# Evidence update of low carbon heating and cooling in non-domestic buildings

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**Disclaimer**

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# List of abbreviations and acronyms

| | |
|---|---|
| CCC | Committee on Climate Change |
| BEIS | Department for Business, Energy and Industrial Strategy |
| BEES | Building Energy Efficiency Survey |
| CO2e | Carbon dioxide equivalent |
| TWh | Terawatt-hour |
| GWh | Gigawatt-hour |
| kWh | Kilowatt-hour |
| BAU | Business As Usual |
| VAV | Variable Air Volume |
| VRF | Variable Refrigerant Flow |
| VRV | Variable Refrigerant Volume |
| AHU | Air Handling Unit |
| ASHP | Air Source Heat Pump |
| GSHP | Ground Source Heat Pump |
| A2W HP | Air to Water Heat Pump |
| HT A2W HP | High Temperature Air to Water Heat Pump |
| A2A HP | Air to Air Heat Pump |
| FCU | Fan Coil Unit |
| CHW | Chilled Water |
| LTHW | Low Temperature Hot Water |
| POU | Point Of Use |
| COP | Coefficient of Performance |
| SPF | Seasonal Performance Factor |
| EER | Energy Efficiency Ratio |
| HVAC | Heating, Ventilation and Air Conditioning |
| DNO | Distribution network operator |

# Executive summary

The decarbonisation of heat is essential if the UK is to meet long-term carbon targets. The UK became the first major economy to pledge to achieve net-zero greenhouse gas emissions by 2050[1], as set out by the Committee on Climate Change (CCC).[2] In line with this target, the UK has committed to reduce emissions by 78 per cent on 1990 levels by 2035. Emissions from non-domestic buildings currently account for around 22 per cent of emissions from buildings, and four per cent of all UK GHG emissions[3]. Under the CB6 Balanced Net Zero Pathway, these emissions will be expected to broadly halve by 2035 and fall to zero by 2050.

This study was commissioned to determine the potential across England and Wales to reduce carbon emissions by implementing low carbon space heating, hot water, ventilation and cooling (HVAC) technologies in non-domestic buildings. Through research conducted between 2019 and 2020, this study provides an evidence base on the applicability and cost effectiveness of low carbon HVAC measures.

As part of this study, the 3,690 non-domestic building records from the Building Energy Efficiency Survey (BEES) (DECC, now BEIS, 2017)[4] were categorised into a set of building 'archetypes' with common HVAC characteristics. A large proportion of buildings supply space heating using gas boilers (52 per cent). Around two-thirds (66 per cent) of buildings use natural gas as the main heating fuel. A further 24 per cent use electricity as the main heating fuel. The most common building archetype – representing 18 per cent of the total by floor area - are those heated with a natural gas boiler via either radiators or fan coil units[5] (most commonly radiators) and with no cooling plant on site.

[1] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
[2] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/
[3] Table 1.2 (commercial and misc, and public sector) https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2019
[4] https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees
[5] A fan coil unit (FCU) consists of a heat exchanger (coil) and a fan and makes up part of HVAC systems that use ducted split air conditioning or with central plant cooling. A fan coil unit is often connected to a thermostat to regulate the temperature of spaces and support the central air handling unit if combined with a chiller. The thermostat controls the speed of the fan and in some applications the throughput of water to the heat exchanger.

# Background

## Policy context

The decarbonisation of heat is essential if the UK is to meet long-term carbon targets. The UK became the first major economy to pledge to achieve net-zero greenhouse gas emissions by 2050,[6] as set out by the Committee on Climate Change (CCC).[7] In line with this target, the UK has committed to reduce emissions by 78 per cent on 1990 levels by 2035, and consistent with the sixth carbon budget (CB6) period (2033-2037) recommendation by the CCC.[8] As part of this, under the CB6 Balanced Net Zero pathway, direct emissions from buildings will be expected to almost halve from 2019 levels, reducing from 91 MtCO2e to 47 MtCO2e in 2035, and to just 1 MtCO2e by 2050.[9] Non-domestic buildings currently account for around 20 MtCO2e of emissions (around 22 per cent of buildings, and four per cent of UK GHG emissions)[10] - under the CB6 Balanced Net Zero pathway, these will be expected to fall by around 12 MtCO2e in 2035, and to zero by 2050.

## The Building Energy Efficiency Survey (BEES)

BEES, which has subsequently been used as the starting point for the CCC's CB6 modelling of non-residential abatement, set out to improve and update the evidence of how energy is used, and to provide an assessment of the abatement opportunities for all non-domestic premises across England and Wales. The study identified abatement potential of around 39 per cent of energy consumption in England and Wales.[11]

The BEES project split the non-domestic stock into 10 sectors, and 38 sub-sectors, collecting data on building characteristics for 3,690 non-domestic buildings, using a telephone survey. The survey gathered basic information relevant to energy use for each building and included sub-sector-specific questions to gather further data on the most significant energy end uses. The results from this exercise were used to generate a prediction for each building's energy consumption, disaggregated into end uses using definitions adapted from CIBSE's TM 22 guidance.[12] This project used these building records and predictions as its modelling frame, to develop baseline energy consumption and identify abatement potential.

The potential for alternative low carbon heating measures was not assessed during BEES. The telephone survey questionnaire did however include a series of questions relating to the

[6] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
[7] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/
[8] https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035
[9] https://www.theccc.org.uk/publication/sixth-carbon-budget/ (Figure 3.2.d)
[10] Table 1.2 (commercial and misc & public sector): https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-to-2019
[11] Table 4.1 at https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees
[12] A more detailed account of the methodology and data collection approach is provided in Section 1.3 of the BEES Overarching Report; at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565748/BEES_overarching_report_FINAL.pdf

existing level of HVAC servicing in the respondent's building. Appendix A provides a full list of these questions.

It is important to note that no new primary evidence for the BEES building records was gathered for this project. The data collected during the telephone surveys was used as the basis for understanding the type of HVAC system in place in each building but this information was supplemented with additional assumptions to generate a more detailed picture for each building record.

## Research questions and overall approach

This study was commissioned to determine the potential across England and Wales, to reduce carbon emissions by implementing low carbon space heating, hot water, ventilation and cooling (HVAC) technologies in non-domestic buildings. In doing so, we have addressed the following research questions:

- Which factors affect the application of a given technology type?
- What are the costs associated with alternatives to traditional fossil-fuel based HVAC measures?

The study provides an evidence base on the applicability and cost effectiveness of low carbon heat measures.

# HVAC in the non-domestic building stock

According to BEES the non-domestic stock in England and Wales comprises 1.83 million premises[13]. 1.57 million of these were within the scope of BEES[14] with a gross internal area (GIA) of 784 million m². As outlined in BEES, the non-domestic building stock is very diverse, predominantly due to three defining characteristics:

- Building type: the purpose of a premises, its age, the way it is serviced and the degree to which both fabric and services have been updated.
- Scale: the size of a premises and whether it constitutes a whole building, part of a building or a collection of related buildings.
- Activities: the types of activities and processes that are carried out inside premises (or in their associated surroundings), the intensity of such use and its duration.

The energy consumption of the non-domestic stock, as estimated by BEES, is presented in Figure 1. 92 per cent of non-electrical energy is attributed to natural gas use; the rest comprising district heating or bulk fuels such as oil or LPG. This figure shows the split in HVAC related end uses, by energy type, illustrating that the majority of HVAC energy consumption (59,300 GWh) is used in non-electrical space heating.

As part of this study, the 3,690 non-domestic building records from BEES were categorised into building 'archetypes' with common HVAC characteristics. A full description of the methodology for applying these archetypes is provided in the Methodology section. While there is significant diversity in the non-domestic building stock, there are a small number of HVAC systems which are much more common than others. These are captured in the eight archetypes outlined in Table 1, which represent 72 per cent of all non-domestic buildings in England and Wales.

[13] The Non-Domestic National Energy Efficiency Data Framework (ND-NEED) shows 1.76 million buildings as of 2022: https://www.gov.uk/government/statistics/non-domestic-national-energy-efficiency-data-framework-nd-need-2022
[14] Known exclusions were sub-sectors deemed 'de minimis' (53 million $m^2$) plus: Agricultural buildings/horticultural glasshouses (24 million $m^2$), Bank/insurance/building society branches (4 million $m^2$), Data centres (1 million $m^2$) and Post Office sorting centres (1 million $m^2$).

**Figure 1: Breakdown of electrical and non-electrical energy consumption by energy end use category - HVAC and other**

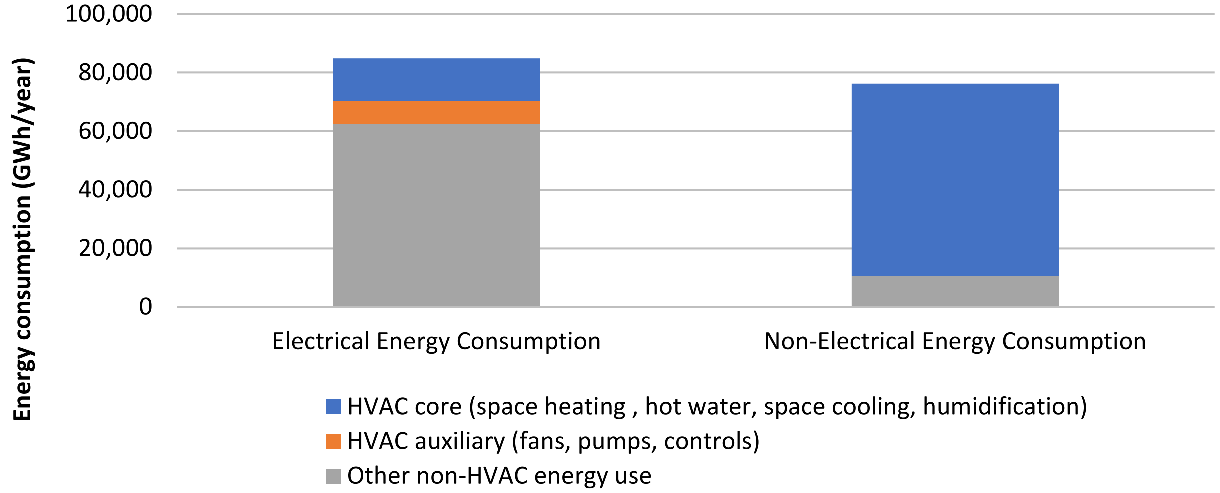



**Table 1: Summary of eight most common HVAC building archetypes in BEES data**

| Building arche-type number | Summary description of heating/cooling system | Total number of buildings | Floor area of buildings (millions m²) | % of total non-domestic floor area | Most common building sectors (millions m²) |
|---|---|---|---|---|---|
| 1 | Gas boiler with radiators. No cooling system | 383,000 | 145 | 18 | Place of worship =30<br>Office = 25<br>State primary school = 13 |
| 3 | Gas boiler with radiators or fan coil units (FCUs). Local refrigerant cooling system | 57,000 | 93 | 12 | Warehouse = 15<br>Office = 13<br>State secondary school = 11 |
| 12 | Direct gas warm air heating. Mixed cooling systems | 53,000 | 84 | 11 | Factory = 44<br>Warehouse = 21<br>Large Distribution Centre = 9 |
| 2 | Electric resistive heating. No cooling system | 472,000 | 84 | 11 | Small shop = 24<br>Warehouse = 15<br>Workshop = 12 |

| Building arche-type number | Summary description of heating/cooling system | Total number of buildings | Floor area of buildings (millions $m^2$) | % of total non-domestic floor area | Most common building sectors (millions $m^2$) |
|---|---|---|---|---|---|
| 4 | Gas boiler with radiators or FCUs. Central water-based cooling system | 49,000 | 70 | 9 | Office = 22<br>Hospital = 15<br>Hotel = 6 |
| 11 | Direct gas radiant heating. Mixed cooling systems | 53,000 | 66 | 8 | Factory = 34<br>Workshop = 16<br>Warehouse = 10 |
| 5 | Gas boiler with radiators or FCUs. Central air-based cooling system | 43,000 | 62 | 8 | Hospital = 14<br>Office = 10<br>Large food shop = 6 |
| 13 | Bulk fuel boiler with radiators | 73,000 | 42 | 5 | Workshop = 17<br>Factory = 4<br>Large Distribution Warehouse = 3 |
| Others | | 345,000 | 147 | 18 | |
| TOTAL | | 1,532,000 | 799 | 100 | |

The most common building archetype found in the non-domestic stock (archetype 1) are those heated with a natural gas boiler via either radiators or fan coil units (FCUs) and with no cooling supply on site. These buildings are typically naturally ventilated. Where hot water is supplied it is typically provided via electric point of use taps/showers or with a dedicated gas-fired water heater/boiler. These buildings account for 18 per cent of the non-domestic stock. Buildings fitting this archetype are highly diverse in terms of activity and are represented in all 37 BEES sub-sectors of the non-domestic stock. They most commonly arise in offices, schools and places of worship.

The second most common archetype (archetype 3) is similar to archetype 1 in terms of heating arrangements. Buildings in archetype 3 have localised cooling in certain spaces. This archetype accounts for 12 per cent of the non-domestic stock. Much like archetype 1 these buildings are diverse in activity and are found in 34 sub-sectors of the non-domestic stock, most notably warehouses, offices and schools.

Figures 2 and 3 show the distribution of both electrical and non-electrical energy consumption across HVAC and non-HVAC related energy end uses for the above eight archetypes which, together, constitute approximately 85 per cent of all energy used for HVAC in the non-domestic stock.

