Title: Practical considerations in the deployment of ground source heat pumps in older properties – a case study

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Highlights

- GSHP installed in off-gas grid 1800s residential building to replace oil heating
- ESP-r modelling of building and local weather used to determine the heating needs
- GSHP sized according to modelling results, SAP assessment would lead to oversizing
- There is a trade-off between reducing the size of the heat pump and energy savings

Abstract

A ground-sourced heat pump (GSHP) was installed in a former Vicarage in Cambridgeshire, with a mix of solid wall structure built in the late 1800s and cavity wall section built in the 2000s, previously heated by oil. This type of building is usually considered unsuitable for heat pumps, unless substantial

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insulation work and extensive replacement of radiators are undertaken. Although the building had undergone a degree of retrofit to increase insulation, the GSHP was installed with the existing radiators. A detailed thermal model for the house was built in ESP-r and validated against experimental measurements taken from sensors in every room. The expected heating demands were computed from the model based on weather data and the GSHP system was designed accordingly. A compromise was made between minimizing the size of the heat pump and the achievable energy savings, which could have important implications for the way incentives for low-emissions heating systems are set up. Using the initial SAP assessment would have led to a substantial oversizing of the heat pump. The data collected so far show that an SPF of 2.9 has been achieved whilst maintaining comfortable (18 °C) internal temperatures and emissions of CO_2 have been reduced by 70%.

Keywords: GSHP; pre-1900 building; ESP-r modelling; SAP; oversizing; energy savings; existing iron cast radiators.

Introduction

The United Kingdom has ambitious targets for reducing the emissions of greenhouse gases (GHG) with a target of 80% by 2050, compared to 1990 levels (HM Government, 2008). To date the majority of savings have come from the decarbonization of electricity generation, combined with effectively exporting emissions through imports and improved waste management (BEIS, 2017a; DEFRA, 2015). In 2013, space heating and hot water accounted for approximately 40% of total final energy consumption in the UK (BEIS, 2016) and 20% of UK GHG emissions (CCC, 2016). Domestic buildings were responsible for the major share of energy use for space and water heating (Figure 1). Overall, space and water heating in buildings is still overwhelmingly provided by fossil fuel sources, with natural gas supplying 70% of the energy demand with oil and electricity each accounting for 8%. Whilst insulation improvements can lead to some reduction in final energy use, the move to heating based on heat pumps is seen as a key low-carbon heat technology by the Department for Business, Energy & Industrial Strategy (BEIS) and the Committee for Climate Change (CCC) (CCC, 2015; DECC, 2011), especially in buildings off the gas grid (CCC, 2016). Heat pumps can extract heat from the air, the so-called air source heat pump (ASHP) or the ground, the ground source heat pump (GSHP). Projected numbers of new installations over the coming years are shown in Table 1, along with the actual number of devices already installed in existing properties. The latest numbers for installations in the UK point to a total of only 100,000 air and ground source heat pumps (CCC, 2015). The CCC estimates that an additional 200,000 installations are required between 2015 and 2020 to stimulate the market for heat pumps in the UK and keep on track to meeting the 2035 GHG emission budgets.

The GSHP has the advantage that the temperature of the ground does not vary as much as that of the air, with the particular benefit that in winter, the period of maximum demand, the ground is still relatively warm. In contrast, the ASHP can encounter difficulties with icing of the heat exchanger in cold weather when of demand is highest though in summer the air temperature is often warmer than the ground. However, the air source system is easier to install, despite potential issues with noise if sited too close to neighbouring properties and buildings, hence the cost is lower. In the case of the GSHP, either boreholes or ground loops are needed unless, exceptionally, a body of water is available. Boreholes are expensive and access is required for the specialist equipment. Trenching for ground loops (‘slinkies’) is in principle straightforward but requires a large ground area and is disruptive. These factors no doubt explain why relatively large numbers of ASHPs have been installed despite the existence of substantial subsidies (the renewable heat incentive (RHI)) (BEIS, 2017b; Ofgem, 2017).

Further issues relate to the design and operation of heat pump installations. General practice in the UK has been to heat with gas, or to some extent oil, fired boilers (Figure 1). Installers are familiar with these devices and sizing proceeds from guidelines based on the floor area of the property and the type of construction; examples of these can be found on manufacturers’ websites. The aim is to ensure adequate heat output on cold (-5°C in England) days with the expectation that the heating will be on for a relatively short period in the morning and a longer time in the evening so there will be high transient demands. Combined with installers' natural desire to avoid customer complaints about being cold, this process leads to boilers of high rating, multiples of actual demand for much of the time (Bennett et al., 2016; The Energy Saving Trust, 2009).

The extra cost of a larger gas or oil boiler is not great and indeed the cost of the boiler is not a dominant element in the cost of a whole heating system (up to 25% of total cost of the system). In contrast, heat pumps are expensive and there is therefore a strong incentive to not to oversize the system, especially for GSHPs where an increase in output requires additional ground loops or boreholes. The use therefore of heat pumps poses linked challenges for installers and users. From a user perspective, mixed experiences have been reported, both anecdotally and in the literature (Boait et al., 2011; Energy Saving Trust, 2011; 2013; DECC, 2013). Individuals used to the rapid warm-up characteristic of gas fired systems may find the slow response of a heat pump based system frustrating; others have bemoaned the lack of controllability and have resorted to temperature management by opening windows to release excess heat (Boait et al., 2011; Liu, Shukla, & Zhang, 2014). Many of these issues stem from the design of the system, reflecting installers' lack of understanding and experience, and the intrinsic limitations of some heat pumps.

There are also definite views on the type of property suited to heat pumps systems (Jenkins et al. 2009; Fawcett, 2011; Arteconi et al., 2013; Judson et al., 2015; Ali et al., 2016). It is widely asserted that they are only appropriate for very well insulated, typically new build, houses with underfloor (low temperature) heating. Whilst there is no doubt that these building are well suited, if there is to be a significant move to heat pump based heating systems, as hoped for by BEIS and CCC, then a wider range of building types must be considered. In fact, the largest CO_2 savings are likely to come from applying heat pumps to houses off the gas grid which are currently heated by oil (CCC, 2016; Gupta and Irving, 2014; Hannon, 2015; Kelly et al., 2016). Although it may be simpler in principle to move to gas heating, there have been no significant extensions to the gas network in recent years and it is unlikely that there will be in future. Houses in this category often have quite high heating loads so the CO_2 savings will be considerable and often have the land required for the installation of ground loops or boreholes; exceptional cases include Castle Howard where heat is extracted from a lake (MBS, 2011).

This paper investigates the practicalities of heat pump installation in older houses currently heated by oil. The work is based on a case study of a former Vicarage in Cambridgeshire. The study began by building a detailed thermal model for the house and verifying this against experimental measurements taken from sensors in every room. The expected heating demands were then computed from the model based on weather data and the GSHP was designed accordingly. The system was then installed and initial operational data are presented.

In the longer term, there is an interest in seeing what coefficient of performance is achievable as reports suggest that this deteriorates with time (Banks, 2008; Underwood, 2014), principally as a permanent depression of ground develops (this is not an issue for ASHPs). It may also be that manufacturers quote optimistic and possible unrealistic performance data for their heat pumps.

