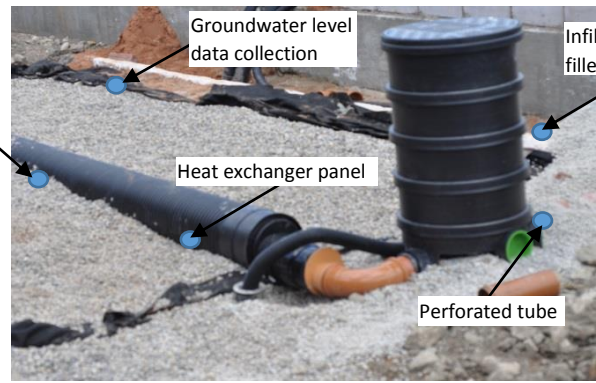


Figure 1: A schematic of the heat pump system of a double heat exchanger loop with infiltration trench.



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



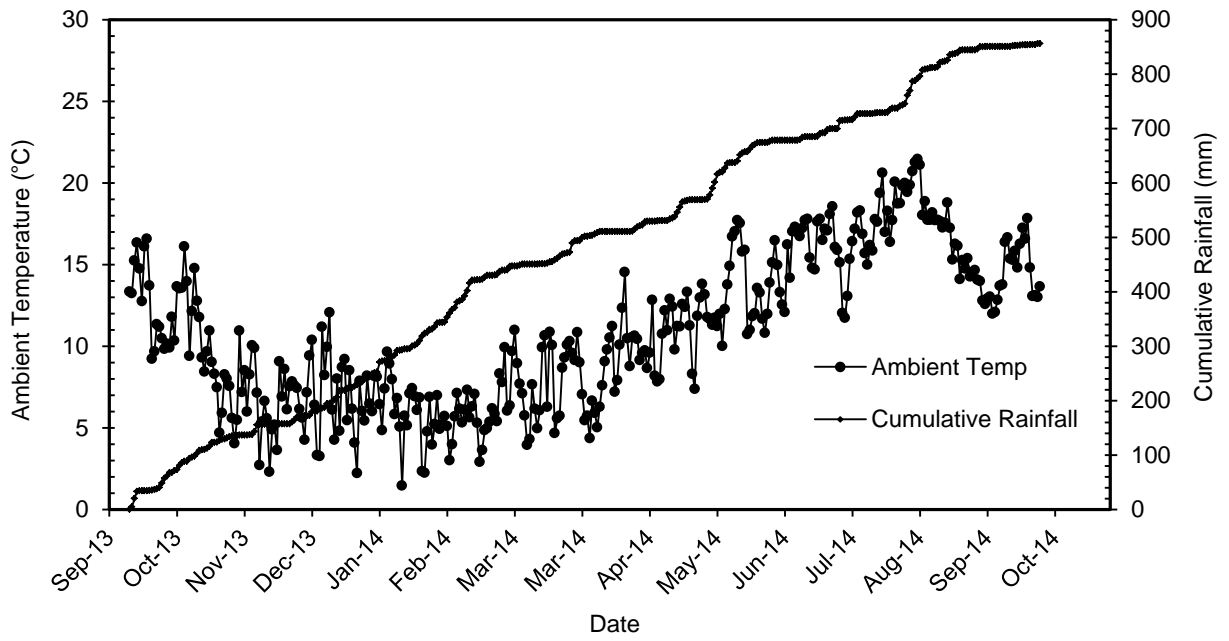


Figure 3: Cumulative rainfall and outdoor ambient temperature.