**Figure 2: Distribution of total energy consumption across HVAC and non-HVAC related energy end uses for eight of the largest building archetypes in study (by total energy consumption)**

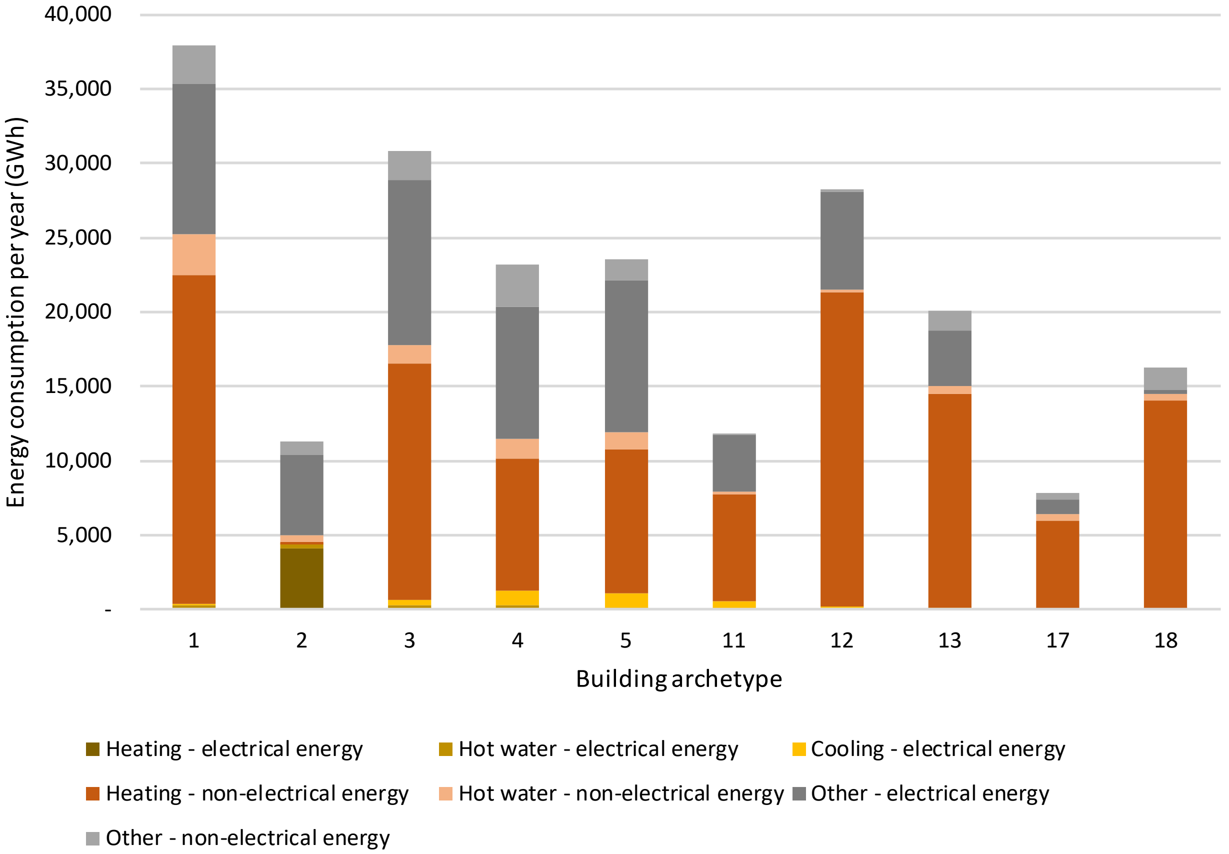
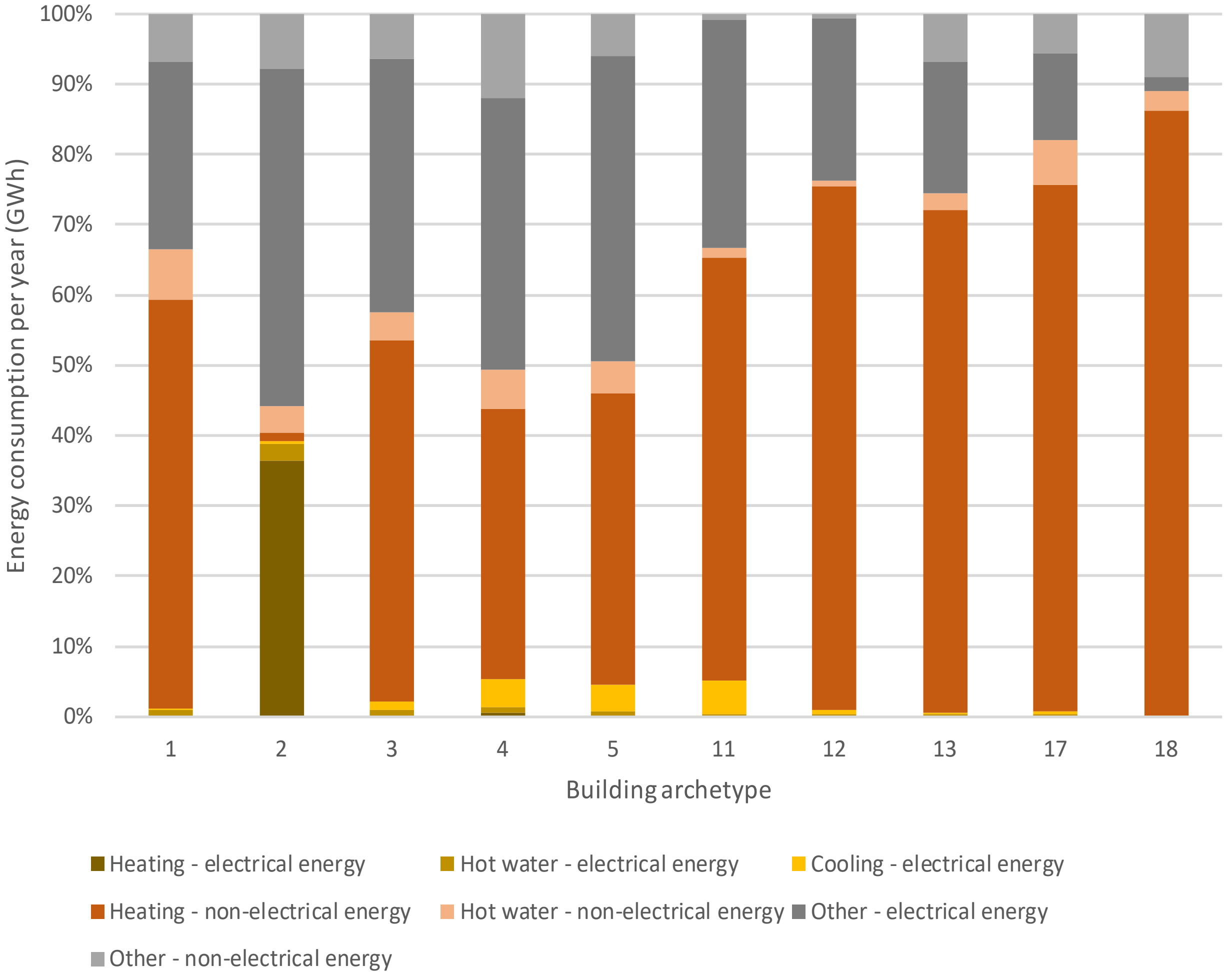


**Figure 3: Distribution of proportionate energy consumption across HVAC and non-HVAC related energy end uses for eight of the largest building archetypes in study (by total energy consumption)**




For readers interested in more detail of HVAC characteristics within non-domestic buildings, Appendix B provides a discussion on this, as it applies to six building types which account for almost half of the non-domestic building stock in England and Wales.

# Low carbon HVAC technologies

The majority of non-domestic buildings in England and Wales provide heating to spaces using either natural gas-fired boilers, direct gas or electric radiant heaters, or electric panel heaters. Cooling is typically provided using air- or water-cooled chillers, and domestic hot water supplied by electric point-of-use water heaters, dedicated gas-fired water heaters/boilers, or using heat from the main central heating system.

This section introduces four key low-carbon HVAC technologies considered in this study: air source heat pumps, ground source heat pumps, biomass boilers and electric resistive heating technologies (electrical convector panel heaters/radiant panel heaters). As part of this study the project team also engaged with a panel of HVAC experts, at a workshop, to discuss challenges in retrofitting these low carbon HVAC technologies. The most material of these challenges are outlined in Appendix C.

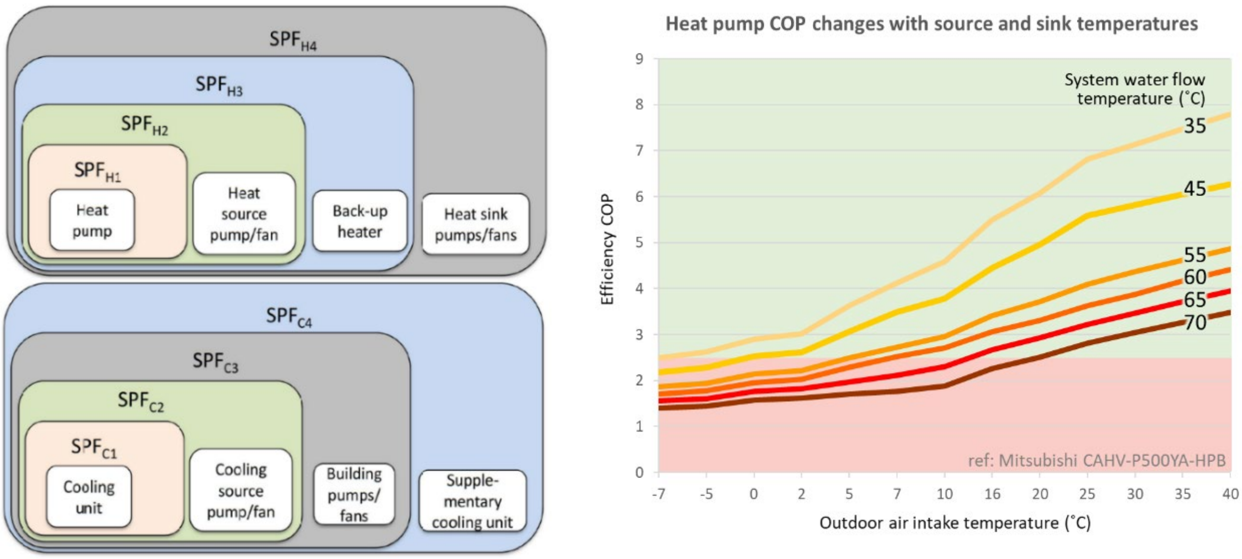
## Heat Pumps

Heat pumps are a very commonly installed low carbon HVAC technology. A liquid refrigerant – which boils at a low temperature – is heated by an external heat source and a compressor. The heat is then transferred to the heating and hot water circuits of the building. The external heat source determines the type of heat pump and is either outside air (air source heat pumps - ASHPs) or underground (ground source heat pumps - GSHPs). As the compressor is electrically powered, the carbon intensity of a heat pump is dependent on that of the electricity procured for their operation and the efficiency of the system itself.

The operational efficiency of a heat pump continually varies (unlike a boiler) dependent on a number of variables. These include system size, external temperature, hours of operation and the temperature gradient between the flow and return water. Figure 4(a) shows a selection of different measurement boundaries used for measuring Seasonal Performance Factors (SPF)[15]. The use of SPFs is intended to account for the continually varying efficiency (COP) across a typical year. Figure 4(b) shows how the efficiency of a heat pump can vary with source and sink temperatures.

[15] The Seasonal Performance Factor (SPF) is the average Coefficient of Performance (CoP) of a heat pump over the full heating season. The CoP is the ratio of heat output (in kilowatts) over the electrical input (in kilowatts) at any one time.

**Figure 4: (a) Selection of different SPF measurement boundaries, (b) heat pump COP changes with source and sink temperatures**




As part of this study a review of literature describing heat pump efficiencies was undertaken. These included academic papers, manufacturer information and field trial information. The median SPF quoted was lower than the median COP, as the SPF considers all-year round efficiency. SPF and COP values quoted by manufacturers are in general higher – this is anticipated to be due to the measurements being undertaken in laboratory conditions more favourable to efficient performance than field trials. COP figures across different studies are challenging to compare robustly as the results are dependent on test conditions. SPF figures can also vary significantly depending on the system boundary being considered.

The median SPF figure identified by this literature review for air source heat pumps was 2.8, with an interquartile range from 2.6 to 3.1. For comparison, the median SPF figure identified for GSHPs was 3.1, with an interquartile range from 2.7 to 4.0, suggesting a higher efficiency for ground source heat pumps compared with air source heat pumps. For the purposes of this study, given the large uncertainties in building operational factors, a median efficiency value was used in the performance modelling of both types of heat pump.

Besides the main generation plant, the replacement of a natural gas or bulk fuels fired boiler with a heat pump may require wider changes to a buildings HVAC system. A heat pump typically operates on a significantly smaller temperature gradient between flow and return temperature than a boiler. This may require heating emitters with a larger surface area to transfer the same level of heating supply to a space. Changes may also be required for auxiliary plant such as fans and pumps. With a lower temperature gradient, water circulation flow required is likely to be higher. In accordance with the scaling laws for pump and fans, the resulting increase in energy demand for the system will increase by a factor equivalent to the cube of the increase in flow rate. Aside from the increased energy cost, the increased flow rate of the water may extend beyond the working range for the HVAC distribution system, which may cause problems with leakage and water tightness. The above effect may be partly mitigated because existing heating systems tend to be oversized for short boost capacity.

The efficiency of a heat pump can also vary significantly with the operational regime, which is fundamentally different from that of a conventional natural gas boiler. During cold winter months, typically a natural gas boiler in a non-domestic building will employ a ‘pre-occupancy boost’ to ensure that the temperature within the building is sufficiently comfortable for occupants at the start of the working day. This may lead to the heating being switched on 1-3 hours before staff or members of the public arrive. Due to the lower temperature gradients present in heat pump systems, they are typically operated using extended pre-heat hours, which may be overnight. Operating a heat pump in the same way as the boiler would therefore reduce its effectiveness, an issue that would be further emphasised in the colder months due to the reduced efficiencies of heat pumps operating in cold climates.

Hot water storage and smart control systems can also be used to ‘smooth’ the output of a heat pump through the course of a day to maximise utilisation. This may allow a smaller heat pump to be installed, reducing capital costs.

Further detail specific to either air source or ground source heat pumps is provided below.

## Air source heat pumps

ASHPs use heat from the outside air to provide heating to internal spaces. An air-to-water system will transfer heat to a water-based central heating system which provides heating to internal spaces using emitters such as radiators, fan coil units or underfloor heating. An air-to-air system will warm air directly for circulation within the building, or via a central air handling unit (AHU) system. These are more common in industrial applications where a water-based central heating system is less likely to be present.

The cost of air source heat pumps was investigated as part of the literature review. The size of the system was one determinant of the system cost. Larger systems were found to benefit from economies of scale. Comparing the costs within this range is made challenging by the fact that they differ in terms of the scope of works within each retrofit (with some including installation and auxiliary plant costs within the £/kW figure). The median figure reported was £600/kW.

It is worth noting that in addition to the distinction between ‘air-to-water’ and air-to-air’ heat pumps used in this study, a further distinction was also made between ‘low temperature’ and ‘high temperature’ air-to-water heat pumps. In a low temperature heat pump system, the heat pump produces water for circulation at around 40-55ºC, lower than a traditional gas boiler-based system. In order to supply the same level of heating to internal space, it is assumed in this scenario that the heating emitters in the building – whether perimeter radiators, fan coil units, or otherwise – require replacement. In a ‘high temperature’ scenario it is assumed that the heat pump Is capable of delivering hot water with a circulation temperature of 70-80ºC, closer to that in a traditional gas boiler-based system. In this scenario, emitters do not need to be replaced.  The standard currently emerging in the market is a circulation temperature of 55ºC as a compromise between system modifications and heat pump efficiency.  This increases the likelihood that existing emitters (with their spare boost capacity) do not need replacement. It should be noted that the ‘flow to return’ temperature drop is larger for a gas boiler system. On average emitter temperatures may typically be 10ºC lower than the flow temperature. In a heat pump system the average emitter temperatures are typically 3ºC lower than flow temperature. This means that in some cases the installation of low temperature heat pumps may not necessitate extensive distribution system replacement.

