Heat Pumps in Historic Buildings

Air Source Heat Pump Case Studies – Large Buildings

Summary

Electrifying heat is key to reducing reliance on fossil fuels for historic buildings. No technology is better placed to electrify heat for space heating than heat pumps. The technology is mature, and if the whole heating system is well designed it will deliver comparable running costs to a natural gas system. Air source heat pump (ASHP) technology can be installed quickly and has lower capital costs than other heat pump technologies. This makes air source a key technology in the decarbonisation of space heating.

This report is a continuation of the previous study 'HEAG0316: Heat Pumps in Historic Buildings, Air Source Heat Pump Case Studies – Small-scale Buildings', and focuses on five large historic buildings across 4 sites. In 2022, we commissioned environmental building services engineers, Max Fordham LLP to review the performance of ASHPs in larger historic buildings. The research aligns directly with Historic England's climate change and sustainability objectives.

The four site visits took place between November 2022 and February 2023. The engineers from Max Fordham LLP carried out visual inspections of the ASHP installations and associated heating systems. They also interviewed building users to gauge their opinions on running costs, thermal comfort, noise, cold air plumes and visual appearance. The engineers took as many quantitative measurements as possible, but time constraints and minimising the intrusiveness of site visits meant that most of the findings were qualitative. Assessing running costs was particularly challenging. Where data were available, they came in the form of energy bills. This made it difficult to make quantitative comparisons before and after installing the ASHP. The users' perceptions of running costs are reported, but the information is highly subjective according to each individual's expectations.

The key findings were:

- ASHPs work well in historic buildings and are a readily available means of decarbonising heating systems.
- Issues with the heating system's performance were usually caused by the design of the heating distribution or delivery, rather than by the ASHPs themselves. For example, convectively heating draughty areas with a high air change rate can be problematic, regardless of whether the heat source is a boiler or a heat pump.
- The visual and noise impacts of the ASHP units were not an issue for any of the users, as also was the case in the previous ASHP study.
- Carbon dioxide (CO_2) refrigerant systems present unique opportunities for reusing existing pipework, reducing embodied carbon emissions, and reducing unintended emissions caused by refrigerant leaks.
- Building users need to have a good understanding of how to use system controls to maximise the efficacy of the system.

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Front cover: One of four sets of air source heat pump evaporators (right), pictured with the gas main (left).

Contents

1. Introduction

This report is a continuation of the research carried out in '[HEAG0316: Heat Pumps in Historic Buildings, Air Source Heat Pump Case Studies – Small-scale Buildings]' (2023). While the first report includes domestic buildings, this report mainly looks at non-domestic buildings.

Data was gathered from five ASHP installations around the UK: Sites 1-4b. As before, the aim was to evaluate the efficacy of the ASHP at each site, and to not only identify examples of best practice but also common mistakes that led to poor system performance. This information can be used to inform future work and strategy when installing and operating ASHPs in historic buildings.

The first half of this report summarises the key findings across all four sites and discusses key lessons to be learnt. The second half presents the detailed findings of each individual case study.

The aim of the report is not to evaluate the sites against one another, but rather to report findings that are specific to each site.

Figure 1: Locations of case study sites.

Case studies evaluation parameters

The ASHP at each site was evaluated to assess its efficacy. The building service engineers considered:

- visual appearance
- noise
- electrical design
- manufacturer’s guidance
- hydraulic design, including heat emitters
- maintenance
- defrost cycles
- controls
- performance issues
- thermal improvements to the building
- refrigerant used
- running costs
- occupants’ experience.

Case studies limitations

The available data for running costs were in the form of energy bills. Some of these were based on estimates or did not cover the appropriate time periods. 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 difficult to make quantitative comparisons before and after the ASHP was installed. The users’ perceptions of running cost have been reported where available, but they are highly subjective according to each individual’s expectations.

The case study findings are based on a single visit to each site and dependent on the weather that day. The site visits were carried out between November 2022 and February 2023.

Although each case study survey was thorough, it was not possible to inspect those parts of the property that were covered or inaccessible at the time of the visit.

2. Method

For each case study, the building services engineers did a non-intrusive site survey. A staff member, typically the facilities manager, gave a tour of the site, and the system was then inspected.

This included:

- taking photographs of the installation
- measuring the free area around the ASHP
- measuring the distance to the closest noise-sensitive location
- taking thermal images of the ASHP
- 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's fluid.

Relevant staff, tenants and owners were asked a prepared set of questions about their experience living with the ASHP heating system, including:

- 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?
- do you know 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?

3. Key observations and findings

The observations and findings drawn from the case studies cover:

- buffer vessels
- comfort temperature
- system design temperature
- heat loss
- difficult to heat spaces
- running costs
- backup heat sources
- refrigerants
- controls.

The findings of the previous heat pump investigation show that ASHPs are a viable alternative to fossil-fuelled heating systems in historic buildings. Why then do some buildings that use ASHPs have uncomfortable conditions or higher running costs than expected?

Where suboptimal outcomes were observed in the case studies, they were not caused by the failure or unexpected behaviour of the ASHP itself. How an ASHP performs is not guesswork. The temperature of the water leaving the ASHP at any given time is the key driver of the ASHP's efficiency, and the design of the heating system determines the water temperature required. Good system design aims to satisfy a building's heat requirements at the lowest possible flow temperature. To achieve the required building temperatures at an acceptable running cost, it is essential to have correctly sized heat emitters and to use a control system that modulates flow temperature.

Several factors may contribute to poor outcomes:

- It is common for buildings that are not occupied permanently to be left to cool down before the heating system is switched back on. This could lead to the ASHP being operated at high flow temperatures , which can be inefficient and more expensive to operate when trying to warm up a building quickly (system design temperatures are explained later in this section).
- The heat emitters may not be appropriately sized to deliver the necessary heat at an optimal, lower ASHP flow temperature. This could be because the building's heat loss was not taken into account when calculating the size of the heat emitters.
- If the ASHP is frequently switching on/off (cycling), it may be due to the design of the hydraulics (pipework and equipment) or insufficient output being available from the heat emitter at the minimum ASHP output. To improve efficiency and reduce energy consumption, it is important to minimise the amount of time the ASHP spends in start-up mode. Frequent cycling can also cause wear and tear on the ASHP's compressor.

In the case studies, there was a big variation in the installed heating capacity as shown in Figure 2.

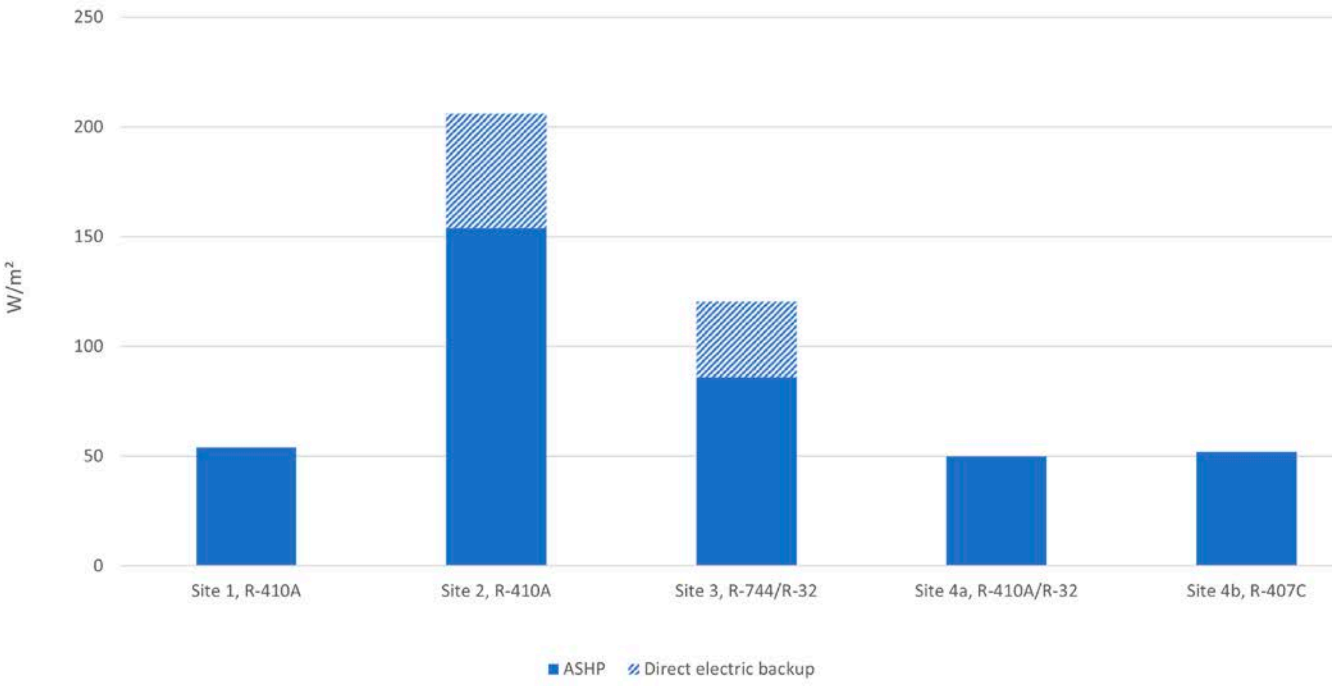

Figure 2: Installed heating capacity per m².

Buffer vessels

Buffer vessels are only used with monobloc ASHPs. Buffer vessels are insulated tanks designed to provide additional water volume to the system. Two of the systems in this study had no buffer vessel, at Site 1 and Site 4a. These are both relatively small systems, and there were no observed downsides to not having a buffer.

During certain external weather conditions, frost will form on an ASHP's external evaporator. The frost must be periodically melted to allow the ASHP to continue to operate. This is known as a defrost cycle. The radiators at these two case studies provide enough system volume (the total volume of heated water in the heating system) for the ASHP to defrost effectively. At Site 3 and Site 4b, the buffer vessel provided system volume and also stored energy for generating domestic hot water.

Table 1: Buffer vessel size

Site	Buffer vessel volume (l)	Buffer volume per kW of ASHP capacity (l/kW)
Site 1	n/a	n/a
Site 2	200	9
Site 3	3000	40
Site 4a	n/a	n/a
Site 4b	223	25

System design temperature

In this report, we refer to low and high temperature heating systems. When discussing low and high temperatures in the context of ASHPs, low temperatures are less than or equal to 55°C and high temperatures are usually greater than 55°C.

Before condensing gas boilers were introduced, it was common for heating system design temperatures to be 82/71°C (system flow/system return). These temperatures will occur when the weather is coldest outside with the heated water leaving the boiler at 82°C and returning to the boiler at 71°C. The advent of condensing gas boilers meant that systems were being designed to achieve a maximum return of 55°C, and a common system design is 70/50°C. This was a step in the right direction in terms of efficiency and system design temperature.

Building regulations now stipulate that all new heating systems, regardless of heat source, should be designed to operate at a maximum temperature of 55°C. Building Regulations make exceptions for historic buildings, where conservation needs may conflict with energy efficiency requirements. For more information, refer to Historic England's guidance on complying with building regulations at historicengland.org.uk/advice/technical-advice/building-regulations/

For some historic buildings, upgrading the heating system to operate at a low temperature (less than or equal to 55°C) may not be possible. In such cases, it could be appropriate to use an ASHP at a high temperature and accept the associated increase in running costs as a means of achieving some decarbonisation at least. At today's (spring 2023) energy prices, a system would need to be designed with a maximum temperature of 45°C if it were to cost less to run than a gas-fired alternative. The feasibility of installing an ASHP system that will adequately heat the building should be determined in the context of the energy market at the time of the project.

Some ASHPs now use refrigerants, such as CO_2, which can efficiently produce flow temperatures above 55°C (see the 'Refrigerants' section).

Comfort temperature

To achieve a particular internal comfort temperature, the heat input to a space must allow for the heat loss from the space.

The required comfort temperature is determined by the way the space is used. The users' activity and clothing heavily influence whether a temperature is perceived as comfortable. For example, if a person is shopping with a coat on , a space temperature of 16°C should provide a good level of comfort, whereas 22°C may be more appropriate for a restaurant where a person is without a coat and sitting still.