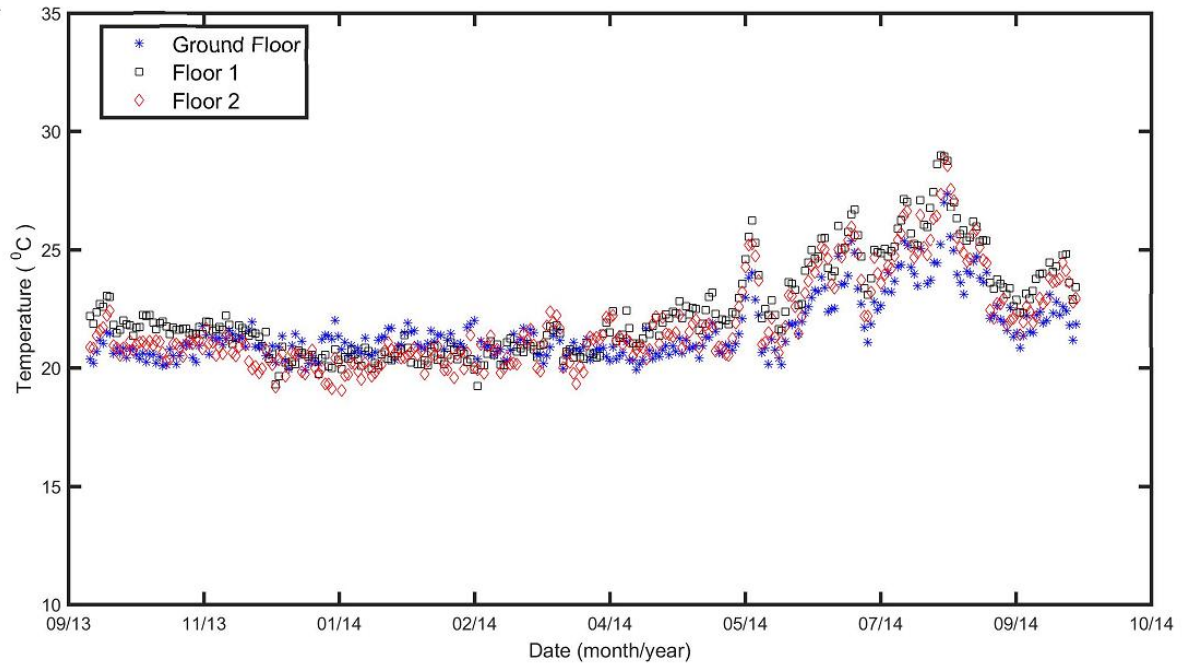


Figure 4: Ambient temperatures for House 1.

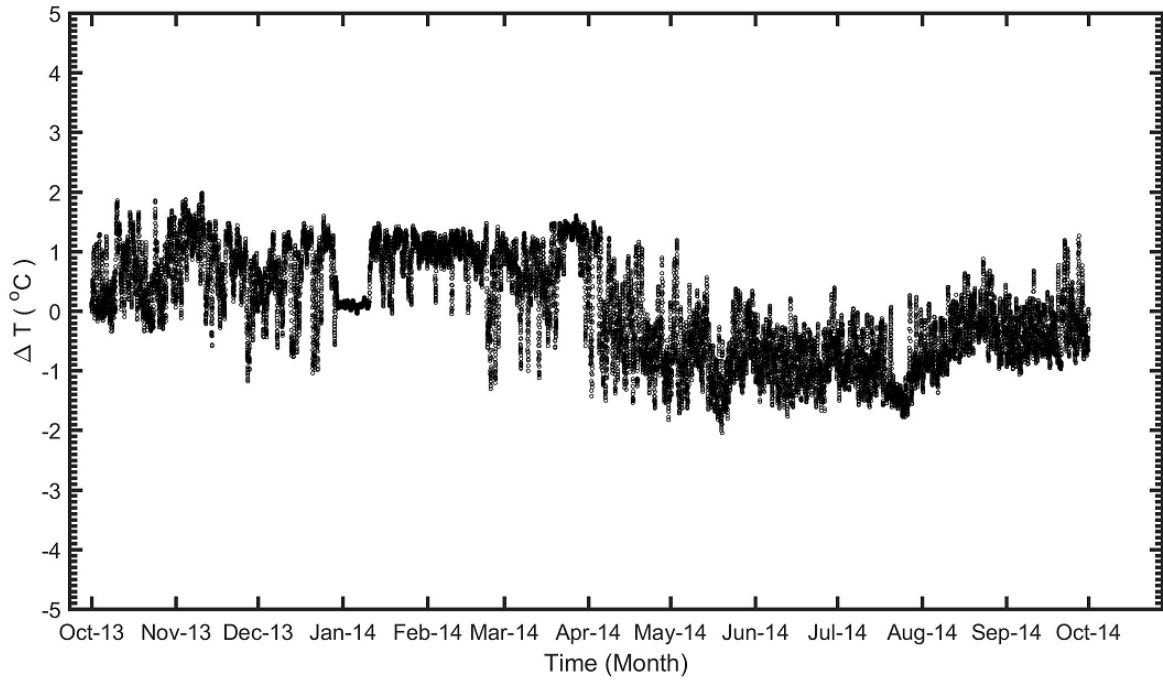


Figure 5: Temperature gain ($Tf_{outlet} - Tf_{inlet}$) for house 1. Data was smoothed using a moving average of 21 points to show variations every 7 hours.