### Ground source heat pumps

GSHPs function in a similar way to ASHPs but use the relatively constant temperatures found underground as the heat source. The reliability of this underground temperature – at a constant 13ºC all year round – means that GSHPs can outperform ASHPs in terms of both SPF and COP.

GSHPs scan be either vertically or horizontally oriented. Horizontally oriented ground source heat pumps require a large flat area of land to be excavated for heating coils to be laid down. Vertical ground source heat pumps require the digging of boreholes. Boreholes for heat pumps can be located almost anywhere on a site providing ground conditions permit and there is adequate spacing between them.

The experts engaged in the project workshop noted that operational complexity and maintenance issues are key challenges in GSHP retrofit. However, a wider expert engaged in this study noted that a GSHP system normally needs less maintenance than an ASHP system.

The cost of installing a GSHP can be challenging to predict due to large variation in ground conditions, pipework requirements and the condition of existing plant. The literature review found that the range of costs for a GSHP product typically fell within £350-1,000/kW, while the full cost for the product, installation, accessories, and emitters fell within £1,000-2,200/kW.

### Heat pump/gas boiler hybrid

The evidence gathering and industry consultation undertaken during this study identified that a hybrid technology combining electrical and gas-driven heating could be a material part of the future decarbonisation of heat in non-domestic buildings. For this study, a hybrid solution, combining a heat pump with a gas boiler, was considered. A hybrid heat pump/gas boiler system was differentiated from a standard heat pump retrofit in that an existing gas boiler is retained and augmented with a smaller heat pump. In practise this means that the ASHP is used to supply space heating for the majority of the year, while the gas boiler is retained to supply peak heating demands during the coldest periods of the year when heat pump efficiencies might be lower. Experts engaged in this study suggested that a similar hybrid system could be operated with a biomass boiler.

## Biomass boilers

Biomass boilers are similar to conventional gas boilers but use a feedstock such as wood chips or pellets as a fuel source. They save carbon by using a fuel source which is effectively carbon neutral (in terms of combustion, excluding other emissions associated with its production). Biomass boilers normally require more space than fossil fuel-driven boilers for several reasons. Firstly, the feedstock is larger in volume, and an on-site store is typically required. Often biomass boilers will use an automatic feed hopper to reduce the operator cost for frequent manual refuelling.

Biomass use is currently very uncommon in the non-domestic building stock of England and Wales. BEES identified that less than 2 per cent of the energy used for space heating and hot water occurred in buildings using fuels other than gas, electricity, oil, liquefied petroleum gas (LPG) or district heating (it is assumed that this cohort includes but is not limited to buildings using biomass as a main heating fuel).

Interviews with supply chain experts and those responsible for HVAC in a variety of building contexts identified a number of challenges in the use of biomass for non-domestic HVAC:

- **Space and storage.** The applicability of biomass boilers to HVAC retrofit is limited to buildings with certain characteristics. The space requirements for biomass tend to favour rural rather than urban sites, and generally buildings in sub-sectors that have large estates, such as university buildings or hospitals.
- **Maintenance and management.** The relative complexity of operating biomass boilers compared with traditional gas-fired boilers means that they are more suited to sites with dedicated energy management responsibility such as an experienced site energy manager. Common issues cited included the control of the quality of feedstocks, the management of the input supply of feedstocks and maintenance issues. The associated costs also favour large organisations able to justify the capital expenditure.
- **Concerns around air quality.** The increasing attention on improving air quality in the UK by minimising emissions such as fine particulate matter (PM2.5), coarse particulate matter (PM10) and nitrous oxides also acts as a barrier against the uptake of biomass.

## Electric resistive heating

Electrical convection panel heaters and radiant heaters are commonplace in many sectors of the non-domestic building stock today. They represent a potential route to decarbonisation for buildings reliant on fossil fuel driven technologies.

**Radiant heaters** use radiant energy to supply heating. Radiant heaters are typically ceiling mounted and direct heat downwards onto people and workspaces at ground level. This can be particularly advantageous in contexts where the entire space does not need to be heated. Radiant heating is virtually instant and can work well when combined with time controls or presence sensors.

**Convection heaters** use a heating element to create air convective currents to circulate warm air through spaces. Convection heaters are preferable to radiant heaters where heating needs to be provided consistently throughout a room or building. A localised heating system, they may be fitted with time or temperature controls.

# Further technical considerations: Off gas-grid buildings

As given in Table 1, there are estimated to be around 73,000 premises in England and Wales using bulk fuels as their main heating fuel, of which the majority will use oil or LPG.[16] BEES identified that 6 per cent of non-domestic buildings by floor area were supplied with oil or LPG as their main heating fuel or were connected to a district heating system. It is likely that majority of these buildings are off the gas grid. A further 29 per cent of buildings used electricity as their main heating fuel. A sub-set of these buildings are also expected to be off the gas grid. Industrial buildings were the most likely to use bulk fuels as a main heating fuel (oil and LPG heated buildings accounted for 7 per cent of industrial buildings by floor area), followed by buildings in the education sector[17] (6 per cent of total) and buildings in the hospitality[18] sector (4 per cent of total).

Of the total non-electrical energy consumption predicted in BEES for the non-domestic stock, 3 per cent was anticipated to arise from the use of oil for heating and hot water, 2 per cent for district heating systems and 1 per cent from the use of LPG in heating and catering. Oil use represents about 9 per cent by end use for space/water heating and cooking across the non-domestic sector (service and industry) in the UK.[19]

Given the high carbon content of bulk fuels such as oil and LPG, buildings that do not have a mains gas supply are seen as having the greatest potential to reduce carbon emission and energy bills by switching to low carbon HVAC technologies.[20]

Analysis from the evidence review and consultation with industry experts have identified two potential options for buildings off the gas grid. It was noted that the majority of off gas grid buildings, according to BEES, did not require cooling. These two options are therefore driven by the heating and hot water demand for buildings. With cooling almost exclusively supplied electrically for buildings in this cohort, it is anticipated that traditional cooling technologies, such as direct expansion (DX) split units, will remain commonplace for off gas grid buildings that have requirements for cooling.

[16] Additionally, the ND-NEED geographical annex provides figures for buildings in 'off gas grid' areas: https://www.gov.uk/government/statistics/non-domestic-national-energy-efficiency-data-framework-nd-need-2020

[17] This includes nurseries, primary schools, secondary schools and university buildings.

[18] This includes cafes, restaurants, hotels, pub and takeaway food outlets.

[19] ECUK

[20] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/572514/Non-domestic_Heat_in_Buildings_call_for_evidence.pdf

# Methodology

This section provides an overview of the project methodology. Further information particularly relating to the literature review and industry engagement activities is provided in Appendices C and D. The data gathering and research stages were conducted in 2019, while the subsequent analysis was carried out in 2020.

## Modelling

### Baselining

Data from BEES provides a summary description of the way that heating, cooling, ventilation and hot water were supplied to each building record. In order to undertake the cost and performance modelling in this study it was necessary to describe each building's HVAC system in more detail, including the constituent components such as heating and cooling plant, distribution system and type of emitters. Through consultation within the Verco and Currie & Brown teams, a framework was developed, which is outlined in Figure 5.

This framework enabled the study team to assign each BEES building record to a simple but comprehensive description of services. A particular focus during this exercise was given to those components expected to have a material cost of installation/maintenance or to impact the scale and type of energy demand of a building's HVAC system if they were to be replaced or re-specified.

The present heating and cooling situation was expected to be an important determining factor in the choice of preferred HVAC solution in a given building. By developing a common typology this enabled a mapping of existing systems to suitable alternatives. The list of options was tested against BEES data to determine the frequency of different HVAC systems in the non-domestic stock.

It was necessary to consider low carbon HVAC technologies which were not present in the BEES sample data but likely to be part of the long-term strategy for the decarbonisation of heat. These included technologies such as biomass boilers. The study team identified a series of further low carbon HVAC technologies that were not already represented in the framework.

The approach was tested through consultation with third-party experts. Further detail on how the framework above was applied to inform the search fields for the literature review is discussed in Appendix F.

## Figure 5: Framework describing building HVAC system

| | HEATING | | | | | COOLING | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SPACE CONDITIONING | Primary heating fuel | Heating distribution system | Primary heating plant | Secondary heating plant | Heating emitters | Cooling fuel | Cooling system type | Cooling plant | Cooling emitters | VENTILATION | HOT WATER |
| Heating only | Electric | Central with LTHW | Boiler | CHP | Wet radiators (standard) | Electric | Central with air | Electric chiller | FCUs | Natural | Point-of-use electric |
| Heating & cooling | Gas | Central with low temp LTHW | ASHP | Boiler | Wet radiators (low temp) | None | Central with CHW | VRV/VRF | VRV/VRF units | Mechanical | Solar thermal |
| No heating or cooling | Bulk fuel | Central with air | GSHP | ASHP | 4-pipe FCUs with perimeter heating | | Central with refrigerant | None | VAV | | Gas-fired water heater/boiler |
| Cooling only | District Heating | Central with refrigerant | None | GSHP | 2-pipe FCUs with perimeter heating | | Local units with refrigerant | | None | | Dedicated heat pump |
| | Biomass | Central with ambient loop | | None | Electrical convector panels | | None | | | | None |
| | Hydrogen | Local units with refrigerant | | | Direct electric radiant panels | | | | | | |
| | None | Local units | | | Direct gas warm air heaters | | | | | | |
| | | None | | | Direct gas radiant heaters | | | | | | |
| | | | | | Direct electric warm air heaters | | | | | | |
| | | | | | VRV/VRF units | | | | | | |
| | | | | | VAV | | | | | | |
| | | | | | None | | | | | | |

**EXAMPLES**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Heating & cooling | Gas | Central with LTHW | Boiler | None | Wet radiators (standard) | Electric | Local units with refrigerant | None | VRV/VRF units | Mechanical | Gas-fired water heater/boiler |
| Heating only | Electric | Local units | None | None | Electrical convector panels | None | None | None | None | Natural | Point-of-use electric |
| Heating & cooling | Gas | Central with LTHW | Boiler | None | 4-pipe FCUs with perimeter heating | Electric | Central with CHW | Electric chiller | FCUs | Mechanical | Integrated (LTHW) |

## Application to BEES building record data

A mapping between the BEES telephone survey questions and the HVAC system framework was developed. Table 2 summarises this mapping. Across the top row are the twelve components of the HVAC system framework. On the left-hand column are the BEES telephone survey questions providing information relevant to predicting the HVAC arrangements of each building. The red, orange and green boxes in the table indicate where a specific question provided information enabling a particular HVAC element to be predicted for the building. The level of confidence of each mapping varies by HVAC component and is indicated using a High/Medium/Low indicator in Table 2. The level of confidence varies for two main reasons:

- **Lack of evidence from BEES.** In some cases the telephone survey did not capture the required information directly. An example of this is 'Heating emitters'. There was not a question in the BEES telephone survey asking about the type of emitters in place in the building. A series of assumptions were developed based on the study team's understanding of HVAC servicing in non-domestic buildings. This was applied to populate this element of the HVAC system framework.
- **Lack of confidence in BEES responses.** A key challenge faced during BEES arose from the fact that telephone survey respondents did not provide perfectly accurate information on building characteristics. This is particularly the case for HVAC servicing. The telephone survey respondent was often not an energy or facilities manager with detailed technical understanding of the HVAC servicing in the building. Closer inspection of the BEES telephone survey data identified a number of places in which respondent information was contradictory or inconsistent with standards servicing arrangements in their given sub-sector. Details of how this was resolved is documented in the final report for BEES.

**Table 2: Mapping between BEES telephone survey questions and HVAC system framework**

| HVAC framework element | | Space conditioning | Primary heating fuel | Heating system type | Primary heating plant | Secondary heating plant | Heating emitters | Cooling fuel | Cooling system type | Cooling plant | Cooling emitters | Ventilation | DHW system |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Q9 | Which one of these is the main energy source for heating the building? | H | H | H | | | L | | | | | | |
| Q10 | Do you use electricity to heat tap water and/or showers and if so how much? | | | | | | | | | | | | M |
| Q11a | Which one of the following best describes the ventilation in your building? | | | | | | | | | | | M | |
| Q12 | How much of the building has a mechanical cooling or air conditioning system? | H | | M | | | L | | | | | | |
| Q13b | Which low carbon or renewable technologies do you have dedicated to the building? | | | | | | | | | | | | H |
| B52a | What is the most common type of cooling system is installed in the building? | | | H | | | | | M | | | | |
| K2i-K2ii | What is the primary factory space heating method? | | | H | H | | | | | | | | |

The HVAC systems framework outlined in Figure 5 was applied to the BEES dataset of 3,690 building records. Each building's HVAC servicing was described using the 12 elements of the framework. A total of almost 200 unique combinations were identified. Many of the HVAC system combinations differed only slightly. In some cases the type and extent of heating and cooling servicing were identical but differences arose in terms of how hot water was supplied to the building. Some combinations were sufficiently similar that the same low carbon HVAC alternatives might apply. The system combinations were consolidated to support with modelling. To do this it was necessary to develop definitions for a smaller set of building types with similar HVAC characteristics. These were known as building 'archetypes'. A building 'archetype' is defined as a set of buildings with similar characteristics relating to their HVAC systems. Buildings within the same archetype share common features, principally in terms of how heating and/or cooling are supplied. There will be diversity within archetypes, with regards to HVAC, such as the way that hot water or ventilation is serviced. There is also diversity in terms of activity. It is anticipated that for buildings within the same archetype a common set of low carbon HVAC alternatives will be applicable.

The archetypes used on this project were developed by categorising the BEES building records into groups according to the type of HVAC servicing.

The process followed a set of working assumptions:

- The type of distribution system in a building – principally whether centralised or localised, and using which distribution medium - was deemed to be a key differentiator of viability of certain low carbon HVAC technologies. It was therefore agreed by the study team that buildings with differences across these characteristics should be placed under separate archetypes. The rationale for this approach was tested at the industry workshop and met with broad agreement.
- Cooling is almost exclusively electrically powered in non-domestic buildings. In most cases it was therefore agreed that the default scenario for cooling would be that the existing plant (typically an electric air- or water-cooled chiller) would be retained and replaced at the end of its service life, or that a separated heating system (such as a gas boiler and cooling only heat pump) would be replaced with a reversible heat pump system capable of supplying both heating and cooling. Nonetheless, the study still believed that the type of cooling system in each BEES building record would be a driver of the retrofit costs, and that the archetypes should separate buildings on this basis.
- Domestic hot water in non-domestic buildings is usually provided by some combination of a central boiler and point-of-use electric heaters. The boiler, if present, is usually separate from the space heating system but drawing on the same fuel source. The study assumed that electrification of space heating with a wet heat pump would be accompanied by installing a high-temperature ASHP for hot water provision.
- The study team agreed that buildings already using a low carbon HVAC technology – such as air or ground source heat pumps – should be identified separately as there is limited opportunities for carbon emission reductions from HVAC retrofit. These buildings represent approximately 2 per cent of the non-domestic building stock. For these

buildings, the cost predictions in this study assume a business-as-usual replacement of existing plant like-for-like at the end of service life. A further 2 per cent of buildings had no heating or cooling supply in the BEES data and would also not be subject to modelling.

