Historic England MAX FORDHAM

Building Services Engineering Team

The Viability of Air Source Heat Pumps in Historic Buildings

Revision	Amendment	Date	By	Checked
0	First Issue – Draft for comment	04/03/2022	SB/AHLH	AMc
1	Second Issue- Incorporating HE Comments	28/03/2022	SB/AHLH	AMc
2	Final Issue for Publication	06/05/2022	SB/AHLH	AMc

Executive Summary

This research project has been commissioned by Historic England and carried out by Max Fordham LLP. The research aligns directly with Historic England's climate change and sustainability objectives.

The electrification of heat is key to reducing reliance on fossil fuels across the heritage sector. No technology is better placed to electrify heat for space heating than heat pumps. The technology is mature, and if the heating system is well designed can deliver comparable running costs to natural gas systems. Air source heat pump technology can be deployed quickly and with lower capital costs than other heat pump technologies. This makes air source a key technology in the decarbonisation of space heating.

There have been examples of heat pumps installed in historic buildings without any consideration to the building's thermal properties or limitations associated with the existing system.

The research aims to learn lessons from ten properties that have all had air source heat pumps installed as their primary means of space heating. Six of the properties used air-to-water heat pumps (monobloc) with the remaining four utilising some type of air-to-air heat pump (Direct Expansion).

The ten case study visits took place between December 2021 and February 2022. The engineers from Max Fordham LLP carried out visual inspections of the heat pump installations and associated heating systems. Interviews were conducted with the building users to gauge their opinions of running cost, thermal comfort, noise, cold air plumes and visual appearance.

As many quantitative measurements were taken as possible, but the duration and the desire to limit intrusiveness of the site visits dictated that the majority of findings are qualitative in nature. Assessing running costs was particularly difficult. Where data was available, it came in the form of energy bills. This made it challenging to make quantitative comparisons before and after the heat pump installation. The users' perception of running cost has been reported but is highly subjective to the individual user's expectations.

The key findings;

- Visual appearance of or noise generated by external units was not reported negatively in any of the case study projects.
- The type of heat emitter selected must compliment the buildings use pattern.
- 4 out of 10 of the case studies would have benefited from an alternative type of ASHP or heat delivery method.
- Users were not given adequate training to allow them to adjust set points or schedules.
- Users were not informed how to optimise their system to reduce running costs.

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1. Introduction

This research aligns directly with Historic England's climate change and sustainability objectives. It relates to a long-term view of sustainability in which the heritage sector can contribute towards a low-carbon future, whilst also considering aspects of sympathetic and informed upgrades that are not to the detriment of historic buildings.

There have been examples of heat pumps installed in historic buildings without any consideration to the building's thermal properties or limitations associated with the existing system. In the most extreme cases these heat pumps have been removed and replaced with a conventional fossil fuel fired boiler. This is also a challenge for a large number of non-listed domestic properties although the problem is exacerbated in some historic buildings by their higher heat losses and in some cases intermittent occupancy.

This study assesses the performance of air source heat pump installations in historic buildings. A full evaluation of the installation has been carried out to include the heat pumps and heating system both externally and internally.

Data was gathered from ten heat pump installations located around the UK:

- Quarry Cottages, Residential, Chester
- Old Post Office, Residential, Chester
- The Old Coach House, Gym & Therapy Room, Chester
- St Anne's Church, Place of Worship, Cumbria
- Elizabeth Street, Optician, London
- Lowndes Street, Office and Shop, London
- Buckingham Palace Road, Office, London
- Holy Ascension Church, Place of Worship, Cotswold
- Little Trendeal, Residential, Truro
- Plough Court, Residential, Truro

Figure 1 - Location of Case Study projects, Air-to-water (Monobloc) heat pumps shown in blue, Air-to-Air (Direct Expansion, DX) heat pumps shown in red

The visits were made between December 2021 – February 2022 by Max Fordham LLP on behalf of Historic England.

The first half of this report (Section 4) will present a summary of the key findings across all of the case studies, including an introduction to common types of ASHP that are used, and a tabulated rating of the success of each system. The second half of this report (Sections 5-14) will present the detailed findings at each individual case study.

This research will allow lessons, both positive and negative to be learned. It is essential to provide clear advice on how heat pump technology can be integrated successfully in historic buildings.

This research will be used by Historic England to help inform future work and strategy relating to the installation of heat pumps in historic buildings.

2. Brief and Limitations

2.1. Brief

This study evaluates the performance of existing air source heat pump installations in historic buildings. It identifies examples of best practice and the considerations that need to be made when designing heat pump systems for historic buildings. Examples where improvements could be made are analysed so that lessons can be learned and these issues can be avoided in future.

The following parameters have been included during the evaluation of the air source heat pumps:

- Visual check
- Noise impact
- Electrical design
- Generic information on the ASHP
- Hydraulic design, including heat emitter
- Maintenance
- Defrost cycles
- Controls
- Performance issues
- Thermal improvements to the fabric
- Refrigerant

2.2. Limitations

2.2.1. Assessing of Running Costs

Where data was available, it came in the form of energy bills. Bills were often based on estimates or did not cover the time periods of interest. Where bills were available it was often not possible to separate heating and hot water use from other household electrical consumption such as cooking, lighting, and domestic appliances. This made it challenging to make quantitative comparisons before and after the heat pump installation.

The users' perception of running cost has been reported but is highly subjective to the individual user's expectations.

It should be noted that:

- This report is based solely on an examination of the visible areas during the site visit.
- This report is based on the finding from a single visit to each site and the conditions observed were therefore dependant on the weather conditions at the time.
- This report shall be for the private and confidential use of Historic England for whom the report is undertaken and must not be reproduced in whole or part or relied upon by third parties without the express written permission of Historic England.
- Whilst the survey was thorough, it was not possible, without doing damage, to inspect those parts of the property that were covered or unexposed at the time of the survey.

3. Method

The case study was carried out in an observational capacity, with no intrusive tests being carried out on the systems. Upon arrival at the site, the tenant gave an introduction to the property and inspections of the system were then carried out. These included:

- Taking photographs of the installation.
- Measuring the free area around the heat pump
- Measuring the distance to the closest noise-sensitive location
- Measuring noise levels, with and without the heat pump running
- Measuring flow speeds at the heat pump air exit
- Taking thermal images of the heat pump
- Checking for the presence and quality of key installation components, such as anti-vibration mounts and pipework insulation.
- Measuring radiator and pipe sizes
- Measuring the glycol content of the system fluid

The tenant was interviewed with a prepared set of questions about their experience living with the ASHP heating system. Some of the key questions were:

- Have you found the building comfortable since the ASHP was installed?
- How have you found the noise levels coming from the ASHP?
- Has the cold air emitted from the ASHP caused any problems?
- How have the running costs changed, if at all?
- Are you confident in how to use the controller for the heating system?
- Do you understand the maintenance requirements of the ASHP?
- Have you noticed the defrost function causing any drop in comfort?

After gathering all the information from the ten sites, the information was analysed to reach conclusions about the efficacy of the heating system at each site, as well as to determine overarching lessons about the successful implementation of ASHPs in historic buildings.

4. Key Findings and Observations

4.1. Observations of Physical Installations

4.1.1. ASHP Noise

The noise produced from external heat pump units was not reported as an issue at any property. Given that the public discussion around heat pumps often focuses on the noise generated by outdoor units, this was unexpected.

The participants at one property reported being aware when the outdoor unit first started up but could not hear it when it was running. In this case, the heat pump was mounted to the house with a wall bracket with little anti-vibration dampening, which may have allowed the vibration from the initial compressor start-up to be transferred into the house's structure.

4.1.2. Cold Air

No study participants reported an issue with the cold air discharged from the external unit. Heat pumps discharge a plume of cold air while running. This cold air movement can be felt up to three meters away from the unit. Walking briskly through the discharge plume is unlikely to cause discomfort. However, positioning the heat pump where anyone is required to linger in front of it, for example, unlocking a front door, would be uncomfortable and should be avoided.

4.1.3. Defrost

During certain external weather conditions frost will form on an air source heat pump's external evaporator. This frost must be periodically melted to allow the heat pump to continue to operate, this is known as a defrost cycle. Defrost times for modern heat pumps are between 2 and 10 minutes. While the heat pump is defrosting it is normally unable to deliver heat to the building. 9 out of 10 users had never noticed this short interruption to their heating system and were unaware of this function. The heavy weight construction of historic buildings makes them resilient to short interruptions in heat.

4.1.4. Drainage

The general design approach observed for dealing with condensation water from external units was to allow it to run over the ground to a nearby drain. This water will freeze in winter and become potentially hazardous. In all the studied properties, pedestrians did not need to walk between the heat pump and drain. Therefore, ice caused by condensate water was not reported as an issue by any case study participant. In two case study properties, condensate water dissipated through a gravel/slate bed that surrounded the base of the external unit, eliminating any potential hazard.

Figure 2 – Slate bed around base of heat pump to safely dissipate condensate and defrost water.

4.1.5. Visual Impact

Given the historic nature of the case study buildings, the authors hypothesised was that it would be typical for air source heat pumps to be hidden from view. However, this was not the case. Only one out of ten case study properties attempted to conceal the ASHP from view. None of the participants from residential properties expressed any dissatisfaction with how the ASHP looked despite being visible from their private gardens.

The one property that had attempted to conceal the ASHP experienced unintended consequences. To reduce the visual impact of the ASHP the base was sunk by 500 mm from the surrounding landscape level. The drop in level brings the top of the ASHP below the level of the perimeter wall. From the vantage point of any people passing the installation on the nearby pavement, the slight drop in level has a negligible impact on the visibility of the ASHP. However, dropping the level in this manner has resulted in issues with snow build up around the ASHP in winter and leaf build up in autumn. The snow and leaves must be manually removed for the ASHP to operate without fault. Although not reported as an issue in this case, dropping the level in this way could leave the heat pump vulnerable to damage due to flooding.

4.1.6. Electrical Installation

The quality of the electrical installations appeared to be high in all cases. Cables were routed safely and neatly. This is a likely to be a consequence of how prescriptive and regulated the electrical industry is in the UK.

4.1.7. Glycol

Glycol has a relatively high cost associated with it and so may be omitted from systems to reduce install costs. All the monobloc heat pumps in the case study had some level of glycol present in the system.

Monobloc heat pumps need protection against freezing as they contain water. If a heat pump is connected to an electrical supply the internal controls will guard against freezing by activating the heat pump if the temperature of the water inside the unit drops below a defined value.

In the event of a power cut the unit is exposed to freezing. Most manufacturers require glycol to be added to the heating system water to stop the water from freezing and damaging the heat pump. This needs to be considered by the system designers as it reduces the water’s ability to carry heat and makes the liquid more viscous. This has an impact on both heat emitter design, pipe sizing and pump sizing.

In heating systems with a system water volume of greater than approximately 220 litres or 20 kW of heat pump capacity the cost of glycol in the heating system can mean it is cost-effective to install a plate heat exchanger to physically separate the heating water that travels outside and the water that remains in the building.

4.1.8. Buffer Vessels

Buffer vessels are only used with air-to-water (monobloc) heat pumps. None of the case study projects had a buffer vessel installed. Buffer vessels can serve several functions;

- Increase heating system volume to provide energy for defrost cycles without removing energy from the building.
- Increased system inertia to maximise heat pump run times which in turn maximises efficiency.
- If piped to provide hydraulic separation between the heat pump circuit and the building circuit the buffer vessel will provide a means of guaranteeing the minimum system flow rates will be met. A guaranteed minimum system flow rate can also be achieved via the heating system design. For example, leaving TRVs or radiators or control heads off UFH manifolds in zones where the heating thermostat is located.

The design decision whether to include a buffer vessel must be taken on a project-by-project basis, considering the above design considerations and any recommendations from the chosen heat pump manufacturer.

Quarry Cottage	Buffer vessel may help to improve short heat pump run times.
The Old Post Office	Buffer vessel may help to improve short heat pump run times.
The Old Coach House	Buffer vessel could provide hydraulic separation to protect the heat pump from highly variable system flow rates.
St Anne's Church	Not required, large thermal mass of underfloor heating system provides adequate thermal buffering to heat pump.
Holly Ascension Church	A large buffer vessel could be beneficial to the system but is unlikely to solve the systems specific issues.
Penryn Truro	No evidence that a buffer would improve system efficiency.