Table 1 – Current and projected heat-pump installations in existing (retrofit) and new buildings under different future UK energy system scenarios (sources: CCC, 2015; BEIS, 2016; DECC, 2011)

			number of units
Current Installations	2014	ASHP & GSHP	100,000
5^{th} Carbon budget	2035	GSHP – retrofit	up to 102,000
		ASHP – retrofit	up to 5,820,000
		Heat Pumps - new buildings	up to 4,400,000
Carbon Plan	2035	ASHP (retrofit & new)	11,406,152
(core MARKAL)		GSHP (retrofit & new)	5,899,734
	2050	ASHP (retrofit & new)	23,173,830
		GSHP (retrofit & new)	11,986,464

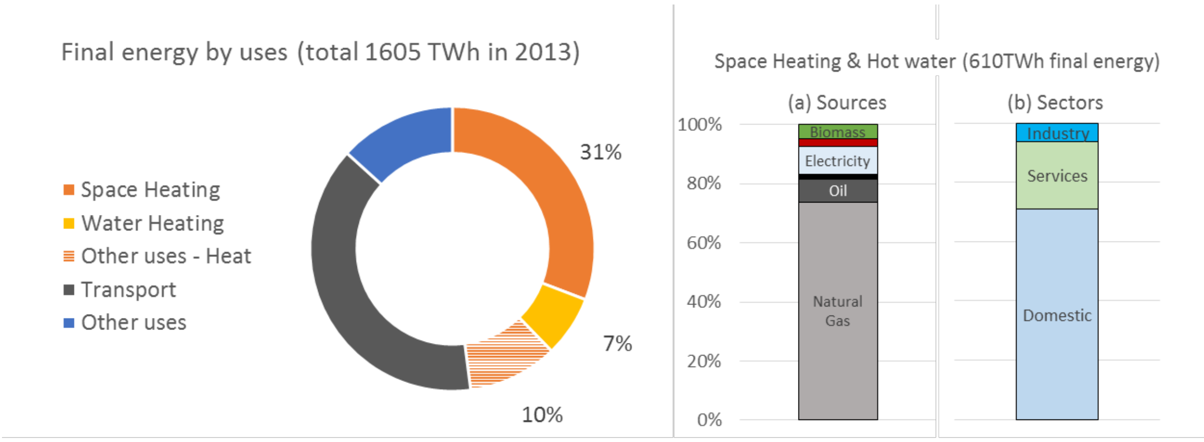

Figure 1 – Space heating statistics 2013 – sectors and fuel use (based on data from (BEIS, 2016)).

2 The building

The property chosen for the study is a former vicarage, a type of building often described as 'un-heatable'. The building is representative of a medium sized country house, the floor area being approximately 3000 sq. ft or 300 m². There are an estimated 700,000 similar properties heated mostly by oil with high potential CO_2 savings (CCC, 2017). The ground floor plan of the house is shown in Figure 2. The original building, constructed between 1871 and 1872, is of mixed construction – the front part is of solid triple brick (13 1/2"/ 343 mm) and the rear part is solid 9" (229 mm) brick. For uncertain reasons the house was never completed as originally designed so the present owners built, more or less to the original plan, a new section in 2000-2001. The construction here was cavity wall, with an outer skin of brick (4 ½"/ 114 mm), 100 mm of Rockwool insulation and an inner skin of 100 mm blockwork.

The roof over the original parts of the house is of the collar type. It was only possible to install 50 mm of semi-rigid Rockwool over the sloping parts of the ceilings because of limited space whereas 200 mm of blanket was placed over the flat surfaces. In the new build part, the first floor ceilings all have 200 mm of Rockwool, the thickness required at the time of construction. The glazing is variable – in the new build with two exceptions sealed double glazed units were employed. In the older part there are single glazed windows with shutters, single glazed windows with additional inner windows and some simple single glazed windows. The ground floors are mostly insulated with 100 mm of Rockwool or fibreglass but there is a small area of uninsulated solid floor in the scullery and pantry. Some measures have been taken to reduce draughts but there are four open fires, three having a register plate or a closer, and a stove. A cellar under the kitchen is a further source of air flow via the cellar steps. The elements are summarized in Table A-1 in the Appendix. Note that although the terminology used by ESP-r may differ from the actual materials in the building; the values used in the modelling are SAP values for the actual elements.

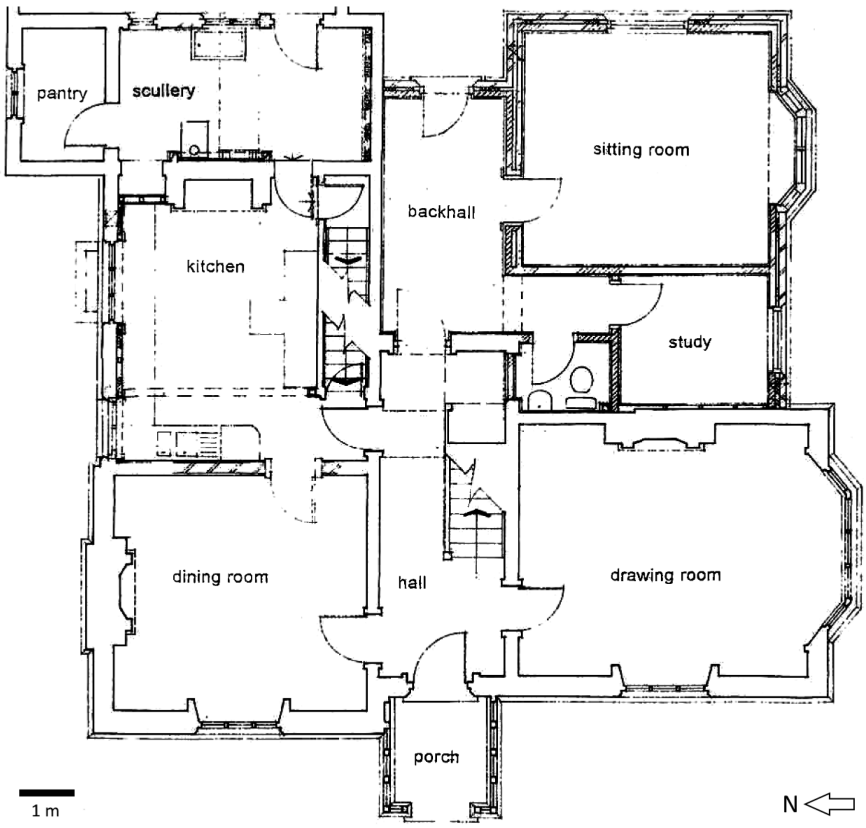

Figure 2 – Ground floor plan

3 Initial planning and building characterization

As part of the planning for the installation of the GSHP, the oil consumption from the time of the completion of the 2001 building works was examined. The data show that the oil consumption for space heating and water was on a steady downward trend, reflecting improvements in thermal performance, as shown in Figure 3. Annual usage was approximately 5000 l, noting that this figure includes use by an oil burning Aga, estimated to be around 2000 l. The space heating input over the year is about 32 MWh, allowing for 2 MWh for hot water. This calculation assumes the calorific value of oil to be 10.35 kWh/l and the boiler's combustion efficiency to be 80% (the manufacturer's declared efficiency for the oil boiler is 84.6%) and the Aga's combustion efficiency in the heating period to be 55% (from SAP).

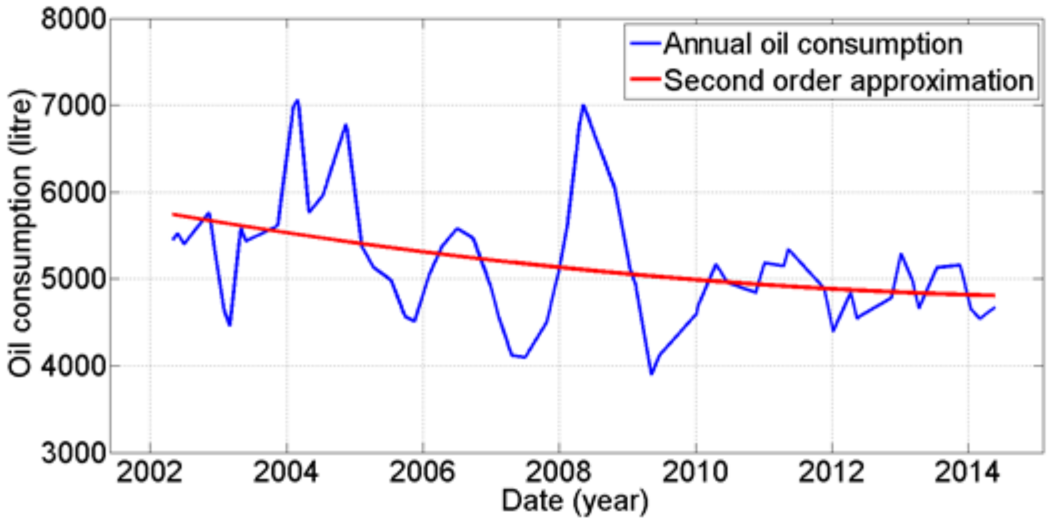

Figure 3 – Total oil consumption for heating and hot water from 2001-2014.