The relative sizes of these cohorts are illustrated in Table 3. These are presented in order of commonality in the BEES building record data. Please note that the archetype numbers were designated before commonality was checked, so do not appear in numerical order. Some archetypes were further redefined during the modelling stage of the project. For clarity these were assigned non-continuous numbers.

The next phase of the analysis required a methodology for mapping between these HVAC system combinations and the potential low carbon HVAC alternatives. Appendix G provides a complete list of the low carbon HVAC technologies selected and key assumptions.

## Screening

With 20 building archetypes and 11 potential low carbon HVAC systems within scope there were more than 200 unique transitions to be considered. While it might be technically possible to retrofit any of the low carbon HVAC alternatives onto any of the building archetypes, there were some combinations which were highly unlikely to be undertaken for reasons of cost, complexity, lack of carbon impact, and in some cases duplication. A set of working assumptions were developed to identify which of the c.200 possible transitions should be modelled. This approach was tested through consultation at an industry workshop. The assumptions are outlined in Appendix H.

**Table 3: Summary of building HVAC archetypes used in study**

| Archetype number | HVAC system summary description | Percentage of total buildings by floor area | Cumulative percentage of total buildings by floor area | Percentage of total buildings by count | Cumulative percentage of total buildings by count |
|---|---|---|---|---|---|
| 1 | Gas boiler with radiators. No cooling system | 18% | 18% | 25% | 25% |
| 3 | Gas boiler with radiators or FCUs. Local refrigerant cooling system | 12% | 30% | 4% | 29% |
| 12 | Direct gas warm air heating. Mixed cooling systems | 11% | 40% | 3% | 32% |
| 2 | Electric resistive heating. No cooling system | 11% | 51% | 31% | 63% |
| 4 | Gas boiler with radiators or FCUs. Central water-based cooling system | 9% | 60% | 3% | 66% |

| Archetype number | HVAC system summary description | Percentage of total buildings by floor area | Cumulative percentage of total buildings by floor area | Percentage of total buildings by count | Cumulative percentage of total buildings by count |
|---|---|---|---|---|---|
| 11 | Direct gas radiant heating. Mixed cooling systems | 8% | 68% | 4% | 70% |
| 5 | Gas boiler with radiators or FCUs. Central air-based cooling system | 8% | 76% | 3% | 73% |
| 13 | Bulk fuel boilers with radiators. No cooling system | 5% | 81% | 5% | 77% |
| 8 | Electric heating, central air cooling | 3% | 84% | 3% | 81% |
| 7 | Electric heating, central chilled water/refrigerant cooling | 3% | 87% | 4% | 84% |
| 6 | Electric heating, local refrigerant cooling | 3% | 90% | 5% | 89% |
| 9 | No heating or cooling | 2% | 92% | 6% | 95% |
| 28 | Electric heating, central air cooling | 2% | 94% | 2% | 97% |

| Archetype number | HVAC system summary description | Percentage of total buildings by floor area | Cumulative percentage of total buildings by floor area | Percentage of total buildings by count | Cumulative percentage of total buildings by count |
|---|---|---|---|---|---|
| 14 | Air source/ground source heat pump. Mixed cooling systems | 1% | 95% | 1% | 97% |
| 15 | Central with refrigerant for heating and cooling | 1% | 96% | 0% | 98% |
| 16 | Boiler, wet system, cooling with VRV/VRF | 1% | 97% | 0% | 98% |
| 27 | Electric heating, central chilled water/refrigerant cooling | 1% | 98% | 0% | 98% |
| 17 | District Heating. Mixed cooling systems | 1% | 99% | 0% | 99% |
| 10 | No heating. Mixed cooling systems | 1% | 100% | 1% | 100% |
| 18 | Biomass boiler. Mixed cooling systems | 0% | 100% | 0% | 100% |

### Calculations

The cost and performance assumptions outlined in this report were incorporated into the BEIS Non-Domestic Buildings Model, accompanying the findings and assumptions around energy efficiency gathered during the BEES project. This model is designed to determine a possible response by the non-domestic sector to a user-designed policy scenario, by determining the optimal abatement measure installation response to some form of target, at the level of individual buildings.

### Weighting

In alignment with the methodology for the original BEES project, all the data generated was weighted upwards to represent the sub-sector population. Individual weighting factors were calculated for each premises based on the estimated prevalence of premises of that floor area in the overall population. The overall sector population statistics were compiled from a range of published sources and have been collated in a population table. This table can be found in the technical annex for BEES.[21]

### Validation

In order to test the findings of this project, a series of study findings were externally tested by third party experts. These are outlined in Appendix I. A series of challenges faced during the methodology and how these were overcome is outlined below.

## Challenges faced during study

This section outlines the main challenges and limitations encountered by the study team during the course of this project, along with the steps taken to address them. These are listed in order of materiality.

**Static energy baseline.** The aim of BEES was to provide a snapshot of the energy consumption of the non-domestic stock. By using the BEES energy consumption prediction as a baseline, this study does not account for any changes in demand. This is acknowledged as a risk, especially given the likelihood of increased cooling demand in the future as a result of climate change. Heating demand may also be aversely affected by more frequent extreme weather events in a changing climate.

**Contradictions and lack of detail in the telephone survey.** This study was reliant on the quality of the BEES telephone survey data to generate predictions about building HVAC systems. With over 80 questions in an average telephone survey there are known instances of respondents providing two or more conflicting responses to similar questions. This was especially relevant to building HVAC systems as a). the questions were generally quite

[21] Building Energy Efficiency Survey (BEES): Technical Annex, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566038/BEES_Technical_Annex_FINAL.pdf

simplified to enable understanding by a layperson, and b). this is an area of building energy consumption where respondent knowledge was found to be poor.

While this was remedied wherever possible in BEES, some of the predictions made in this project are based on the study team's expectations of HVAC servicing of non-domestic buildings and not on primary evidence. One example of this is the type of heating emitters in each BEES record – this was not a question in the telephone survey and so has been inferred based on factors such as the distribution system type and main heating fuel of the building.

One area of the project likely to be impacted by this issue is the allocation of BEES building records to building archetypes. Inconsistencies in the underlying data created 'edge cases' whose archetype could not be assigned with the general algorithm. For these buildings a consistent interpretation was selected by hand. This issue affected fewer than 3 per cent of building records.

**Contradiction between telephone survey and EUM data:** This challenge is related to point (2) above. During BEES the telephone survey responses were used to develop a prediction of the baseline energy consumption of each modelled building record using an energy use model. In some cases where information in the telephone survey was believed to be incorrect, it was superseded with alternative assumptions, but the relevant telephone survey responses were not retrospectively changed. This means that the telephone survey and the energy use model descriptions of each building record were not always entirely consistent. This was problematic in this study as the more detailed descriptions of building HVAC systems were derived using information form the telephone survey responses. Once this issue was identified it was agreed that for the affected records, the baseline energy prediction would be recalculated to account for an improved understanding of the building HVAC system developed during this study. The impact on the predicted baseline energy demand for the non-domestic stock as a whole was immaterial.

**Sample size limitations.** For some BEES sub-sectors there were challenges in collecting data. This means that the sample size for some sub-sectors is small and may not be representative of the wider non-domestic building stock, even after the results are weighted to reflect England and Wales. In some cases, non-standard data collection methods were used – such as completing large numbers of surveys through contacts known to the study team, or in the case of the retail sector the use of mystery shoppers. In these cases, the HVAC systems found in the buildings surveyed may not be representative of the wider building stock and may over- or under-represent certain technologies.

**Weighting factors.** The weighting factors used in this study are taken from BEES and were derived based on certain building characteristics including energy intensity, building size and rural/urban location. When applied to the BEES sample to scale the results, it is assumed that the final outcome will be representative of the overall non-domestic stock. However, it may be the case that the distribution of buildings by these variables is not consistent with the distribution by HVAC system type. This may mean that the final results of this study are not representative of the non-domestic stock as a whole. The study team do not believe that this will have a material impact on the findings.

**Variability and reliability of system performance and cost data.** The literature review conducted for this study showed that the reported performance and efficiency of HVAC technologies – most notably heat pumps – are highly variable and dependent on a large number of factors. Many of these factors are outside the scope of this study and it was necessary to use generic values to expedite modelling. This means that the predictions for heat pump cost and performance at the individual building level may be less accurate.

With regards to performance variables – such as COPs and efficiencies – the inclusion of both field trials, academic studies and manufacturers literature lead to a wide spread of values. Performance data of heat pumps from field trials was expressed differently in terms of test conditions, measurement scope and repeatability.

**Lack of performance and cost data for certain HVAC technologies:** For some low carbon HVAC technologies the market for relevant products is highly immature (or non-existent) and field trials are highly limited e.g. biomass boilers. This meant that cost and performance parameters to be used for modelling were unavailable. To remedy this the study team engaged directly with technology developers to collect best-available cost and performance data where it was not available publicly.

**Challenges in generalising costing approach to all buildings.** This study uses a consolidation approach to categorise the diversity of non-domestic building HVAC systems into a manageable number of building archetypes. A series of costing assumptions are then applied to predict the capital and operational costs of switching these buildings to low carbon HVAC alternatives. This presents challenges because even within carefully defined archetypes, the starting position for each building record in terms of HVAC system will not be exactly the same. Buildings within the same archetype may also vary in other ways that are potentially relevant to the viability and costs of undertaking HVAC retrofit projects. These include their core activity, operating hours, location or whether they provide critical services. The costing assumptions used in this study do not vary with any of these factors – instead they are principally functions of building extent and the heating and cooling demand of each building record. The costing assumptions are also fixed in time and do not include any allowance in the future for cost reductions due to further market penetration of technologies or other changes in capital costs over time. The study team recognise that retrofit cost may vary based on geographical location in the UK.

The study team believe that the approach chosen will provide sufficiently granular predictions for the purposes of this study. Given the uncertainties in underlying information from the BEES telephone survey it is acknowledged that the modelling in this study will not be perfectly accurate at the individual building

**Interaction between HVAC and other energy uses.** This study does not consider any interactions effects between HVAC energy end uses and others within a building. The study team believe that the most material of these may occur in the industrial sector due to the interaction between HVAC systems and incidental heating and cooling from industrial processes. As industrial process energy was not included within the scope of BEES it was not possible to explore this issue in this study.

The study team believe that there may be other instances of interaction between HVAC energy use and other energy uses. This may be an important consideration in selecting an appropriate low carbon HVAC system for a given non-domestic context. Further examples might include the interaction between a building cooling and ventilation systems and the energy used for IT equipment and servers.

**Potential for use of on-site energy/thermal storage or generation.** This study did not consider the potential for the use of on-site energy storage – either in the form of batteries for storing electrical energy, or water tanks or other technologies for thermal storage. This could potentially reduce the capital costs of low carbon HVAC by enabling the storage of thermal or electrical energy to be used during times of peak HVAC energy consumption. In the context of a heat pump, on-site storage could mean that a smaller heat pump capacity is required to provide the same level of servicing. This could significantly reduce the capital cost of such a retrofit project. It might also support a reduction in the operating costs through access to time-of-use energy tariffs in the future.

A related area not explored in this study is the potential for on-site renewable energy generation and associated interactions with low carbon HVAC systems. An increase in on-site renewable generation could facilitate further electrification of building HVAC systems by reducing the burden on the national grid. It could also be used in tandem with storage technologies, using renewable, locally generated sources of energy to provide a portion of the heating or cooling load.

# Cost and performance

Table 4 shows a summary of the assessed cost (exclusive of Value Added Tax, VAT) and performance parameters for the HVAC systems within the scope of the study. These figures were either gathered through the course of the literature review in 2019 or reflect normalised or summarised outputs from the modelling.

The in-situ performance coefficients reflects the efficiency of the system. Systems with a coefficient of less than 1 are typically those using bulk fuels, converting chemical energy into thermal energy, with some losses occurring leading to an imperfect efficiency. Systems with a coefficient above 1 are heat pump technologies that gather ambient local heat from an external source, such as the air or the ground. The efficiency of electrical heating systems is typically 1 or close to 1 as all energy is converted into useful heat.

The typical lifetime of technologies is 15 to 20 years.

The capital costs of the technologies differ significantly. Electric resistive heating through electrical panel radiators or direct electric warm air heaters represent the lowest capital cost at an average of £210/kW capacity. The replacement of gas boilers like-for-like, or oil-fired boilers like-for-like, is estimated to cost an average of £240/kW and £290/kW respectively. It should be noted that these costs include all generation plant and wider installation costs. Table 5 provides a breakdown of this capital cost figure by project stage.  These figures have been rounded to the nearest £10/kW.

Many of the low carbon HVAC technologies are significantly more capital intensive than conventional technologies. ASHPs are estimated to cost in the region of £1530/kW for an air-to-water system and £800/kW for an air-to-air system. This is three to five times more expensive than a gas boiler. For a GSHP system, the costs are even higher at around £2,690/kW – driven by the significant cost associated with groundworks.

Table 5, Figure 6 and Figure 7 shows the proportion of total capital cost by main heating technology that is assessed to fall into each of the four costing stages employed in this project – preparatory works, installation, completion and sundries.

In addition to the itemised costs for installation and completion, the evidence gathered in this literature review of this project highlighted that HVAC retrofit projects often incur further 'wraparound' costs to account for testing and commissioning, 'builder's work in connection' (BWIC) costs[22], M&E preliminaries, design fees and project contingency costs. In order to provide a more rounded estimation of project costs, these have been modelled and applied as a percentage uplift on the total of the itemised cost elements – these are captured in the 'sundries' column.  The costs associated with these processes are estimated as approximately 50% of the sum cost of the other components.

[22] BWIC refers to builder's work that is necessary as a result of other works, typically mechanical and electrical services but also specialist installations.

The technologies in Figure 7 have been arranged in order of the proportion of the total cost in the ‘installation’ category. This category includes the capital cost of the main heating plant and normally forms the largest single component of the total cost. The graph shows that for GSHP, biomass boilers and ASHP solutions, the main generation plant is capital intensive and represents more than half of the total capital cost of the retrofit project (60 per cent, 56 per cent and 56 per cent respectively). In contrast, for the electric resistive heating solution, the capital cost of the main heating plant represents less than 30 per cent of the total retrofit costs. The GSHP and biomass solutions are the most capital-intensive in absolute terms.