4.1.9. Technology Overview

Air Source Heat Pumps (ASHP) come in two types: Monobloc and Direct Expansion (DX). Before the difference can be explained, it is important to understand what is meant by the terms evaporator and condenser. In an air source heat pump the evaporator extracts heat from the outside air. It does this by dropping the pressure in the evaporator so that the refrigerant begins to boil at temperatures below the ambient air temperature. This allows heat to be extracted from the air, even on the coldest days. The condenser is the part of the heat pump that delivers the heat into the building. All ASHPs house the evaporator in the outdoor unit. The difference between the two types of heat pump is the location of the condenser. In a monobloc heat pump, the condenser is located within the outdoor unit. The condenser is located remotely from the outdoor unit in a direct expansion heat pump.

A monobloc (air to water) heat pump connects directly to the heating system of the building. The pipes connecting the outdoor unit and the building are filled with heating system water. The wet heating system can then use traditional heat emitters such as underfloor heating, radiators or fan convectors to deliver heat to the space.

Direct expansion systems transfer heat into the building using refrigerant rather than water. The pipework connecting the outdoor unit with the building will be two different diameters. This diameter difference is often the easiest way of telling a monobloc and DX system apart.

The remote condenser in a direct expansion system can interface with a traditional wet heating system via a heat exchanger or directly with the individual room heat emitters or "indoor units". Systems that use indoor units to deliver warmth are referred to as air-to-air heat pumps. See Figure 3 for an example of room mounted remote condensers often used with air-to-air heat pumps. Most air-to-air systems also allow the unit to be reversed and run in a cooling mode. Care would need to be taken to ensure overall energy consumption did not inadvertently increase by operating in cooling mode in summer.

Figure 3 - Example direct expansion indoor unit for heating and cooling

There are three main families of air-to-air systems: split systems, multi-split systems, and variable refrigerant systems.

Split system

The simplest of air-to-air systems. One indoor unit connects directly to one outdoor unit. A separate outdoor unit is therefore required to extend the system.

Multi-split system

This system allows multiple indoor units to be connected directly to a single outdoor unit. Each indoor unit will control to an individual setpoint, but all the indoor units must be either in heating or cooling mode.

Variable Refrigerant Systems

The most efficient and flexible system comes with the highest initial capital cost. This type of system allows multiple indoor units to be connected to a single outdoor unit and can facilitate simultaneous heating and cooling. To enable this functionality additional equipment located between the outdoor unit and the indoor emitters are required, contributing to the higher capital cost of the system. Traditional variable refrigerant systems have high refrigerant charges which can leak over the life of a system. Hybrid variable refrigerant systems that significantly reduce the amount of refrigerant required are now available.

Monobloc Summary

- Hermetically sealed refrigeration circuit, no on-site refrigeration pipework, reduced chance of refrigerant leaks. Installers do not need to be F-Gas qualified.
- Interfaces with traditional heating systems (radiators, fan convectors and underfloor heating)
- Generates hot water via a storage tank.
- Can utilise natural refrigerants with low environmental impact.
- Maximum distance between outdoor unit and cylinder/connection to heating system around 20 m.

Direct Expansion Summary

- Heat delivered directly from the heat pump condenser to the building air using forced convection.
- Indoor units always incorporate a fan and therefore make noise when heating or cooling, making them less suitable for residential applications.
- Incorporate high capacity heat emitters making them suitable where quick warmup times are required.
- Refrigeration pipework between indoor and outdoor units; F-gas registered installer is needed.
- Increased risk of refrigerant leaks via damage to refrigerant pipework or installation error.
- No systems are currently available that utilise low environmental impact refrigerants.

4.1.10. Case Study Heat Pump Technology Application

The case study projects used all of the above types of systems with the exception of a multi-split DX system. The following section summarises the type of system selected for each property and evaluates if the installed heat pump type could be improved. Additional details are given in each case study section in this report.

Key

Technology Choice

☆☆	Poor	An alternative technology would offer significant or multiple advantages to the installed system
★☆	Good	The installed system is not detrimental to energy use/running cost but an alternative technology may offer other advantages
★★	Excellent	Optimal technology match for the building & use profile

User Comfort

☆☆	Worse	Users expressed dissatisfaction with their thermal comfort compared with their previous heating system
★☆	Neutral	Users reported no change in thermal comfort as a result of installing a heat pump
★★	Improved	Users expressed an improvement in thermal comfort compared to the previous heating system

System Design/ Installation Quality

☆☆	Poor	Specific design choices or installation quality could be contributing to sub optimal efficiency
★☆	Good	Aspects of system design or install quality could be improved but unlikely to impact system efficiency
★★	Excellent	Optimally designed and installed system

Quarry Cottages
Site 1

- Residential
- Monobloc heat pump
- Radiator heating & hot water cylinder

Technology Choice	★★	Monobloc heat pump is ideal for residential application where the outdoor unit can be located close to the DHW cylinder.
Thermal Comfort	★★	Comfort much improved over previous electric storage heaters.
System Design/ Installation Quality	☆☆	Large heat pump (132 W/m², expected range for renovated property 40-65 W/m²) coupled with low loss header and small heating system pipework size may be contributing to short cycle times resulting in sub optimal heat pump efficiency.

Old Post Office
Site 2

- Residential
- Direct Expansion (split) heat pump
- Radiator heating & hot water

Technology Choice	★★	Extended run of external pipework required. DX unit selected to enable +20 m distance between outdoor unit and indoor interface with traditional radiator heating system and hot water storage tank.
Thermal Comfort	★☆	Users reported the kitchen being cold first thing in the morning and using an electric heater to warm the space. Users unaware of how to change heat pump system time periods.
System Design/ Installation Quality	☆☆	Heat pump capacity 94 W/m², expected range for renovated property 40-65 W/m². Low loss header should not be necessary for a property of this size that has undergone renovation. Poor attention paid to airtightness where refrigerant pipes enter/exit the building.

The Old Coach House
Site 3

- Gym & Therapy Room
- Monobloc heat pump
- Radiator heating only

Technology Choice	☆☆	A direct expansion air-to-air system rather than the installed monobloc system could provide quick warmup to the therapy room and provide cooling to the gym area in summer.
Thermal Comfort	☆☆	The tenant is using additional electric heaters to improve warm-up times in the therapy room. User was unable to adjust the time clock settings to activate the heat pump earlier in the day.
System Design/ Installation Quality	☆☆	Heat pump very large for size of property. Heat pump capacity 189 W/m², expected range for renovated property 95-110 W/m². Maintaining minimum heat pump flow rate would be problematic with TRVs and two thermal zones with different requirements.

St Anne's Church
Site 4

- Church
- Monobloc heat pump
- Underfloor heating with top up electric radiant wall panels

Technology Choice	★★	Highly successful implementation, the success of system is closely linked to the building use profile. Building is used throughout the week, allowing the heat pump to deliver a constant temperature over long periods. Electric radiant panels are an excellent choice of supplementary heating for the coldest days as they offer almost instant heat.
Thermal Comfort	★★	Users report a higher level of thermal comfort compared to the previous under pew heating system. Longer heating run times have increased the average internal surface temperature which has improved comfort and eliminated internal condensation.
System Design/ Installation Quality	★★	Simple, robust design, high quality installation.

Elizabeth Street
Site 5

- Shop and Optician
- Direct Expansion (multiple split) heat pump
- Air-to-Air wall mounted only

Technology Choice	★★	The building consists of only two rooms with different characteristics which could require heating and cooling simultaneously. Separate DX split systems for each room offer a cost-effective method of delivering this functionality.
Thermal Comfort	n/a	User was not using the heat pump at the time of the visit.
System Design/ Installation Quality	☆☆	Poor placement of external units. Units placed at ground level in a courtyard with 3 m high walls on all sides. Possible issues with cold air recirculation when in heating mode. Neighbouring cooling unit may help to lessen the impact of this design choice. No issues with installation quality in general.

14/14a Lowndes street
Site 6

- Shop & Offices
- Direct Expansion (multiple splits)
- Air-to-Air FCU & ceiling mounted heating/cooling

Technology Choice	★☆	High number of external DX split units (7 No.), resulting in sub optimal external placement for access, noise & acoustics. Consider a variable refrigerant system to limit the number of external units while maintaining the ability to simultaneously heat and cool.
Thermal Comfort	n/a	Building unoccupied
System Design/ Installation Quality	☆☆	Issues arising from the necessity to place a large number of external units resulting from the technology choice. For the non-roof mounted units the following issues are present. Poor access for maintenance, cold air recirculation and close proximity to neighbouring single glazed windows (acoustic issues).

Buckingham Palace Road Site 7		• Office • Direct Expansion (variable refrigerant) • Fan Coil Units (FCU) only
Technology Choice	★★	Only one external unit, discreetly located on the roof. Each tenancy (single floor) consists of two rooms with opposite aspects. These rooms could require simultaneous heating and cooling. System design limits each tenancy to heating or cooling mode. However, users did not express that this limitation was an issue.
Thermal Comfort	n/a	No direct comparison to previous heating system possible. However, users expressed satisfaction with thermal comfort.
System Design/ Installation Quality	★★	High quality installation.

Holy Ascension Church

Site 8

- Church
- Monobloc heat pump with inline direct electric boiler.
- Underfloor heating only

Technology Choice	☆☆	The chosen heat delivery method of underfloor heating does not compliment the once a week use profile. The heating system would need to be enabled all week to maintain comfort. However, heating all week cannot be justified by the building operators from a running cost perspective. A system with a faster response time would be better suited to an intermittently used building.
Thermal Comfort	☆☆	Heating setback through the week is 7 °C. The target temperature is then set to 18 °C on the Friday evening prior to the Sunday service, returning to 7 °C on the Sunday evening. However, the temperature that is achieved in the service is only 14/15 °C and is not perceived as being comfortable. In previous years the setback temperature was set to 14 °C, it was reported that 18 °C on Sunday could be achieved.
System Design/ Installation Quality	☆☆	In order to improve warmup times a 9 kW direct electric inline boiler was added in series with the heat pump. The warmup limiting factor is the slow response of the underfloor heating, not the heat source. Adding additional heating system capacity in this way has not improved warmup but effetely reduced the combined SCOP of the system to as low as 1.6, SCOP of +3.5 should be easily achievable by a modern heat pump. Every system alteration made to reduce running costs have adversely affected the system efficiency. The church now plans to install an air-to-air heat pump system and abandon the underfloor heating to enable quick warm up times.

Ladock, Truro Site 9		• Residential • Multiple air-to-air, direct expansion splits • Wall mounted air-to-air units
Technology Choice	★☆	Matches the occupants needs, multiple systems installed at different times has resulted in multiple outdoor units. The small amount of noise generated by internal wall units was seen as an acceptable trade-off for an efficient and cost-effective heating system.
Thermal Comfort	★★	High degree of satisfaction with comfort, especially with the quick warm up times provided by the air-to-air system.
System Design/ Installation Quality	★★	Installation quality was high. Internal piping was routed neatly in plastic trunking. From a historical viewpoint the system is not particularly sympathetic, the advantage being that minimal disruption was caused during installation with no floor or floor finishes being disrupted.
Roskrow, Truro Site 10		• Residential • Monobloc • Radiator heating & hot water
Technology Choice	★★	Monobloc ideal for residential application where the outdoor unit can be located close to the DHW cylinder.
Thermal Comfort	★☆	High degree of satisfaction reported, with equal comfort with the previous oil boiler system. User operates the system at a constant set point of 18°C 24 hours a day.
System Design/ Installation Quality	★★	High quality install. Existing heating system radiators and pipework were compatible with the heat pump system.

4.1.11. Installed Heat Pump Capacity

Bigger is not better when it comes to installed heat pump capacity. When heat pumps first start up it takes time for them to reach their peak operating efficiency. Good system design and sizing will allow the heat pump to operate at this peak efficiency for long periods of time. For this to happen the heat output of the heat pump should match the heat demand of the building. Modern ASHPs can adjust their output down to about 1/3 of their peak output. The larger the installed heat pump the more often the minimum heat pump output will exceed the heat demand for the building. In this scenario the heat pump will turn off for a period of time to stop the building from overheating. The larger the heat pump the more often it will have to switch off, resulting in the heat pump spending more time operating in the inefficient start up mode.

The system designer should be trying to balance the system's running cost with the initial capital cost and any space constraints that exist. At the time of writing, a monobloc AHSP external unit costs around 550 £/kW. In contrast, this is 43 £/kW for new gas boilers. To achieve affordable installation costs, it is therefore important not to oversize the ASHP. The same argument is true for selecting heat emitters. Radiators that will allow an ASHP to work at 35 °C rather than 50 °C could be up to 5 times more expensive to buy and will take up more wall space. There is a balance to be struck here, and a good system designer will help select the best solution case by case.