The intended use of the building must be established in the project brief before a detailed design for the heating system is developed. Designers can then make a trade-off between fabric upgrades, which will reduce heat loss from the space, and the size of the heating system, which will increase heat input into the space. Generally speaking, a well insulated building with lower heat losses will have a higher capital cost and lower operational cost. A building with a poorly performing fabric and higher heat losses will have a lower capital cost and higher operational cost. Designers should also seek to understand the embodied carbon associated with fabric upgrades and compare it to the operational carbon savings in a Life Cycle Analysis. This type of analysis measures the true environmental impact of a project over the entire period of its life.

Another factor to consider is that a low temperature heating system requires larger heat emitters to output the same heat as a high temperature system. Adding larger heat emitters will be more expensive, and in some cases, more space may be needed to accommodate them. This may mean that a low temperature heating system – and, by inference, an ASHP –

is not suitable for a particular project. However, decarbonising heating should be a priority, and there are other things that can be done to achieve a comfortable temperature using an ASHP without installing excessively large heat emitters:

- **Better fabric**. The fabric performance of the building could be improved to a point where the low temperature heating system can economically provide enough heat for the user to be comfortable. As long as infiltration rates or ‘leakiness’ can be reduced enough, most historic buildings can be made suitable for most activities. Infiltration is the uncontrolled air movement that occurs through the gaps and cracks in a building.

- **Alternative use**. Where draughts cannot be reduced (perhaps due to a particular construction method or historical feature), the way the space is used can be reconsidered. This should take into account the space temperature that is achievable within the bounds of what is economical for the user. For example, it may not be possible to economically heat a draughty room to more than 16°C. This temperature is suitable for a storage space or an area where outdoor clothing is worn, but it is not comfortable for an office space.

- **Higher flow temperature**. If a change of use is not feasible, and the fabric and heat emitters cannot be improved, it may be possible to increase the flow temperature of the heating system. This may mean that the comfort temperature can be achieved without installing additional heat emitters. However, using an ASHP at a higher flow temperature will decrease its efficiency, resulting in higher operating costs and higher carbon emissions (than a low temperature ASHP system of equivalent size).

- **Bivalent heating system**. Another way to achieve a comfort temperature is to use a bivalent system, in which a fossil fuel or direct electric boiler supports the ASHP on the coldest days of the year.

Heat loss

If the heat loss from a building is underestimated at the design stage, the heating system will not deliver enough heat, and the indoor space will not reach the desired temperature. To correct this, it may be possible to install more or larger heat emitters and to increase the size of the ASHP . If the ASHP capacity is increased but the heat emitters remain the same, comfortable temperatures may be achieved by increasing the flow temperature of the ASHP. However, this will reduce overall ASHP operating efficiency .

If the heat loss is overestimated, the ASHP may be unnecessarily powerful and large. The high capital costs of ASHPs and electrical supply upgrades mean that this would be an expensive mistake. It would also take up more space than needed. Assuming the overestimated heat loss was also used to size the heat emitters, these large emitters should help improve system efficiency by reducing the ASHP flow temperatures. This may mitigate some of the additional capital cost.

An oversized ASHP will spend more time switching on/off (cycling) in mild weather, because ASHPs take time to reach their peak operating efficiency after start-up. The more time running steadily, the better. A certain amount of cycling is inevitable, because the heat demand varies significantly throughout the year, but it should be minimised. An oversized ASHP will be less efficient than a correctly sized one.

It is critical that the entire heating system is sized correctly. To achieve this, there are four questions to consider:

- How big is the building? It should be easy enough to measure it.
- How well insulated is the building? It might be difficult to establish this using a visual assessment only. For example, some insulation may have been poorly installed in areas that are not visible.
- How much air is moved about by the ventilation system? If mechanical systems are installed, flow rates can be measured relatively easily at room grilles. Flow rates through natural ventilators, such as window trickle vents, are more difficult to measure and are subject to external factors such as wind speed.
- How airtight or leaky is the building? This is the most difficult aspect of a building's performance to assess visually.

As mandated by the Microgeneration Certification Scheme (MCS), the current method of assessing heat loss uses a calculation based on visual inspection and estimates based on the building's age. The data are commonly presented as a heat loss parameter, measured in W/m^2K. Although it is possible to measure the size of a building and assess insulation levels and ventilation flow rates to a certain extent, establishing how airtight a building without testing is guesswork, based on its age and form. This makes it extremely difficult for heating system designers to size ASHPs and space heat emitters accurately.

Understanding the performance of the existing building will help improve the accuracy of the new heating system design.

Measuring heat loss

An advantage existing buildings have over new builds is that they already exist, making it possible to take measurements to assess heat loss rather than relying on calculations. All measurements should be made after fabric improvement works are complete, to ensure the building's performance is recorded accurately. The following measurements and data will help formulate a more precise heat loss calculation:

Airtightness

The largest unknown in the heat loss calculation is the building's airtightness. But airtightness testing is mandatory for new-build properties in England, and there is, therefore, an established industry capable of carrying out testing.

To measure airtightness, a fan can be installed in an external doorway to pressurise or depressurise the building. The air leakage rate is calculated in $m^3/h.m^2$.

For large buildings, the process can be costly and disruptive, and it may be more appropriate to carry out a number of smaller sample tests instead of testing the whole building.

U-values

The U-value of a building element, such as a wall, is a measure of how quickly heat passes through it from the inside to the outside. By knowing the U-value of a wall, its surface area and the temperature difference between the two sides, it is possible to calculate the rate of heat loss through the wall. However, accurately determining the U-value can be difficult, especially for historic buildings where construction information may not be available.

In situ U-value testing can be used to accurately measure the U-value. This involves measuring the temperature on both sides of the wall over at least 72 hours, using a heat flow meter, an internal ambient temperature sensor and an external temperature sensor. The readings are used to calculate the average U-value.

Temperature and energy use

To measure temperature and energy use, internal and external temperatures should be recorded over approximately three weeks, and energy consumption data gathered over the same period. Historic buildings may already record these data for conservation reasons.

Some systems add a known amount of heat into a building to monitor how quickly the temperature decays once the heat is switched off. The decay rate can then be used to calculate the heat loss parameter.

Alternatively, a space can be heated constantly to a specific temperature over several weeks, using convective heaters that accurately monitor energy consumption. The amount of energy required to maintain the internal temperature can then be compared to the outdoor temperatures over the test period to determine the heat loss of the building. This method is known as co-heating, and it has to be carried out in an empty building. Occupants will, therefore, need to be temporarily relocated for the duration of the test.

Previous energy use

A quick low-cost option for estimating a building's heat demand uses historical energy data, corrected using weather data (degree days) for the location. Degree days are a simple way to represent outdoor air temperature data over a given period. (More information is available at degreedays.net) This method can also be used to check an existing calculation or measurement.

The following should be taken into account:

- If gas is used for both heating and hot water, the accuracy of the data will depend on whether the hot water supply is sub-metered and, if not, how precisely the hot water load can be estimated.

- Historical data can only reveal how much energy the building required in its state at that time. If fabric improvements are planned, the recorded data will not accurately represent how much energy the building will need when the fabric improvements are complete.

A simple method for calculating heat loss and determining the required heating capacity based on previous energy use, as well as guidance on how to adjust the calculation based on your geographical area, can be found at protonsforbreakfast.wordpress.com/2022/04/05/what-size-heat-pump-do-i-need-a-rule-of-thumb/

It is important to note that this method is based on a set of assumptions about weather and design conditions. It needs to be adapted to the context of each particular building and should be used alongside the other methods of measuring heat loss described above.

Difficult to heat spaces

Areas with high infiltration rates are particularly challenging to heat, and measures should be taken to reduce the airflow where possible. Otherwise, an ASHP may not be a suitable means of heating these areas, and direct electric radiant panels may be a better option.

Entrance/reception space

Achieving thermal comfort for staff working in entrance spaces is tricky. Infiltration rates are generally high due to visitors entering and leaving the building. This issue occurs in both historic and new buildings, but historic buildings may have more limited options to reduce draughts.

To increase visitor numbers, entrance doors are often left open to provide unhindered access to historic buildings. But doors are essential for separating the indoor and outdoor climate. Research shows that people may be deterred from entering a building if a door is closed. To overcome this, signage boards can be placed outside saying, ‘We are open, please come in’, or ‘We are keeping the door closed to save energy’. Press buttons linked to electrically operated doors can help address access issues.

If the entrance is kept open, it is wasteful to try and heat the air inside, because it will quickly be lost to the outside. In this scenario, it is probably more economical to heat the occupants directly, using heat sources such as infrared heat emitters. However, it is usually better to create a barrier between the heated space and the outside. Common options include automatic doors, revolving doors and draught lobbies. A strategy for directly heating occupants should only be considered if such doors cannot be installed.

Two case study projects highlight different approaches to tackling this issue.

Site 1

Figure 3: Reception interior.

- Doors are fully open during opening hours.
- The heating system comprises an ASHP, delivering heat via radiators. Radiators provide most of their heat by convection, meaning they warm the air in the space.
- Any warm air produced by the radiators is quickly lost to the outside, and so provides little comfort to the occupants.
- Staff use portable electric heaters to supplement the heating system.
- It is likely that a comfortable temperature for staff will only be achieved using this heating system if action is taken to reduce the high infiltration rate, for example by installing an automatic sliding door.

Site 4b

Figure 4: Reception interior.

- Entrance and exit doors to the reception area are automatic sliding doors. They provide easy access and keep out the cold when closed.

- An ASHP delivering heat via radiators was proposed for this space. However, the system was never installed. Concerns were raised that it would not provide enough warmth because of the high infiltration rate associated with a busy reception area.

- A radiant heat source in the form of a wood-burning stove provides thermal comfort to staff behind the reception desk. Such stoves emit most of their heat as infrared radiation, which allows the heat to be transferred directly from the stove to the person. Radiant heat sources are less susceptible to high infiltration rates because they are not attempting to heat the air directly.

- For optimum efficiency, a wood-burning stove should operate between 260 and 460°C. They are, therefore, unlikely to be suitable for public areas because they are too hot to touch. Staff need to be aware of how to use a wood-burning stove safely. At this site, the stove is positioned in a staff-only area behind the reception desk and further protected by a small fireguard.

An electric radiant alternative will have a surface temperature between 75 and 100°C. It is not as hot as a wood-burning stove, but care should still be taken when children and vulnerable adults are present. It is common for electric radiant panels to be positioned out of reach at high level.

External toilets

Doors to public toilets are often left open, so users can see that the facilities are available. This raises the same difficulties with heating.

Two of the case study properties include public toilets. However, the different approaches taken to heating mean there are significant variations in overall energy demand.

Site 1

- Convective heat sources in the form of radiators are located in each toilet. Warm air is quickly lost to the outside, so the radiators provide little thermal comfort and use a lot of energy.

- The thermostatic radiator valves are all set to a comfortable temperature (16 to 21°C).

Site 4b

- No attempt has been made to heat the space for user comfort, and so energy use is minimal.

- The expectation is that the users will be wearing appropriate outdoor clothing.

- Direct electric heating elements are installed to prevent the pipes from freezing and causing damage in cold weather.

Running costs

With recent fluctuations in energy prices, the running costs of heating systems has become a big concern for everyone. It has also become a talking point in the debate about ASHPs.

Heating costs vary from building to building. They depend on thermal insulation levels, heating system efficiency, building size, building use, and the energy tariff the building is on. It is, therefore, difficult to compare heating costs, even when data for multiple buildings are known. Relevant comparison metrics are kWh/m^2 or £/m^2 for a set period. This can be calculated utilising the energy usage in kWh or cost in £ from gas or electric bills, and the known floor area of the building as follows:

$$\frac{\text{Energy usage in kWh (or cost in £)}}{\text{Building floor area in m}^2}$$

The calculation can be used to compare either energy usage or heating costs between buildings, regardless of size.

Table 2 shows the expected heat load for different types of buildings (BSRIA, *Rules of Thumb*, 5th Edition). This has been converted to kWh/m^2 for an annual heat load by assuming the heating is on 16 hours a day for half the year. The assumed prices are 10.3p/kWh for gas and 33.2p/kWh for electricity. These prices were based on the energy price cap at the time of writing and current energy costs must be used in any calculations. The ASHP annual costs are compared for two different coefficients of performance (COP). The COP is the efficiency of the ASHP and it is determined by the ratio between the electricity consumed and the heat transferred to the condenser. A higher COP indicates a more efficiently operating ASHP.

Table 2: Rule of thumb heat loads for different types of buildings, with conversions to heating costs.