**Table 4: Summary of the assessed cost and performance parameters for the HVAC systems within scope of study**

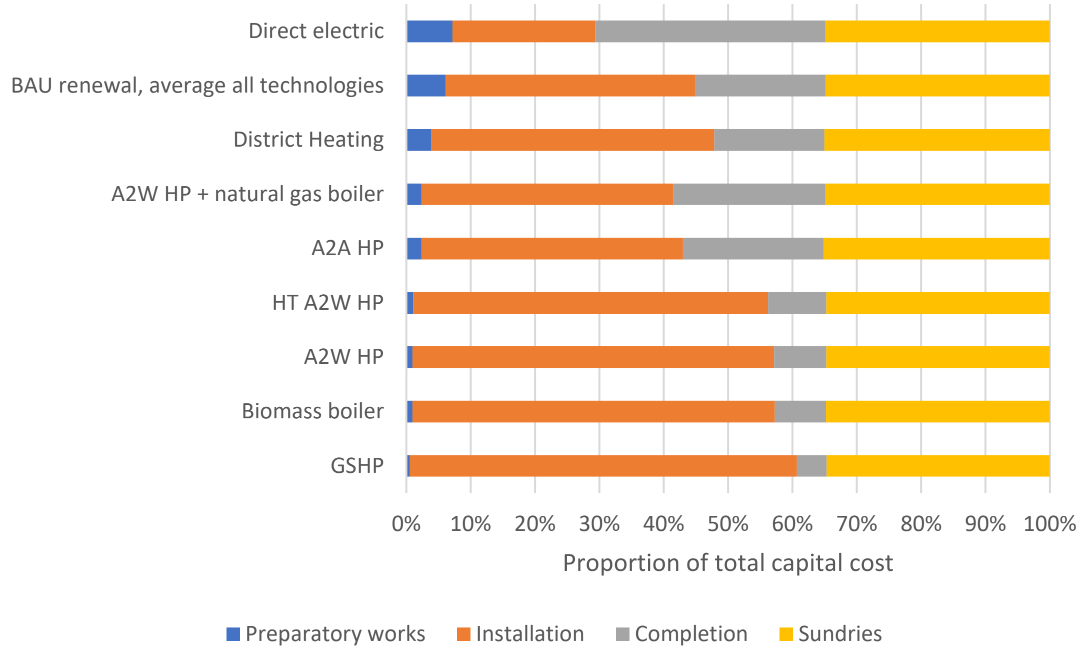
| Technology | In-situ performance Coefficient | Lifetime | Capex, £/kW (exclusive of VAT) | Opex, £/kW/yr[23] (exclusive of VAT) |
|---|---|---|---|---|
| Ground source heat pump | 3.12 | 20 | 2,690 | 6 |
| Biomass boiler | 0.78 | 20 | 1,560 | 13 |
| Air-to-water heat pump | 2.83 | 20 | 1,530 | 6 |
| High temperature air-to-water heat pump | 2.27 | 20 | 1,370 | 6 |
| Air-to-air heat pump | 2.83 | 20 | 800 | 10 |
| Air-to-water heat pump/Gas Boiler Hybrid | n/a[24] | 20 | 630 | 9 |
| District heating | n/a[25] | 25 | 380 | 0 |
| BAU renewal, average all technologies | 0.86 | 15-20 | 240-290 | 6 |
| Electric resistive | 1.00 | 15 | 210 | 3 |

[23] This excludes fuel costs
[24] Air-to-water heat pump/gas boiler hybrid systems will have an in-situ perf coefficient that is dependent on the relative utilisation of the two technologies. This has not been assessed in detail in this study.
[25] The efficiency of district heating systems is dependent on the choice of input fuel and other system parameters, which are often driven by highly context-specific variables. District heating was not actively explored in the modelling for this commissions but summary outputs from the literature review are presented in this table. District heating costs and service life figures relate to equipment cited within the building.

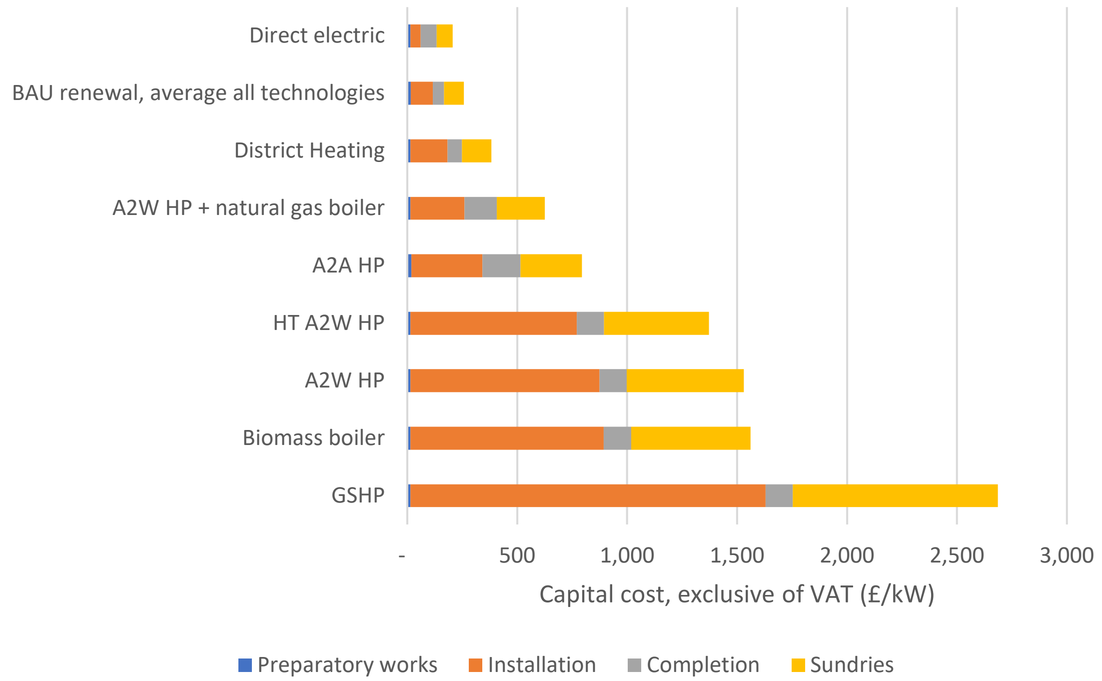
**Table 5: Breakdown of system capital costs by stage**

| | Capital cost, exclusive of VAT (£/kW) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Technologies** | **Preparatory works** | | **Installation** | | **Completion** | | **Sundries** | | **Total** |
| GSHP | 15 | 1% | 1,620 | 60% | 120 | 5% | 930 | 35% | 2,690 |
| Biomass boiler | 15 | 1% | 880 | 56% | 120 | 8% | 540 | 35% | 1,560 |
| A2W HP | 15 | 1% | 860 | 56% | 120 | 8% | 530 | 35% | 1,530 |
| HT A2W HP | 15 | 1% | 760 | 55% | 120 | 9% | 480 | 35% | 1,370 |
| A2A HP | 19 | 2% | 320 | 41% | 180 | 22% | 280 | 35% | 800 |
| A2W HP + natural gas boiler | 15 | 2% | 250 | 39% | 150 | 24% | 220 | 35% | 630 |
| District Heating | 15 | 4% | 170 | 44% | 70 | 17% | 130 | 35% | 380 |
| BAU renewal, average all technologies | 16 | 6% | 100 | 39% | 50 | 20% | 90 | 35% | 260 |
| Electrification | 15 | 7% | 46 | 22% | 74 | 36% | 72 | 35% | 210 |

## Figure 6: Proportion of assessed system capital costs by stage




## Figure 7: Breakdown of absolute system capital costs by stage



# Appendix A: BEES questions relating to HVAC

| Question Code | Question | Relevant HVAC component |
|---|---|---|
| Q8 | Does the premise you occupy have its own dedicated building services plant (e.g. heating, and ventilation or cooling if present) or is this provided from central systems serving the whole building? | HVAC in general |
| Q9b | Which one of these is the main energy source for heating the building? | Heating |
| Q9bi | What is the fuel used to generate the heat for the district heat system? | Heating |
| Q9c | How much of the building is heated in winter? | Heating |
| Q10 | Do you use electricity to heat tap water and/or showers and if so how much? | Domestic Hot Water |
| Q11a | Which one of the following best describes the ventilation in your building? | Ventilation |
| Q11b | Approximately how much of the building uses mechanical ventilation? | Ventilation |
| Q12 | How much of the building has a mechanical cooling or air conditioning system? | Ventilation/Cooling |
| Q13b | Which low carbon or renewable technologies do you have dedicated to the building? | Heating/Cooling |
| BS1a | How old are the boilers providing heating for the building? | Heating |
| BS1b | What heating controls do you have in the building? | Heating |
| BS1c | How comfortable is the temperature in the building in winter? | Heating |
| BS2a | What is the most common type of cooling system is installed in the building? | Cooling |
| BS2b | How old is the cooling plant? | Cooling |
| **Question Code** | **Question** | **Relevant HVAC component** |
| BS2ci | What cooling controls do you have in the building? | Cooling |
| BS2cii | Which of the following applies to your building in terms of cooling? | Cooling |

| | | |
|---|---|---|
| BS2d | How comfortable is the internal temperature in warm summer weather? | Cooling |
| BS3a | What type of mechanical ventilation is most commonly used in the building? | Ventilation |
| BS3b | How old are your air handling units which provide central ventilation? | Ventilation |
| BS3c | How good are the ventilation controls you have in the building? | Ventilation |
| BS5 | How well or poorly do you think energy is managed in your building? | HVAC in general |
| Q16 | Which of the following would you say describes the attitude of your organisation towards energy consumption? | HVAC in general |
| Q17 | Who is responsible for energy management in your building? | HVAC in general |
| Q18b | How recently have your building services and/or external spaces been subject to a major refit? | HVAC in general |
| Q19 | How old is the building? | HVAC in general |
| Q20 | How would you describe the general condition of your building, especially the fabric (i.e. the walls, roof and floors)? | HVAC in general |

# Appendix B: HVAC in six key building types

The following sections provide a discussion of HVAC characteristics in six key building types within the non-domestic stock. These were selected for closer inspection either because they represent significant proportions of non-domestic HVAC energy use or are considered to have more complex HVAC systems, or both. Together they account for 49 per cent of the total energy use within non-domestic buildings, and 49 per cent of the total energy used for HVAC in non-domestic buildings. Table 6 provides a summary of key HVAC characteristics for the six building types.

**Figure 8: Energy consumption by end use by sector**

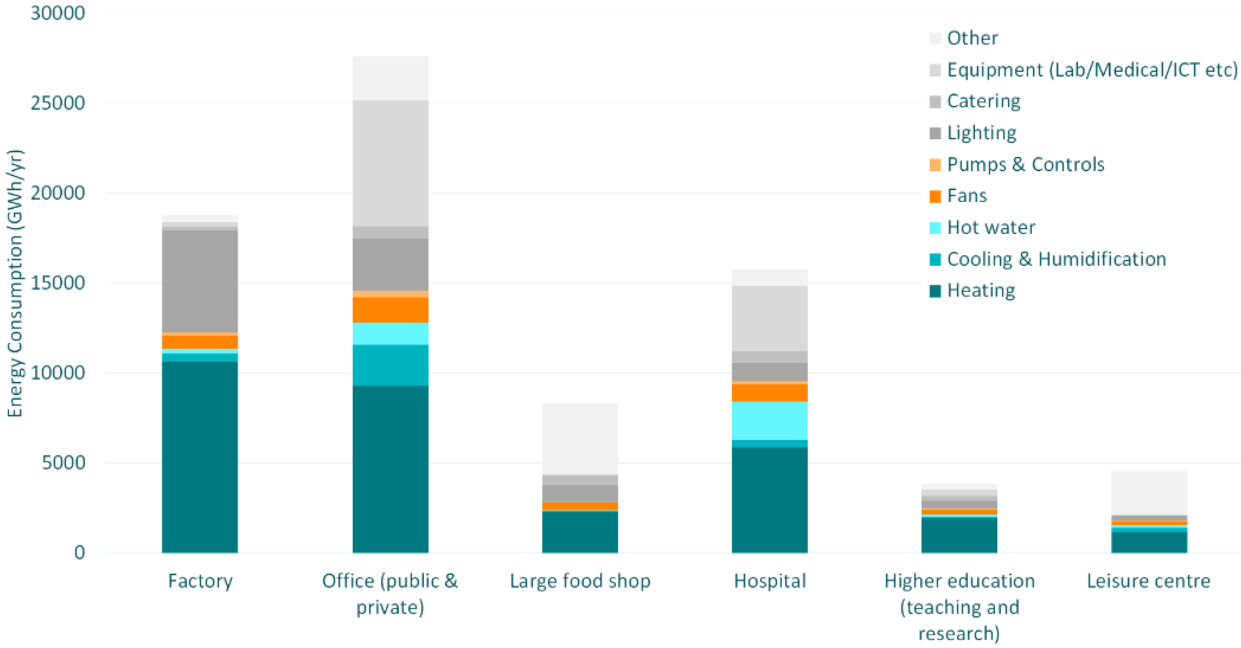


**Table 6: Summary of key HVAC characteristics for the six building types**

| | Offices | Factory | Hospital | Large food shop | Higher education | Leisure centre | Total |
|---|---|---|---|---|---|---|---|
| Total energy consumption (GWh/yr) | 27,620 | 18,840 | 15,780 | 8,310 | 3,870 | 4,590 | **79,010** |
| % of total UK non-domestic energy consumption | 17% | 12% | 10% | 5% | 2% | 3% | **49%** |
| Total energy consumption for HVAC (GWh) | 14,480 | 12,290 | 9,550 | 2,850 | 2,480 | 1,830 | **43,480** |
| % of total UK non-domestic energy consumption for HVAC | 16% | 14% | 11% | 3% | 3% | 2% | **49%** |
| Median energy intensity (kWh/m$^2$/yr) | 156 | 80 | 390 | 581 | 192 | 500 | |
| % of median energy intensity used for HVAC | 78% | 78% | 59% | 33% | 74% | 43% | |

# Factories

BEES reported that industrial and storage buildings account for 24 per cent of the total energy use for non-domestic buildings and 28 per cent of the total energy use for HVAC.[26] Factories, workshops and large industrial buildings were the three categories of industrial buildings defined by BEES.[27] Factories specifically account for 14 per cent of all energy use for HVAC in non-domestic buildings.

Analysis of data from BEES allowed for an understanding of the characteristics of HVAC use in factories. More than half of buildings in the sector use a localised heating and/or cooling system. Most commonly this is natural gas-fired, such as gas-fired direct warm air heaters or gas-fired radiant panel heaters (80 per cent of buildings by total floor area), or electrical radiant or convector panels. Where a wet central heating system is used, this is commonly gas-fired, although there was a larger proportion of such systems using bulk fuels or biomass as the main heating fuel in industrial buildings than in other non-domestic sectors. Where cooling is required, it is commonly supplied using a central chilled water-based system (37 per cent of total) or local, refrigerant-based systems such as DX split units[28] (14 per cent of total). The majority of industrial buildings are mechanically ventilated (56 per cent of total).