The results for the monobloc and direct expansion systems have been separated when comparing the installed capacities of heat pumps verses the area of the building. This is because the W/m^2 installed capacity of direct expansion tend to be larger than monobloc systems because of the sizes of units available to purchase.

The Old Post Office has been included in the monobloc section despite having a direct expansion heat pump because it delivers heat through a traditional wet heating system.

Monobloc Systems

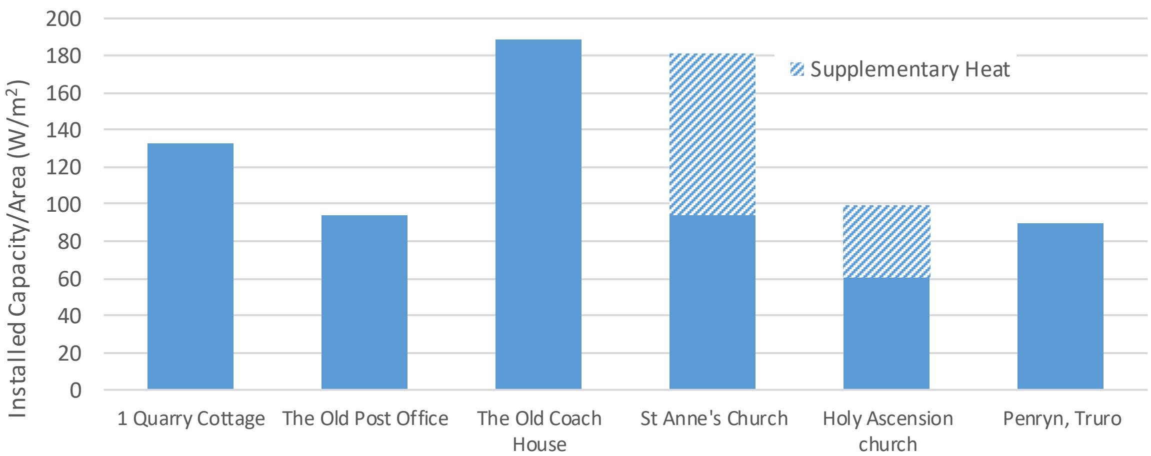

Figure 4 - Installed capacities of monobloc heat pumps

Figure 4 shows the installed capacity per m^2 of floor area for the different properties.

There is quite a significant variation between the properties, and a high installed capacity does not always correspond to a comfortable or efficient building.

	Installed Capacity W/m^2	Expected Range W/m^2	Commentary
Quarry Cottage	132	30 - 65	Oversized heat pump installed for a property that underwent extensive insulation improvements.
The Old Post Office	94	30 - 65	Potentially oversized heat pump for a property that has undergone a recent refurbishment.
The Old Coach House	189	95 - 110	Oversized heat pump for the size of building despite limited thermal upgrades to the building fabric.
St Anne's Church	94 (182 with wall panels)	95 - 110	Heat pump is well sized. Radiant panels are an ideal top up as they are fast acting.
Holly Ascension Church	60 (99 with electric boiler)	95 - 125	Undersized heat pump for size of heating load. Direct inline electric boiler brings the total installed capacity inline with the expected capacity, however, it becomes expensive to run.
Penryn Truro	90	30 - 65	Potentially oversized, however, exact thermal performance details of fabric are unknown.

Table 1 - Monobloc heat pump installations installed capacity vs expected capacity

Table 1 compares the installed heat pump capacity with the expected heat pump size, given what we know about the thermal upgrades made to the building.

The steady state heat loss from a solid wall building with single glazed windows and no loft insulation should not exceed 110 W/m^2. The average capacity of the three renovated residential projects is 105 W/m^2. This suggests there is a tendency to oversize heat pumps.

Direct Expansion Systems

The capacities of Air-to-air systems tend to be larger as they are often sized to provide large summer cooling capacities. As the heating and cooling is provided by the same unit this artificially pushes up the installed heating capacity.

Figure 5: Installed capacities of direct expansion (air-to-air) heat pumps

	Installed Capacity W/m^2	Expected Range W/m^2	Commentary
Elizabeth street	432	95 - 110	Cooling capacity dominant, driven by large shop windows.
14 Lowndes street (Shop)	316	95 - 110	Cooling capacity dominant, driven by large shop windows.
14a Lowndes street (Offices)	121	65 - 85	Cooling capacity dominant, driven by office heat gains in summer (lighting, IT equipment and people)
Buckingham Palace Road	112	65 - 85	Cooling capacity dominant, driven by office heat gains in summer (lighting, IT equipment and people)
Ladock, Truro	119	95 - 110	Correct sizing, lower capacity split units are not available.

4.1.12. Refrigerants

There are several refrigerants available on the market today. European manufacturers no longer use refrigerants that damage the Ozone layer. However, many of the commonly used refrigerants are potent greenhouse gases. If the refrigerant was released into the atmosphere, the Global Warming Potential (GWP) of that refrigerant allows you to calculate the equivalent effect on global warming compared to CO_2. The overall environmental impact depends on more than GWP, but for this discussion, the GWP of the refrigerant will suffice. The Table below sets out the GWP associated with a selection of common refrigerants.

Refrigerant	R-410A	R-32	R-290 (Propane)	R-744 (CO_2)
GWP	2088	675	3	1
Typical Charge (kg)	2	2.2	0.9	2.3
CO_2 equivalent of full leakage ($kgCO_2$)	4176	1485	27	2.3
No. of case study properties	6	4	0	0
F-Gas Regulations	Phasing out in small systems from 2025	Phasing down	n/a	n/a

Table 2 – Common refrigerants properties

Replacing a natural gas boiler with a heat pump will reduce the CO_2 emissions associated with the heating system for a typical UK home by around 3000 kg per year. The effect of a complete gas leak from a typical domestic heat pump that uses R410A would be the equivalent of 1.4 years of carbon savings associated with the running of that heat pump system.

All of the ASHPs in this study use either R410a or R32 refrigerant. A key goal of F-gas regulations is to phase down use of refrigerants that make significant contributions to global warming (GWP) when released into the atmosphere. High GWP refrigerants will have a more constrained supply, meaning the price is likely to rise unless demand reduces. This is important, as it means that the costs of maintaining existing R410a ASHPs will likely increase. R32 has a much lower GWP than R410a, and so will be less likely to be limited in the short term. However, R32 is not a long-term solution. Natural refrigerants such as R290 can achieve a much lower GWP and are now becoming commonly available in consumer ASHPs. The F-gas regulations are due to be reviewed soon and may define a phasing out for R32.

As can be seen from Table 2, the use of natural refrigerants such as R-290 (Propane) or R-744 (CO_2) is effective at reducing the danger of unintended global warming impacts from refrigerant leaks. However, they introduce other design challenges, summarised in Table 3.

Refrigerant	R-410A	R-32	R-290 (Propane)	R-744 (CO_2)
Flammability to ISO 817	A1 (Non-Flammable)	A2L (Lower Flammability)	A3 (Higher Flammability)	A1 (Non-Flammable)
Air-to-Water Monobloc	Yes	Yes	Yes	Yes
Air-to-Air Direct Expansion	Yes	Yes	No	No

Table 3 - Flammability and Application of common refrigerants

At the time of writing, there are no low GWP air-to-air (Direct Expansion) heat pumps available on the market. The advantages associated with air-to-air systems in commercial properties, principally the ability to deliver cooling, make them key decarbonisation technologies despite the higher GWP of the refrigerants. Each case should be assessed on its merits; a badly specified low GWP air-to-water heat pump may not deliver the desired user outcomes, and an air-to-air solution may be a more appropriate solution.

4.2. User Experience Observations

4.2.1. User Thermal comfort

The heat pump's outlet water temperature dominates the ratio between electricity in and free heat out. For example, on a cold 2°C day, a modern ASHP heat pump can deliver heat at approximately 8.0 p/kWh when the water leaving the ASHP is at 35°C. This 35 °C water would be warm enough for an underfloor heating system or a generously sized radiator system. If the same heat pump were required to provide 50 °C water, for example, to serve smaller radiators, the efficiency would drop and deliver heat at approximately 11.8 p/kWh. For comparison, a modern mains gas boiler will provide heat at between 7.4 and 8.1 p/kWh, depending on the system design and how well it has been commissioned.

Increasing the heat emitter sizes is not the only way to allow the heat pump flow temperature to be lowered. Improving insulation levels should always be considered as the first step to reducing energy consumption and running costs. When insulation is added to a property, the existing heat emitter can deliver the required heat at lower temperatures, thus improving heat pump efficiency.

Another way to ensure the system runs at the lowest possible temperatures is to enable heating for extended periods. It is generally cost-effective for a building occupied throughout the week to run the heating continuously at low temperatures. When buildings are intermittently occupied (holiday homes, churches etc.), it is not necessarily the case that running the heating when the building is unoccupied will be the cheapest option. Each case would need to be assessed on its merits.

When a heat pump starts, it takes time to settle down and begin working at its peak efficiency. Long run times reduce the number of these inefficient start-up periods, which improves the average heat pump efficiency. There are benefits to the wear and tear of the compressor. However, modern inverter-driven air source heat pumps will slowly bring the compressor up to speed, which reduces the impact of this type of stop/start wear and tear.

For the reasons described above, a heat pump delivers cost-effective heating at low temperatures and when it is allowed to run for long periods without interruption.

Those who operated their heat pumps continuously had the best perception of thermal comfort and were generally happy with their heating system.

The users who were unsatisfied with the temperatures of their properties in the morning did not have the necessary knowledge to extend their system run times and would benefit from additional training.

4.3. System Optimisation

The radiators in a room are sized to keep the room warm when it is very cold outside (- 3°C is a common design temperature). For the majority of the year, the outside temperature is much warmer. The implication is that for much of the year radiators could run cooler while still maintaining comfortable room temperatures. Most modern heat pump control systems adjust the output temperature automatically using the outside temperature to determine a suitable flow temperature. This type of control is known as weather compensated control. The controller will change the flow temperature between a maximum and minimum value that the commissioning engineer defines. This process is referred to as setting the heating curve.

Lowering the heating curve will reduce energy use and cost to the user. However, lowering it too far will result in the property not reaching the desired comfort temperature. There is an incentive for the person commissioning the system to set the heating curve slightly too high to avoid complaints. Optimising requires knowledge of the heating system, building insulation values and user expectations. Therefore striking the correct balance between comfort and running cost is best done by the user. The settings to optimise the heating curve often require that the user be familiar with their controller's advanced features.

In the properties with this type of system, users typically do not understand how to optimise the heating curve to reduce running costs.

5. Quarry Cottages (Site 1)

1 Quarry Cottages is a two storey, two bedroom residential property belonging to the Grosvenor Estate that underwent significant renovations in October 2020. The works included the addition of internal mineral wool wall insulation to all external walls, as well as the installation of a monobloc 8kW Hitachi RASM-3RVE ASHP that distributes heat through a radiator central heating system. The ASHP also provides all of the domestic hot water (DHW) for the property, which is stored in a hot water cylinder. There is also a wood burning stove in the living room which serves as an additional heat source or backup. Previously the property was heated by electric storage heaters, which did not achieve comfortable temperatures.

Figure 6: 1 Quarry Cottages.

5.1. Findings

5.1.1. Technology Choice

Property Type	Residential
Heat Pump Technology	Monobloc heat pump (air-to-water)
Heat Pump Capacity	132 W/m²
Heating System	Wet radiator system, no buffer vessel, low loss header installed
Hot Water System	DHW storage cylinder
Use Pattern	Semi-continual occupation – Occupant in full time employment
Technology Choice	★★

- Monobloc ideal for residential application where the outdoor unit can be located close to the DHW cylinder.