	Rule of thumb		Annual heating cost (£/m2)			
Building type	Expected heat load (W/m^2)	Expected annual heat load (kWh/m^2)	Gas (£)	Direct electric (£)	ASHP (£) (COP of 2)	ASHP (£) (COP of 4)
Residential buildings	60	176	18	58	29	15
Offices	70	205	21	68	34	17
Industrial buildings	80	234	24	78	39	19
Educational buildings	87	255	26	85	42	21
Retail buildings	100	293	30	97	49	24

Determining the running costs of the ASHP for the different sites was difficult because certain information was not available:

- A lack of sub-metering meant that the amount of electricity used by the ASHP could not be differentiated from that used for other purposes.
- There had been no previous heating system on site with which to compare the ASHP.
- For newer systems , energy bills had not yet been received for a full heating season.

This lack of information also limited the comparison of running costs between sites, and also from before and after the ASHP was installed.

At Site 3, the gas consumption for heating was known for the years before the ASHP was installed and the electrical consumption of the ASHP was also known for a short period of time. The electrical consumption of the ASHP is 66 per cent of the gas consumption in kWh. The cost difference of this will vary because the prices of gas and electricity vary. The ASHPs at Site 3 were still undergoing seasonal commissioning during the site visit, so it is expected that their efficiency will improve after this has been completed.

It is also worth noting that three of the sites receive renewable heat incentive (RHI) payments, which impact the affordability of the ASHP heating system. The RHI scheme is now closed to new applications, and so future projects will not be able to benefit from this funding.

In order to optimise a heating system once it has been installed, it must be monitored using appropriate metering. Sub-metering the electrical supply to the ASHP, and installing a heat meter, can allow for accurate running costs and efficiencies to be calculated.

Backup heat sources

Both electric and fossil fuel heating systems use electricity to power them and will not operate during a power cut. In a town or city, it is unlikely that power cuts will cause any significant issues, because on average they occur for around half an hour per year (annualreview2019.ukpowernetworks.co.uk/annualreview2019/operational-performance/network-reliability). With the average UK home losing heat at a rate of 3°C per hour, an interruption due to a power cut is unlikely to cause a health risk. However, restoring power for rural properties can take days, especially after extreme weather events.

A wood-burning stove does not require electricity to operate. As such, it can provide a simple backup source of heating, cooking and lighting in case of a prolonged power cut.

A battery backup may offer a more comprehensive solution. Not all home batteries will provide backup electricity during a power cut. However, many now do so either for whole-house backup or to provide power to a dedicated circuit. Combining battery technology with an ASHP will allow one unit of stored electrical energy to be converted into three or four units of heat to keep a building warm during a power cut.

Refrigerants

The type of refrigerant that an ASHP uses can greatly affect the emissions it produces over its lifetime, and there are several different types available on the market today.

Refrigerants can cause atmospheric ozone depletion, measured in ozone depletion potential. European ASHP manufacturers now only use refrigerants with an ozone depletion potential of 0, meaning they cause no harm to the ozone layer. If a refrigerant were released into the atmosphere, its global warming potential (GWP) allows you to calculate the equivalent effect on global warming compared to CO_2. For example, R-410A is a commonly used refrigerant with a GWP of 2,088. If 1kg of R-410A were released into the atmosphere, it would be the equivalent of releasing 2,088kg of CO_2. Table 3 sets out the environmental and technical considerations of some common refrigerants.

Table 3: Common refrigerant properties.

Refrigerant	R-410A	R-32	R-290 (Propane)	R-744 (CO_2)
Global warming potential	2088	675	3	1
Ozone depletion potential	0	0	0	0
Fluorinated gas regulations	Phasing out in small systems from 2025	Phasing down planned, timeline tbc	n/a	n/a
Flammability to ISO 817	A1 (Non-flammable)	A2L (Lower flammability)	A3 (Higher flammability)	A1 (Non-flammable)

The BEIS report 'Energy Follow Up Survey: Household Energy Consumption and Affordability' (2021) gives a median annual gas consumption for a UK home of 12,400kWh. The Government Standard Assessment Procedure for energy performance certificates gives carbon intensity factors for gas and electricity of 0.21 and 0.136 $kgCO_2e$ /kWh, respectively. (CO_2e means 'carbon dioxide equivalent' and allows for the environmental effects of various greenhouse gases emitted by a process to be represented by a single value.)

Carbon intensity factors indicate the amount of carbon dioxide emissions that are emitted for every kWh of energy. Using these figures, the potential carbon savings associated with replacing a natural gas boiler with an ASHP operating at a COP of 3 can be estimated: it would reduce the CO_2 emissions associated with the heating system for a median UK home by around 2,000kg per year. However, if there were to be a total refrigerant leak from a typical domestic ASHP that uses R-410A, that would be equivalent to releasing 3,300kg of CO_2 into the atmosphere. This would cancel out 1.6 years of the carbon savings associated with the running of that system.

Although ASHP systems have measures to prevent refrigerant leaks, the risk can never be eliminated. Where a blend of refrigerants is used, even a small leak can necessitate a full system recharge. This is because it is difficult to determine the remaining quantities of each refrigerant in the mix.

Selecting an ASHP with a low GWP refrigerant is essential for minimising the system's emissions. Figure 5 shows the full leakage emissions and system output for each of the ASHPs in this report, based on the GWP of the system refrigerant. It does not account for the embodied carbon that is emitted during the manufacturing of the refrigerant.

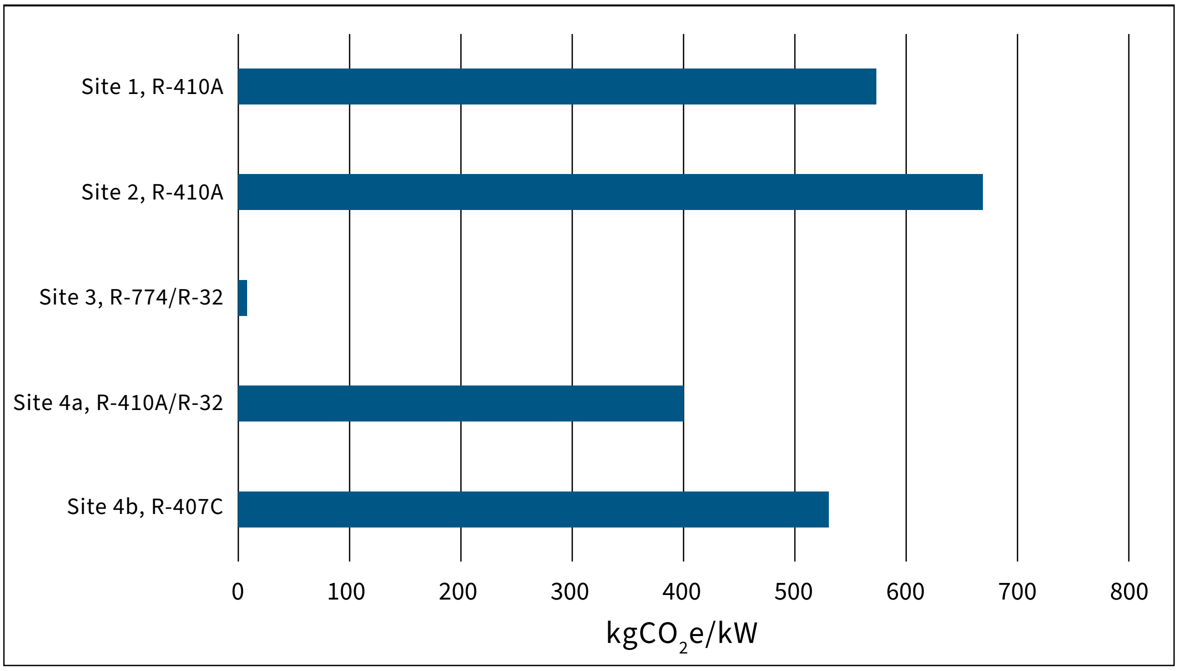

Figure 5: Total refrigerant leakage emissions per kW of installed system output.

Site 3 stands out because the full leakage emissions are extremely low, despite the system output being around 70 times greater than a typical domestic heating system. This is because the ASHP uses R-744, which is a CO$_2$ refrigerant with a low GWP of 1.

System designers should select a low GWP refrigerant ASHP to minimise the equivalent emissions in the event of a leak. Furthermore, a key goal of Fluorinated gas (F-gas) regulations is to phase down using refrigerants that have significant GWP when released into the atmosphere, such as R-410A. These high GWP refrigerants will, therefore, have a more constrained supply, meaning the price is likely to rise significantly. This is important because it means that the costs of repairing R-410A ASHPs will likely increase. R-32 has a much lower GWP than R-410A, and so is less likely to be limited in the short term. However, R-32 is likely to be a target of future F-gas phasedowns. Selecting a low GWP refrigerant will help reduce the maintenance cost of the heating system by avoiding F-gas driven refrigerant price increases. Further information on F-gas regulations can be found at www.gov.uk/guidance/fluorinated-gases-f-gases.

Natural refrigerants such as R-744 and R-290 have a much lower GWP and are now becoming commonly available. They are also outside the scope of F-gas regulations . However, their use introduces other design challenges and requires additional safety measures. R-290 has higher flammability, and R-744 requires high operating pressures. As a result, these refrigerants cannot currently be used with direct expansion (air-to-air) systems (ASHP systems that use piped refrigerant between the outdoor and indoor units).

The choice of refrigerant has a significant effect on the temperatures at which the ASHP can efficiently operate. CO_2 ASHPs can produce high temperature water (~70°C) far more efficiently than ASHPs that use conventional refrigerants. Additionally, they require a low return temperature (~30°C) for operation, meaning a high temperature difference (~40°C between the flow and return) and a low system flowrate. This is particularly advantageous in a building that already has a wet heating system designed for a gas or oil boiler, because the existing pipework will likely have been sized for a lower temperature difference of 11°C which would have a higher system flowrate. Since the CO_2 ASHP operates with a temperature difference of 40°C, the required flowrate is lower, meaning the existing pipes are oversized and the required pumping energy is reduced. Existing pipework may be able to be used with a CO_2 ASHP, which may not be the case for other low temperature ASHPs. This can deliver significant cost savings, but CO_2 ASHPs are typically bespoke, therefore capital costs will be higher. And the low return temperatures that CO_2 ASHPs require are not straightforward to achieve (see 4.3 Site 3).

Controls

Across the four sites, users had different levels of understanding of the controls for the heating system, which correlated with the system’s overall success.

At Site 1, the building user would have benefited from further instruction on how to operate the system. At the time of the visit, the system was providing domestic hot water (DHW) only and no space heating. The user could not decipher the control panel to turn on the space heating and had struggled to get an appropriately skilled engineer to assist them. They were understandably frustrated with the situation.

Conversely, at Sites 4a and 4b, the users were enthusiastic about their ASHP systems and were eager to use the ASHPs correctly and get the most out of them . Particularly at Site 4b, the tenant showed a detailed understanding of the system controls and was able to improve efficiency by minimising flow temperatures (with weather compensation) and reducing cycling. The touchscreen controller at Site 4b (Figure 6) was far more intuitive than the older Daikin controller at Site 1 (Figure 7).

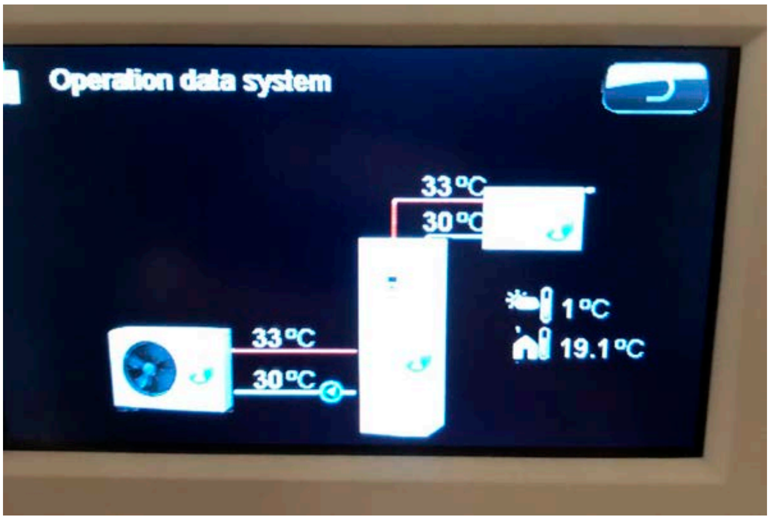

Figure 6 (left): Site 4b controller. Figure 7 (right): Site 1 controller.