Also as part of the planning, the installer calculated, using standard methodology (SAP), the expected heating and hot water demands and found these to be 52 and 3 MWh, respectively, substantially greater than the actual figure. Some adjustments, primarily allowing for the heat output from the Aga, were made to the calculations to produce a figure (32 MWh) that more reasonably aligned with actual consumption. It is the case that one of the bedrooms with the poorest thermal properties is not heated but on the other hand the heating periods are considerably longer than normal, in particular continuous heating throughout the night. As part of the application for the Renewable Heat Incentive (RHI), it was necessary to obtain an Energy Performance Certificate. The house's Energy

Efficiency Rating was E41, with a rating of F32 for environmental impact. The estimated heated requirement was 52 MWh over a year, again higher than the actual heating requirements, even with an additional 3 MWh for water heating. Understanding the reasons for the significant differences was a driving factor in building a detailed thermal model of the house, both to enable a more accurate sizing of the heat pump and to understand the origin of the why the SAP method leads to such an overestimate.

As further preparatory work, temperature and humidity sensors were placed in all rooms and in the attic spaces, all wireless connected to a data hub with an internet connection. Readings of temperature, accurate to ±1°C are taken every 30 minutes. The heating regime, during the working days, was 4.30 pm to 8.30 am the following day and was continuous at weekends. All radiators have thermostatically controlled valves As an example of performance, Figure 4 shows temperatures of the dining room, the bedroom over and the kitchen, the latter containing the Aga, for a day in March 2015. The attic temperature is a proxy for the outside temperature, which fluctuates between 6 and 10°C. The stability of the internal temperatures during the heating period are evident, as is the decay of temperature in the bedroom and dining room once the heating is stopped. A fall in temperature occurs in the kitchen, despite the presence of the Aga, suggesting a significant degree of thermal coupling to the rest of the building, noting that there is no radiator in the kitchen.

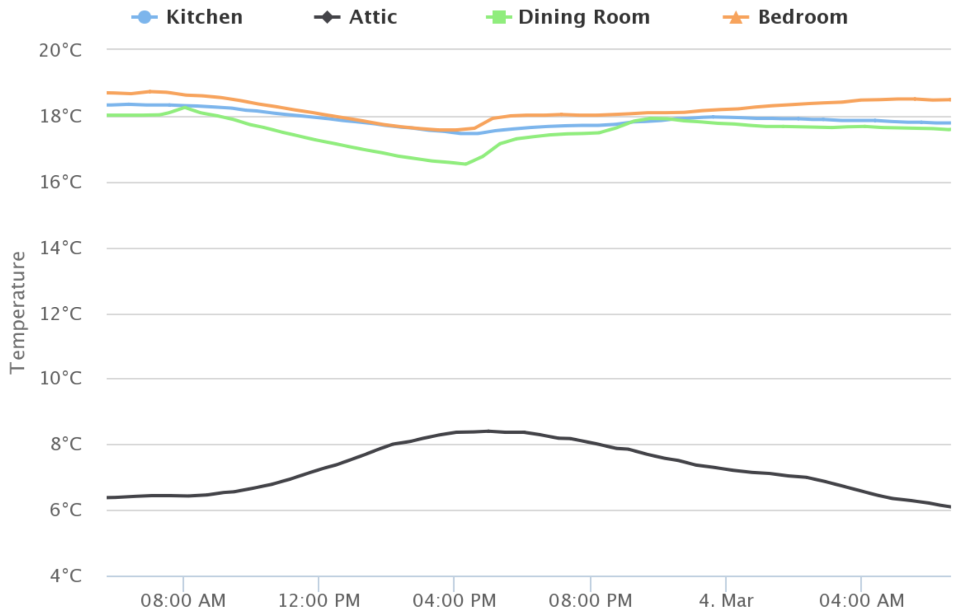

Figure 4 - Room temperatures over a 24 hour period on 3rd – 4th of March 2015 (from temperature logging).

The long thermal time constants evident, of the order of 24 hours or longer, are not unsurprising as the construction of the house is relatively massive, with almost all internal walls being of 9" brickwork. The high thermal mass combined with moderate values of thermal conductivity leads to long time constants. Experiments were made to extract time constants by shutting off the radiators in a room and dissipating a known power from an electric heater until an equilibrium temperature was obtained followed by cooling. A fitting algorithm was then used to obtain time constants but there was considerable variability in the results and the time constants for heating and cooling could be quite different. One obvious problem is that for best results the outside temperature has to be nearly constant, a condition only obtained on overcast winter days. In addition, rooms are thermally coupled, complicating behaviour. Overall, this is an area where experimental techniques need to be developed, probably in conjunction with sophisticated thermal models.

Recognizing that the temperature of the water for the central heating from a heat pump would have a maximum value of 55°C, and ideally less, the thermostat setting on the oil boiler was reduced in autumn 2015 to its lowest value, producing an exit temperature of about 55°C but with a peak of about 60°C just before the burner shuts off.

Although the radiator thermostatic valves have a constant setting, there is a clear temperature droop and recovery. As the heat loss increases with falling outside temperature, there has to be an ever greater difference between the set and actual temperatures to increase the output from the radiators. This difference is exacerbated by lower circulating water temperatures; in control terms the gain of the feedback loop is proportional to the difference between room temperature and circulating water temperature so the smaller the difference the bigger the temperature error. Whilst a slump of 3°C is not large in absolute terms, it is significant in terms of human comfort and in addition the cooler outside walls will reduce the perceived temperature (which takes into account radiation) even further.

Several important conclusions were drawn from the initial investigations. It was reassuring to know that the heating system could function in terms of an adequate heat output with a circulating water temperature in the range achievable with a heat pump. Temperature control with thermostatic valves would, however, be less precise. This could be overcome by electrically actuated valves but the extent of cabling to implement this measure is a drawback although there are now battery operated TRVs. There is the option of manual advance of settings in critical areas, notably bedrooms and bathrooms; the living areas have supplementary heating anyway. A further option is making the circulating water temperature dependent on the outside temperature (possible with the GSHP) to give a feed-forward effect though the achievable degree of compensation was not certain.

The manner of operating the system is also a consideration. In fact the long thermal time constants of the building lend themselves to heating with a heat pump; the expectation is that the interior of the building will be maintained at essentially a steady temperature. It is accepted that the house will take a considerable time to heat up from cold, or indeed change temperature rapidly. In other words, the heating system will not behave like a traditional gas or oil fired system.

4 Thermal model, including verification

Thermal modelling was performed with the ESP-r software package (William, 2015). The complex model encompassed 29 zones, 16 of which refer to home divisions, 4 to halls and passageways, another 4 to separate sections of the roof, 1 to the underfloor volume, 1 to the cellar, and 3 to the fireplaces and respective chimneys. It was initially built as closely as possible to reflect the geometry and indoor areas (Figure 5), materials and constructions (Table A-1) and infiltration rates previously gathered and used for the SAP evaluation.