5.1.2. System Measurements and Observations

ASHP Unit Installation

- The ASHP uses R32 refrigerant.
- An 8 kW ASHP was installed, installers heat loss calculation property results in a 4.4 kW peak heat loss.
- Installed heat pump capacity equates to 132 W/m², this is higher than would be expected in a non-refurbished solid wall property.
- The installers heat loss calculations resulted in a 4.4 kW property heat loss. This equates to 73 W/m². This is higher than the 40-65 W/m² that would be expected for a fully renovated property.
- The large heat pump capacity will contribute to short cycling, which reduces operating efficiency and results in increased wear and tear on the compressor.
- The ASHP is installed at the rear of the property on a wall mounted bracket, as shown in Figure 7.
- Being located at the rear of the property, the ASHP has a low impact on the external appearance, and benefits from being installed against a similarly coloured wall as shown in Figure 7.
- This raised mounting provides sufficient clearance from in the case of heavy snowfall or flooding
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- There are some small anti-vibration dampers between the ASHP and the mounting bracket, and between the mounting bracket and the wall.
- Condensate drainage has been accommodated for and presents no risk of freezing over walkways
- Pipework is well insulated.
- The ASHP appeared to be cycling (operating for short periods of time and then switching off), which is an inefficient way for a heat pump to operate as the compressor does not reach its ideal operating conditions for long before switching off.
  - This can be a common issue at milder temperatures, when the heating load of the building is below the minimum output of the heat pump, causing it to cycle on and off.
  - On the day of the visit the outside temperature was approximately 12°C.
- During operation, the noise levels were in the expected range.
- During operation, the air speed at the ASHP outlet was found to be within the manufacturer's stated air speeds.

Figure 7: ASHP installation at rear of property

Hydraulic System Design

A heating system designed for a heat pump will be capable of delivering the following:

- Heat delivery at low system flow temperatures - Impacts radiator sizing
- Minimum heat pump flow rates - Impact on pipe sizing
- Maximising run times - System Volume
- Cater for defrost cycles - System Volume

These points will be discussed in turn to highlight best practices in heat pump hydraulic design.

Radiator sizing was consistent with best practice design. The radiators were large enough to deliver adequate heat to the rooms at temperatures that allowed efficient heat pump operation. Figure 8 shows one of these radiators, located in the kitchen

The radiator pipework was smaller than would be expected in best practice design. This may have led to other design decisions which impact optimum system performance.

Figure 8: Kitchen radiator with 10mm connecting pipework

Heat pump manufacturers specify minimum water flow rates through their systems. These minimum flow rates are typically two to four times higher than an equivalent fossil fuel boiler. The system pipework should be designed so that the heat pump's integrated circulation pump can achieve this minimum flow rate without any additional pumps. The majority of the pipework that could be observed at Quarry Cottage was 10 mm microbore copper. For a property of this type, it was expected that 15 mm pipework would be required. While sub 15 mm pipework can form part of a modern low energy house system, it is unlikely to provide a sufficient flow rate for a retrofitted building.

In order to guarantee minimum system flow rates, the installation incorporated a low loss header between the heat pump and the heating system, and a secondary pump on the radiator circuit. This arrangement guarantees the minimum flow rate through the heat pump at all times. However, it also adds additional cost and complexity to the system and, in this instance, maybe contribute to sub-optimal heat pump performance. Heat pumps take time to reach their peak operational efficiency. For this reason, it is desirable for a heat pump to start up and remain running for as long as possible. The heat pump was observed to run for short (sub-4-minute*) cycles during the visit. We believe that the short cycling is caused by a discrepancy between the flow rate on the heat pump side of the low loss header and the heating system side.

*It should be noted that the visit took place during mild weather, and this may have contributed to the very short cycle time.

Heat pump manufacturers will also specify a minimum system volume. The system volume has two effects, the first impacts heat pump run times. In a system with a large water volume it will take more time for the water to complete a cycle through the system pipework, radiators and back to the heat pump. The longer the journey time for the water, the longer the heat pump will be able to run, which maximises run time and, therefore, overall efficiency. If these minimum volumes are not achieved, water will circulate around the system quickly, resulting in short heat pump cycle times and a reduction inefficiency.

At Quarry Cottage, the minimum system volume recommended by the manufacturer is 28 litres. We estimate the water volume of the installed heating system to be 50 litres.

If the system volume is too low -> Larger bore pipework will help, and a small buffer would help to increase the overall system volume.

It is our conclusion that the low loss header was not necessary and is, in fact, detrimental to the efficiency of the heat pump system at Quarry Cottage.

Summary

- The radiators appear to be well sized, reflecting the larger sizes required for a 5°C ΔT system.
- Most of the radiators were connected to the heating circuit with 10 mm mini-bore pipework, which is not advised for heat pump systems, as the high flow rates required in heat pump systems lead to excessive pressure drop in these smaller pipes.
- The glycol concentration of the system was measured and should prevent freezing down to -10°C.
- Plantroom pipework is well insulated to minimise heat loss.
- The use of a secondary circulation pump and the associated low loss header (LLH) was unexpected.
    - The ASHP contains a circulation pump that can provide approximately 70kPa of external pressure, which should be sufficient for most home heating systems.
    - However at Quarry Cottage the system uses an additional external pump and a LLH, which allows the circulation pump in the ASHP and the external pump to operate separately without interference.
    - This LLH may cause distortion of the flow and return temperatures, reducing efficiency.

Figure 9: Low Loss Header in the plant room

5.1.3. Pipework Pressure Drop Analysis.

To evaluate whether a secondary circulation pump and the associated LLH was required, a closed circuit pressure drop calculation was carried out. The precise details of the pipework layout and sizes are unknown due to the observational nature of the study, so these calculations are an estimate, based on the available floor plans and the visible pipework.

Based on a design ΔT of 5°C, a mean fluid temperature of 42.5°C, and a heating load of 4.4kW as calculated by the installer, the index run pressure drop was calculated to be approximately 70 kPa, at a flow rate of 0.2 l/s. From the heat pump manufacturer's specifications, the available external pressure at this flow rate is approximately 55kPa, indicating that the installed secondary pump and LLH is required. Doing the same calculation with larger pipe sizes gives a pressure drop of approximately 31kPa. Therefore a secondary pump and LLH would not have been required if 15 mm pipework was used in the system. This would have reduced the overall system costs and improved the system efficiency.

5.1.4. Tenant Experience Interview

During the interview the tenant reported:

- They have no issues with the heat pump
- System was set to target a constant temperature of 16°C, a lower than usual target temperature, but the tenant finds this comfortable.

- It can feel a bit too hot in the summer, so the windows are open most of the time. It is unclear if this is due to the insulation improvements or an over-active heat pump.
- The noise of the heat pump has not been an issue at all
- The cold air emitted from the heat pump has not been a problem
- They do not know how to use the programmable thermostat, so the temperature is always set to 16°C and manually adjusted when required.
- The legionella cycle was originally occurring every day, which meant the heat pump was working hard on raising the temperature of the stored DHW. As a result, the radiators were not getting up to temperature. The legionella cycle has now been set to occur once a week and the issue has been resolved.
- It isn't noticeable when the heat pump goes into defrost mode.

5.1.5. Energy Consumption

The heat pump was installed with a sub-meter to allow the electrical consumption of the heating system to be measured separately from the rest of the electrical demand at the property. This is an important feature to allow the tenant to understand where their energy demand is coming from. Figure 10 shows the meter reading as of 18/11/21. The total demand of the property from October 2020 to November 2020 was 4183.6 kWh. The heat pump accounts for 73% of the total demand. The bills provided by the tenant had significant time gaps so did not allow for an analysis of the real costs for this report.

Figure 10: Electricity meter, showing ASHP consumption at the top

5.2. Discussion

While the heating system has been installed to a high technical standard, with good insulation and layout, the system design is sub-optimal.

Our calculations show that the internal circulation pump and low loss header (LLH) are required due to the undersized radiator pipework. These reduce the efficiency of the system and increase the capital cost of the installation. If appropriately sized pipes were used, the internal pump of the ASHP would provide sufficient pressure and the additional pump would not be needed, reducing the capital and operating costs of the system. This highlights the importance of whole system design optimised for a low temperature ASHP systems. The LLH may be part of why the heat pump was cycling on and off during the visit, but this could also be due to the milder autumn outdoor temperatures.

From the perspective of the tenant, the system has been working well and they are pleased with the performance. There does seem to be an issue with the system control, as the tenant stated they do not know how to time program the thermostat. Assisting the tenant with learning to operate the time control would allow them to make more energy savings, for example by establishing a lower ‘setback’ target temperature at night, or when away from home.

6. The Old Post Office (Site 2)

The Old Post Office is a Grade II listed Building dating back to the 17th century. It is now a two bedroom, two storey residential property owned by the Grosvenor Estate. The current 10kW Hitachi RAS-4WHVNPE split unit ASHP paired with the RWM4.0NE internal unit was installed in 2019, replacing a smaller ASHP that was not able to provide enough heating for the space. The ASHP also provides DHW, via a hot water cylinder. There is a wood burning stove in the living room which serves as an additional heat source or backup.

Figure 11: The Old Post Office (Google Maps)

6.1. Findings

6.1.1. Technology Choice

Property Type	Residential
Heat Pump Technology	Direct expansion (air-to-water)
Heating System	Wet radiator system
Hot Water System	DHW storage cylinder
Use Pattern	Continual occupation – Retired occupants
Technology Choice	★★

- Monobloc heat pumps are limited to a maximum of around 20 m between the outdoor unit and the DHW cylinder. Direct expansion heat pumps can accommodate distances of up to 50 m.
- Direct expansion heat pump means that pipework leading to the outside unit is hydraulically separate from the radiator circuit, so the circulation pump only

needs to provide pressure for the radiator circuit. This also means that freezing of outdoor heating system water is not an issue.

- Interfacing the DX system with a hydraulic unit (Hitachi Yutaki-Split RWM4.0NE) allowed a traditional wet radiator system to be used for space heating and a hot water cylinder for domestic hot water.

6.1.2. System Measurements and Observations

ASHP Unit Installation

- The refrigerant is R410A
- The ASHP is installed at the rear of the property on a wall mounted bracket. It is neatly contained in an existing low walled area.
- It is a direct expansion unit, so the external evaporator is piped with refrigerant to the internal condenser.
- The use of a split system allows for the external unit to be located far away from the main living spaces without the problem of freezing that water would have in a long outdoor pipe run.
- It is only visible from part of the rear garden, minimising the impact on the appearance of the building.
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- There are no anti-vibration mounts between the ASHP and the building, occasionally vibration from the compressor starting or stopping can be heard within the property.
- Condensate drainage has been accommodated for with the ASHP installed above an existing drain, so there is no risk of freezing over walkways
- Outdoor pipework insulation has been severely damaged by birds, exposing the bare pipework in many places.
- The outdoor unit is sub-metered, allowing the energy consumption of the heating system to be separated from the rest of the property.
- The ASHP appeared to be cycling (operating for short periods of time and then switching off), which is an inefficient way for a heat pump to operate as the compressor does not reach its ideal operating conditions for long before switching off.
    - This can be a common issue at milder temperatures, when the heating load of the building is below the minimum output of the heat pump, causing it to cycle on and off.
    - On the day of the visit the outside temperature was approximately 12°C.
- The mean air speed at the ASHP air outlet was found to be within manufacturer's stated windspeeds.

Figure 12: ASHP at rear of property

Plant Room and Radiators Installation

- The radiators appear to be well sized, reflecting the larger sizes required for a 5-10°C ΔT system.
- There is no glycol in the heating circuit to provide anti-freeze. Given that the water piping is entirely indoors with refrigerant outdoors this is not a problem.
- Poor installation practices observed where refrigeration pipework enters the house. Oversized hole was not sealed around pipework. Daylight clearly visible around pipework.
- The use of a secondary circulation pump and the associated low loss header (LLH) was unexpected

6.1.3. Tenant Experience Interview

During the interview the tenant reported:

- Most of the time, the property is warm enough, except for the early morning (around 7am) when they use an electric heater to supplement the heat pump in the winter.
- One of the bedrooms has been too hot for the tenant to sleep comfortably, so they have had the window open constantly, but still hasn't reached their comfortable sleeping temperature. They were told that they shouldn't use the TRV to adjust the radiator output.
- The noise of the heat pump is barely perceptible from indoors when running. One of the tenants can hear it switching on and off when they are in the kitchen, which is the room closest to the heat pump.
- There have been no complaints from neighbours about the noise
- Cold air emitted by the heat pump hasn't been a problem.

- The tenant doesn't know how to use the controller. They know it comes on from 6am to 10pm but don't know how to change it.
- The heat pump performs the DHW legionella cycle on Tuesdays, the tenant notices the increased hot water temperature in the morning.
- It is perceived by the tenant that the property landlord have a limited number of staff with the knowledge necessary to help with operating the heat pump.

6.2. Discussion

The system appears to be well installed, except for the hole in the wall where the pipework enters the building. As with 1 Quarry Cottage, the use of a secondary circulation pump and low loss header shouldn't be necessary given the size of the property. As large portions of the external pipework insulation have been destroyed by birds, insulation should be reapplied with mechanical protection as this lack of insulation will be causing significant losses in efficiency.