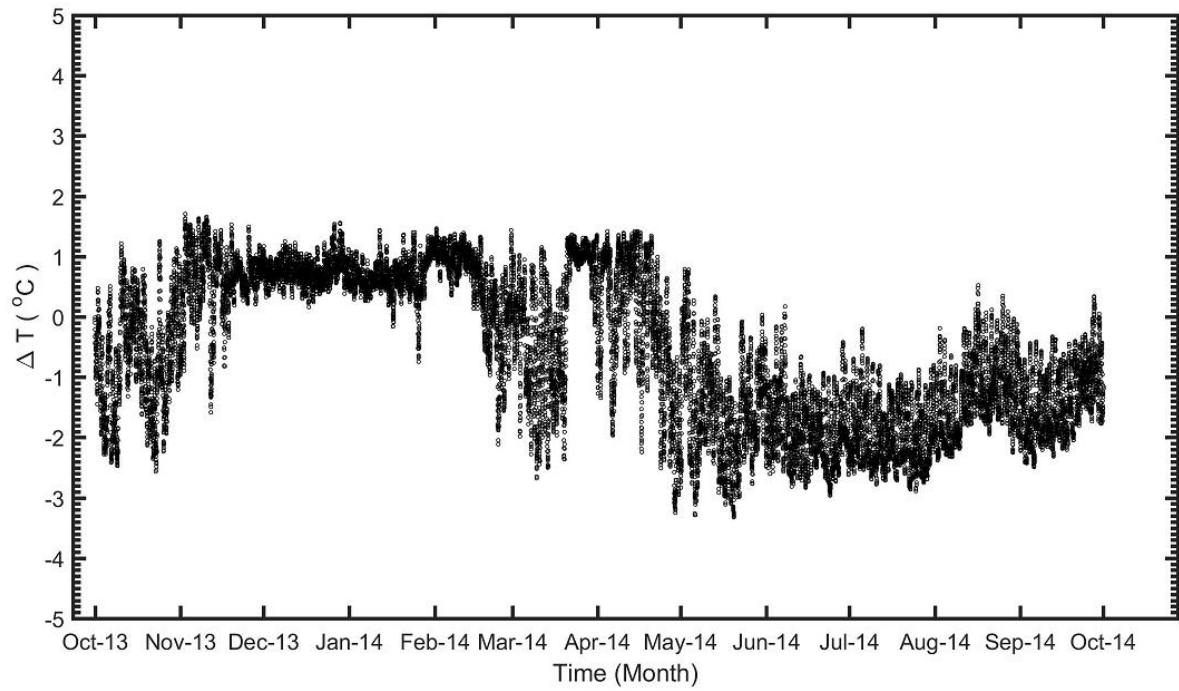


Figure 6: **Temperature gain** ($Tf_{outlet} - Tf_{inlet}$) for house 2. Data was smoothed using a moving average of 21 points to show variations every 7 hours.