The model was further refined using the sensors' temperature measurements for each room and calibrated, particularly in terms of air infiltrations and air exchange rates between rooms, with the experimental data collected during the determination of time-constants. Heating periods, set-points and space occupation were modelled according to actual conditions. The AGA stove in the kitchen, operating continuously, was included in the model as a constant heat source of 1.37 kW during the heating season (note that during the project the AGA was converted to electrical heating so actual electricity consumption measurements became available) and then slightly lower over the summer months, due to the lower temperature differential with the kitchen's air temperature.

The closest ESP-r weather data included in ESP-r is for London, which is itself based off Gatwick airport data, about 75 miles south of the building location. Cambridge University's Digital Technology Group, however, located just over 4 miles away, have compiled an archive of weather data since 1995 which is freely available online (DTG, 2016). Using this data, Gatwick's ESP-r data file was modified to account for Cambridge's conditions in the years from 2009 to 2015, thus creating one file for each of those 6 years. This meant replacing dry-bulb temperatures, humidity and dew-point temperatures by the measurements done by the Cambridge University's meteorological station. Given the absence of local solar radiation measurements, Gatwick's data were used instead. This is a source of error that must be kept in mind when comparing the model performance with the data from the temperature and humidity sensors in the house.

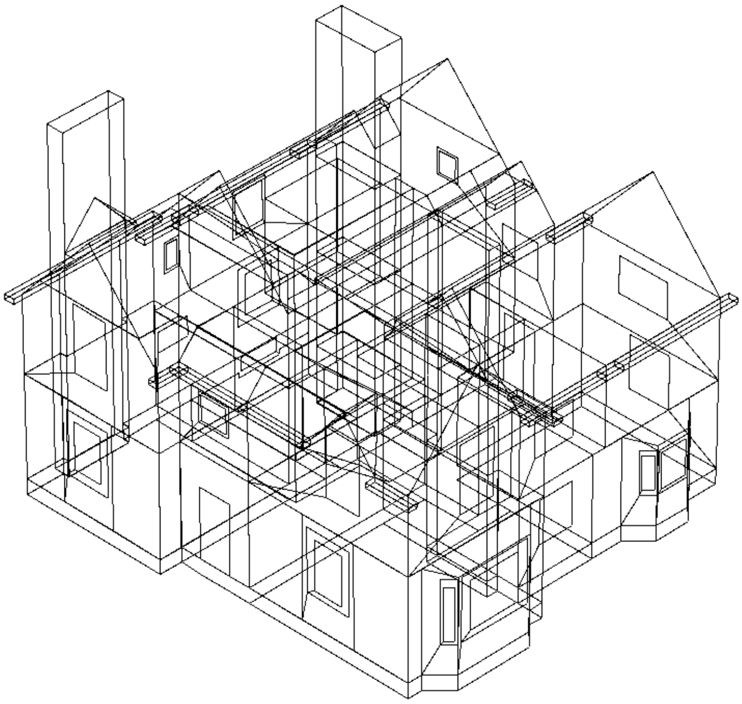

Figure 5 – Screenshot of the model (in ESP-r)

The weather file also has information about monthly ground temperatures at multiple depths, but these are only relevant for exposed soil. Soil temperature below the house and in contact with the cellar has had the time to settle at a generally higher temperature. To adjust for this discrepancy, the monthly ground temperature profiles were iteratively calibrated in such a way that modelled temperatures in the cellar (almost fully underground) closely tracked the corresponding sensor temperature readings.

Given the lack of information for local wind speeds and direction around the building, constant yearly average infiltration rates were used instead, in accordance to the SAP methodology (one air-change per hour for most rooms and two air-changes per hour for bathrooms and kitchen). Continuous air exchanges between rooms were set at 20% to 50% of the infiltration rates taking into consideration typical door opening periods. As with the solar radiation data, the lack of wind and infiltration rate information does ultimately limit the precision of the model.

During the heating season, running from mid-October to mid-April, the space heating system is typically turned on between 4:30pm and 8:30am on workdays and continuously over the weekends. This is considered the *current* usage scenario. Three other heating scenarios were also tested: *continuous* (running 24 hours per day), *shorter* (more closely tracking occupation periods in different rooms), and *setback* (similar to the *shorter* pattern but keeping the heating system on at a lower temperature of 16°C instead of completely turning it off with the aim of reducing energy consumption). Figure 6 shows the schedules for each of the tested scenarios. Depending on the spaces' real usage and on the building's thermal characteristics, different scenarios might perform better or worse, be it from an energy expenditure perspective, from a comfort perspective or even from a system's dimensioning perspective. Given that the main purpose of the modelling exercise was to size the heat pump system more precisely, it was very relevant to explore these different usage patterns. For instance, in principle, heating for shorter periods may result in lower energy expenditure but generally might require higher power requirements.

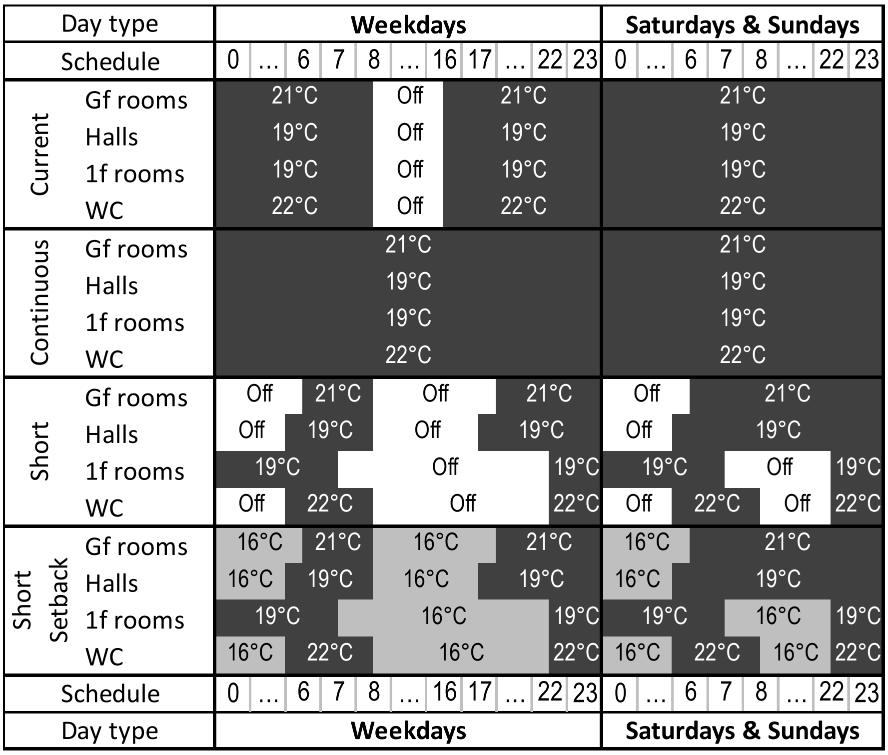

Figure 6– Heating system operating periods and temperature set-points for different rooms, according to the four different patterns explored, i.e. current usage, continuous heating, shorter heating periods, and shorter heating periods with a setback temperature of 16°C. (Gf – ground floor; 1f – 1st floor).

The main aim of the modelling exercise was to get a better estimate for heat required to keep the building within comfortable conditions, tracking the real-world sensor temperatures as well as the hourly heat flux and maximum aggregate hourly heating power. Since the model assumes simple heat injection into each space, the results are independent of any particular heating equipment, but the maximum heat flux in each room was limited according to the characteristics of the existing radiators. These were determined during the SAP and range from 3.5 kW in the largest space (drawing room), to 1 kW in the smaller rooms.