The tenants do not have a good understanding of how to control their heating system, which is important to get the best performance out of the heat pump. More education on how to control when the ASHP switches on will help alleviate the problem of the property being too cold in the morning.

Additionally, the advice given to the tenant to not use the TRVs to reduce the bedroom temperature seems to be unhelpful. It is likely that this advice was given with the aim of maintaining minimum system flow rates. Without TRV control the tenant has been leaving the bedroom window permanently open in an attempt to reduce the room temperature, which will lead to increased energy consumption and high running costs. It is very likely that any efficiency gained by reducing the cycling of the heat pump is overshadowed by the heat wasted from having a window permanently open. This again indicates the need for clear and quality advice for the tenant on how to use their heating system. Bedrooms are sensitive locations that need additional temperature control.

7. The Old Coach House (Site 3)

The Old Coach House is a small commercial property owned by the Grosvenor Estate in Chester, currently used for sports massage therapy business. Previously heated by direct electric fan heaters, the property was converted to an 8.5kW Mitsubishi ASHP central heating system in March 2021. DHW is provided by a separate small direct electric heater. No changes were made to the building fabric at the time. Due to logistical issues, this property was only inspected externally, followed by an online interview with the tenant.

Figure 13: The Old Coach House

7.1. Findings

7.1.1. Technology Choice

Property Type	Commercial – Gym & therapy room
Heat Pump Technology	8.5kW Monobloc heat pump (air-to-water)
Heating System	Wet radiator system
Hot Water System	Direct electric under counter hot water
Use Pattern	Commercial – Mon-Fri 09:00 to 17:00
Technology Choice	☆☆

- Monobloc systems better suited for buildings with a DHW load
- Only two internal spaces, each requiring different internal temperatures
- Wet heating system too complex for simple building
- Quick warmup to the therapy room could be achieved with a direct expansion system.

- Split or multi-split system could provide cooling to gym space in summer.

7.1.2. System Measurements and Observations

ASHP Unit Installation

- The ASHP uses R32 refrigerant
- The ASHP is installed on the gable wall of the property, in the car park of a neighbouring building.
- It is quite visible and distinct from the original style of the building, with plastic pipe housing running up the wall.
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- The ASHP is installed on anti-vibration mounts
- The pipework insulation was loose and did not seal all the way round the circumference of the pipe. It was also quite thin (~15mm).
- The ASHP was found to be clean and in good cosmetic condition
- Condensate drainage has been accommodated for with the ASHP installed near to a drain, which the ground directs the flow towards. This poses little risk of condensate freezing over walkways.
- On the day of the visit the building was not in use, and the heat pump was not operating so sound and wind speed measurements could not be made.
- As the visit was purely external the sizing and placement of the radiators cannot be evaluated.

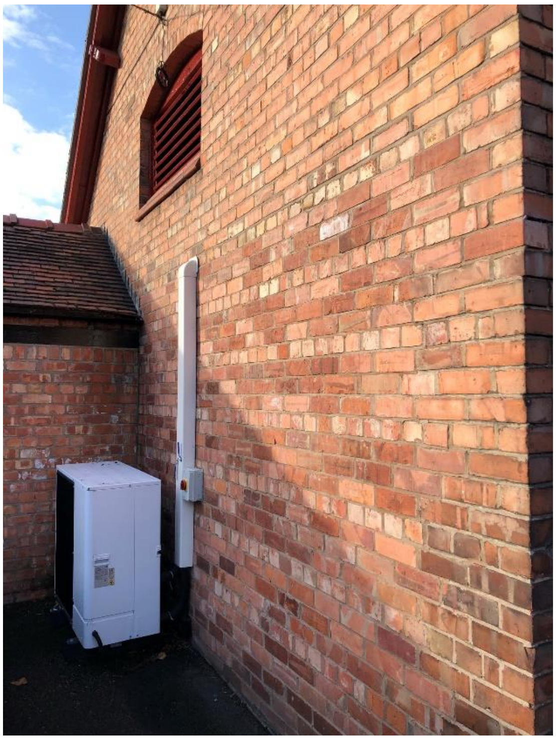

Figure 14: ASHP Installation at the Old Coach House

7.1.3. Tenant Experience Interview

The tenant reported that:

- There are two rooms with quite different heating requirements- the massage space needs to be quite warm, while the main room is used for treadmill training, and needs to be cooler for the inhabitants to be comfortable.
- The ASHP heats the space a lot slower than the previous direct electric heaters. Because of this, the tenant frequently uses additional direct electric heaters to ‘boost’ the heating of the space in the mornings, as clients have complained about it being too cold.
- The ASHP switches off when it detects that the target temperature has been reached with the help of the heaters, but when the heaters are switched off the ASHP takes too long to turn back on again and the temperature drops.
- The tenant is quite actively trying to control the temperature by switching direct electric heaters on and off, rather than having a steady comfortable temperature.
- They like that they are doing something good for the environment, but if they have to use additional electric heaters, it’s not ideal.
- They don’t know how to use the programmable thermostat- they keep trying to read the manual to understand how to have it come on earlier in the morning so that the building is warm when they arrive but haven’t been able to get it to work. They have asked the property landlord for help with this.
- The windows are quite draughty on a windy day, closing the blinds helps keep the heat in more.
- They feel that the addition of radiators to the walls takes away from the historic nature of the building.
- The noise from the ASHP is quite loud but not audible within the building.
- The cold air emitted from the ASHP has not been a problem at all, as it is located in a separate neighbouring car park.
- They don’t know if there have been any changes in running costs.
- No maintenance of the unit has been carried out yet.

7.2. Discussion

The heat pump seems to be well installed and should be able to heat the space well. However, the tenant’s experience is not ideal, with constant fluctuations in temperature and manual operation of supplementary heaters. With a typical gas boiler or direct electric heating system, the tenant can often have good level of thermal comfort without the use of a programmable controller, due to the quick response time of these systems. However, with a heat pump, programmed heating becomes essential so that the slow rise in temperature can be accommodated. Tenants need to be well educated on how to control their systems so that they can get the most out of them.

A multi-split DX system would likely be a better solution, allowing for varied heating in the two different spaces, providing a faster heat-up through air-air heating.

8. St Anne’s Church (Site 4)

St Anne’s Church is a grade II listed building in Ings, Cumbria, dating back to 1743. It is owned by the Church of England. Previously the building was heated by direct electric under-pew heaters, which were quite comfortable when sat in the pews. The heating was only switched on 24 hours prior to Sunday gatherings, meaning that the building fabric remained cold, leading to condensation and cold draughts. In 2012 the church underwent major renovations, involving the installation of an 14kW underfloor heating ASHP system with 13kW of backup direct electric radiant wall panels. Fabric improvements were also made, adding floor and loft insulation, and secondary glazing. Since these renovations, a small extension to add a toilet was made, but this is not connected to the UFH heating circuit and instead is heated by a direct electric towel rail radiator.

Figure 15: St Anne's Church (Exterior) (Google Maps)

Figure 16: St Anne's Church (Interior)

8.1. Findings

8.1.1. Technology Choice

Property Type	Church - Place of worship/multifunctional space
Heat Pump Technology	Monobloc heat pump (air-to-water)
Heating System	Wet underfloor heating system
Hot Water System	Direct electric
Use Pattern	Occupied for 1 or 2 weekday evening and church services on Sunday
Technology Choice	★★

- Radiant heat a good choice
- Low temperature and long run hours
- Underfloor heating, silent in operation
- Success of system is closely linked to building use profile. Building used throughout the week, allowing the heat pump to deliver a constant temperature.

8.1.2. System Measurements and Observations

ASHP Unit Installation

- The refrigerant is R410A.
- The ASHP is installed on rear side of the building, out of view of the road that accesses the church.
- The pipework runs straight into the building and doesn't run along the exterior wall, minimising visual impact.
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- The airflow leaving the ASHP does cross a path leading to the rear of the church graveyard, but there is a 2m separation and this pathway is not part of the regular use of the building.
- The ASHP is installed on anti-vibration mounts
- Condensate drainage has been accommodated for with the ASHP installed above a shale soakaway.
- Outdoor pipework insulation is well insulated, although there is a small, uncovered area as the pipework meets the wall.
- The ASHP appears to be in good condition, with some exterior dirt the only sign of age.
- The mean air speed at the ASHP air outlet was found to be within the manufacturer's stated airspeed.

Figure 17: Mitsubishi Zubadan ASHP Unit at St Anne's

Plant Room and Heat Emitter Installation

- The pipework, pumps and UFH manifold are easily accessed and neatly contained within a storage cupboard in the church porch.
- UFH heating circuit covers the main seating area, as shown in Figure 18.
- Pipework is well insulated, however many of the valves are exposed which will increase losses.
- The backup radiant panels are distributed though the nave and can provide heat in the case of extreme cold or heat pump failure.

Figure 18: UFH pipework being laid down during refurbishment works

8.1.3. Tenant Experience Interview

- The space is much more comfortable than before. The previous heating system was under pew direct electric, which was quite comfortable, but limited the flexibility of the space.
- The congregation are really happy with the system too. They were surprised at the improvement.
- The underfloor heating system helps the building fabric to stay warmer, reducing cold draughts and condensation significantly. This has helped to preserve the building.
- The heat pump can't be heard at all from inside the church, and neighbours have never complained.
- Occasionally condensate does freeze onto the tarmac path, but not many people go round that side of the building.
- Heating costs have stayed about the same, but they are using the building about two or three times as much as previously, so it's a big improvement in efficiency.
- They are confident in controlling the system as a member of the church designed it.
- The heating typically needs to be switched on 24 to 30 hours prior to occupation to get the building up to a comfortable temperature from cold. This is not perceived as a negative by the building users, simply something to be taken account of when planning.
- Low running temperatures allow the heat pump to operate at high efficiencies.
- Long run times allow the fabric of the building (walls etc) to warm up over time which improves the mean radiant temperature of the space.

- The thermostat is 7 day programmable.
- In future they would like to be able to remotely control the heating schedule and target temperatures to avoid having to travel to the building to make any control changes.
- Maintenance has been carried out a couple times since the system was installed.

8.1.4. Energy Bills

The current tariff is daytime, night-time and weekend tariff. Night-time and weekend rate is about 10p/kWh, and the daytime rate is about 15p/kWh. The church has found that their energy use and associated costs have stayed about the same as before the renovations, but the use of the building has tripled.

8.2. Discussion

The success of this project has come about through carefully adapting an existing building to provide a flexible and comfortable space for its users. The fabric upgrades reduced drafts and minimised heat loss from the floor, roof, and windows, while the underfloor heating delivers heat in a flexible way. The massive reduction in condensation is of great benefit to the health of the building fabric. The underfloor system has been perfectly matched with an air source heat pump to provide a low cost heating source that requires very little maintenance. A unique factor in the success of this system is that the system was designed by member of the church with an engineering background, who continues to ensure the correct operation of the system today.

This project should be viewed as a success from every angle. Not only does this historic building benefit from a low carbon heat source but by improving the flexibility of the space it can now serve more of the community.

9. Elizabeth Street (Site 5)

The building is owned by Grosvenor Estates London and the current tenant, Cubitts Optician, moved in during December 2021. There is a shop at ground floor level and an optician treatment room, staff area, and toilet at basement level.

As part of the recent refurbishment the landlord installed two 5.4 kW Toshiba inverter ASHPs (DX single split systems) that provide heating and cooling through wall mounted condenser units. Heating and cooling is provided to the shop and treatment room only. No heating is provided to the basement ancillary spaces.

Domestic hot water is supplied via a small electric water heater in the kitchen. At the time of the visit the tenant was not aware of how to use the AHSP system and was using direct electric heaters throughout the shop to provide heating.

Figure 19 - Elizabeth street commercial property

9.1. Findings

9.1.1. Technology Choice

Property Type	Commercial – Optician
Heat Pump Technology	Direct expansion, 2 No. split systems (air-to-air)
Heating System	Wall mounted condenser
Hot Water System	Direct electric
Use Pattern	Open 7 days a week
Technology Choice	★★

- Only two spaces that require heating
- Simultaneous heating and cooling may be required, but the system is too small to justify a variable refrigerant system.

- Installed heating capacity 432 W/m^2. The equipment selection will have likely been driven by cooling capacity to counteract the large shop windows which dominate the equipment selection.