Larger systems, such as that at Site 3, are inherently more complex to control (Figure 8). They require close communication with the manufacturer so that the system can be both commissioned and operated correctly.

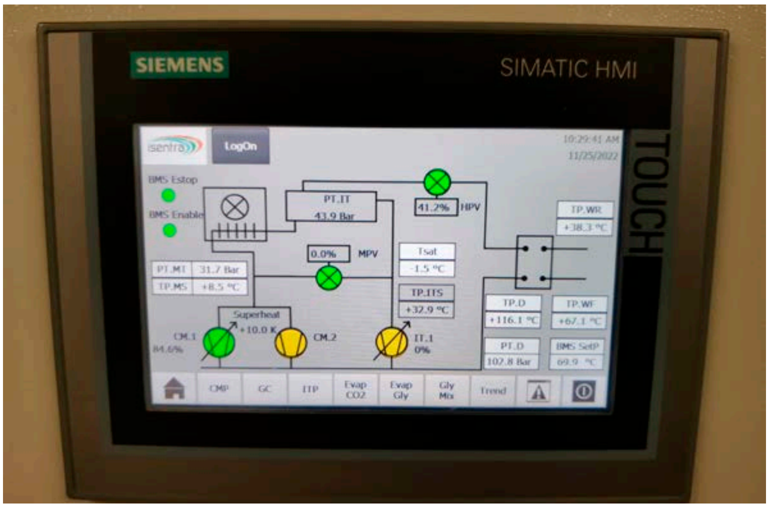

Figure 8: Site 3 controller.

Clients should request that installers provide an in-person demonstration of the system's controls, including basic functions such as adjusting weather compensation and domestic hot water storage temperatures. Instructions should also be available in simple written form to ensure that knowledge of how to operate the system is not lost when the end user changes. Leaving the user with a pile of manuals is not sufficient. When the end user understands how the ASHP works and how to adjust basic settings, it creates a greater sense of ownership over the whole system. As a result, they are more likely to get optimal performance.

4. Case Studies

The following section discusses each site in detail. The ASHP installations were graded for technology choice, thermal comfort and system design/installation quality.

System details 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 type of building and its use.

Thermal comfort

☆☆	Poor	Users expressed dissatisfaction with their thermal comfort.
★☆	Good	Users reported satisfaction with their thermal comfort most of the time.
★★	Excellent	Users reported satisfaction with their thermal comfort at all times.

System design/installation quality

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

4.1 Site 1

Building history and overview

The workshops at Site 1 were built in the 19th century as agricultural buildings and were used as open cart sheds. They are Grade II listed buildings and have been renovated to be used for a visitor centre, workshops and office space. This work was completed in 2018.

Heating system

The workshops use two air-to-water ASHPs, consisting of separate pairs of outdoor and indoor units. The two ASHPs are isolated systems that serve different parts of the building. The installation also includes a 260-litre hot water cylinder. The ASHPs were installed as part of the renovation work to turn the agricultural buildings into a visitor centre and office space. As well as the ASHPs, additional insulation and a new radiator system were installed in the visitor centre.

The two ASHPs are used to heat the building and to provide domestic hot water to sinks in the bathroom and the office next to the plant room. Additional sinks elsewhere in the building have hot water provided by point of use heaters. The ASHPs and hot water cylinder are manufactured by Daikin.

Figure 9: Site 1.

Summary

Property type		Commercial (visitor centre and workshops)
Heat pump technology		Split ASHPs (air-to-water)
Installed heat pump capacity		16kW and 11kW
Heat pump capacity/m^2		54W/m^2
Heating system		Wet radiator system
Hot water system		Domestic hot water storage cylinder (260 litre), plus electric point of use heaters
Use pattern		Visitor centre opens daily from 10:30am to 4pm between March and October, and from Friday to Monday 10:30am to 4pm from November to February. The tenants in the workshops have different opening times, with at least one tenant open every day of the week all year round.
Technology choice	☆☆	The convection-based radiators do not match the use of the building because the doors of the visitor centre and toilet are left open. This means the heated air leaves the building through the open doors.
Thermal comfort	☆☆	No previous heating system in the building to compare thermal comfort. Staff at both the visitor centre and workshops wear coats and use additional electric heaters. During the visit, an issue with one ASHP meant that no heating was being provided .
System design/ installation quality	☆☆	With two ASHPs, the capacity for the entire building is 54W/m^2. However, with one ASHP out of use, the capacity is reduced to 32W/m^2. The typical heat output for an old building that has had some fabric improvements is around 120W/m^2. The pipes within the plant room have no insulation, and a lack of mechanical protection has led to one ASHP being decommissioned due to damage.

ASHP unit observations

- 11kW and 16kW split Daikin ASHPs were installed, with the manufacturer's internal 'hydroboxes'. A hydrobox is a pre-assembled unit containing the majority of the heating system plant, including a compressor, plate heat exchanger, expansions vessel and pump.

- One of the ASHPs was decommissioned due to internal damage caused by vermin.

- External units were installed at the rear of the property, within gardens open to the public. They were behind a hedge in a secluded part of the garden to reduce their visual and noise impact.

- The secluded location probably increased the likelihood of vermin damaging the units. It also made maintenance harder, with leaves building up and clogging the ASHPs. The overgrown hedge reduced the amount of space available to access the ASHPs for maintenance.

- There were no comments from visitors or garden staff about the noise or visual impact of the external units.

- External pipework was insulated but had limited mechanical protection. Vermin had damaged the insulation, increasing thermal losses.

- Pipework in the plant room was uninsulated, increasing thermal losses.

- The ASHPs used R-410A refrigerant with a GWP of 2,088. The operational part of the system had a refrigerant charge (the total amount of refrigerant contained within the system) of 4.4kg. A leak of all the refrigerant in the system would be the equivalent of 9,187kg of CO_2 being released into the atmosphere.

Heating system observations

- Heating was provided by large double-panel radiators throughout.

- During the visit, the operational ASHP was providing heat for domestic hot water but not heating. The reason for this was not known.

- There was no buffer vessel in the system.

- The ASHPs only provided hot water to four sinks (three in bathrooms and one in an office). The 260-litre hot water cylinder was oversized for this purpose. Another 10 sinks in the building used direct electric heaters.

- Staff were unsure how to use the heating system controls.

- There was a larger than usual number of radiators for the area they heat. However, there was also limited fabric insulation , and external doors in several areas were kept open when the building was in use.

- There was previously no heating system installed in the buildings, so no analysis of costs or performance with a former system could be made.

User interview

- Workshop tenants and staff were cold, but they used electric heaters and wore coats to remain comfortable.

- Owners were not happy with the aftercare from the installer and no longer contacted them. It had been a challenge to secure a maintenance contract with the current contractor, who performed annual checks, and to find alternative contractors who were trained in maintaining ASHPs.

- The owners were having issues with funding through the RHI scheme. An assessor was saying there was a missing immersion heater from the schematics submitted with the original application and was asking for revised schematics. Looking at the original schematics, the ‘missing’ immersion heater was never planned or installed. Without support from the installer, the client was finding it difficult to resolve the issue.

- A ground source heat pump served the main house. The site managers were very happy with it.

Discussion

Building fabric and use of building

When installing the ASHPs, some upgrades were made to the building fabric. These focused on the roof and walls.

One wall of the visitor centre and each workshop space was dominated by a large door, half of which was a single-glazed window. There was a considerable gap between the door and the floor, with clear light visible underneath the door. The doors to the toilets and visitor centre were propped open when the site was open to the public. All the heated spaces had strong draughts – especially the toilets and visitor centre – thus undermining any benefits provided by the fabric improvements. Most of the heat emitted by the radiators escaped through open doors.

In the toilets, the radiators could be replaced with direct electric radiant panels, which heat the person rather than the air. A draught lobby could be installed in the reception area to stop heat escaping from the building. This may conflict with conservation principles, so another option would be to use radiant heat panels placed close to where the reception staff work. These solutions could also be applied to other occupied areas within the building.

The ASHP contractors designed the system to somewhat account for the large heat losses through open doors by specifying large radiators. There were four double-panel, finned radiators in the reception: two 260cm and two 180cm long. At a 30°C temperature difference between the radiators (assumed 45°C) and the air (assumed 15°C), the total radiator output of the visitor centre was calculated to be approximately 5.9kW. This equated to a heating capacity of approximately 148W/m^2. With the doors closed, this is a typical heating capacity for a property of this type.

The site manager revealed that staff and tenants often wore coats and used portable electric heaters, even when heating was provided by the ASHP. The inadequate heating was not a fault of ASHP technology specifically, and a gas boiler would face the same difficulty. This raises the question as to whether radiant heat panels would be more suitable at this site, or whether it is appropriate to heat this space at all, given its current very draughty condition.

Maintenance

To reduce the visual impact of external ASHP units, it is common to install them away from well-used areas and behind obstacles. This can affect their efficiency, either due to limited airflow or extended external pipe runs. It can also cause issues with maintenance if the ASHP is placed too close to an obstruction and there is not enough room to safely work on it. During the site visit, it was clear that it was difficult to access the ASHPs. There was no clear pathway to reach them, and there was a lack of space around them to carry out maintenance (Figure 10).

Figure 10: ASHP at the rear of Site 1 workshops.

When ASHPs are out of view, the area around them is often overlooked during general building maintenance checks. This can lead to a build-up of leaves and rubbish, as well as plants growing over the units. As a result, air inlets can become clogged and block the airflow.

Limited foot traffic by the external units can lead to an issue with vermin. If the enclosure does not have adequate protection, vermin may be able to damage the internal structure of the unit. Mechanical protection can be installed on external pipework insulation to prevent such damage.

All these maintenance issues were observed during the site visit.

ASHPs are no longer a new technology, but there was a skill shortage in terms of installation and maintenance in the local area around this site. Originally, the ASHP installer provided maintenance services. When the site owner decided to change the maintenance contractor, they were able to secure annual service checks with a new contractor but could not obtain a contract for call-outs and maintenance. This lack of call-out support led to extended periods in which the ASHPs were unable to provide space heating.

Heating controls

The facilities manager and site staff had limited knowledge of how to use the heating controls. The older generation Daikin controller was not intuitive and required close reference to a manual. This reduced the efficiency of the heating system because key parameters, such as temperature difference, target temperatures and run times, were not optimised. Installers should provide comprehensive instructions on how to control the heating and domestic hot water system as an essential part of the handover process.

Figure 11: ASHP controller.

4.2 Site 2

Building history and overview

The barn at Site 2 is a scheduled monument built in the 15th century. It was expanded and altered from the 17th to 19th centuries. Only a section of the central internal wall separating the visitor centre and restaurant is from the original building, and the rest is later additions. Renovation on the barn started in 2020 and was completed in 2022. It is now a visitor centre and retail space on the ground floor, with a restaurant on the first floor.

The adjacent court is open to the public as a dressed monument. The visitor centre and restaurant are open daily from April to October. From November to March, they are both closed on Mondays and Wednesdays.

Heating system

At Site 2, there are two Vaillant aroTHERM air-to-water monobloc ASHPs. The external units are in a separate enclosure away from the barn, and power cables and pipes between the ASHPs and the barn run underground. The ASHP enclosure features an acoustic louvred screen to reduce noise pollution. A ground-bearing concrete slab has been installed with a slight outfall towards the front of the enclosure to allow water to drain.

The ASHPs are connected to an underfloor heating system, with additional trench and electric heat emitters. These were all installed as part of the 2022 renovation. The system contains a 200-litre buffer vessel. Hot water is provided by an 80-litre direct electric hot water cylinder.

At the time of the visit, the site was still in the seasonal commissioning process and had not undergone a full heating season.

Figure 12: Site 2.