Comparing the calibrated model running in the *current* scenario with the real-world sensor measurements, room temperatures are tracked fairly satisfactorily, albeit not perfectly (Figure 7). The testing period ran from 25th of January 2015 (when sensor readings started) to the 6th of September 2015 (when the testing period ended). This encompasses approximately 12 weeks of conditioned operation (until the 15th of April) after which the building's heating system is turned off and the model operates in free-float mode. Within this period average temperature differences between model and sensor readings for each room were generally within ±1°C, with standard deviations ranging from approximately 1°C in the halls and kitchen, to close to 2°C in rooms with less predictable usage and heating patterns, such as, for example the drawing room (the log-burning stove in the fireplace is used sporadically).

In some instances, differences of up to ±6°C were seen between real-world sensors and model results. There are a number of aspects that keep the model from better tracking the real-world temperatures, namely: unpredictable user operation of doors, windows, curtains and shutters was either ignored or integrated in simplified ways (e.g. closing shutters at night and opening during the day, regardless of real conditions); the sporadic use of fireplaces, cooking, and other heat-releasing equipment was not considered; detailed local solar radiation data was not available thus Gatwick's was used instead; local wind speed measurements and building air permeability were absent, thus building ventilation was simplified to constant airflows according to SAP recommended values; the model does not account for the impacts of any indoor furniture. The impact of these aspects can be clearly seen in the comparison of indoor temperatures shown in Figure 7. For instance, during the hottest period, around July, frequent window and door opening and extensive building ventilation resulted in significantly lower indoor temperatures than the ones predicted by the model. During the conditioned period, where the simulation more closely follows real building operation, model temperatures track the sensor readings significantly better.

Despite the less than perfect tracking, for the purpose of more precise sizing of the heat pump equipment, these results were considered to provide a good balance between calibration effort and accuracy of simulation. While it is clear that dynamic building simulation would provide much better estimates of the heating demand of the building than simpler methodologies, and in particular SAP, it is also recognized that the estimates can never be perfect. At some point, the effort required in further refining and calibrating the model would outweigh the usefulness of the added precision.

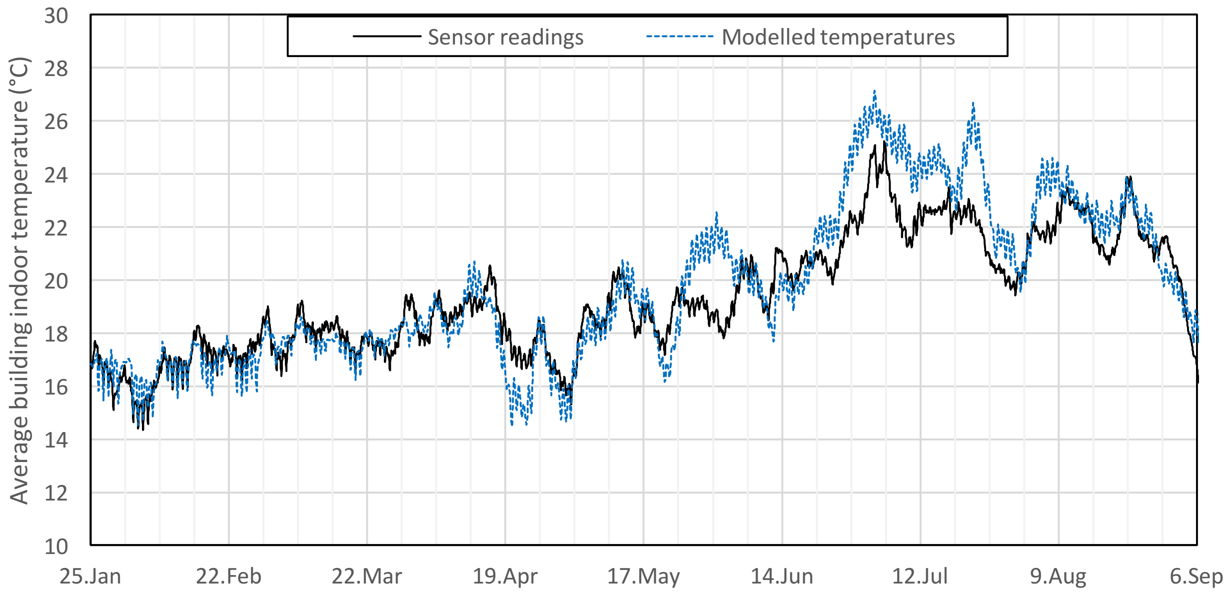

Figure 7 – Comparison between sensor readings and modelled whole building average indoor temperatures for the testing period (from 25th January to the 6th of September of 2015)

Between 2009 and 2015, 2010 was the coldest year in Cambridge. For that year the model estimates annual heating needs at 31.5 MWh while using the *current* heating pattern (Table 2). Those needs change to 34.3 MWh, 23.9 MWh and 26.9 MWh if heating *continuously*, for *shorter* periods or using a *setback* temperature set-point instead of turning the system off, respectively. However, for 2014 the estimates are approximately 30% lower, as a clear demonstration of the impact that weather can have in energy requirements for space heating. These results exclude the AGA output, which contributes around 9 MWh over the year.

Table 2 - Estimated yearly heating needs (in MWh) for the warmest and coldest years since 2009 (i.e. 2014 and 2010, respectively) and according to different heating patterns.

	Heating pattern			
Year	Current	Continuous	Shorter	Setback
2010	31.5	34.3	23.9	26.9
2014	23.0	25.2	17.2	18.7

Considering the worst case scenario, i.e. continuous heating during the coldest year (34.3 MWh), the space heating needs calculated through thermal modelling still end up being approximately 1/3 lower than the SAP calculation of 51.7 MWh/annum. Discrepancies between the SAP calculations and real-world energy needs, especially for buildings built pre-1900, are well known and the results here presented seem to corroborate this (Laurent et al., 2013; Gupta and Irving, 2013; Summerfield et al., 2015; Gupta and Gregg., 2016). In particular, it presents an argument against using SAP estimates for sizing heating systems.

The modelled space heating power requirements traced for different years and heating patterns should be a better strategy for correctly sizing new heating systems and avoiding oversizing. Figure 8 shows the power requirements for 2014 and 2010, the warmest and coldest years since 2009 in Cambridge, and for different heating patterns. Without changing the *current* heating pattern, the highest estimated power output required to meet the heat demand all of the time is just over 16.5 kW, for the year of 2010. However, if setting the target at meeting the hourly heating power demand only 95% of the time, then 12 kW should be enough. This would mean failing to meet demand for approximately 55 hours in 2010 (but only 5 hours in 2014). Since most of these hours occur right after the system is turned on, the issue would manifest itself in indoor temperatures taking somewhat longer to reach comfortable levels.

As shown previously, the current heating pattern turns off the heating system during the middle of the weekdays (from 8:30 to 16:30), when residents are off for work. When the system is turned on at the end of the afternoon, the estimated power demand tends to be higher, since the building has been cooling down for 8 hours. If, instead, the space is *continuously* heated, power requirements for meeting demand 95% of the time are reduced to just over 10 kW. Conversely, operating the heating system in *shorter* bursts would get power requirements up to close to 20 kW for meeting demand all the time. Interestingly, whilst an extra 5 kW in heating power is required to supply the final 5% of demand in the *current* heating pattern, only a further 2 kW is required if heating *continuously*. An additional 8 kW are needed if running for *shorter* periods, and 4 kW if using a *setback* strategy.