9.1.2. System Measurements and Observations

ASHP Unit Installation

- The ASHPs use R32 refrigerant
- The ASHPs are located in 7.35 m^2 outdoor courtyard which complies with the maintenance space required by the manufacturer.
- The ASHPs were not running at the start of the visit.
- External courtyard is surrounded by 3 m high walls on all sides. Cold air from the external units in winter will sink to the floor of the courtyard where it will be drawn back into the external units. The air in the courtyard will become colder and colder and the heat pumps will become less and less efficient. Fortunately a neighbouring property has also installed a heat pump in the courtyard. At the time of the visit this heat pump was providing cooling and was therefore expelling hot air. As long as the neighbouring heat pump is operating in this manner the issue with cold air recirculation may be mitigated. The heat pumps would benefit from being installed as high from the ground level as possible, this would be balanced by the need to provide safe access for maintenance.
- Condensate drainage is allowed to run freely from the external units across the courtyard to a yard gully drain. In winter this may present a slip hazard.
- Pipework is well insulated against outdoor conditions.
- The external evaporator is piped with refrigerant to the internal condensers which runs vertically up the outside of the building before entering close to the location of the internal condenser.
- No measures have been taken to conceal the pipework and wires on the outside of the building, however the rear of the building is not overlooked.
- The indoor units have been painted to match the internal wall colour. They were therefore very discreet.

Figure 20 - ASHP installation at Elizabeth street. Left- External Units. Right- Internal unit, painted to match the internal décor.

9.1.3. Tenant Experience Interview

- The tenant was not aware that they had a heat pump heating and cooling system.
- Painting of the internal condensers allowed them to blend in so well that the shop staff had never noticed them and therefore had never questioned what they might be used for.
- Electric heaters were being used to provide heat throughout the shop. When the store was getting too warm, the tenant would open the door to provide cooling. This is a very expensive way to heat the space.
- The installation date of the two ASHPs is unknown and the use of the ASHPs by the previous tenants is assumed given the weathering to the outside units.
- The instruction manual was located next to the kitchen water heater. The heat pumps were turned on and an explanation of how to use the system was given. The staff turned off the electric heaters and began using the ASHPs for heating.

9.2. Discussion

The lack of guidance given to the tenant/shop assistants on how to use the ASHP system has resulted in direct electric heaters being used as the primary source of heating. Resulting in running costs 3 to 4 times higher than would be expected compared to a well-functioning ASHP system.

The decoration of the internal wall mounted units made them very discreet, which may have led to them going unnoticed by the building users.

The large W/m^2 heating capacity value is common for split systems of this type. It is rare that systems can be purchased small enough to closely match the load of small rooms. Capacity is driven by the cooling capacity of the units.

The use of two split air-to-air systems is a sensible choice for this type of building. The two rooms have different heating/cooling profiles. The shop is likely to require cooling on sunny days through the year due to the solar gain through the large shop display windows. While the basement treatment room will require heating. In order to provide simultaneous heating and cooling with a single outdoor unit an expensive variable refrigerant direct expansion type heat pump would be required. However, this type of system is likely to be a more expensive solution at this scale.

10. 14 and 14a Lowndes Street (Site 6)

14 and 14a Lowndes street are commercial properties owned by Grosvenor Estates London, both have been recently refurbished which has included adding ASHPs for heating and cooling. 14 Lowndes street is a shop, the sales area is located at ground floor level with two ancillary support rooms located in the basement. 14a Lowndes street is an office on the upper three floors above the shop. Consisting of main office spaces, a kitchen, WCs, and a shower room. Both 14 and 14a do not currently have tenants.

Figure 21 - Entrance to the office and shop in Lowndes street

The refurbishment makes extensive use of split air-to-air heat pumps. The shop sales area is heated and cooled via two ceiling mounted evaporators. The offices are heated and cooled via floor standing, wall mounted evaporators. Because of the chosen strategy of using direct expansion split type ASHPs space for eight external units had to be accommodated. Four of the external units are located on the roof, with good access for maintenance and replacement. The remaining four have been placed in an area that is difficult to access and is close to neighbouring windows.

10.1. Technology Choice

Property Type	Commercial – Office & Shop
Heat Pump Technology	Direct expansion, 8 No. split systems (air-to-air)
Heating System	Office – Floor standing a/c units, Shop – Ceiling mounted a/c units
Hot Water System	Direct electric
Use Pattern	Unknown - Currently unoccupied
Technology Choice	★☆

- High number of external units, resulting in sub optimal external placement for access and noise.
- Rear courtyard was noticeably noisy with equipment belonging to the neighbouring properties. There was a general background hum from other

ASHP external units, however the soundscape was dominated by a single kitchen extract fan.
- A solution that did not add to this poor acoustic environment would have been preferable to the multi split solution.
- Variable refrigerant system to serve shop and offices would provide comparable user functionality with only one external unit. This single external unit could have been placed on the roof.
- Ample rooftop space to mount the single external unit.
- An advantage of the multiple split system approach is the ease of sub-metering heat and coolth, simply by measuring the electricity consumed by each unit. However, variable refrigerant systems can be purchased with additional sub-metering capability to allow the energy used by each internal unit to be calculated separately. This information can then be used for sub-billing tenants.
- A variable refrigerant system can take advantage of simultaneous heating and cooling demands which helps to increase system efficiency and lower running costs.

10.2. Findings

10.2.1. System Measurements and Observations

ASHP Unit Installation General

- The ASHPs use R32 refrigerant.
- Outdoor pipework is well insulated.

ASHP Unit Rooftop Units

- Location hidden from the neighbours.
- Nearest noise sensitive location more than 5 m from units.
- Installed in accordance with manufacturer's installation requirements for access and airflow.
- No condensate drainage route was defined, water flows directly across the flat roof to the nearest roof outlet. This could present a slip hazard when frozen.

Figure 22 - ASHP units installed on the roof

ASHP Unit Courtyard Units

- Wall-mounted on brackets on a wall at the rear of the property.
- 1.8 m separates the face of the ASHPs with neighbouring single glazed windows. It is likely that any noise from these four units would be masked by the other noise sources in the vicinity. However, this should not be a reason to place units where they may cause a noise problem.
- The neighbouring windows are obscured with an opaque window film, therefore the ASHPs are hidden from the view of neighbours.
- It is not obvious to the observer how maintenance on these units would be carried out. The ground floor window into the courtyard area is too small for a person to fit through. Access would need to be from above via an area of flat roof. Ladders could be lowered down to allow a scaffold to be erected.
- Condensate drainage drops into the courtyard to run along the floor which might freeze in winter. This is not an issue as the area is not used for regular access.

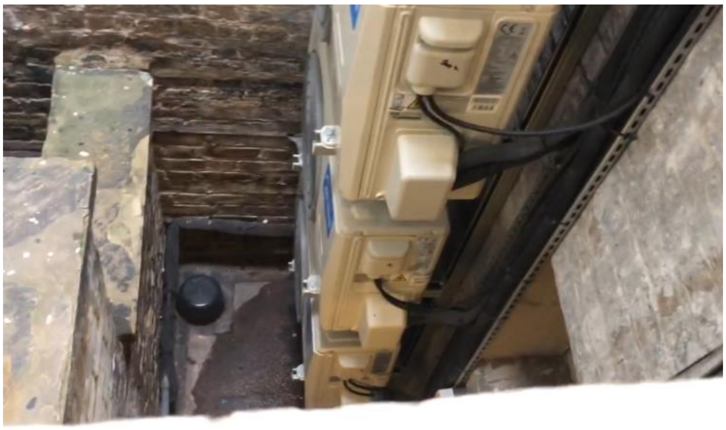

Figure 23 - Wall mounted external units, with poor access and close proximity to neighboring windows

Heat and Coolth Delivery

- Internal units are sympathetically installed with concealed pipework and custom made boxing around floor standing units.

Figure 24: Left: Floor mounted condenser. Right: Ceiling Mounted condenser

- Unit capacities are consistent with units that have been selected to cope with the peak cooling demand of around 100 W/m^2.
- No backup system has been integrated.
- High degree of robustness provided by the individual unit as the majority of open plan spaces have at least two heat emitters powered from separate outdoor units.
- It is assumed that the domestic hot water is provide by a hot water cylinder with a direct electric immersion coil. It was not possible to locate this but there were storage cupboards that were locked at the time of the visit. No evidence of any gas appliances in the building. Hot water for showering was provided by an electric shower.
- No evidence of any gas appliances in the building.
- Hot water for showering was provided by an electric shower.

10.3. Discussion

The internal units appear to be well installed with attention being paid to discreetly hiding pipework.

However, the decision to use multiple split systems rather than a single variable refrigerant system has resulted in external units being installed in compromised locations in terms of safe access and acoustics.

The courtyard units will be expensive to maintain as a scaffold will need to be erected to provide safe access. This may discourage maintenance from being carried out or encourage maintenance activities being carried out from ladders and thus presenting unnecessary risks to maintenance personnel.

In areas with low background noise levels it would not be appropriate to position external units in such close proximity to a neighbouring window. Given the high levels of background noise present in the vicinity it is unlikely that the noise added by the courtyard ASHP units will be a source of complaint.

11. Buckingham Palace Road (Site 7)

52 Buckingham Palace Road is a grade II listed building near Grosvenor Garden and is currently a multi-tenancy office building. The building was renovated in 2021, the works included; internal wall insulation, secondary glazing, and a variable refrigerant type air-to-air ASHP. Each tenancy is laid out on a single floor and consists of two rooms with opposite aspects. The case study looked at a single tenancy.

The office comprised two rooms heated and cooled by floor standing fan coil units which are powered by a communal 23.2 kW Daikin VRV ASHP located on the roof. The ASHP provided space heating and cooling only. Domestic hot water is provided by undercounter direct electric water heaters.

Figure 25 - Buckingham Palace Road

11.1. Technology Choice

Property Type	Commercial – Office
Heat Pump Technology	Direct expansion, variable refrigerant (air-to-air)
Heating System	Office – Floor standing condensers
Hot Water System	Direct electric
Use Pattern	Monday to Friday
Technology Choice	★★

- Each floor (single tenancy) can be run in either heating or cooling mode.
- The VRV system design allows for each floor to be set to either heating or cooling mode. On a single floor both rooms must be in the same mode. The two open plan offices on each floor have opposite aspects, south-east and north-west respectively. Because of this is it likely that the two spaces will have conflicting heating and cooling requirements at certain times. A system configuration that would allow simultaneous heating and cooling on a single

floor could result in higher heating and cooling efficiencies. However, this configuration would require additional equipment to be installed on each floor. Which may not have been possible to install because of space constraints.

- The one external heat pump unit is discretely located on the roof away from any noise sensitive locations.

11.2. Findings

11.2.1. System Measurements and Observations

ASHP Unit Installation

- The refrigerant is R410A.
- Installed on an anti-vibration mount and seems installed to a high standard.
- Condensate drainage has not been accommodated and will flow across the roof to the nearest rainwater outlet.
- The heat pump has sufficient airflow.
- The pipework is insulated for outdoor conditions.
- Noise from the unit cannot be heard from the inside the building.

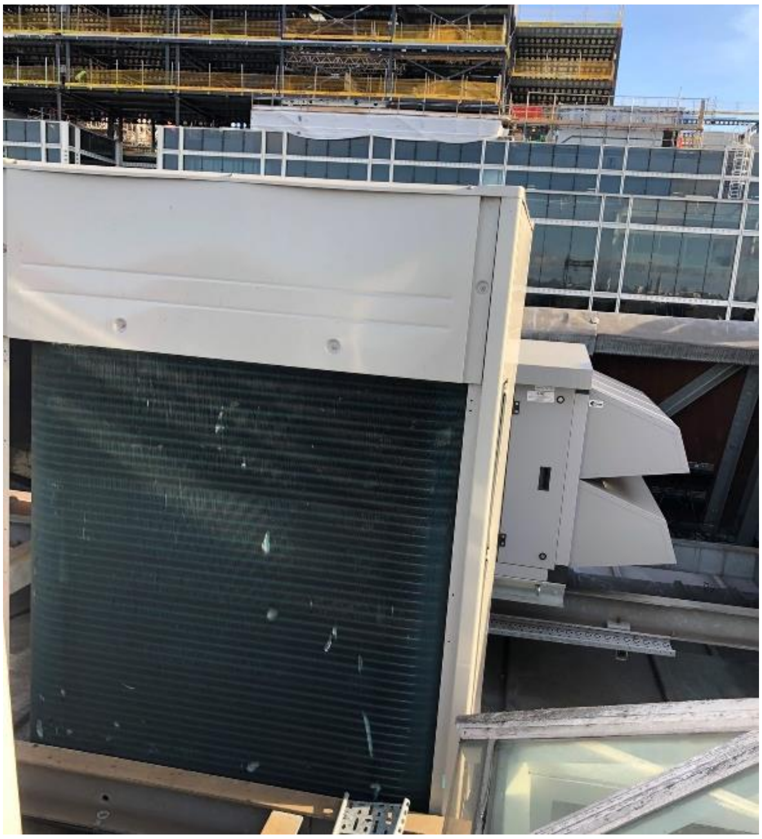

Figure 26 - ASHP unit located on the roof

11.2.2. Tenant Experience Interview

- No issues reported with the heating/cooling system.
- They use the fan coil unit for heating and cooling, setting the required temperatures using the handheld remote control.
- The temperature is set at 19 °C at the time of the visit.
- There have been no issues with the controller. The tenant had received some guidance on how to use the remote but considered it to be self-explanatory.
- The floor standing fan coil units need maintenance once a year unless there is an error light showing on the unit.
- If the red maintenance light is illuminated the tenant informs the landlord that the filters need replaced.
- They have no issue with the noise emitted from the ASHP, however it is located on the roof of a 4 story building and the case study floor was located on the 3rd floor.
- They do not have any energy bills or knowledge about the running cost of the ASHP.