Engagement with industry experts in a semi-structured interview format provided further detail on the extent of HVAC servicing in factories. Respondents reported that many industrial buildings do not require substantial space heating due to the heat generated by the processes. Overheating of spaces can often be the main challenge in industrial buildings from an HVAC perspective. This is discussed further in a later section. The use of space cooling for the comfort of occupants is also uncommon. Where space heating does exist, large industrial spaces are typically heated using localised heating technologies such as gas radiant panels in order to "*heat the people rather than the air*".

Space heating was reported to be a useful 'low grade heat sink' – on some industrial sites waste heat from industrial processes is redirected to office areas, sometimes in separate buildings, to provide heat for space heating and hot water. While industrial process energy use was outside the scope of BEES, around one-fifth of buildings in the industrial and storage sectors reported that recovered heat from industrial processes was the main source of space heating and hot water. The interaction between processes and HVAC in industrial buildings raises technical considerations around the decarbonisation of manufacturing processes as well as space heating and hot water in an industrial context.

[26] These include factories, workshops, large industrial buildings, stores, warehouses and large distribution centres. These building types are linked by typically having only a small proportion of their space heated. Often this uses local heating which is particularly hard to decarbonise: there may be no alternative to resistive/high-temperature electrification.

[27] Factories' refers to buildings used for manufacturing or assembling goods. This may include heavy industry, large scale manufacturing, chemical, food, metals, minerals, brewing and other large scale production & processing activities. Typically a factory includes a main production area that has high-ceilings and contains heavy equipment used for assembly line production. Gross floor area should include all space within the building(s) at the plant, including production areas, offices, conference rooms, employee break rooms, storage areas, mechanical rooms, stairways, and lift shafts.

[28] This refers to a direct expansion air conditioning system which directly cools air supplied indoors using a condensed refrigerant.

Experts involved in HVAC in industrial contexts were engaged as part of this study. They highlighted what they perceived as a significant opportunity to increase the use of industrial waste heat recovery for space heating and hot water. In general, the level of comfort heating and cooling required is reported to be lower in industrial spaces – the average set point temperature for heating systems quoted by BEES respondents in industrial buildings was lower than in offices or retail premises (16-19ºC, compared with 20-22ºC respectively). One respondent who worked for a major industrial business reported that the energy used for lighting and ventilating spaces constituted less than 5 per cent of their site's total energy consumption and was met using energy recovered from thermal processes. A further respondent working in a similar industrial context noted that energy use for HVAC comprised less than 1 per cent of the energy use in the business. The overheating of spaces as a consequence of industrial process loads was also noted as a challenge in some industrial contexts which could become more problematic in the future.

One option for the decarbonisation of HVAC in industrial buildings cited by multiple respondents in this study is the use of heat pumps to uplift waste heat from industrial processes. One respondent noted that this can lead to heat pump efficiencies ranging from 4 to 11. Mechanical ventilation exhausts may also be a viable source - even in cases where passive heat recovery already exists, adding a second stage using a heat pump will generally increase efficiencies above standard heat pumps sourcing heat at external ambient air temperatures.

Respondents also noted challenges in the use of industrial waste heat for HVAC. In some contexts the industrial processes may be constant (such as a 24-hour operational manufacturing process) while the space heating demand (which may be for staff in a service office) may not. To use recovered heat for space heating and hot water may require another use for the heat outside of the hours in which occupied spaces need to be serviced. By contrast, industrial process may actually be irregular and not match the profile required for space heating. This can make control of occupant comfort difficult, although this can be overcome with a thermal store on the heating circuit. Hot water supply was noted by one respondent as a better application for recovered industrial heat than space heating since all that is required is a simple hot water tank, rather than a supply and return of hot water for space heating.

In this study the increased use of industrial waste heat to supply space heating and hot water for buildings was not modelled. The evidence base from BEES did not allow further investigation into this potential as the characteristics of the industrial processes being carried out in each building record were not known with confidence. Industrial processes were outside the scope of the BEES study.

## Offices

Offices account for 17 per cent of the total energy use from non-domestic buildings and 16 per cent of the total energy use for HVAC in non-domestic buildings.

Offices within the BEES dataset are highly diverse in terms of their HVAC servicing arrangements. The majority of office buildings (70 per cent by total floor area) were provided with both heating and cooling, with most of the remainder requiring heating only. Around half of offices (49 per cent) are mechanically ventilated.

Cooling systems found within offices are diverse in terms of the type of distribution system and emitters. The majority of offices with cooling used a centralised system for cooling, with chilled water distribution from a central chiller or set of chillers being the most common arrangement (28 per cent of office buildings by floor area). Centralised cooling systems using cold air and refrigerant based systems represent a further 19 per cent and 9 per cent of office buildings. The remaining 13 per cent of offices with cooling use local, refrigerant-based cooling plant. Offices with a centralised cooling system were on average larger than those with a localised cooling system (on average private offices with a localised system were c.500 $m^2$ in floor area, compared with 1,000-1,500 $m^2$ for a centralised system). Many office buildings – particularly large offices – use combined HVAC systems capable of supplying both heating and cooling.

The majority of office buildings use natural gas boilers and a low temperature hot water distribution system to supply heating (65 per cent of total). A small number of office buildings use bulk fuels (2 per cent) or biomass (<1 per cent). The majority of office buildings using a centralised boiler-based heating system use radiators as the system emitters (48 per cent of office buildings in total). 13 per cent of office buildings are understood to use FCUs to supply heating, while a further 11 per cent using Variable Air Volume systems.

Electrically heated office buildings represent around one third of the total (35 per cent). The majority of these buildings use electrical convector panels as the main heating system.

Engagement with an industry expert in a semi-structured interview format provided insight on the challenges of decarbonising HVAC in office buildings. The respondent reported that electric resistive heating was expected to become more attractive from a carbon emissions reduction perspective, driven by ongoing reductions in the grid electricity carbon intensity in the UK. A further expert engaged on this project noted that finite grid capacity may be likely to lead to this approach being penalised or disincentivised via tariffs.

The respondent noted that there has been a tendency within the industry to overstate the heating requirements of office buildings, with an inclination on specifying heating systems (often gas boiler led) that look at a ‘full heat up’ scenario with no consideration of internal gains. The expert respondent was optimistic that air source heat pumps could be applied widely across the office building stock of England and Wales. For office buildings that are already electrically heated and without a wet central heating system, air-to-air heat pump technology was seen as an attractive option for decarbonising HVAC.

The respondent noted that a number of low carbon HVAC technologies present challenges around retrofit in the office building context. Biomass boilers raise concerns around air quality and space requirements. As a result, the respondent did not expect biomass to be a statistically significant portion of the office stock in the future. Combined Heat and Power (CHP) was also deemed unlikely to feature in the future for similar reasons, and due to the decarbonisation of grid electricity diminishing the carbon savings derived from CHP. GSHPs were also noted as challenging for retrofit due to the space and cost requirements of installing ground loops. Vertically aligned ground source heat pumps require the digging of boreholes, while horizonal ground arrays require large unbuilt site areas.

The timing of low carbon HVAC retrofit in office buildings was discussed. The replacement of traditional HVAC systems with lower carbon alternatives was noted as more likely to occur when plant is nearing the end of its service life. The respondent cited that in their experience of buildings with both boilers and chillers, chillers required more frequent replacement or servicing, with a lifetime of between 15-20 years compared with 25 for a boiler.

### Large food shops

Large food shops were defined in BEES as premises used for the retail of food products and items, with a total floor area exceeding 750 $m^2$. This includes supermarkets. Large food shops account for 4 per cent of the total energy use from non-domestic buildings and 2 per cent of the total energy use for HVAC in non-domestic buildings.

Large food shops typically have a high degree of HVAC servicing. Buildings in this sector within the BEES dataset were relatively homogenous in contrast with other sectors. It should be noted that limited engagement by respondents resulted in an insufficient sample size for telephone surveys or site surveys via the standard method during BEES. To address this, non-standard methods of data collection were used, ranging from using data from existing research programmes, specially arranged site surveys or use of mystery shoppers. The mystery shopper methodology involved a site surveyor visiting a premises posing as a casual shopper to collect basic information. The information collected via this method excluded what could not be identified through visual surveys of the customer areas or outside of the store. It is anticipated that this will limit confidence in the findings for this sub-sector relating to HVAC systems. The details of this are outlined in the BEES Overarching Report.[29]

Almost all buildings in the dataset under this category are mechanically ventilated (99 per cent) and 85 per cent are provided with both heating and cooling. The majority of buildings use a natural gas fired boiler to supply heating and hot water (97 per cent).In terms of cooling systems, 45 per cent of buildings reported having a centralised cold air-based cooling system distributed with Variable Air Volume terminal units. 48 per cent of buildings reported having localised refrigerant-based cooling units, distributing via Variable Refrigerant Flow terminal units.

Engagement with an industry expert in a semi-structured interview format provided insight on the challenges of decarbonising HVAC in retail buildings. The respondent noted that a number of HVAC technologies within the scope of this study present logistical and commercial challenges for retrofit in a retail context. Biomass boilers were noted as being expensive to install and prone to maintenance issues by comparison with cheaper and more reliable gas boilers. The space requirements of biomass fuel storage were also quoted as a challenge.

29 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/565748/BEES_overarching_report_FINAL.pdf

CHP was also noted as not being appropriate for a retail context due to the relatively low heating and hot water requirements of such buildings, which can be met with more conventional technologies (such as gas-fired boilers).

GSHPs were not seen as an attractive option for retrofit due to the prohibitive costs and challenges around space. While district heating was seen as a potential option for the decarbonisation of heating and cooling, the respondent noted challenges from their experience due to high cost of energy (taking both unit cost and standing charges into account), water quality issues and the need for the returned water from the system to meet a specified temperature, which can be difficult to achieve. However this is highly contingent on the fuel source for the district heating system – gas-fired systems offering little if any carbon savings compared with electrified options.

Solar thermal technology was seen as having useful applications for large retail buildings with available roof space in supplying hot water or supplementing central heating systems by pre-heating the water. However, the current cost of the technology was seen as a barrier and domestic hot water is typically a small component of energy demand for this building type.

### Hospitals

Hospital buildings generally have high levels of HVAC servicing. This is driven by their long hours of operation, with many hospitals operating 24 hours per day and the need for high levels of air conditioning to maintain hygiene levels. Analysis of BEES data found that the vast majority of hospital buildings were supplied with both heating and cooling (98 per cent by floor area) and a large proportion were mechanically ventilated (83 per cent).

The vast majority of hospitals use natural gas-fired boilers and a wet central heating system to supply heating via radiators (54 per cent of total hospital buildings by floor area), fan coil terminal units (19 per cent) or Variable Air Volume terminal units (26 per cent). A further minority were connected to district heating systems (1.5 per cent of the total) or were electrically heated (1.5 per cent).

Engagement with industry experts in a semi-structured interview format provided further detail on the extent of HVAC servicing in hospitals. Respondents reported that air conditioning in hospitals tends to be concentrated in theatres and transitional care unit (TCUs). Heating in hospitals is usually provided using steam or medium/high temperature hot water provided by boilers.

Respondents noted the need for hospitals to be able to operate resiliently, often employing a secondary form of heating supply as a backup to ensure that critical services are not interrupted by disruptions to the power supply or maintenance issues with HVAC plant. This suggests that where low carbon HVAC plant is retrofitted to hospital buildings, the existing plant may be retained and become the back-up. GSHPs were deemed unlikely to be applicable as the sole heat source for hospitals owing to challenges around ground space for installing arrays. One respondent noted that a ground source heat pump at the scale of 1-4 MW would be necessary to provide sufficient heat load for an acute hospital. This would require a large array, demanding a large amount of space typically not available on hospital estates.

The respondents noted challenges relating to the widespread deployment of heat pump technologies in hospitals. Firstly, they noted constraints around network capacity. Secondly, they noted concerns around the potential transition costs. With many hospitals using steam or medium temperature hot water as a distribution medium in HVAC systems, switching to a technology using low temperature hot water could require significant changes to wider plant. The expense and logistical challenge of replacing or modifying radiators, fan coil units and air handling units in an average large hospital could be prohibitive. While high temperature heat pumps are an option, in the experience of the respondents these tend to be water-source rather than air-source heat pumps, which restricts their availability.

The respondents noted that the carbon saving potential of CHP has fallen significantly, with most hospital CHP schemes driven by economic incentives. With respect to biomass as an alternative to fossil fuels for heating plant, a number of challenges were noted. This included issues with storage, the sourcing of feedstocks and local air quality – challenges common in other non-domestic sectors. Unique challenges of using biomass in the health sector were also noted. This included those of access and congestion common around hospital buildings and the importance of avoiding dust accessing clinical areas such as cancer wards due to potential health hazards.

Thermal storage was noted as a potential enabling technology for low carbon HVAC systems in the future.

### Higher education buildings for teaching and research

This sub-sector refers to premises used for the purposes of higher education. This includes public and private colleges and universities but excludes residential buildings. This includes a very high diversity of buildings containing classrooms, laboratories, offices, cafeterias, maintenance facilities, arts facilities, athletic facilities, storage rooms.

It should be noted that the sample size from BEES for this sub-sector was small. Due to challenges in data collection most of the telephone survey records in this sub-sector were collected via non-standard methods through known contacts within the sector. Consequently, the diversity of HVAC systems within the sample is expected to be lower than the full cohort of such buildings in England and Wales.

The mix of HVAC servicing in buildings within this sub-sector is notably more diverse than the other sub-sectors analysed in this appendix. This is understood to reflect the relative diversity of building applications in this sub-sector. The majority of buildings require some level of heating and cooling (85 per cent of total by floor area). Half of buildings are mechanically ventilated (50 per cent), with the remaining half naturally ventilated. The vast majority of heating systems use natural gas as the main heating fuel and boilers as the main heating plant (75 per cent of total). A further 7 per cent of buildings were connected to a district heating system, and a further 5 per cent were electrically heated. The majority of buildings are anticipated to use radiators as the main heating emitters (77 per cent). 14 per cent of buildings reported that heat pumps (air source or ground source) were the main heating plant for the building.

Cooling is typically supplied via localised refrigerant based cooling units (59 per cent of buildings). 26 per cent of buildings use a centralised cooling system, either water based (18 per cent) or air-based (8 per cent). Where the system is water-based, cooling is typically supplied using fan coil units. Where air-based cooling is typically suppled via Variable Air Volume systems.

Engagement with an industry expert in a semi-structured interview format provided further detail on the challenges and opportunities of HVAC low carbon HVAC technologies in the higher education sector. For the purposes of this discussion, university accommodation buildings were also included with scope. The respondent noted that where a building already has a 'wet' (i.e. water-based) heating distribution system, it is difficult to justify replacing this as part of a retrofit due to the 'sunk costs' and the potential for disruption (e.g. partial or full building shutdown) to complete the works, although it was noted that works can typically be scheduled during summer holidays for the higher education sector. In contrast it was deemed better to utilise an existing system where possible.