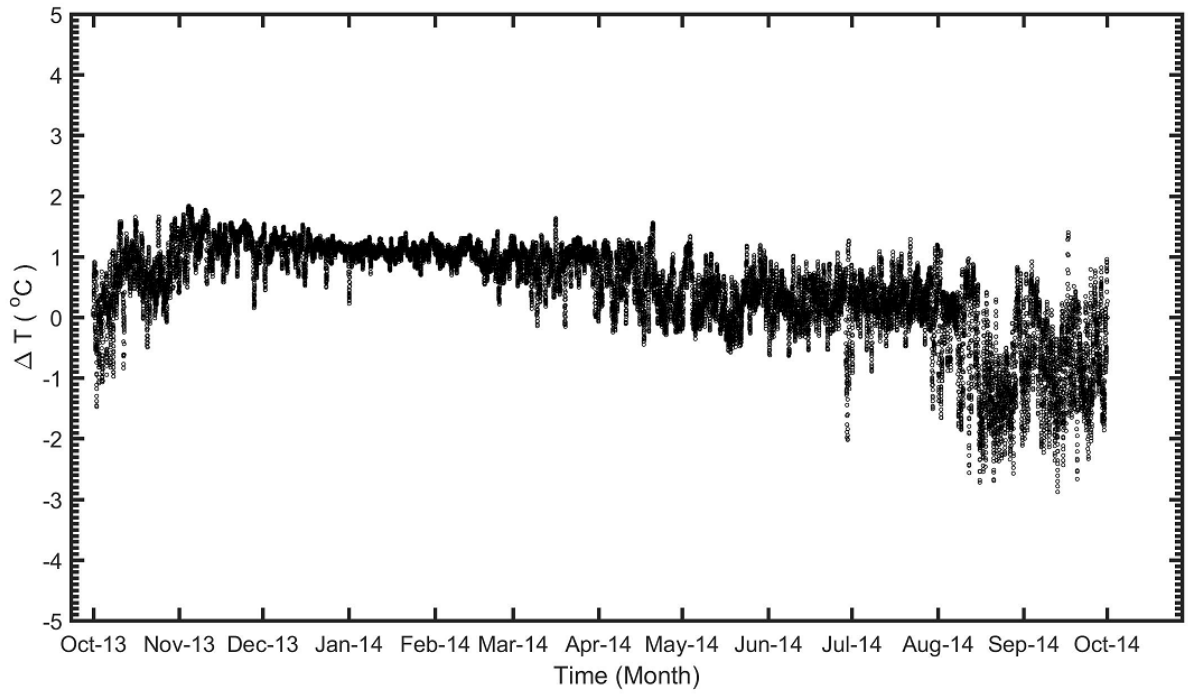


Figure 7: Temperature gain ($Tf_{outlet} - Tf_{inlet}$) for House 3. Data was smoothed using a moving average of 21 points to show variations every 7 hours.

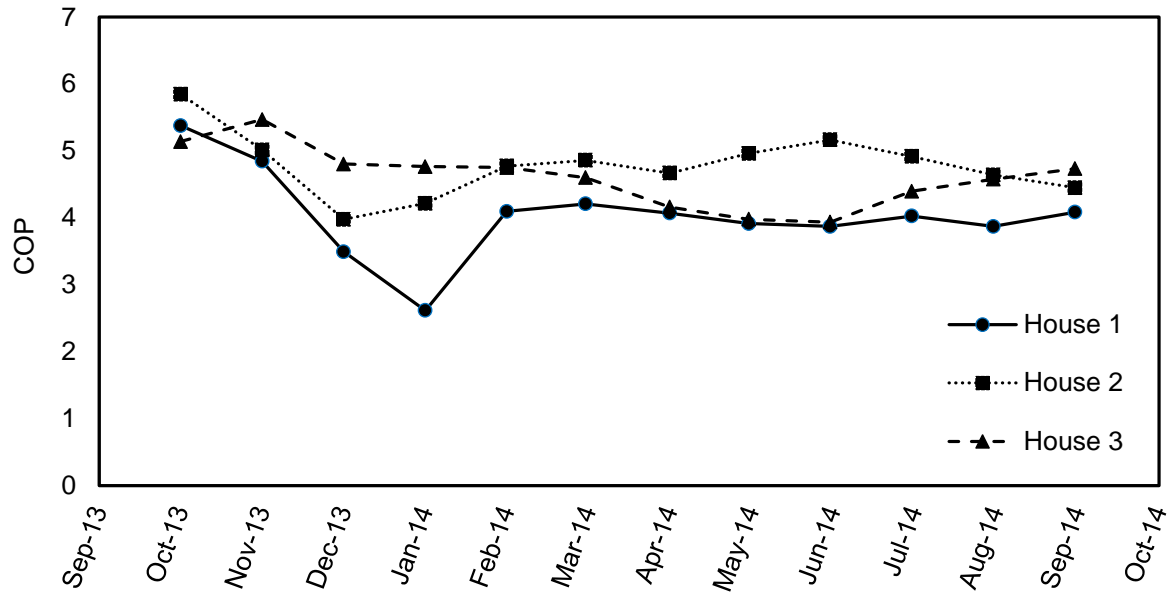


Figure 8: COP of the three heat pump systems.