11.3. Discussion

The system appears to work well and has been well designed. The renovation was completed a year ago and the tenants have had no issues with the heating or cooling. The tenants have a good understanding of how to use the heating/cooling system.

The system could be enhanced by allowing simultaneous heating and cooling of each office on a single floor. However, users were aware of the limitation but did not express that this had ever been an issue.

A discreet and sensitive location was found for the single external unit on the roof. This is a major advantage of a variable refrigerant system over multiple split systems as was seen in 14 and 14a Lowndes Street (Site 6).

12. Holy Ascension Church (Site 8)

Holy Ascension Church is a grade II listed church located in Oddington, Gloucestershire. It is owned by The Church of England. The church underwent a significant renovation in 2012. No thermal improvements were made to the walls, roof, or windows during the renovation. Insulation was added to the floor as part of the new underfloor heating system.

Figure 27 - Holy Ascension Church (Google Maps)

One aim of the renovation was to increase the use of the church throughout the week by attracting community use. To increase the flexibility of the space the pews were removed and replaced with flexible seating. Previously the building was heated by an oil-fired boiler distributed through cast iron radiators and trench heaters. To support the aim of flexibility a new underfloor heating system powered by a monobloc (air-to-water) heat pump was installed.

Figure 28 - Holy Ascension Church (interior)

The aim of increasing usage throughout the week has not been realised, despite the church now being able to offer a flexible and beautiful space. It is likely that this is due to the community hall situated close to the church being able to offer an equally flexible space with additional amenities such as more toilets & kitchen facilities. The church continues to be occupied on average once a week. Because of the limited occupation its custodians feel that it is wasteful and expensive to maintain a background level of heat in the building during the week. This creates a self-fulfilling situation, the church is less likely to be used because it can't offer comfortable temperatures compared to the community hall.

The heating system is currently enabled on a Friday evening to provide heat for the Sunday service, but comfort is never achieved during winter and the running costs are perceived to be high.

Other technical issues relating to the installation have come to light since the 2012 renovation. Attempts to remedy the installation by the original system designers may have left the church with an expensive system to operate that fails to provide thermal comfort at a sustainable running cost.

The church custodians are now investigating alternative heating options which would better match the buildings use profile.

12.1. Technology Choice

Property Type	Place of Worship
Heat Pump Technology	Monobloc Heat Pump (air-to-water)
Heating System	Wet underfloor heating system
Hot Water System	Direct electric
Use Pattern	Used one average once a week
Technology Choice	☆☆

- Underfloor heating, whether powered by a gas boiler or electric heat pump is an inherently slow response heating system. Heat should be delivered to underfloor heating in a continuous manner rather than trying to pulse heat into it. Underfloor heating lends itself to providing continuous stable conditions. Heat pumps complement underfloor heating as they operate most efficiently at low flow temperatures with long run times. This makes underfloor heating and heat pumps an efficient combination for spaces requiring stable temperatures.
- The chosen space heating strategy of underfloor heating and monobloc heat pump heat source was a good match for the intended use profile of the refurbished building. However, underfloor heating does not complement the actual use profile of the building.
- Underfloor heating does not compliment the once a week use profile. The heating system would need to be enabled all week to a relatively high set back temperature to maintain comfort. However, heating all week cannot be justified by the building operators from a running cost perspective.
- A system with a faster response time would be better suited to the current use profile.
- The church custodians are actively investigating options to replace their air-to-water monobloc heat pump with an air-to-air system. Care should be taken when designing this system to avoid warm air stratifying at high level, leaving the congregation uncomfortable.

12.2. Findings

12.2.1. System Measurements and Observations

ASHP External Unit Installation

- The refrigerant is R410A which is now being phased down. Replacement refrigerant will become more expensive to source over time.
- The ASHP is installed on the left-hand side of the church in a small recess. It is presumed that the drop in height was to bring the top edge of the heat pump below the level of the perimeter wall.
- The placement of a heat pump in the recess causes leaves and snow to collect and does little to hide the heat pump. It would be better to have it installed at ground level to avoid leaf and snow build up.
- The heat pump was surrounded by a hazel fence, the majority of which has now been destroyed by high winds and has not been replaced.
- No issues of flooding were reported, however installing the equipment below the level of the surrounding landscape does leave equipment susceptible to localised flooding.
- The pipework between the external unit and the church basement runs buried underground. Where pipework is exposed it is insulated.
- The location meets all the manufacturer's installation space requirements for access and airflow.
- No noise sensitive locations are present within 5 m of the heat pump.
- Condensate drainage dissipates via a gravel soakaway that surrounds the heat pumps concrete mounting base.
- The ASHP appears to be in good condition with normal levels of weathering for its age.

Figure 29 - ASHP external unit location, Left: close-up, Right: View from rear of grounds

Heating System

- The underfloor heating manifold and controls are easily accessed and neatly contained within a storage cupboard in the church office.
- The underfloor heating manifold incorporates a mixing/blending circuit. Historically mixing/blending circuits have been provided on underfloor heating manifolds to allow the high output temperatures of a fossil fuel heat source to be mixed down to suitable UFH temperatures before entering the floor pipes.
- Heat pump systems do not always need mixing/blending valves. There is a danger that using them results in unwanted mixing which will artificially degrade the flow temperature to the underfloor heating. This may result in the heat pumps flow temperature having to be increased which leads to reductions in heat pump efficiency. However, this is unlikely to be the source of problems being experienced by the users in this case.
- No buffer vessel is installed, however ample system buffering should be provided by the thermally massive underfloor heating system.
- Care should be taken to ensure minimum system flow rates are maintained. In an UFH system this can be achieved my leaving the actuator heads off the loops that serve the same area as the main thermostat.
- Pipework is well insulated, however many of the valves are exposed which will increase losses.
- The 14 kW heat pump can provide 60 W/m^2 of space heating to the main church area. This is smaller than expected for a building that has not undergone any fabric improvements.
- Small heat pump capacities don't automatically result in poor performance. Oversized heat pumps can have an equally detrimental effect on system efficiencies.

System Alterations

- The church custodians were initially happy with the thermal comfort the system provided. That was, until they received their first electricity bills.
- Comfort was only achievable when operating the system on a continuous basis. This is expected for a system of this type and consistent with churches using underfloor heating powered by gas boilers.
- It is understood that the heat pump was capable of providing comfort under these conditions.
- Driven by the unjustifiable bills for a building that was used once a week, the set point during the week was lowered to 14 °C.
- The heating set point was then brought up to 18 °C on the Friday evening before the Sunday service.
- It was observed that in very cold weather the heat pump was consuming a lot of electricity and the church was not achieving the target heating temperature.
- It is thought that this is a symptom of the small heating capacity of the heat pump compared to the large heat load provided by the cold church, coupled with non-continuous running.
- When a heat pump first starts up it expects to see a rise in system temperature/pressure in its internal refrigeration circuit. If the

temperature/pressure is not achieved within a given period the heat pump can assume that the lack of heat in the system is due to frosting on the evaporator. In the scenario at Holly Ascension church this is not the case, the reason for the lack of temperature in the system is that a small heating device is trying to heat a very large cold stone church. When the heat pump mistakenly attempts to defrost the evaporator by triggering a defrost cycle heat is taken out of the heating circuit. Once the heat pump has completed the defrost cycle it then tries again to deliver heat to the cold church, and the cycle continues. This cycle is known as a ‘defrost frenzy’ which consumes high amounts of electricity and delivers little heat. Electricity bills remain high but very little heat is delivered to the space.

- It is likely that is a symptom of allowing the church to get cold during the week. If the heating was activated in autumn when the external temperature is mild and the stone walls and floor still retains some of the summer warmth the heat pump would be able to deliver heat without entering a defrost frenzy.
- The church custodians approached the original installer to remedy the situation. The installers solution was to install a 9 kW direct electric heater between the heat pump output and the underfloor heating input. A thermostat was set to activate this top up heater when the outside air temperature was below 5 °C.

Figure 30 – Inline Backup/Top-up direct electric heater

- This solution has, as far as anyone is aware, solved the issue of the heat pump entering a defrost frenzy.
- The combined output of the heat pump and direct electric heater can now provide 99 W/m^2 of space heating.
- The inclusion of a direct electric heater has significantly reduced the system COP. For example, a COP of +3.5 should be easily achievable by a modern heat pump. Combining the heat pump with a direct electric heater would lower the COP to around 1.6.

- Alternative alterations such as providing a valve to mix the heat pump output water back into the heat pump return would have protected the heat pump from the very low return temperatures from the underfloor heating circuit and allowed the heat pump to work within its operational temperatures. This would not have improved the system warm-up times as this is dominated by the performance of the underfloor heating.
- The system capacity could have been increased using a buffer vessel, allowing the small heat pump to store up heat over an extended period (preferably using the off-peak electricity period) ready to be deployed into the heating system on the Friday evening.
- The church custodians have attempted to reduce the running costs by lowering the heating setpoints over time.
- Heating setback through the week is 7 °C. The target temperature is then set to 18 °C on the Friday evening prior to the Sunday service, returning to 7 °C on the Sunday evening. However, the temperature that is achieved in the service is only 14/15 °C and is not perceived as being comfortable. In previous years the setback temperature was set to 14 °C, it was reported that 18 °C on Sunday could be achieved.

12.2.2. Tenant Experience Interview

- The tenant is very unhappy with the performance of the heating system. Experiencing poor thermal comfort and high energy bills.
- It takes too long to heat it up. When switched on 48 hours prior to the Sunday service, the building still does not achieve a comfortable temperature.
- The church is rarely comfortable using this approach, but this is to balance the energy bills.
- The new heating system is more comfortable than the previous oil boiler.
- They have no issue with the noise or the airflow from the ASHP.
- They have an issue with leaves and snow collection because the ASHP is located in a recess.
- They are on a renewable energy tariff, however, 75% of the time the heating system is operating during the peak tariff therefore not taking advantage of the off-peak costs.
- In the future, they would like to replace the entire heating system to have a faster response time when the heat pump is on. The system change will likely include 4 No. air-to-air ASHPs on the rear of the church. Abandoning the use of the underfloor heating with floor standing direct expansion fan coil units.

12.2.3. Energy Bills

- The church have a renewable energy tariff with peak and off-peak tariff options.
- Due to the mode of operation (Friday to Sunday warmup) 75% of the buildings electrical energy is consumed at peak times.
- Comparing the energy consumption of St Anne's church with Holly Ascension church reveals that Holly Ascension is on spending approximately an additional 37% on electricity. This is surprising given the higher usage of St Anne's through the week and its more northernly and exposed location.
- There is not enough data available to make firm conclusions.

- The cost of one unit of heat from the heat pump in the off-peak period is approximately 23% cheaper than the heat pump & direct electric unit during peak time. Utilising this may help to control bills.

12.2.4. Optimisation Options

- Aim, to reduce the use of the 9 kW top-up heater and therefore maximise input from the heat pump. Take advantage of off-peak electricity rates. By keeping some heat in the floor slab all week, there will be a better chance that the heat pump will manage on its own without entering a defrost frenzy.
- When the floor slab is warmest, turn off the power supply to the direct electric heater to ensure that it does not contribute to the heating system. The efficiency of the heat pump on its own might be around 300%, in conjunction with the direct electric heater, the efficiency might be down at 160%.
- Adjust the heating programmers to bring the heat pump on for the full off-peak periods as per the following schedule.