The respondent noted a preference for simple HVAC solutions, citing systems such as hybrid heat pumps as requiring twice as much maintenance to manage two systems (heat pump and a boiler). Electric resistive heating systems were cited as offering advantages including simpler and less expensive distribution systems and more responsive, controlled heating. In one example building project overseen by the respondent, a new university accommodation building was constructed with electric resistive heating that was controlled at the level of individual rooms, with heating units switching off when a window was opened. A further expert engaged in this project noted that this strategy is likely to become less attractive should peak heat demand tariffs be introduced creating financial penalties or disincentives.

Further low carbon HVAC technologies were also discussed. Biomass was not an area that the respondent had actively looked into, in part driven by concerns around the complexity of the system and uncertainty around the carbon savings. CHP systems were cited as a useful way of reducing energy cost, driven by the price difference between gas and electricity. In the past CHP systems had offered material carbon savings as well as cost savings, but the decarbonisation of the grid was eroding this saving.

The respondent noted the importance of addressing improvements in building fabric first, before considering replacement of HVAC generation plant. This ensures that the energy demand of the building for heating and cooling is minimised and avoids over specification of plant.

### Leisure centres

Leisure centres are buildings with high levels of HVAC servicing. Leisure centres buildings within the BEES sample were predominantly serviced with heating and cooling (97 per cent of sub-sector by floor area). The vast majority (81 per cent) were mechanically ventilated. 80 per cent use natural gas boilers as the main form of heating. A further 12 per cent of leisure centres use electricity as the main heating fuel, while 6 per cent are connected to a district heating system. 2 per cent of buildings reported using bulk fuels.

The distribution of heating within leisure centres is supplied via a mix of systems – 40 per cent of buildings use radiators, 36 per cent use fan coil units and 18 per cent are understood to use Variable Air Volume systems. Engagement with an industry expert involved in low carbon HVAC retrofit projects in leisure centres revealed the extent of underfloor heating employed in leisure centres. It is anticipated that the BEES data under-predicts the prevalence of underfloor heating in the building stock – buildings with underfloor heating are likely to be reported as using radiators in the BEES data.

65 per cent of leisure centres use a centralised cooling system, either via circulated chilled water (39 per cent), cold air (23 per cent), or refrigerant-based system (2 per cent). A further 32 per cent use localised cooling plant such as DX split units. Cooling is supplied in 97 per cent of leisure centre buildings.

# Appendix C: Challenges of low carbon HVAC retrofit in non-domestic buildings

This appendix outlines a set of challenges generic to all types of non-domestic buildings.

**Network challenges of wide-scale electrification of non-domestic heating and hot water**

The wide-scale electrification of heating and hot water in buildings is expected to require a significant increase in installed generation capacity in the UK. Analysis by Imperial College London for the Committee on Climate Change (2018)[30] has found that in a scenario involving full electrification of UK heat demand, installed generation capacity in the UK would need to total more than 450 GW by 2050 from around 80 GW in 2018[31]. To deliver the carbon savings required to achieve net zero by 2050, this will require significant investment in low carbon electricity generation capacity. It will also require significant distribution network reinforcement to accommodate additional renewable energy generation and demand side flexibility. The generation of hydrogen through electricity-driven processes such as electrolysis may also introduce further reinforcement costs.

A 2019 study by the Committee on Climate Change into the costs of grid reinforcement in response to wide-scale electrification of heat and transport reported that uptake of hybrid heat pumps and electric vehicles could increase total expenditure on distribution networks by £50 billion by 2035 or £1.8 billion per year, representing 4 per cent of the total cost of the electricity system.[32] The National Infrastructure Commission undertook analysis in 2018 to investigate the impacts to peak load electricity by 2050 under various electrification scenarios. Their analysis found that under one scenario the contribution of heating to peak load electricity will reach 49 GW and lead to an additional discounted system cost of £21 billion for reinforcement of the distribution and transmission grid.[33] The costs associated with grid reinforcement are not included in the cost estimates in this study.

The current profile of heat demand in the UK is reflective of the predominance of on-demand, gas driven heating systems. The aggregate peak demand for heat is approximately five times greater than that for electricity. The widespread deployment of technologies such as heat pumps, which operate more efficiently over longer hours. The opportunity to change the demand profile for heating in the UK could reduce the need for increased generation capacity and grid reinforcement.

There is another facet of heat pump performance that creates a challenge for the widescale electrification of heating. The efficiency of heat pumps varies with the temperature gradient between the inside and outside air. On the coldest days of the year, when this temperature difference is very large, the efficiency of the heat pump will be lower. This exacerbates the

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30 https://www.theccc.org.uk/publication/analysis-of-alternative-uk-heat-decarbonisation-pathways/
31 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820708/Chapter_5.pdf
32 https://www.theccc.org.uk/wp-content/uploads/2019/05/CCC-Accelerated-Electrification-Vivid-Economics-Imperial-1.pdf
33 https://www.nic.org.uk/wp-content/uploads/Element-Energy-and-E4techCost-analysis-of-future-heat-infrastructure-Final.pdf

effect of the increased heat demand and means a proportionally larger increase in local distribution networks and generation capacity.[34]

**Capital costs**

Low carbon heating technologies are on average more expensive than traditional fossil fuel equivalents. This study found that the total retrofit costs of a natural gas boiler replacement was on average £240/kW capacity, while for an air-to-water heat pump the equivalent cost was more than £1,500/kW (assuming that the system would be operating over similar hours). Furthermore, the operating costs of low carbon alternative can also be higher. Although heat pumps operate at high levels of efficiency by extracting heat from the external air (typically at efficiencies exceeding 250 per cent, compared with a natural gas boiler at between 87-92 per cent), the difference between the unit price of electricity and natural gas still mean that, on average, the cost of running a heat pump is higher than that of a natural gas boiler.

The replacement of heating and cooling plant in a non-domestic context typically occurs at or towards the end of life of the existing plant, or when there is a change of lease or activity for a building. When considering replacing an existing fossil fuel-based heating system (such as a natural gas boiler) with a like-for-like replacement, or with a low carbon alternative (such as a heat pump), the higher capital and operating costs for the latter can be a high barrier to uptake.

The most commonly perceived barriers to energy efficiency in BEES were economic. For major capital expenditure measures low capital availability was perceived to be the key barrier. Respondents in BEES noted that in many cases measures were not sufficiently profitable to meet internal investment requirements. Evidence from BEES suggests that investments in energy efficiency and carbon abating technologies are typically only made in a commercial context when there is a financial payback, with the most commonly cited threshold being three years.

**Deployment of unfamiliar technology**

As discussed at various points in this report, the operating regimes of low carbon HVAC systems such as heat pumps can be less familiar to building owners and operators than conventional technologies. The technology behind ASHPs may be familiar to energy or building managers for large serviced buildings such as commercial offices, where heat pumps are commonly used for cooling. They may not be familiar to those responsible for smaller buildings. Other technologies, such as biomass boilers are much less common and unlikely to be well understood.

The ubiquity and perceived incomplexity of gas-fired boilers was noted by several participants in this project. The ‘unknown’ element of alternative technologies is perceived as a barrier to entry for retrofit. Barriers related to competency around energy management were commonly cited in BEES. The most commonly cited enablers in BEES - factors that respondents believed

[34] https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

would help them implement energy efficiency measures on site - included improved energy management knowledge.

The lack of system familiarity can lead to poor system specification and management. Participants in the study workshop cited a significant knowledge gap in the industry around low carbon heating system, with upskilling required to support wider uptake. System performance was cited as typically lower than expected due to poor commissioning, maintenance of control. The respondents felt that there is a significant learning rate required for industry, and an improved understanding required around which technologies are scalable to the wider non-domestic stock.

**Other drivers for HVAC replacement**

This study was focussed on the replacement of traditional fossil fuel driven HVAC technologies with lower carbon alternatives to reduce carbon emissions from buildings. However, there may be other reasons for replacing building HVAC systems which are not accounted for in this study. These may be context-specific and dependent on the type of non-domestic building in question.

One illustrative example of this is the replacement of radiators with underfloor heating to facilitate anASHP. The change of emitter system may offer a number of benefits beyond energy efficiency and carbon savings:

- The use of radiant heating, rather than convective heating, may create a more even distribution of building temperature and improve occupant comfort. Radiator-based systems are more prone to overheating due to the more uneven temperature distribution. This can lead to further comfort problems when remedied by building occupants, such as by opening windows.
- The removal of potentially hot surfaces and pipework can offer safety improvements. This may be particularly important in a context where children or the elderly may be present, such as nurseries, schools, nursing homes and hospitals.
- Radiators occupy space within a room – the replacement of radiator with underfloor heating may create more space and be more aesthetically pleasing.

**Wider building-side system changes**

The replacement of traditional heating generation plant with low carbon equivalents may require wider changes to a building HVAC system:

- **Emitters** may need to be resized to increase surface area and provide the same heating supply with a large temperature difference between the flow and return water. Consultation with industry HVAC experts revealed a difference of opinion on this matter. Respondents in some building sectors reported that they believed that heating emitters were in general oversized, with figures cited of between 20 to 50 per cent. One respondent in the office sector believed that the heating demand of office buildings was typically overstated by a factor of 2, with heating plant often specified based on a one-off 'heat up' scenario with no allowance for internal gains from building occupants or IT equipment. In some instances where the fabric condition of an office is adequate, the waste heat from a cooling system may be sufficient to supply all the heating needs of an office building.

- **Fans and pumps** may need to be resized to increase the flow of water or air through the central heating system. This may lead to further capital costs. The operating costs will also increase as energy consumption increases.
- **Controls systems** may need to be re-specified or replaced. With heat pumps employing a different operational regime, a more extensive controls system replacement may be required. This may include room thermostats, radiator controls, wiring and energy sub-metering.

**Disruption**

The retrofit of non-domestic buildings can be disruptive, particularly in cases when major changes are required to distribution systems or emitters. Some retrofit projects may take several days or weeks to complete and may require partial or full shutdown of entire buildings. Some non-domestic buildings, such as hospitals, health centres or emergency service buildings, provide critical services that cannot be interrupted for long periods of time. It may be challenging to reschedule retrofit works.

The most economically advantageous time to undertake a low carbon HVAC retrofit will be at the end of serviceable life of existing plant. These refresh points should be targeted for the introduction of low carbon HVAC technologies.

Some buildings with large heating or hot water demand, such as hospitals, will already have a secondary, backup source of power. This means that the building may be able to operate while heating and cooling generation plant is being replaced with lower carbon alternatives.

**Limitations to the deployment of biomass**

The quantitative modelling in this study assumes no constraints on biomass availability. In reality we anticipate that there will be a finite supply of biomass feedstocks that can be deemed low-carbon. The geographical location and urban/rural setting of each BEES building record did not inform the modelling as these fields were not part of the weighting process designed to create results representative of the non-domestic stock. This is particularly relevant to the modelling of the biomass HVAC solution for which we anticipate local considerations of setting to be applicable, as well as heat pump solutions in buildings which may in reality be cited close to sources of ambient heating beyond the scope of this study, such as water or sewage source heat pumps. The lack of information known about each building's location surroundings means that this granularity of modelling is not possible.

# Appendix D: Project evidence gathering process

**Evidence Gathering**

The literature review was guided by the following research questions:

- Which HVAC technologies are currently employed across the non-domestic building stock of England and Wales?
- Which low carbon HVAC technologies are recognised by the industry as likely to be part of a strategy to decarbonise the supply of heating, cooling, ventilation and hot water in non-domestic buildings in England and Wales?
- How do these technologies compare in terms of cost and performance?

The literature review was designed to gather data points to be used in subsequent modelling to predict the cost and carbon impact of low carbon HVAC technologies. The following information was identified by the study team as a requirement of the literature review:

- **Performance** parameters (e.g. coefficients of performance, asset lifetimes, typical capacities) to enable modelling of the performance implications of low carbon HVAC alternatives;
- **Cost** parameters (e.g. cost of heating plant such as heat pumps, cost of emitters such as radiators) to enable modelling of the costs associated with low carbon HVAC alternatives. These include capital costs of key plant and operational and maintenance costs;
- Information relating to the **technical or commercial constraints** affecting low carbon HVAC technologies in certain contexts. This may allow model tailoring to reflect non-financial barriers (e.g. the typical space requirements for installing aGSHP);
- As a lower priority, **contextual data required for long-range modelling** (e.g. commodity prices for natural gas and electricity, predictions of long-range cost savings for key technologies).

Gathering this breadth of data required a wide search strategy employing a number of different techniques. A series of activities were proposed to collect this data:

- **Literature review:** A desk-based evidence-gathering exercise to identify, review and extract relevant data points from key literature.
- **Industry engagement:** A series of stakeholder engagements, including interviews with experts in key non-domestic building sub-sectors, and experts within the supply chain for HVAC technologies. This is intended to validate data collected during the literature review and address any gaps identified.

## Literature review

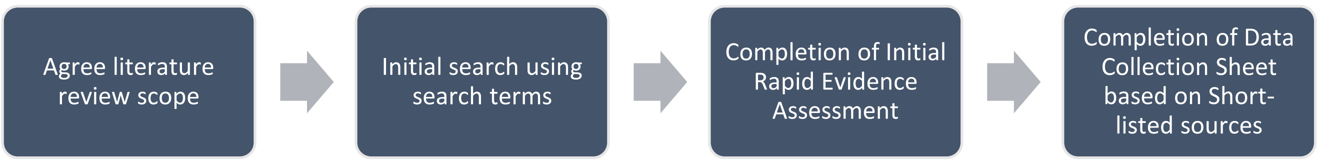
### Literature review preparatory work

Before commencing the literature review, a series of preparatory tasks were undertaken to define the scope of the technologies and exact data points required.

### Literature review methodology

This section outlines the methodology employed in gathering evidence during the literature review. This is summarised below. This followed four steps as illustrated in Figure 9.

**Figure 9: Literature review stages**




### Scope

The review followed the scope outlined in Table 7 below.

**Table 7: Scope of literature review**

| Attribute | Essential | Acceptable |
|---|---|---|
| Geography | England and Wales | Rest of World |
| Time period | 2015 onwards | 2005 onwards |
| Sector | Non-domestic buildings (within scope of BEES) | Domestic buildings<br>Non-domestic buildings (Outside scope of BEES) |
| Technology | Low carbon HVAC technologies | Not applicable |
| Sources | Government literature<br>Independent product field trials | Grey literature |

### Search strategy

The searches were not designed to be exhaustive but to provide at least one data point relating to cost and performance for all of the HVAC technologies within scope. Priority was given to low carbon HVAC technologies over fossil fuel-based technologies given the project focus on identifying a route to decarbonisation for non-domestic building HVAC.