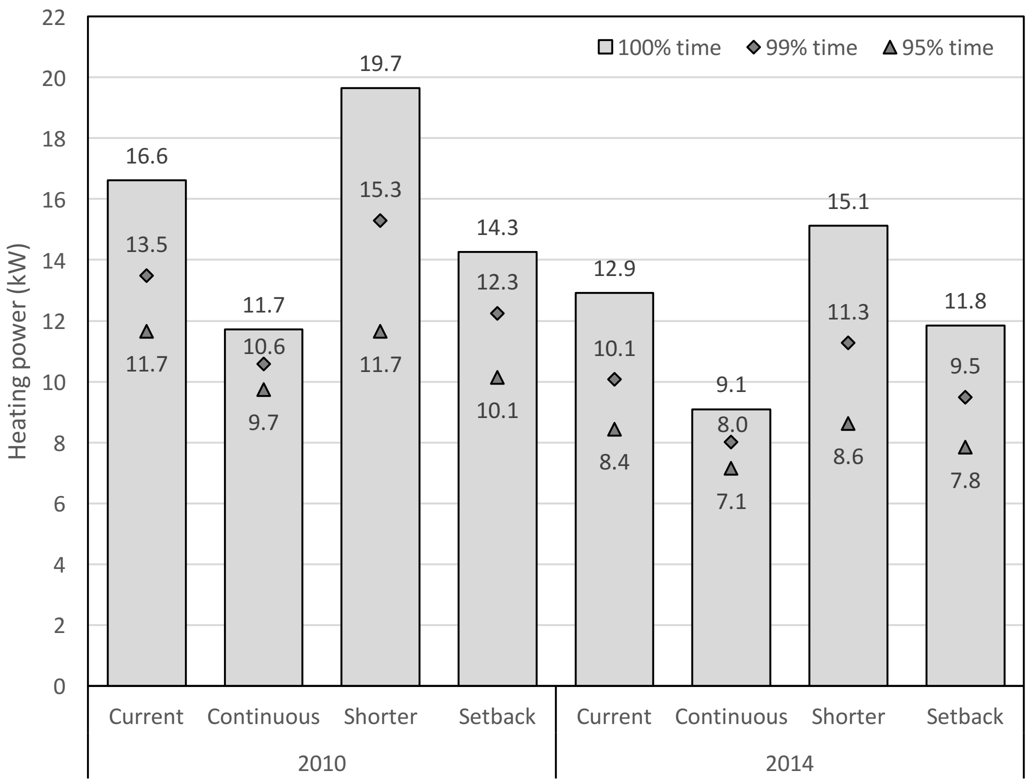

Figure 8 – Estimated heating power requirements needed to cover 100% (bars), 99% (diamonds) and 95% (triangles) of the time space heating is required. Showing the results for 2014 and 2010 (warmest and coldest year since 2009, respectively) and for the tested space heating patterns.

These results also show that there is a balance to be established between energy saving and equipment power requirements. While the *shorter* heating pattern saves the most energy (about 25% compared to *current*), it requires a significantly more powerful system for meeting the last 5% of heating demand (up to 18% more). The opposite is found when running the system *continuously*, requiring the lowest system power (approximately 20%) while demanding the highest total energy expenditure (9% higher than *current*). A good balance appears to be achieved by using the *setback* strategy, which simultaneously requires lower power (roughly 10%) and saves energy (about 15%) when compared to turning off the system completely during the middle of weekdays as in the *current* pattern. These results favour a judicious adjustment of heating schedules as a way to optimizing the use of appropriately sized heat pump systems.

5 GSHP system design and installation

The starting point was the choice of heat pump. During the planning of the project a modulating heat pump came on to the market, manufactured by Mastertherm, with an approximately 3:1 output range. This device appeared attractive as for much of the heating period the actual heating demand is quite modest, with peak demand occurring for only a relatively few days. It is desirable to limit the cycling of heat pumps and this is usually achieved by a suitably sized buffer tank. If the heat pump can reduce its output then the size of buffer tank can be reduced. From the thermal modelling, a capacity of 16 kW would have sufficed for all recent years except the coldest (2010) when it would have been inadequate for just 5 hours.

Whilst Masterthem produces a 16 kW pump, the preferred supply is three-phase and the house only has a single phase supply, albeit with a 100 A rating, noting that the house at one point had electric storage heaters. A quotation was obtained from the local Distribution Network Operator for a three-phase connection but the cost was prohibitive; it would have added about 40% to the project cost. Therefore the 12 kW heat pump was chosen, recognizing that this would 'brown out' for several days each winter (e.g. 218 hours in 2010), to see how tightly the rating could be specified. As a result supplementary heating would be needed either by boosting the output of the heat pump with its integral electrical heater or by the use of an existing log-burning stove or open fires or even free-standing electric heaters. The occasional inconvenience was considered acceptable.

The worst case for heat pump cycling can be shown to be at half its minimum output. In the case of the chosen model, this is 4 kW so to keep starts to three per hour for a change in water temperature of 5°C with a heating load of 2 kW, a tank capacity of 114 l is needed. As there is a considerable volume of water in the primary circuit pipework, a 100 l tank was specified. For heating loads above 4 kW, the heat pump is able to operate continuously. The system diagram is shown in Figure 9.

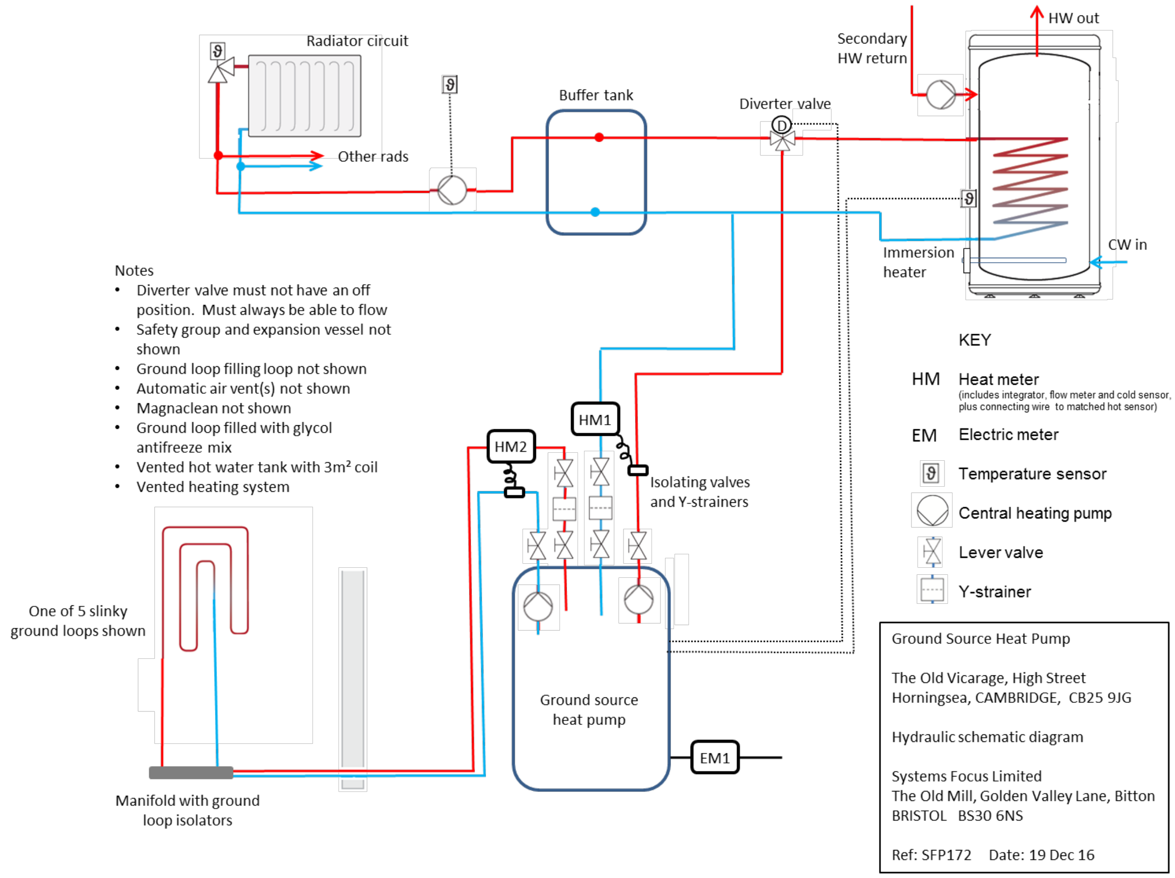

Figure 9 – GSHP system diagram.