Day	Period	Target Set Point
Monday -Thursday	00:00 to 07:00 (off-peak)	16 °C
Monday to Thursday	07:01 to 23:59 (peak)	14 °C
Friday	00:00 to 07:00 (off-peak)	18 °C
Friday	07:01 to 23:59 (peak)	16 °C
Saturday	00:00 to 07:00 (off-peak)	18 °C
Saturday	07:01 to 23:59 (peak)	16 °C
Sunday	00:00 to 07:00 (off-peak)	18 °C
Sunday	07:01 to 23:59 (peak)	16 °C

Table 4 - Suggested Temperature settings to maximize off-peak consumption

- To ensure that the heat pump is operating at its most efficient, obtain the operating instructions and work out how to set the flow temperature to approximately 35 °C or make sure weather compensated regime is enabled with a peak flow temperature of 40 °C at -3°C external. A heat pump loses about 2.5% efficiency for every 1-degree increase in flow temperature, so lowering the flow temperature is always worth considering. The danger is that when the original installer was trying to sort out the complaints, they increased the flow temperature from the heat pump to a level that has impacted its operating efficiency.

12.3. Discussion

The two churches in this case study installed similar heating systems yet had completely different user experiences. One viewing it as a great success while the other views it as a disaster for the church. The table below sets out the differences in refurbishment and heating system design of the two church case studies.

	Holly Ascension Church	St Anne's Church
Heat pump capacity	60 W/m^2	94 W/m^2
Combined heat pump and top-up capacity	99 W/m^2	182 W/m^2
Heating top-up system	Slow response direct electric boiler piped into underfloor heating system	Fast response direct electric radiant heating panels around perimeter of main seating area
Thermal Improvements	Floor insulation only	Floor and attic insulation, secondary glazing
Occupancy Profile	Once a week	Two to three times a week

Table 5 - Differences between church case studies

This project has not been a success for the church. Thermal comfort is achievable, but not at a cost that the church can justify. The decisions the church is making to limit running costs are leaving them with poor thermal comfort.

Of all the differences highlighted in Table 5 it is the authors opinion that it is the occupancy profile which has had the most profound effect on the success of the project.

Any church wishing to follow a similar route to decarbonisation should carefully consider their use profile. If maintaining a level of heat in the building while it is unoccupied is not going to be acceptable then a fast response heating system should be considered.

13. Little Trendeal (Site 9)

1 Little Trendeal is a two storey, two-bedroom residential property built in 1800. In 2017 the first of two Daikin air-to-air air ASHPs was installed in the kitchen, which is the primary living area. A second air-to-air system was installed the following year to provide heat to the upstairs of the property.

The house was previously heated solely using electric storage heaters. The storage heaters are still used on the coldest days of the year to take advantage of off-peak electricity prices.

The domestic hot water system is provided by an immersion heater within a hot water cylinder which can also take advantage of off-peak electricity pricing.

Secondary glazing has been installed to improve the thermal performance of the existing single glazed windows. Modern levels of loft insulation have not been installed in the property.

Figure 31 - Little Trendeal residential property

13.1. Technology Choice

Property Type	Residential
Heat Pump Technology	Direct expansion 2 No. split systems (air-to-air)
Heating System	Wall mounted condenser
Hot Water System	Direct electric immersion heater to storage cylinder
Use Pattern	Residential, retired occupant
Technology Choice	★☆

- Heating system has been upgraded with the use of two 2.5kW Daikin air-to-air ASHPs.
- Two split systems have been installed at different times. The first in the kitchen and the second in the upstairs hallway.
- Two splits result in two separate outdoor units. A small multi-split may have been a more cost-effective solution.
- High degree of satisfaction with comfort, especially with the quick warm up times provided by the air-to-air system.
- Matches the occupants needs, the small amount of noise generated by internal wall units was seen as an acceptable trade-off for an efficient and cost effective heating system.
- Installation quality was high. Internal piping was routed neatly in plastic trunking. From a historical viewpoint the system is not particularly sympathetic, the advantage being that minimal disruption was caused during installation with no floor or floor finishes being disrupted.
- The ASHP can provide heating and cooling however the tenant has only used it for heating as the property does not overheat in summer.

13.2. Findings

13.2.1. System Measurements and Observations

ASHP Unit Installation

- The refrigerant is R410A, no low GWP alternative is currently available for small DX systems.
- The external units are installed on wall mounted brackets facing the driveway.
- Mounting position is elevated, protecting them from any potential flooding or snowfall.
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- Pipework is well insulated.
- Condensate drainage from the external units is allowed to fall onto the driveway below. There is a land drain that the water makes its way to. Freezing could present a slip hazard, however, the user has never perceived this to be an issue as there is ample space to avoid the wetted section of driveway.
- The heat pump seems to be well designed and installed, with no need for maintenance since the installation.

Figure 32 – Left: ASHP units installed on the side wall of the property. Right: hallway condenser unit

13.2.2. Tenant Experience Interview

- The tenant has no issue with the heat pumps. The two inside units heat up the rooms quickly and are cheap to run.
- Since the installation of the heat pump, the space is much more comfortable and the inside unit in the kitchen can heat the entire cottage.
- If standing outside, the heat pump is audible, however, the tenant cannot hear it from the inside.
- The busy road traffic masks much of the noise from the ASHPs.
- The tenant has no issue with the cold air coming out of the ASHPs.
- The temperature is set to 19°C and the tenant tends to have it between the range of 19-22°C as not much difference in running cost is observed.
- The tenant uses the controller to switch the units on/off and to control the set point temperature. No time clock function is used as spaces heat up very quickly when switched on.
- Five years warranty is provided with the heat pump, and every two years maintenance is carried out to check the level of refrigerant in the DX system.
- The inside unit filters are cleaned once a month by the owner.
- No issues have occurred since installation in 2017.

13.2.3. Energy Bills

The owners view was that it was a very economical form of heating. This was supported by the decision to install a second system of the same type at a later date.

13.3. Discussion

The success of the original installation of the DX system in 2017 by improving the thermal comfort and the cheap running costs resulted in the addition of another ASHP in 2018. The tenant sometimes uses the existing storage heaters to take advantage of off-peak electricity prices.

Small split systems are widely used in mainland Europe for residential heating and cooling. They are a less common solution in the UK as the internal units make noise inside the home when delivering heating/cooling. Most UK homes do not require cooling and therefore, why choose a heating system that makes a noise when you can have a silent running radiator or underfloor heating system? This case study has shown that small air-to-air systems are a good solution for some applications and should not be dismissed as an option.

14. Plough Court (Site 10)

8 Plough Court is a three bedroom residential barn conversion, developed in the 1990s. Originally the heating and hot water was provided by an oil boiler. The decision to replace the system in 2018 with an ASHP was driven by a desire to lower the occupants carbon footprint.

An 8.5 kW Mitsubishi- Ecodan monobloc ASHP was installed on the existing oil tank plinth. A new heat pump compatible hot water cylinder was installed as part of the system upgrade. This is common as heat pump compatible cylinders contain a larger heating coil to allow the heat pump to heat the water in a comparable time to a higher temperature oil or gas system. However, the existing radiator and pipework system did not need altering, which made this a straightforward retrofit with minimal disruption to the owner.

The property has double glazed windows in addition to loft and wall installation. Insulation levels cannot be verified, they are assumed to be in line with Building Regulations at the time.

Figure 33 - Plough Court, monobloc AHSP located on old oil tank plinth

14.1. Technology Choice

Property Type	Residential
Heat Pump Technology	Monobloc (air-to-water)
Heating System	Wet radiator system
Hot Water System	DHW storage cylinder
Use Pattern	Residential, retired occupant
Technology Choice	★★

- Monobloc heat pumps are ideal for residential application where the outdoor unit can be located close to the DHW cylinder.
- Existing radiators and pipework compatible with new system flow rates.

14.2. Findings

14.2.1. System Measurements and Observations

ASHP Unit Installation

- The refrigerant is R410A, now being phased down.
- The ASHP is installed in the driveway of the property on a concrete plinth where the oil tank was located.
- The location meets all of the manufacturer's installation space requirements for access and airflow.
- No system buffer vessel is installed.
- The heat pump is quiet, and the closest noise-sensitive point is 8m away.
- Pipework is well insulated both externally and internally.
- Condensate drainage is allowed to disperse through the gravel driveway. No issues of freezing were reported.
- The ASHP is located around 2 m from the interior hot water cylinder.

Figure 34 - ASHP installed on the side of the property

Plantroom and Radiators Installation

- The radiators appear to be well-sized, reflecting the larger sizes required for a 5-10° ΔT system.
- Most of the radiators were connected to the heating circuit with 15mm copper pipework with the main distribution using 22mm pipework.
- The existing radiators have been retained for use with the heat pump system.

- Glycol concentration level provided freezing protection down to -3°C.
- The heating is enabled 24 hours a day and is controlled by the manufacturer's room thermostat set to 18°C.

14.2.2. Tenant Experience Interview

- No issues with the heat pump.
- The system is set to target 18°C, 24 hours a day.
- Weather compensation automatically adjusts the heating flow temperature to match the buildings heat loss based on external air temperature.
- Good thermal comfort in the property, not much difference with the previous oil system.
- No changes were made to the existing radiator system which has resulted in a cheaper and less disruptive ASHP installation.
- The noise of the heat pump has not been an issue for the occupant.
- Neighbours have never mentioned hearing the external unit.
- The condensate discharge from the heat pump has never caused an issue with freezing in the local vicinity.
- The tenant is well supported by the installation company and informed on how to use the control or how heat pumps work.
- The tenant has an annual maintenance contract of £150 per year where the installer comes back and checks over the system.

14.2.3. Energy Bills

Since the installation of the ASHP the energy bills of the property have increased compared to the previous system. The energy tariff used by the tenant is a renewable electricity tariff from Octopus Energy. This was chosen to help reduce carbon emissions, but the tenant is conscious that the energy prices are rising.

14.3. Discussion

This cast study demonstrates how straight forward a switch to a low carbon heating system can be. The understanding of how to operate the system to achieve the best performance has resulted in a comfortable, low carbon home.

15. Conclusions

The overwhelming impression from the tenant interviews was that the appearance of the external units was not an issue for them. Given the historic nature of the case studies, it was assumed by the authors that a variety of mitigation measures would have been used to lessen the visual impact of external units. However, only a single project had taken measures to hide the unit behind a fence. The fence was not repaired when over half of it was blown down in high winds, suggesting that the unit's appearance was not seen as an issue.

The noise and cold air produced by the external heat pump units were also non-issues for the study participants. All the residential projects enjoyed external unit sighting in locations away from noise-sensitive locations and where cold air plumes were not problematic.

Monobloc air-to-water and direct expansion air-to-air systems each have their strengths and weaknesses. These differences should be considered when selecting the type of ASHP technology to match the needs of the building. Several projects had a high install quality but let down by the choice of heat emitter or the detailed hydraulic system design.

Designers should consider how the chosen heat emitters will match the occupancy profile of the building. A slow response underfloor heating system is well suited to a building that is used several times a week. At the same time, it leaves the users of an occasionally occupied building feeling like they are wasting money heating an empty building. The two church case studies demonstrated this point. They had almost identical solutions installed, yet the outcomes for the users were very different.

A reoccurring theme of the case study projects was the lack of knowledge of how to adjust time clock settings. To provide comfortable conditions first thing in the morning, several users resorted to plugging in electric heaters rather than extending their heat pump run times. Controllers seem not to be intuitive enough for people to operate without support.

Small changes in heat pump flow temperatures can significantly affect running costs. The owner is the person best placed to tune these temperatures over time to best match their property's characteristics and drive down running costs. Flow temperatures are typically set by the installer when they commission the system. Not wanting to be called back because the occupant is too cold, the installer may be incentivised to set the flow temperatures a little high. Typically, users are not shown how to optimise their systems. It is unlikely that they would be able to assimilate this knowledge during a short handover. Landlords could upskill in this regard and support tenants to help them minimise their heating bills.

Only one residential case study considered their ASHP heating system to be a cheap alternative to other forms of heating. This is likely to be because of the approximately 4:1 ratio between the price of electricity and gas. To improve the economic feasibility of ASHPs, the UK Government have committed in principle to reduce the gap between electricity and more polluting fossil fuels.