Summary

Property type		Commercial/hospitality (visitor centre and restaurant)
Heat pump technology		Monobloc ASHP (air-to-water)
Installed heat pump capacity		2 × 11kW
Heat pump capacity/m^2		154W/m^2 (206W/m^2 including the electric panel heaters)
Heating system		Wet underfloor heating system, with wet trench heaters. Additional electric panel heaters
Hot water system		Direct electric tank (80 litre)
Use pattern		Visitor centre opens daily from 10am to 4pm between April and October. Open Wednesday to Sunday from 10am to 4pm from November to March. Restaurant additionally open 6pm to 9pm
Technology choice	★★	The set opening hours of the visitor centre and restaurant mean that the heating is programmed to allow plenty of time for the building to warm up before it opens to the public. Underfloor heating has been installed, which allows the ASHPs to operate at low and efficient temperatures. The long heat-up times and low heat output of the underfloor heating benefits the historic building because they reduce the risk of condensation. Radiant heat provided by underfloor heating is less likely to be lost to draughts, compared with convective heat.
Thermal comfort	★☆	No previous heating system in the building to compare thermal comfort. The visitor centre staff reported a high level of thermal comfort and had no complaints. The site visit took place in November, and some staff were comfortable in just polo shirts. The restaurant staff reported a low level of thermal comfort. They had received comments from customers about being cold despite the additional electric panel heaters to supplement the underfloor heating. After the site visit, the end user reported that all areas of the building were too cold at various points through the winter months.
System design/ installation quality	★☆	The system is installed to a high quality, with all external and plant room pipework insulated. Pipework between the ASHPs and plant room and from the plant room to the visitor centre runs underground. The system is controlled by a thermostat in the plant room, giving suboptimal control of the system.

ASHP unit observations

- Two 11kW ASHP were installed to give a total capacity of 22kW.
- Installed heat capacity was 154W/m^2.
- The ASHPs were located at the rear of the property, in a purpose-built enclosure next to a picnic area.
- The enclosure was designed to reduce the noise impact of the ASHPs for people using the picnic area.
- The noise of the ventilation system for the restaurant’s kitchen was more noticeable than the noise of the ASHPs. The ASHPs were running at maximum capacity at the time of the visit.
- Two sides of the enclosure were made from the same stone as the joining rear wall, with an acoustic louvre to the front. The enclosure neatly hid the external units from view.
- The external units were raised above the ground on mounts. They were on gravel at the rear of the unit and sloped concrete at the front. These features helped with drainage of condensate and reduced the likelihood of flooding.
- The architect’s drawings for the enclosure showed that the ASHPs did not have the required clearance stated by the manufacturer at the rear of the unit. However, on site, the ASHPs had enough clearance at the rear but less than the recommended clearance at the front. The minimum clearance requirement is based on a solid obstruction, but the obstruction at the front of these ASHPs was a permeable acoustic louvre, which could be fully opened for maintenance.
- External pipework was well insulated, but some valves were uninsulated. Pipework between the ASHP enclosure and plant room was run underground.
- Pipework within the plant room was well insulated. Pipework between the plant room and reception/shop area was run underground outside.
- The ASHPs used R-410A refrigerant (GWP of 2,088). The system had a total refrigerant charge of 7.06kg. A leak of all the refrigerant in the system would be the equivalent of 14,741kg of CO_2 being released into the atmosphere.

Heating system observations

- As part of the renovation, underfloor heating was installed in the visitor centre and restaurant. No underfloor heating was installed in the lobby/toilet area for the restaurant.

- Original stones had been lifted and placed back on top of the underfloor heating pipes to preserve as much of the original barn as possible.

- Trench heaters were installed in the visitor centre by the doors.

- The floor finish in the areas heated by underfloor heating varied. In the visitor centre and lobby the floor was stone slabs, and the restaurant floor was timber.

- The system was controlled by a remote thermostat in the plant room. This room was a warm space and was not thermally representative of the rest of the building. To keep the heating system on regardless of the temperature in the plant room, the thermostat was set to the maximum target temperature of 30°C. It was not clear if this was enough to keep the system running, as the small plant room might reach 30°C and disable the heating.

- Hot water for the restaurant was provided by an 80-litre direct electric heater, and there had been no instances of the kitchen running out of hot water. For a restaurant of 34 people, CIBSE guide G recommends 187 litres of storage. By providing a smaller storage volume, the standing losses from the cylinder were decreased (the heat loss from the heated cylinder to the plant room) and the water turnover period for the tank was reduced (the amount of time it takes for the hot water in the cylinder to be used and replenished), which helped to maintain water quality.

- There was a 200-litre four-pipe buffer vessel installed.

- There were electric convective radiators in the main restaurant area and restaurant lobby. These were added to the design when the client changed the space use from a casual cafe to a high-end restaurant during the construction period.

- Two 1.5kW electric panel heaters were installed in the lobby. Three 1.5kW panel heaters were installed in the restaurant. This took the heating capacity in the lobby to 3kW and to 13kW in the restaurant (8.5kW underfloor heating and 4.5kW electric panel heaters). The installed heating capacity was 176W/m^2.

- During the visit, four additional portable electric heaters were in use. This was because the ASHPs had been offline for a couple of weeks before the visit.

- There was previously no heating system installed in the buildings, so no analysis of costs or performance with a former system could be made.

User interview

- The building owner was very happy with the heating system.

- Staff in the visitor centre were happy and had no complaints about the ASHPs.

- Staff in the restaurant commented that the restaurant was frequently cold and that this was often reported by their customers.

- Online restaurant reviews showed that some customers recommended wearing a coat while visiting. However, the temperatures did not seem to have impacted the review ratings, and the restaurant consistently scored a high level of customer satisfaction.

- In the restaurant, consistent cold draughts were felt from the eaves. Periodically, strong cold draughts were experienced from the unheated ground-floor area, especially when a door was opened.

- These draughts limited the levels of thermal comfort that could be achieved.

- No noise complaints from neighbours were reported. This had been a major consideration when installing the ASHPs, and an enclosure was built to reduce noise. The nearest neighbours were approximately 30m from the external units.

- Defrost cycles had no noticeable effect on internal comfort.

- After the site survey, the end user reported that the ASHP, pipework and ground of the enclosure had been subject to ‘icing up’ during the winter months.

Discussion

Acoustic enclosure

A common concern when considering ASHPs is the noise they generate. To mitigate this, an acoustic enclosure can be installed around the external units. Such enclosures also reduce the visual impact of ASHPs, especially if they use the same material as adjacent structures.

Acoustic enclosures can be costly. A fully enclosed prefabricated enclosure for the smaller external units of a split system can cost around £1,300. Costs for a bespoke design for a larger ASHP system start at about £3,000. If the enclosure is custom designed to blend into the environment, costs will likely be higher.

Vaillant state that the sound power level (a measure of the acoustic energy) of the ASHP when tested to international standards is 65dB(A). With no barrier, this relates to a sound pressure level of 47dB(A) at a distance of 5m from the ASHP. The combined sound pressure level of both ASHPs is 50dB(A). For reference, a normal conversation being held at a distance

Figure 13: ASHP enclosure at Site 2.

of 1m has a sound pressure level of 60dB(A) (https://svantek.com/academy/sound-pressure-level-spl/), twice as loud as the combined sound pressure level of both ASHPs at a distance of 5m. Even without an acoustic enclosure, the noise from the ASHPs should have minimal impact on people using the adjacent picnic area.

It was unclear whether the noise from the ASHPs at Site 2 warranted an expensive acoustic enclosure. However, the site is located within the Bannau Brycheiniog National Park. Although no clear guidelines on noise levels are given, part of the National Park Management Plan includes an objective to minimise light and noise pollution.

The planning permission did not specifically state that an acoustic enclosure was needed for the ASHPs, but the original planning application included one, and no objections or comments were made. The site is in a rural village, where the background noise level is generally very low. An acoustic enclosure was installed at Site 2 to ensure neighbours were not disturbed by noise.

Acoustic enclosures have the potential to negatively impact ASHP performance. If an acoustic enclosure blocks or reduces the flow from the ASHP exhaust, this flow is likely to be diverted around the ASHP back to the inlet. This reduces the temperature of the intake air, thereby causing the ASHP to expend more energy extracting heat from the air.

During the site visit, temperature loggers were placed by the air intake and exhaust areas of the external ASHP units . An additional sensor was placed further away from the unit to record the ambient temperature. The results from these loggers are shown in Figure 14.

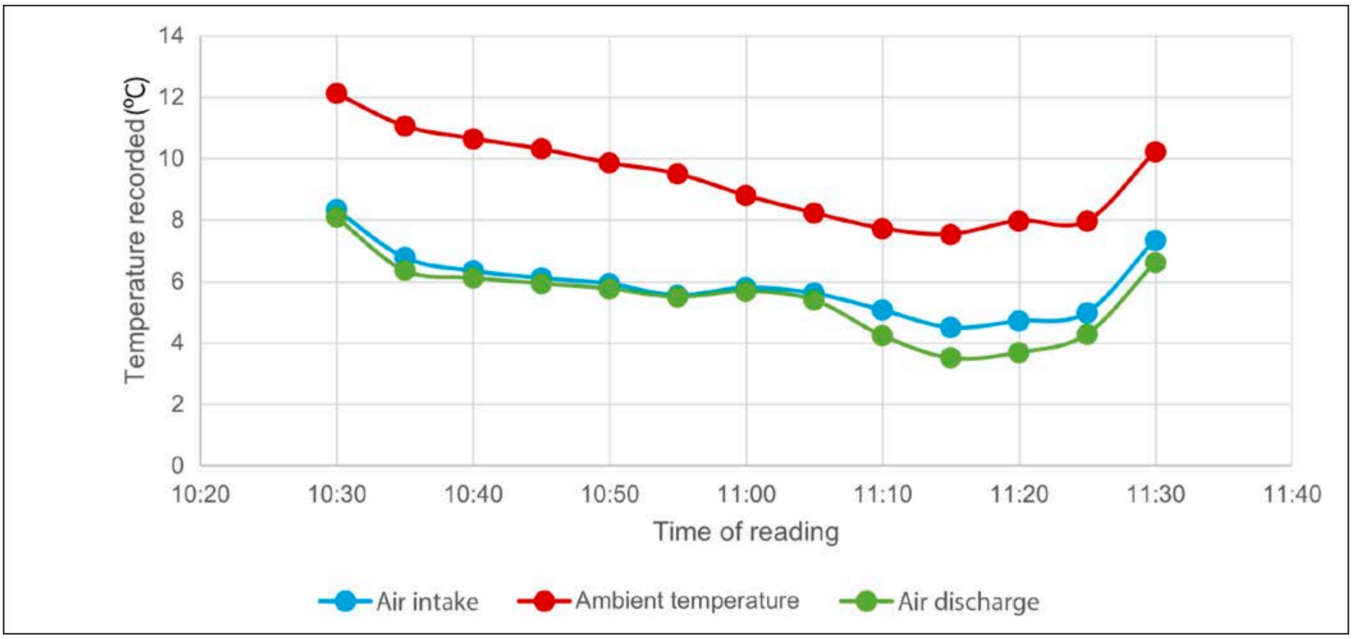

Figure 14: Recorded temperature readings taken at the intake and outlet of the ASHP and the ambient air temperature.

The data show that the temperature of the discharge air from the ASHP was lower than the ambient air temperature, as expected. The data also show that the air temperature by the intake was on average more than 3°C lower than the ambient air temperature. The decrease in air intake temperature compared to ambient air temperature was assumed to be caused by the recirculation of air from the discharge, which, in turn, was likely caused by the enclosure. This temperature decrease reduced the efficiency of the ASHP and, therefore, increased running costs.

Such a reduction in efficiency varies between ASHP models and capacities. Using a formula for calculating the COP of an ASHP, the difference between the intake air temperature and the ambient air temperature was causing a reduction in the COP of the ASHPs at Site 2 of approximately 0.3. At the measured air intake temperature, the estimated COP was 3.66, and at the ambient air temperature the estimated COP was 3.98. This shows that the enclosure may have caused an 8 per cent reduction in COP, which led to an 8 per cent increase in running costs and CO_2 emissions. It is important to note that this figure is approximate, as it only considered the temperature difference recorded using simple temperature loggers over a one-hour period. The air intake and air discharge temperatures would vary over time as the ambient temperature varies.

The distance between the external ASHP units and the closest building not associated with the site was approximately 30m, as shown in Figure 15. With no barrier, the calculated sound pressure level from the ASHPs at the closest noise-sensitive location was 34dB(A). With the acoustic enclosure in place, the sound pressure level was expected to be negligible.

There was a picnic site within 5m of the ASHPs. During colder periods, the ASHPs will have a higher output and generate more noise, but it is less likely that the picnic area will be in use. In spring and autumn, when heating is still required but the weather is mild enough for the picnic area to be in use, the acoustic enclosure is expected to benefit those using the picnic area.

Figure 15: A satellite view showing the distance between the ASHP enclosure and the nearest neighbour. Google Maps, Map data © 2025. Markup added by Historic England.