Overall control is by the existing programmer which has separate control of hot water and heating. When the heating is active, the heat pump circulates primary water through the buffer tank; for this to happen the diverter valve must be energized. Water is circulated through the radiators by a separate pump irrespective of circulation from the heat pump. The heat pump will act to maintain the primary circulation within a target temperature range, either by modulating its output or by shutting off for periods. The target temperature range can be set to reflect the outdoor temperature determined by a separate sensor.

Domestic hot water has priority. A temperature sensor in the domestic hot water cylinder signals to the heat pump if heat is needed. If heating is active, the diverter valve is de-energized, transferring flow to the hot water cylinder, otherwise flow is already through the cylinder. Heating continues until the required cylinder temperature is reached, noting that the target temperature for this is independently set. There is provision for a sterilization cycle involving heating the hot water to 60°C.

The primary water temperature for the central heating will have a maximum value of 50°C. All the radiators were assessed to see if they would have adequate output at this temperature. Fortunately, many rooms have cast iron radiators with rated outputs specified for 60°C water temperature and these turned out to be sufficiently generously sized that acceptable performance could be expected at 50°C. In contrast, some rooms had steel panel radiators with rated outputs specified at 70°C water temperature and not all these may be able to perform satisfactorily with the reduced water temperature. It was decided to see how well they worked and replace as needed. Overall, the philosophy was that in cases of inadequate output, in the first instance measures should be looked at to reduce heat loss.

Knowing the rating of the heat pump allowed the ground loop to be specified. A cautious view of the loading of the ground loops was taken partly because of a desire to avoid the risk of icing and partly to allow for some increase in heat pump capacity in the future. The design called for five loops each of 300 m of pipe in parallel, each circuit pre-formed by the supplier into 50 loops each using 4 m of pipe and with a repeat distance of 1 m, with a 25 m tail and a 75 m return pipe. The site, although having overall adequate space, was rather awkward. Three circuits could be accommodated in a lawn to the west of the house and the other two in a lawn to the south but in both cases in serpentine trenches which complicated excavation.

After discussion with the installer it was decided to place the loops in the vertical plane, minimizing the overall amount of spoil. The main trenches were 2 m deep, giving nominally 800 mm of cover over the apices of the coils, and 300 mm wide. The trench carrying the go and return pipes to the west lawn were 1 m deep and 1 m wide to enable the go and return pipes to be separated. All pipes were buried directly in earth, with care taken to avoid pressure points from sharp stones, except where they passed under a driveway and a terrace in which cases they were placed in ducts. A marker tape was placed over pipe runs. Care was also taken not to bend the pipes around too tight a radius or rest on sharp corners. The ground conditions were variable with bands of so-called lower chalk (a mix of clay and chalk), sand and gravel. Some of the lower chalk was quite hard, slowing excavation. In the one area the bottom of the trench was below the water table at the time of excavation which could be helpful but the level of the water table does fluctuate.

Excavating a trench for one circuit took one to two days, with backfilling taking a similar time. Care was taken to reserve top-soil to aid the restoration of the lawn and whilst this was largely achieved, the serpentine structure evident in Figure 10 made excavation and backfilling difficult. During backfilling there was a heavy rainstorm which caused considerable additional compaction of material; it was difficult to achieve good compaction initially as the trench was narrow and deep. Subsequently the trenches were flooded in turn to ensure good compaction as a ready supply of water was available from an old well. The five loops were terminated in a manifold on the exterior of the house with go and return pipes going through a wall to the heat pump. The loops were flushed, antifreeze introduced followed by water before being de-aerated in turn using the valves on the manifold and an external pump. The circuits were found to be leak tight.

The heat pump itself was installed on the other side of an external wall to the manifold, allowing a straightforward connection (Figure 9). The ground loop was pressurized to 1.5 bar using a normal pressurizing vessel as used in closed heating systems. A slow fall of pressure was noticed but this was due to a small leak in one of the manifold connections – this was remedied by tightening the joint. Flow meters were fitted in the ground loop and the output circuits along with temperature sensors so that the heat inputs and outputs can be measured. The electrical input is also monitored, enabling the coefficient of performance to be estimated but accuracy is limited by the fact that there are two circulating pumps in the unit, one for the ground loops and the other for the primary circulation.

Figure 10 - Photo of ground loop excavation.

The installation of the buffer tank was next. Providing separate circuits for hot water and heating so that the buffer tank could be adjacent to the heat pump was initially considered but this idea was rejected as duplicating the existing pipe runs to the airing cupboard would mean lifting recently re-laid floors. The buffer tank has therefore been sited in the airing cupboard above the existing hot water cylinder, accepting the drawback that the water in the pipework between the heat pump and airing cupboard, containing approximately 40 l of water, could cycle in temperature and to a degree compromise the efficiency of the heat pump. Reconfiguration of the pipework was also necessary; the final arrangement is shown in Figure 9.

6 Preliminary results

Although the ground loops had been installed by the autumn of 2015, further design work was needed on the configuration of the indoor system so the final implementation was postponed until the end of the heating season in spring 2016. During the summer of 2016 the production of domestic hot water was studied and it was noted that even at the minimum heat output the primary water temperature rose quite rapidly whilst the secondary water was still cool with a temperature difference around 8°C being seen. The consequence was excessive cycling of the heat pump. The poor performance arose as the existing hot water cylinder had a heat exchanger area of 0.6 m^2. A new 160 l cylinder with a 3 m^2 heat exchanger was chosen but delivery was delayed so the new cylinder was not installed until the end of the heating season in April 2017, completing the changes to the plumbing system.

Operational data have been recorded from December 22nd 2016, with an all-day heating regime being operated until February 19th 2017 when it was changed to the reduced hours scheme, namely off between 8.30 am and 4.30 pm. The heat pump's external temperature feature was used with a linear variation in the temperature of water supplied for heating between break-points of 30°C at 15°C external temperature and 47.5°C at -5°C outside temperature. The heat delivered to the house was measured using a Vuheat grade 2 heat meter and the electrical input was recorded using a standard kWh meter. Over the all-day heating period 2626 kWh of electricity were consumed and 7691 kWh delivered as heat, giving a ratio of heat to electrical input of 2.93. The lowest return temperature to the ground loop observed was 1 °C.

Daily thermal output rose to about 170 kWh during periods of below freezing outside temperatures but interior temperatures were maintained at around 18 °C. Under these conditions the average heat output of just over 7 kW meant that the demanded output was within the heat pump's modulation range so operation was continuous. The average interior temperature over the period was 18.8°C, excluding Bedrooms 3 and 4 and the scullery which were not heated. The heat pump was also providing domestic hot water requiring an estimated 320 kWh based on an annual demand of 2 MWh. However, the Aga contributed 1940 kWh and some use, particularly in the evenings, was made of the wood burning stove in the drawing room (30 occasions) and the open fire in the dining room (18 occasions); the heat contribution is estimated to be 250 kWh. Making these adjustments gives a heating input of 9561 kWh for the period.

Modelling was performed to determine the expected consumption over the period in question, adjusting operation to mimic the real conditions. This meant using continuous heating, turning off heating in bedrooms 3 and 4, including on the access corridor, decreasing air-changes between these and other adjacent spaces (i.e. assuming that doors were kept close most of the time), and removing the heat input on the scullery that was previously a result of heat losses in the oil boiler and exposed piping network. The modelled result of 9328 kWh for the period is in good agreement with the real-world heating contribution from the heat pump. This includes a modelled AGA contribution of 1973 kWh but does not take into consideration the needs for heating the domestic hot water.