An acoustic enclosure reduces the noise and visual impacts of an ASHP, but a cost-benefit analysis needs to be done before installing one. This should consider both the upfront cost of the enclosure and the enclosure's effect on the performance of the ASHP, as discussed above.

At Site 2, an 8 per cent decrease in COP was deemed relatively minor. However, some prefabricated enclosures include a roof, which may further restrict airflow and impact the performance of the ASHP. Any physical restriction to airflow will increase the static pressure that a fan must overcome to provide the required flow rates. ASHP manufacturers should be engaged in the design of acoustic enclosures to ensure they do not impede the operation of ASHP units.

Building fabric and insulation

As the barn at Site 2 is of medieval origin, thermal comfort was likely not a consideration of the original design. During the recent renovation, alterations were made to the original building fabric. These were balanced with conserving the original building, so were not as extensive as they could have been.

The fabric improvements included new doors and windows in the occupied area of the building, as well as new walls and new floors to meet the new layouts. Traditional methods were used to seal the roof and walls. These improvements seem to have been effective in the visitor centre. Staff reported being very happy, and during the site visit in late November, they were comfortable wearing polo shirts .

The experience in the restaurant on the first floor was different. The staff said they received comments and complaints from customers about the cold, even though they used additional portable electric heaters to support the existing underfloor heating and electric panel heaters. During the site visit, a strong draught was felt in the restaurant, due to a full height historical barn area that is open to the restaurant to allow interpretation of the exposed historic wall. A draught was also experienced throughout the visit. The latter was likely caused by the lack of modern insulation in the roof, multiple gaps in the building fabric around the roof and doors, and high airflow speeds between open doors. Using a convection-based heating system with electric panel radiators also meant that heat rose past the occupied area of the restaurant and into the high ceiling/roof.

As the building is Grade II listed and a scheduled monument, any building alterations have to obtain listed building and scheduled monument consent. This can limit the amount of fabric improvements that can be made, particularly if the building structure or material have been deemed historically significant.

Heating system

Site 2 uses underfloor heating in the visitor centre and restaurant as the primary heating method. Warm air can quickly be lost in draughty spaces, so a heat source that transfers heat using radiation is a good choice because it is less affected by air movement. Underfloor heating emits 60 per cent of its heat by radiation according to the BSRIA underfloor heating guide, with the other 40 per cent emitted through convection.

In addition to heating the occupants directly, underfloor heating heats an area more evenly than standard radiators. Heating a building in this way reduces the risk of condensation, which can damage historically significant building fabric and cause mould. Underfloor heating is an ideal heat emitter for historic buildings if it can be installed without damaging historically significant floors, and if the building is used regularly. If the building is used intermittently, then the time required to heat the building fabric should be considered. The system may take a long time to achieve comfort temperatures before periods of occupation, which can be costly. A radiant heating system should be cheaper to run than a convective heating system in draughty spaces. The amount of radiative heat energy produced by underfloor heating means that it can achieve thermal comfort at a slightly lower air temperature. However, the system will still be controlled by an air temperature sensor and most underfloor heating systems can still achieve a good air temperature.

The low temperature difference and high flow rate that underfloor heating requires are ideal for obtaining optimal performance from ASHPs. During the project, the use of the first-floor space changed from a light cafe to a high-end restaurant (Figure 16). To improve the internal temperature, three 1.5kW direct electric panel heaters were installed, with another two in the lobby.

Figure 16: Restaurant at Site 2.

The visitor centre had a combination of original and new stonework for the floor surface. Stone floors have a high thermal conductivity, so do not impede the transfer of heat from pipes to the floor surface. The restaurant had a timber floor, with a laminated wood finish. Wood floors tend to have less thermal mass than solid floors, so respond more quickly to changes in the heat output of underfloor heating. Wood has a high thermal resistance to heat flow and as such reduces the output of the heating system. Most suppliers of wood and vinyl flooring set a maximum floor temperature of 27°C if it is to be used with underfloor heating. This limits the heat output of the underfloor heating system when compared to stone and other hard floor finishes, which can tolerate higher temperatures.

It is for these reasons that the CIBSE underfloor heating design and insulation guide states: 'Some refurbishment projects, such as barn conversions, can require high heating outputs, where much greater care is required and hard floor surfaces such as tiles or stone may be the only options.' The BSRIA underfloor heating guide says that underfloor heating installed on a solid floor can expect to produce outputs of around 100W/m^2, but this can drop to around 70W/m^2 on intermediate timber floors such as those installed in the restaurant at Site 2. (The schematics for the underfloor heating say the required heat output equates to 115W/m^2.) The BSRIA guide also says that lightweight buildings with high ventilation rates and poor insulation are not usually suitable for underfloor heating. This is due to concerns about achieving the required heat output from the floor to compensate for the high heat losses.

Some fabric improvements had been carried out at the barn, but the restaurant area still suffered from draughts and high ventilation rates. While underfloor heating is ideal for use with ASHPs, it is not always suited to the building, especially if it has high thermal losses. At Site 2, the thermal comfort of the restaurant could be enhanced by improving airtightness and replacing the wooden floor with a solid floor, finished with a material with a lower thermal resistance, such as ceramic tiles or stone. Other improvements include separating the ground-floor area from the restaurant above, by installing a solid floor or glazing. This would be a costly alteration and may not be viable, depending on the areas of the barn that need to be conserved. It would, however, prevent cold draughts from the unheated ground-floor area affecting the thermal comfort of those in the restaurant. From an aesthetic point of view, a glazed floor would be preferable because restaurant visitors would still be able to view the historic area underneath. A cheaper and less intrusive option would be to make the external doors to the historic area airtight. Other options include reducing or eliminating the openings at the eaves.

Heating controls

The plant room contained the heating system control thermostat. Having the thermostat in the plant room was not ideal, because numerous pipes and equipment meant the temperature there was quite high. To compensate for this, the target temperature was set to the maximum of 30°C, in the hope this would prevent the thermostat from disabling the heating system. However, during the visit, the thermostat was close to 30°C, which would cause the heating system to shut off even though heating was needed in the visitor centre and restaurant.

The thermostat functionality could be disabled, so the controller works as a simple timer. Using a timer may be suitable for a building with established occupancy times, such as a restaurant, but it can result in inadequate or excessive heating.

The thermostat could be moved from the plant room to a space that is occupied by people. To prevent tampering from the public, it would be best to position it behind the counter at the visitor centre or behind the bar in the restaurant, or even behind a locked panel. To minimise visual or historical impact, a subtle sensor and/or thermostat could be used instead of a wall fitting.

The restaurant and visitor centre could be designed as separate heating zones with independent thermostats, to provide better control over the temperature in each area. This would be particularly beneficial because the two areas have different opening hours and temperature needs.

It is crucial to design the heating zones so that the system flow rates remain at a minimum level when the zones are turned on or off. In buildings where not all zones are used, the ASHP may cycle on and off due to the limited load, resulting in the ASHP running for shorter periods. This could lead to greater wear and tear on the ASHP's components.

Most of the ASHPs available today are inverter driven. This means they can adjust the output of heat instead of operating at a constant maximum output and switching on and off. By adjusting the output, the ASHPs can provide greater control over the heat output and reduce temperature fluctuations for both the heat emitters and building occupants. The efficiency of the ASHP varies, with lower efficiency at the lowest and highest outputs, and optimum efficiency somewhere in the middle. Each ASHP will have its own efficiency curve across the range of turndown. There will be a minimum turndown, below which it will need to cycle on and off to reduce the heat output further. In cases where two or more ASHPs are installed at a site, they can be cascaded to allow for even greater control over the heat output. During periods of low heat demand, a single ASHP can run continuously, instead of two ASHPs cycling on and off. Additionally, each zone can be heated by a separate ASHP if each pump has enough capacity. This would create two separate heating systems but would allow each ASHP to be optimised to the specific requirements of the load. When using multiple ASHPs, it is essential to have an effective control strategy in place.

4.3 Site 3

Building history and overview

The main building at Site 3 is a Grade II listed building. The University College expanded in 2008, when a large accommodation block was added. As part of the site's plan for decarbonisation, major renovation work took place in 2022, including replacing windows with triple glazing to improve insulation and replacing gas boilers with ASHPs. Photovoltaic panels are also being installed as part of the decarbonisation project.

Site 3 consists of two adjacent main buildings, with multiple outbuildings. Some of the buildings are occupied for part of the year, but the offices are occupied all year.

Figure 17: Aerial view of Site 3. © Vortex Drone

Heating system

The main building is served by a large bespoke air-to-water ASHP, designed by Isentra and Seward Refrigeration. The external evaporator units are located within the undercroft car park and use a CO_2 refrigerant (Figure 18). An additional five domestic R-32 ASHPs cover the domestic hot water distribution losses (the energy lost when hot water is circulated in pipework), ensuring that hot water is always available. The existing radiator and distribution system was reused, and the original single-glazed windows were upgraded to triple glazing.

The new heating system was installed in 2022. At the time of the visit, the site was still in the seasonal commissioning process and had not undergone a full heating season.

Figure 18: One of four sets of ASHP evaporators (right), pictured with the gas main (left).

Summary

Property type		Residential/education/hospitality
Heat pump technology		Split CO_2 and multiple monobloc R-32
Heat pump capacity		700kW + 5 x 75kW
Heat pump capacity/m2		86W/m^2
Heating system		Wet heating system. Mainly using radiators, with some fan coils
Hot water system		Plate heat exchangers from buffer vessel
Use pattern		Year-round use, with reduced occupation in summer
Technology choice	★★	The CO_2 ASHP allowed the existing distribution system to be reused, providing large cost and time savings.
Thermal comfort	★★	Users seem pleased with the thermal comfort of the building.
System design/ installation quality	★★	The system is carefully designed and installed at a large scale.

ASHP unit observations

- The building was heated by a 700kW custom-built CO_2 ASHP, and five 75kW domestic R-32 ASHPs for hot water distribution losses.
- Four sets of evaporator fans were located in the undercroft car park. They took up about six former car parking spaces. The ASHPs were entirely within the existing building footprint and were largely out of sight from the main paths around the site.
- The evaporators were clean and free of debris.
- The evaporators blew onto existing metal grating. In cold weather, ice may form on the grating and block airflow.
- Condensate pumps served each of the groups of evaporators to remove water that collected inside the units.
- There were some residential rooms directly above and across the street from the evaporators.
- CO_2 compressors and condensers were contained within an internal plant room.
- The internal plant room had acoustic insulation in the ceiling because it is directly below residential rooms.
- A domestic R-32 ASHP was located inside the plant room to make use of waste heat from the CO_2 ASHP.
- External pipework was well insulated, including valves.
- A new substation providing 1,000kVA electrical supply to the site was required to power the ASHPs.
- The main space heating ASHP used 150kg of R-744 refrigerant with a GWP of 1. The five hot water return ASHPs used a total of 7kg of R-32 refrigerant with a GWP of 675. The system had a refrigerant charge of 150kg. A leak of all the refrigerant in the system would be the equivalent of 6,765kg of CO_2 being released into the atmosphere.

Heating system observations

- Existing radiators, fan coils and distribution pipework had been reused.
- Return temperature limiting (RTL) valves were installed on all the radiators to control the temperature of water returning to the ASHP.

- Domestic hot water production was centralised in the plant room. The previous system had produced domestic hot water at numerous locations across the site.

- A 3,000-litre four-pipe buffer vessel was used to ensure sufficient system volume was provided, and to produce domestic hot water via plate heat exchangers.

- Internal pipework was well insulated, although some valves were uninsulated.

User interview

- The client was pleased with the system, and it was a key part of their decarbonisation strategy.

- There had been no complaints about noise.

- Government Salix funding directly made the project possible.

- The client was aware that building users needed to know more about how the system was designed to operate, including lower average radiator temperatures.

- There was no gauge for running costs because the client had yet not been through a full heating season.

- Defrost cycles had no noticeable effect on internal comfort.

Discussion

Refrigerant choice

This case study stands out for a number of reasons, not least because of its use of CO_2 as a refrigerant. Refrigerant choice is a key factor in the environmental impact of an ASHP system, managing concerns of high GWP, toxicity and flammability. The market supply of high GWP refrigerants, such as R-410A, is being phased out by F-gas regulations, and systems that use these refrigerants will become increasingly expensive to maintain.

CO_2 is a natural refrigerant with a GWP of 1, low toxicity and low flammability. However, the nature of the CO_2 refrigeration cycle means that some of the rules of conventional hydrofluorocarbon ASHP efficiency (low flow temperatures, low ΔT) do not apply, so the system must be designed accordingly.

While hydrofluorocarbon refrigerant ASHPs suffer a significant drop in COP at high flow temperatures (>60°C), CO_2 ASHPs can efficiently produce high flow temperatures in excess of 70°C. The nature of the transcritical CO_2 refrigeration cycle means the COP is optimised when the return temperature is kept very low, and the efficiency drops off as the return temperature of the system increases (Figure 19). Above a certain return temperature, a CO_2 ASHP will be unable to operate and will switch off. This means that a CO_2 heating system must operate with a high temperature difference and a low flow rate, compared to a hydrofluorocarbon system. This is advantageous when replacing an existing gas- or oil-fired heating system, because the pipework will have been sized for high temperature differences and low flow rates. It may, therefore, be possible to reuse the existing pipework.

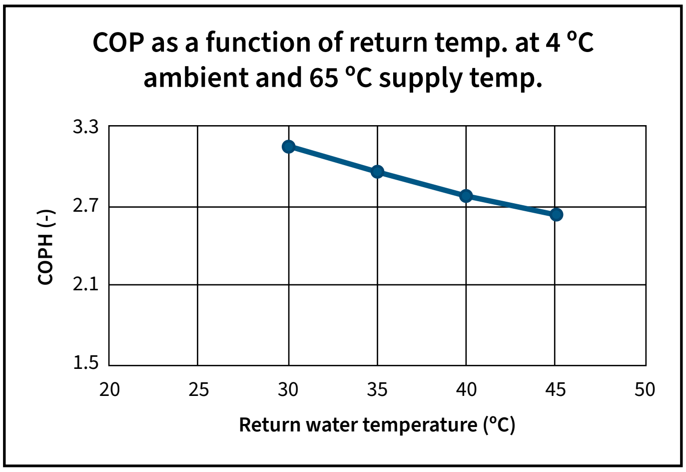

Figure 19: CO_2 efficiency at varying system return temperatures (COPH is the heating COP) © Clade Engineering. https://clade-es.com/how-to-use-co2-for-heating-and-hot-water/

The CO_2 refrigeration cycle operates at higher pressures than other common refrigerants. Installers and maintenance engineers working on split systems must be certified against the Pressure Equipment Directive. This may make it more difficult to find a suitably qualified contractor to maintain the system.

Heating system

At Site 3, the cost and disruption of replacing all the pipework and heat emitters would have made the project prohibitively expensive. Choosing CO_2 as the refrigerant was a key decision.

The system is designed to operate at 70°C flow, 30°C return to optimise the efficiency of the CO_2 ASHPs. A temperature difference of 40°C means the flow rates through heat emitters are extremely low. Conventional commissioning is not capable of delivering accurate flows at these low rates. The system deals with this issue by using return temperature limiting (RTL) valves (Figure 20). These valves are connected to the return connection of the heat emitters (predominantly radiators) and only allow water to enter the return when the water temperature is at or below the value set on the valve.

There is a significant capital cost in fitting RTL valves to every heat emitter. This must be balanced against the savings that can be realised by a high ΔT system.

Occupants may confuse RTL valves with thermostatic radiator valves. The RTL valve must be tamper-proof to prevent the system return temperatures being altered.

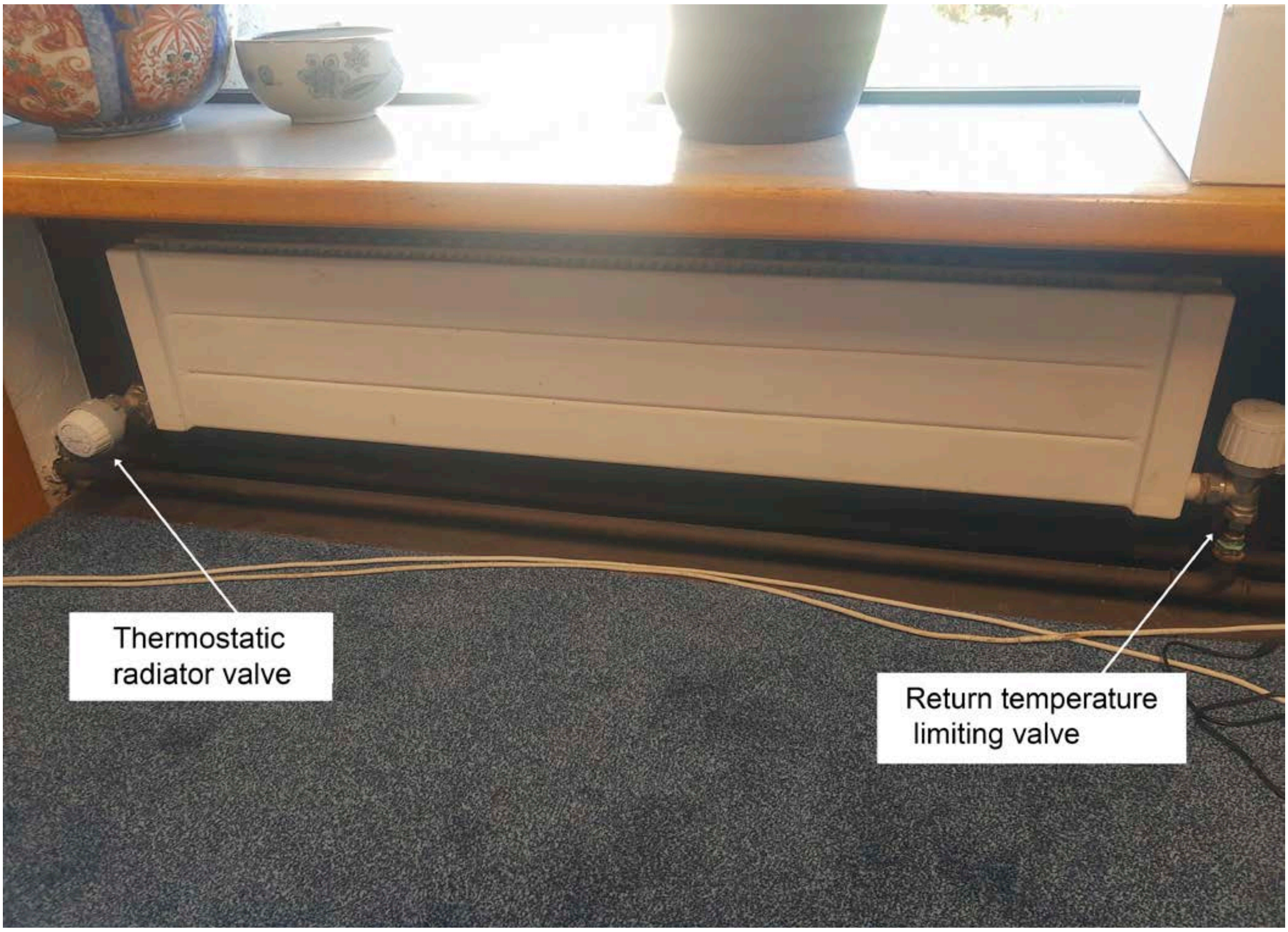

Figure 20 : Office radiator with a thermostatic radiator valve and an RTL valve.

While RTL valves can effectively control the return temperatures from the radiators, there is still an ongoing commissioning process at Site 3 to bring the overall system return temperature down to 30°C:

- Insulation upgrades to the windows are incomplete. In rooms that do not yet have upgraded windows, a higher average radiator temperature is required. A CO_2 ASHP allows for higher average emitter temperatures, because the temperature setting of each emitter RTL valve can be increased. However, this then raises the overall system return temperature. Controlling the heat emitter temperature locally via its RTL valve is very useful and means that rooms that have not yet received fabric upgrades can still be comfortably occupied under the new heating system. Once all insulation works are completed, the RTL valve s can be turned down, decreasing the average temperature of the radiator s and decreasing the overall system return temperature.

- As the existing distribution pipework has been reused, there are numerous system bypasses that need to be located and controlled to prevent the hot flow from short-circuiting to the return. The large scale of the system makes locating these bypasses difficult.

Domestic hot water system

In the previous gas system, domestic hot water was generated at nine different plate heat exchangers across the site. The heat exchangers were supplied by the same low temperature hot water system that served the space heating. This arrangement meant that low temperature hot water had to be pumped 24 hours a day to local plate heat exchangers so they would be ready to produce domestic hot water on demand.

The new system generates domestic hot water via two plant room plate heat exchangers powered by CO_2 ASHPs. The domestic hot water is then distributed across the site. During periods of low demand, the flow in the pipework is reduced to the level required to keep the pipe warm, thereby reducing the pumping energy of the system. Figure 21 shows a schematic diagram of the system.

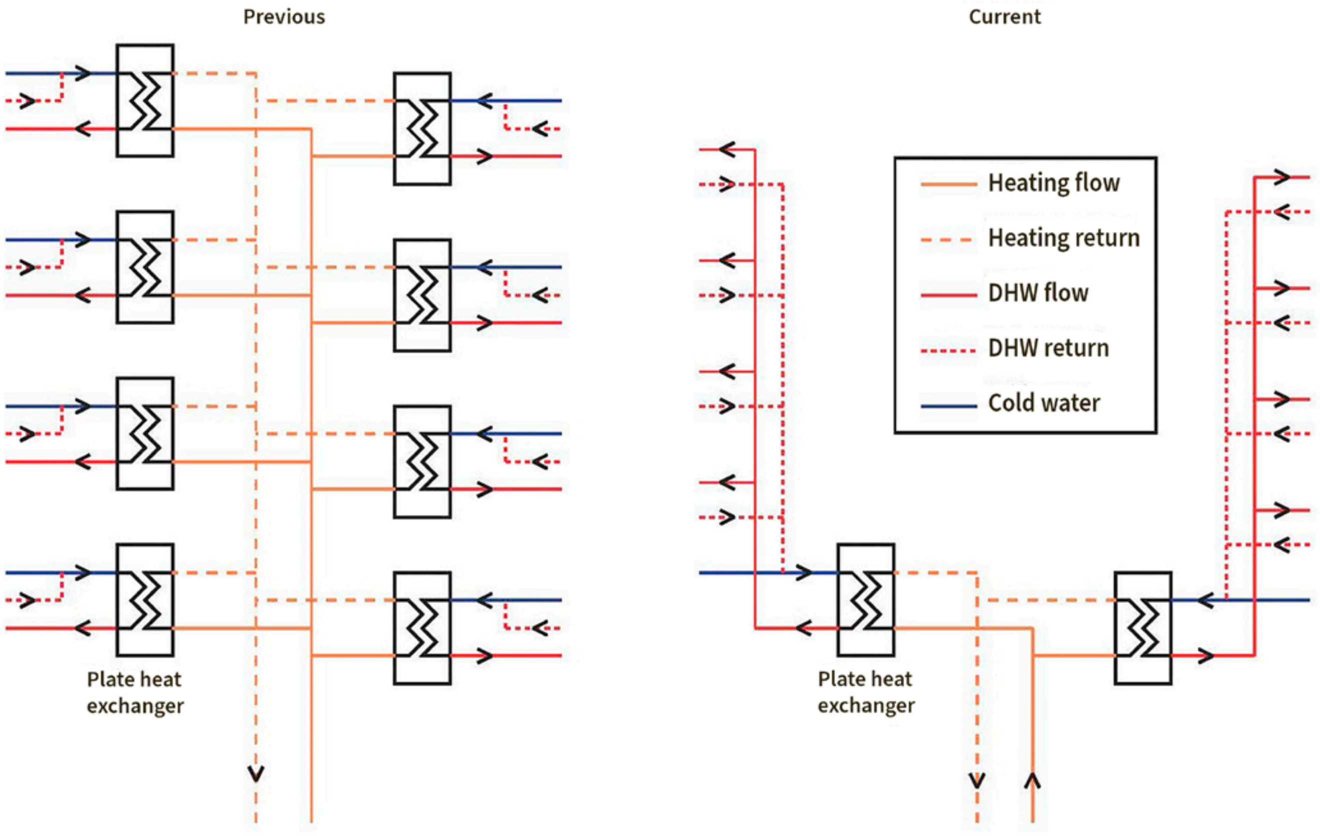

Figure 21: Schematic showing the previous and current domestic hot water system arrangements.