Based on these results, if oil had been burnt to generate 7.69 MWh of heat with a calorific value of 10.35 kWh/l and a CO_2 intensity of 3.18 kg/l, and assuming a boiler efficiency of 0.85, 2.78 t of CO_2 would have been released. The electricity used, assuming a CO_2 intensity of electricity consumption of around 305 g/kWh[2], involved the release of 800 kg of the gas, a saving of 1.97 t. Over a year the predicted saving is approximately 7 t and this saving will increase as the production of electricity is decarbonized.

7 Discussion and conclusion

Results to date support the initial proposition that, with careful design, a GSHP based system can replace an oil boiler and thereby lead to substantial savings of CO_2 in the type of property considered. Key to the design has been the detailed thermal modelling which provided the confidence to use a heat pump with a modest rating which reduces costs in important areas such as the construction of the ground loop array, the heat pump itself and possible increasing the capacity of the electricity supply as the installed cost worked out at approximately £2,000/kW. The significant differences between the modelling undertaken for this project in terms of predicted heating needs, which tallies with actual previous experience, and the standard assessment procedure is a matter of concern as the latter leads to significant oversizing of plant. From an RHI perspective it also leads to higher payments

[2] Average CO_2 intensity for electricity consumed over period from 1st of December 2016 to 1st of March 2017, as calculated from electricinsights.co.uk (Drax, 2017), following the methodology presented in (Stafell, 2017). As a guide, BEIS estimates average 220gCO_2 per kWh of electricity produced for whole of 2016 (BEIS, 2017a), which is generally lower than the coefficient used here since it is an average for whole year and also does not include emissions from imported electricity and emissions from transport of imported biomass to the UK used in electricity generation.

to householders, as these are on a deemed basis related to the expected heating needs, though this will not be unwelcome to householders. Clearly there is much to be gained by good thermal modelling but achieving this may not be realistic unless persistent weaknesses in the SAP approach can be identified and corrected. Historic fuel consumption records are another way of building confidence. The project was financially attractive although the installation, especially of the ground loops, was disruptive. The project cost was just over £20,000 and the RHI was initially £5491 per annum but this is indexed. Expected annual electricity consumption is expected to cost about £1200 so, even making allowances for maintenance, the payback time will be five to seven years.

User behaviour and expectations are important in a successful project. In the present case, radiators with thermostatically controlled valves were retained so relatively good temperature control of individual rooms was achieved, notwithstanding the increased degree of temperature droop. In this regard the heating system has familiar characteristics but on the other hand if the blast of heat first thing in the morning is an important part of the user's experience then the system will be a disappointment. Significant night time setback is impossible anyway given the thermal time constants involved so a cooler night-time temperature is not practical. In the present house this is circumvented by a separate dressing room. All parties had extensive discussions about what was expected and trials in advance of the project established the acceptability of the proposed mode of operation.

Good support from the installer was very valuable. Unusually the installation company was led by a Chartered Engineer which facilitated discussions on the basis of engineering principles as opposed to simply trade experience. The subtlety of system design can be beyond the knowledge of an electrician or plumber even if they have attended specialist courses which are no substitute for degree-level understanding.

The installation of the ground loops was successful but it is clear that it is much easier to deal with one straight trench per circuit both in terms of excavation and manipulation of the slinky assembly. A heat pump is somewhat larger than an oil boiler and the buffer tank has to be accommodated though size is not so much of an issue in larger houses. The modifications to the plumbing arrangements can be awkward though in this case a lot of time invested in design of a suitable layout made it possible to make the changes in under two days, minimizing the time without hot water. Electrical reconfiguration was somewhat tedious as the heat pump takes in low voltage control signals whereas as conventional heating controls work at mains voltage so it was necessary to make a custom relay box. Finally, as noted in what is believed to be the first domestic heat pump installation (Haldane, 1930), there is the question of noise and vibration. In the present installation the heat pump is sited in an extremity of the house so noise from the heat pump itself not an issue but some vibration is being transmitted through the fixings for the primary pipework. Means of mitigating this are being investigated.

Long term monitoring of the project is underway to track the co-efficient of performance of the heat pump, to determine if there is a significant depression of ground temperature around the ground loops, to see if the overall heat output is adequate for most days, to see if the any upgrading of radiators is needed and to assess the quality of the user experience. The results are expected to support the initial conclusion that successful GSHP installations can be made in properties that have not generally been considered suitable provided that careful assessment and design work are undertaken. It is the authors' intention to publish these results in due course with full details of the instrumentation used. Finally, it is not argued that conventional radiators systems are the preferred choice for use with heat pumps, rather that there are many older properties of the type considered in this study where the installation of say underfloor heating is not practical in terms of cost, structural limitations or simply a preference for traditional suspended wooden floors. In the British Isles alone there are potentially around 700,000 of off-gas grid solid wall homes in similar conditions (CCC, 2017) and there are more in regions with a similar climate and building traditions e.g. northern France where oil accounts for 16% of the total energy for heating in residential buildings (Ministère de la Transition écologique et solidaire, 2015). To exclude these properties would forego a substantial step towards decarbonization of domestic heating.

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Appendix

Details of elements and their thermal properties

Table A-1 - List of constructional elements used in the model and their elements

Construction	U-Value (W/m².K)	Elements/materials	Thickness (mm)	Therm. cond. (W/m.K)
Original 13.5'' external brick wall	1.561	Brick (UK code) Dense plaster	343 12.5	0.77 0.50
Original 9'' external brick wall	2.031	Brick (UK code) Dense plaster	229 12.5	0.77 0.50
Insulated original 9'' external brick wall (used in the kitchen)	0.895	Brick (UK code) Glasswool (generic) Dense plaster	229 25 12.5	0.77 0.04 0.50
Recent external insulated brick wall	0.286	Brick (UK code) Fiberglass batt insulation Vermiculite insulating brick Dense plaster	114 100 100 12.5	0.77 0.036 0.27 0.5
Original 9'' internal brick wall	1.933	Dense plaster Brick (UK code) Dense plaster	12.5 229 12.5	0.5 0.77 0.50
Internal partition cavity brick wall	0.884	Dense plaster Vermiculite insulating brick Air gap/cavity Vermiculite insulating brick Dense plaster	12.5 100 50 100 12.5	0.50 0.27 0.14 0.27 0.50
Internal partition wall	1.930	Plasterboard (UK code) Breeze block Plasterboard (UK code)	12.7 100 12.7	0.21 0.44 0.21
Roof	6.346	Clay tile Roofing felt	6 2	0.85 0.19
Roof on 1st floor sloping ceiling sections	0.686	Clay tile Roofing felt Glasswool (generic) Dense plaster	6 2 50 25.4	0.85 0.19 0.04 0.50
1st floor ceiling (20 cm insulation)	0.185	Hardboard (standard density) Glasswool (generic) Plasterboard (UK code)	25 200 12.7	0.13 0.04 0.21
Ground floor ceiling	1.548	Wilton weave wool carpet Hardboard (standard density) Air gap/cavity Plasterboard (UK code)	5 25 75 12.7	0.06 0.13 0.14 0.21
Ground flooring (with 10 cm insulation)	0.328	Wilton weave wool carpet Hardboard (standard density) Glasswool (generic) Plasterboard (UK code)	5 25 100 13	0.06 0.13 0.04 0.21
Ground flooring (with 5 cm insulation)	0.572	Wilton weave wool carpet Hardboard (standard density) Glasswool (generic) Plasterboard (UK code)	2 25 50 13	0.06 0.13 0.04 0.21