All the domestic hot water is now produced centrally, and there are significant distribution heat losses as the hot water travels across the building to the points of use. A hot water return system is used to ensure that the hot water stays at the required temperature within the pipework (normally 55°C). As CO_2 ASHPs require a low return temperature to operate efficiently, they are not well suited to provide the slight rise in temperature required to maintain domestic hot water at the target temperature. Instead, a bank of five domestic Samsung R-32 ASHPs are used to raise the hot water temperature. One of these R-32 units is located in the plant room. It makes use of waste heat from the CO_2 ASHP and simultaneously mitigates plant room overheating. During the summer, when demand for hot water is lower, these domestic ASHPs almost cover the full hot water demand of the site.

With nine plate heat exchangers, the original system spent a lot of electrical energy on inefficient pumping of low temperature hot water. In Q3 (summer) of 2021, prior to this project, the site's total electrical consumption was approximately 335MWh. In Q3 of 2022, after the ASHP installation, the site's total electrical consumption was approximately 328MWh. Despite providing all the heat electrically, in summer the new hot water system consumes a similar amount of electrical energy as the previous gas-fired system.

Location

Given the large heating demand of the building, the external evaporators require a significant amount of space. They are neatly sited in two undercroft car park areas, at the expense of some car parking spaces. Other historic buildings may not have the benefit of such a discrete option. These units create a significant flow of cold air, but most of the walkways are far enough away for this not to be an issue. In one area, there is a barrier to protect people accessing the nursery (Figure 22).

Figure 22: Barrier to divert flow of cold air from the evaporators away from the nursery entrance.

There have been no noise complaints from the residential spaces above and across the street from the evaporators. There is a separate internal plant room containing the ASHP compressors and heat exchangers. As the ASHP is custom built, it likely needed more space in the plant room than a mass-produced ASHP. It is expected that in due course the original gas boilers will be removed from the old plant room, which will free up more space.

A close working relationship with the ASHP designer has been beneficial. For example, locating the outdoor evaporators in the undercroft significantly reduced the impact of the ASHP on the site. Many mass-produced ASHPs at this scale blow air directly upwards. This would not work efficiently in the undercroft area, as air would blow directly onto the undercroft ceiling, thus limiting the airflow rate. The ASHP at Site 3 was custom designed so the evaporators discharge air horizontally.

Funding

Making a financial case for decarbonising heating systems can be challenging, and this project was made possible by government funding via Salix. Phase 2 of the Public Sector Decarbonisation Scheme opened to applications in April 2021 and required funded projects to be completed by March 2022. This incentivised the pace of the project, preventing scope creep (significant changes to the project brief) and ensuring decarbonisation was delivered as fast as possible. For more information on Salix funding, see www.salixfinance.co.uk.

CO_2 ASHPs are becoming well established, and there are some mass-produced products now on the market. Typically, these do not cost more than equivalent hydrofluorocarbon refrigerant ASHPs.

4.4 Site 4

Building history and overview

The park was purchased in 1771. The existing house was demolished, and the current house was built on the site. In 1952, work to restore and modernise the building was carried out, including installing central heating and modern kitchens and bathrooms.

The site comprises three main buildings. They are currently used as a museum, tearoom and staff offices. There is also a stable yard, which houses a small seasonal cafe, shop and staff accommodation.

Heating system

There are two ASHP systems at the site. One provides heating and hot water to one of the main buildings (Site 4a), and the second provides heating and hot water to the staff cottage in the stable yard (Site 4b). The other two main buildings are conservation heated by a ground source heat pump system.

Summary

	Site 4a	**Site 4b**
Property type	Commercial	Residential
Heat pump technology	Monobloc R-410A, R-32	Monobloc R-407C
Heat pump capacity	28kW (2 x 14kW)	9kW
Heat Pump capacity/m^2 (approximate)	50W/m^2	52W/m^2
Heating system	Wet heating system using double-panel radiators	Wet heating system using triple-panel radiators
Hot water system	Domestic hot water storage cylinder	Domestic hot water storage cylinder
Use pattern	**Year-round**	**Year-round**
Technology choice	★★ The ASHP is well suited to this location. It makes no visual impact on the site.	★★ The ASHP is well suited to this location. It makes minimal visual impact on the site.
Thermal comfort	★★ Tenants reported good and consistent thermal comfort.	★★ Tenants reported good and consistent thermal comfort.
System design/ installation quality	★☆ The system is designed and installed to a very high standard. The hot water cylinder is significantly oversized.	★★ The system is designed and installed to a very high standard.

Site 4a

ASHP unit observations

- The building was served by two monobloc 14kW Mitsubishi Electric Zubadan ASHPs, totalling 28kW. These provided space heating and hot water.

- One of the units had been replaced due to a fault, and so there was one R-410A unit and a newer R-32 unit.

- The units were located in a small courtyard and were completely out of the view of visitors.

- Units were installed next to the plant room so the pipe run distance was minimal.

- External pipework was appropriately insulated with a closed cell nitrile rubber product. No external protection had been applied, and there was visible degradation to the surface of the insulation.

- Units were installed within the manufacturer’s space requirements.

- There was piped condensate drainage from both units. The user reported that ice occasionally forms underneath the units, indicating that the pipework does not capture all of the condensate.

- The units were mostly clean, except for a small amount of debris in one of the heat exchangers.

- There were no windows to noise-sensitive locations near the outdoor units.

- The noise from the tearoom kitchen extractor fan was far louder than that from the ASHPs.

- The ASHPs used 4.3kg of R-410A refrigerant with a GWP of 2,088, and 3.3kg of R-32 refrigerant with a GWP of 675. A leak of all the refrigerant in the system would be the equivalent of 11,206kg of CO_2 being released into the atmosphere.

Figure 23: ASHPs at Site 4a.

Heating system observations

- The heating system operated on a weather compensation curve from 30 to 50°C (this compensates the flow temperature based on the external temperature to save energy).
- The plant room installation was high quality, with extensive insulation.
- Some valves were uninsulated.
- A large magnetic filter was emptied every three months due to the large amount of sediment that collected from the system.
- Pipe supports clamped directly onto the pipework, rather than onto rigid insulation, thereby increasing heat losses.
- Double-panel radiators heated the staff offices.
- The hot water calorifier had a storage volume of 293 litres and served some bathroom basins.
- There was no buffer vessel.

Site 4b

ASHP unit observations

- The stable yard cottage was served by a 9kW ASHP manufactured by CTC, which provided both space heating and hot water. There was also a wood-burning stove in the living room that was used when outdoor air temperatures were low.

- The outdoor unit was clean and had been installed within the manufacturer’s spatial guidelines.

- The unit was very quiet in operation.

- The unit was connected to an indoor hydraulic station and hot water cylinder.

- The hot water cylinder operated on a weekly legionella cycle.

- Condensate dripped onto a concrete slab and then drained into a large gravel bed.

Figure 24: ASHP at Site 4b.

Heating system observations

- The system was set to a target air temperature of 18°C at all times, with the thermostat located in the cottage hallway. Manufacturer's controls were used with weather compensation.
- At the time of the visit, the system was targeting a flow/return temperature of 33°C/30°C, at an outdoor air temperature of 1°C. The internal air temperature was 19°C.
- The manufacturer's internal unit had a 223-litre buffer vessel. This was used to instantaneously heat domestic hot water.
- Triple-panel radiators were used throughout the cottage.
- The cottage had a solid concrete floor, loft insulation and secondary glazing.
- Although the staff cottage was directly connected to the visitor reception, the reception was heated separately by an 8kW wood-burning stove. The doors to the reception opened frequently, and so heating that space with an ASHP would probably have been inefficient.

User interview

- The users were grateful for the ASHP systems and wanted to treat them well.
- They were glad to move away from oil boilers, as an oil leak would have caused very serious problems due to the site layout and the need to protect the historic landscape.
- The cottage tenant was enthusiastic about the ASHP and showed a comprehensive understanding of how to maximise the efficiency of the system via weather compensation.
- The renewable heat incentive provided significant payouts and had been important in making the project viable.
- A bespoke maintenance contract was agreed with the installer, with annual maintenance checks being carried out.
- Defrost cycles had had no noticeable effect on internal comfort.

Discussion

Both of the heating systems at Site 4 appear to have been designed to meet the requirements of each building, and they represent an excellent renewable transition away from oil heating. Units are positioned to avoid any noise or visual impact on the historic buildings they serve. The ASHPs are well understood by their users, in contrast to other sites. Using weather compensation curves minimises the flow temperature of the systems and drives up efficiencies.

Hot water storage

Hot water is provided by the ASHPs and an immersion heater. The hot water tank at Site 4a is significantly oversized (293 litres) for serving a few basins. It will have cost more than necessary to install and increases the heat losses of the system. The user reported that the system designer misunderstood which hot water appliances were in active use and which were part of the museum. As a result, the storage volume was sized for running baths that were actually for display only. This highlights an issue specific to historic buildings, where the use of the building may be misunderstood at design stage. Clients should provide a clear brief to system designers so they can size systems appropriately and minimise capital and operational costs.

Heating high airflow spaces

During the installation of the ASHP at Site 4b, it was decided to exclude the reception area from the system. The reception has automatic doors and regular foot traffic, which means that a lot of heat is lost to the outside. As discussed in the case study at Site 1, in such situations it is inefficient to try and provide thermal comfort through heating the air. Low temperature ASHPs with radiators are not well suited to heating such spaces. Instead, radiant heating is a more appropriate option, in this case provided by a wood-burning stove.

It should be noted that burning wood emits a high amount of CO_2 and other harmful emissions that would otherwise remain embodied in the wood over the tree’s natural lifespan. Radiant heating can also be achieved using direct electric radiant panels. These have much lower operational emissions, depending on the national grid energy mix. As renewable generation continues to be deployed, the grid will continue to decarbonise, and the emissions of electric heating will reduce even further. Additionally, wood-burning stoves operate at surface temperatures between 260 and 460°C, and so require measures such as safety guards to prevent direct contact. Electric radiant panels generally operate at temperatures between 75 and 100°C, which is significantly lower but does not eliminate the risk of burns altogether.

Wood-burning stoves require frequent cleaning, unlike electric panel radiators, but they do have the distinct advantage of working during a power cut. An electric heating system can be backed up with battery storage, but the cost of a battery large enough to run an electric heating system for any length of time is often prohibitive.

5. Conclusions

Blanket assumptions such as ‘ASHPs do not work in historic buildings’ are often heard in discussions and in the media. These case studies show that ASHPs are, in fact, viable in both domestic and commercial historic buildings, providing a path to decarbonisation that is available right now. They can deliver good levels of user comfort at running costs that are equivalent to or lower than a gas- or oil-fuelled system. And they can do so without the planning and programme delays that ground or water source heat pumps can involve. At each site, there were no issues with electrical infrastructure, planning permission and listed building consent that limited effective ASHP operation.

On site, the ASHPs were rarely noticed by visitors or tenants. Issues with noise, cold plumes, defrost cycles or aesthetics were not reported in any of the case studies, even though such concerns are often cited in the media. Sensible design decisions can prevent these problems with minimum financial impact. In some cases, the ASHPs were perhaps too well hidden and more could be done to draw public attention and promote the positive impact that the technology delivers for the site.

Alternative refrigerants such as CO_2 are becoming more common and can be of particular use in historic buildings due to the higher flow temperatures available. However, the system design required for good efficiencies differs from conventional ASHPs and needs careful planning.

The ASHP revolution could be seen as two major revolutions in one: the transition to ASHPs as a heat source, and the transition to efficient low temperature heating. Ideally, the latter would have occurred in 2005 when condensing gas boilers were made mandatory. Condensing gas boilers work most efficiently at low temperatures. But cheap energy prices and a lack of environmental concern have delayed the transition until now. Across the case studies, problems with the heating system were not caused by the ASHPs per se. Rather, there were issues with heating distribution, emitter design and understanding the controls. Continued focus to improve these elements is required to maximise ASHP efficiencies. Some of this should be straightforward, for example, giving the end user basic education about how to control their particular system.

Modern ASHPs are sophisticated products with decades of innovation behind them. Successful ASHP projects require good design practise to ensure that the best heating strategy is adopted which also considers the heating distribution, emitters and controls.

6. Acknowledgements

Contributors

The authors would like to thank the landlords and tenants for allowing the heating systems to be appraised publicly, and for contributing their valuable time. Their willingness to participate is testimony to their determination to drive forward the process of decarbonising heat in the UK's building stock.

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