An initial rapid evidence assessment (REA) was first undertaken to identify the number and types of sources available. This was undertaken via web-based searches using target search terms. Composite search terms were generated using combinations of key information sources (e.g. BEIS, DECC, Gov), key technologies (e.g. air source heat pumps), key geographies (e.g. UK) and other relevant terms (e.g. low carbon heating, low carbon HVAC). Examples of some of the search terms employed are listed in Table 8. These search terms were used in standard internet searches and using proprietary academic databases.

**Table 8: Examples of search terms used in REA**

| **Search Term** | |
|---|---|
| low carbon heat UK | low carbon heat retrofit |
| absorption chillers UK | non-domestic building services |
| absorption cooling UK | non-residential building services |
| air source heat pump UK | Retrofit HVAC performance non-domestic buildings UK |
| air to air heat pump UK | Retrofit HVAC performance non-residential buildings UK |
| biomass heating UK | reversible air to air heat pumps |
| commercial biomass UK | solar heating |
| industrial biomass | solar industrial heating |
| commercial chiller | UK heat networks |
| District heating UK | water to air heat pump |
| energy efficiency non-residential | water to water heat pump |
| ground couplet heat pump | UK low carbon HVAC |
| ground source heat pump | BEIS low carbon heating |
| HVAC performance non-domestic buildings UK | DECC low carbon heating |
| HVAC performance non-residential buildings UK | Gov.uk low carbon heating |
| HVAC system performance | UK low carbon heating review of evidence |
| hybrid ground coupled heat pump | UK heat pumps review of evidence |
| industrial chiller | low carbon heat committee on climate change |
| Industrial decarbonisation | |

The following sources were identified as likely to provide useful cost and performance data for this study. Some of these were incorporated into the search terms.

- Central and Local Government (e.g. BEIS, GLA)
- Industry reference Guides on cost and performance (e.g. SPONS)
- NDPB Reports (e.g. Committee on Climate Change)
- Professional bodies (e.g. CIBSE)
- Industry groups/trade associations/think-tanks (e.g. Federation of European Heating, Ventilation and Air Condition Associations)

- Academic literature
- Grey literature i.e. manufacturer published materials for key HVAC technologies
- Case study data from Currie & Brown's costings database

The database of sources, including basic information such as title, author, URL, key topic areas and data of publication were provided to BEIS as a deliverable.

In addition to desk-based web searches, further strategies were employed to identify additional sources of evidence:

- **Internal information requests:** A call for evidence was issued within BEIS by the Project Officer to relevant colleagues asking for information. An information request was also issued within the Verco team and further sources were identified. A further request for information was issued within the Currie & Brown team and sources identified that had not already been collected in the literature review.
- **Review of BEES data:** A review of the reference sources employed in developing the BEES Energy End Use Model and Abatement Model yielded further sources which were added to the Data Collection Sheet.
- **'Trawling' of document referencing:** The literature review process was iterative in that key references within each of these reports selected for detailed review were themselves checked against the list of sources and additional sources added. These are included in the total number of sources identified.

**Completion of Initial Rapid Evidence Assessment**

This REA led to the identification of 121 sources. The sources were initially scored according to quality and relevance to the goals of this commission. To enable this, the study team captured the information outlined in Table 9 for each source.

**Table 9: Table of information captured during REA**

| Section | Parameter |
|---|---|
| Reviewer | Date of review |
| | Reviewer ID |
| Study details | Study ID |
| | Study Title |
| | Link |
| | Author |
| | Publication Date |
| Scope | Geography |
| | Technology |
| | Sectors considered |
| Quality | Purpose and methodology of study |
| | Study type (qualitative/quant etc.) |
| Applicability | Useful for study? |
| | Number of performance-related data points |
| | Number of cost-related data points |
| | References explored for other sources? |
| | Comment |

At this stage, 69 sources were excluded on the grounds of one or more of the following criteria:

- **Time period:** it was deemed that sufficient time had elapsed for the source to be unrepresentative of current cost and performance standards for HVAC technologies;
- **Geography:** the findings of the source were not relevant or well suited to the context of the UK, either for climatic or political reasons or for reasons of commercial context;
- **Context:** this study is focussed on the use of HVAC technologies in a commercial or non-domestic context. Many information sources were undertaken in a domestic context and were deemed unsuitable for this commission’s purposes.
- **Other:** a small number of sources were screened out before more detailed review for various other reasons. These included sources which covered the relevant topic area at a high-level (therefore lacking technical detail).

**Completion of Data Collection Sheet based on short-listed sources**

Following this step, the sources deemed most likely to provide important cost and performance parameters were reviewed in greater detail. Some sources were discarded from the detailed review following further investigation, and others were re-included once the team had fully reviewed the content. The team identified 52 sources for more detailed review.

Cost and performance parameters relevant to any of the HVAC technologies within the scope of this project were extracted and documented in a Data Collection Sheet. The structure of the Data Collection Sheet was designed to maximise flexibility by allowing the study team to capture all types of cost and performance parameter relevant to each technology. Evidence sources are first recorded in the 'Source overview tab' and key contextual data entries populated, such as the author, date and coverage of the source in terms of technology and geography. If cost and performance parameters are provided by the source, these are entered in the 'Data Collection Sheet Extract' tab. The completed Data Collection Sheet is available as part of this project's deliverables.

## Gap analysis

Following the literature review, the data captured in the Data Collection Sheet was reviewed against the requirements to ensure coverage. The HVAC technologies outlined in Table 10 were selected for further investigation. To address these evidence gaps, a programme of stakeholder engagement with supply chain experts and experts in specific non-domestic building sectors was proposed. The details of this are outlined in the accompanying note entitled 'BEIS low carbon HVAC - interview plan'

**Table 10: HVAC technologies identified as requiring further investigation following literature review**

| HVAC technology | Proposed remedy | Comment |
|---|---|---|
| Electric resistive heaters/radiant panel heaters<br>Electric convector panels | Focus technology for supply chain interviews | Forms of resistive and radiative heating are anticipated to be a viable alternative to natural gas heating for industrial applications, but cost and performance data was not sufficiently comprehensive from a review of literature. |
| Ground source heat pumps | Focus technology for supply chain interviews | While performance data was comprehensive from the literature review, costing information was highly varied and was contingent on local context in many examples. Some costing figures included distribution and emitters, while others did not. |

# Appendix E: Project industry engagement approach

A requirement of this study was to undertake in-depth analysis of specific sub-sectors of the non-domestic stock that either represent significant proportions of non-domestic HVAC energy use or are considered to have more complex HVAC systems, or both. The six sub-sectors outlined in Appendix B were selected for this review.

As part of this analysis, a series of engagement activities were required with relevant experts in each of the building types above. A programme of semi-structured interviews were therefore organised. The purpose of the interviews was to:

- validate the project approach to modelling low carbon HVAC for key BEES sub-sectors
- address evidence gaps identified during the literature review;

A total of eight interviews were undertaken. The interviews were semi-structured to allow for consistency of outcomes, but also allow for the exploration of sub-sector specific issues relevant to the wider evidence gathering and modelling undertaken on this project.

The interviews covered the following thematic areas:

1. HVAC configurations common to the relevant sub-sector;
2. Possible low carbon HVAC alternatives relevant to the sub-sector;
3. Implementation challenges/constraints for low carbon HVAC alternatives;
4. Relevant case study examples of low carbon HVAC retrofit in the sub-sector;
5. Relevant sources of cost and performance data for HVAC technologies in the sector.

The projects interviews each lasted approximately 50 minutes and were conducted via telephone. Minutes were noted using a data collection sheet. A ‘topic guide’ was used to steer the discussion, providing details on the topic areas and questions to be discussed along with scripted prose for key sections of the questionnaire.

To address points a). and b). above the participant was presented with a schematic summarising the consortium’s understanding of the most common HVAC system configurations in place in the participant’s sector of expertise. This was based on analysis undertaken by the consortium as outlined in the bulk of the report. The participant was invited to comment on this diagram and its consistency with their professional experience. Observations were recorded in a data collection sheet. An example of such a schematic is provided in Figure 10 for the ‘industrial’ sector.[35]

[35] This is a wider definition than merely Factories, also including the sub-sectors ‘Workshops’ and ‘Large Industrial’

The left-hand side of the schematic shows the five most common HVAC archetypes in the 'industrial' sector based on analysis of BEES data weighted up to the non-domestic building population. These five archetypes cover 87 per cent of the retail building stock. 51 per cent of buildings (by total floor area) use localised gas heating (such as gas radiant panel heaters). This is the most common archetype in the industrial sector. The second most common archetype are those buildings with a natural gas boiler supplying fan coil units or radiators, with local refrigerant cooling in certain spaces where required. Three further archetypes are also presented. The right-hand side of the schematic is a list of low carbon HVAC alternatives considered in this study, with the lines from left to right showing which solutions are being considered as technically feasible for each archetype.

Table 11 provides a summary of the organisations and sub-sectors represented by the sub-sector expert interviewees. Candidates for interviews were identified by the study team through known contacts within the industry.

**Figure 10: Example of sub-sector deep dive interview reference schematic for industrial**

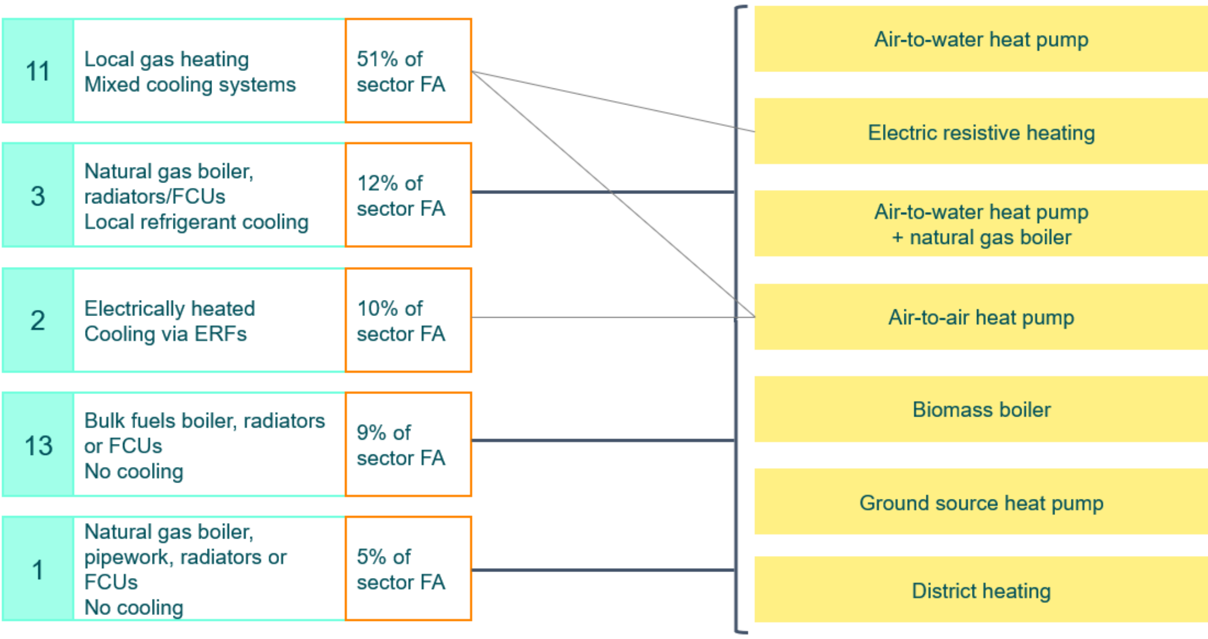



**Table 11: Summary of organisations represented by sub-sector expert interviewees**

| Sub-sector | Organisation summary |
|---|---|
| Factories | Energy efficiency consultancy |
| Factories | Manufacturer of construction materials |
| Factories | Manufacturer of dairy products |
| Higher Education | UK university |
| Hospitals | Energy project developer |
| Large food shops | Large retailer |
| Leisure centres | Swimming pool ventilation contractor |
| Office | Professional services firm |

The findings from the interviews were summarised in a separate document can be found documented throughout this report in the discussion of findings.

**Supply chain engagement**

In addition to sub-sector experts, the study team engaged with stakeholders involved in the supply chain for low carbon HVAC technologies of interest. The supply chain tends to be a reliable source of performance and cost data, provided that bias is considered and corrected for. The purpose of this engagement was to:

- Provide generic costing information for systems that the respondent is specialist in;
- Address specific knowledge gaps in the cost and performance data gathered through the literature review.

Subsequent to the literature review outlined above, the following areas were identified as requiring further exploration through engagement with supply chain experts:

- Cost and performance information for GSHP technologies and insight on applicability to retrofit in non-domestic sector;
- Cost and performance information for ASHP technologies and insight on applicability to retrofit in non-domestic sector;
- Cost and performance information for cooling technologies.

These areas were chosen either because the literature review did not provide sufficient quantity or quality of data to close off investigations, or because the technologies were deemed to be material to the low carbon HVAC strategy for England and Wales and therefore merited further investigation, in particular around applicability to certain non-domestic contexts.

The interviews covered the following thematic areas:

- Technology and cost parameters collected during the literature review for the participant's technology specialism;
- The challenges and opportunities in implementing the expert's specific technology;
- The participant's involvement in any low carbon HVAC studies'
- Any further evidence or industry case studies that the participant was aware of that may have been of relevance.

Table 12 provides a summary of the organisations and technologies represented by the supply chain expert interviewees.

**Table 12: Summary of organisations represented by supply chain interviewees**

| HVAC technology | Organisation summary |
|---|---|
| Cooling plant including chillers, air handling units, fan coil units and chilled beams | Two air-conditioning engineering firms |
| Fuel cell technology | Fuel cell CHP technology developer |
| Ground source heat pump | UK ground source heat pump manufacturer and installer |
| Air source heat pump | Energy efficiency consultancy |

As part of these interviews the participants were presented with a table or set of tables summarising cost and performance data for the technology of their specialism. This information had been gathered during the literature review. The participant was invited to comment on this diagram and its consistency with their professional experience. Observations were recorded in a data collection sheet. An example is provided in Figure 11 showing performance parameters for ground source heat pump technology.

**Figure 11: Graphic used during interview with ground source heat pump supply chain expert**

**Examples of performance data for GSHPs from literature review**

| COP value | Conditions |
|---|---|
| 3.85 | GSHP @ 35 ° flow temperature |
| 3.65 | GSHP @ 45 ° flow temperature |
| 3.35 | GSHP @ 55 ° flow temperature |
| 3.05 | GSHP @ 60 ° flow temperature |
| 2.85 | GSHP @ 65 ° flow temperature |

**Source:** Low Carbon Heat: Heat pumps in London, GLA (2018)

| COP value | Conditions |
|---|---|
| 2.94-4.69 | Kensa G2W - manufacturer test data |

**Source:** Low Carbon Heat: Heat pumps in London, GLA (2018)

| SPF value | Conditions |
|---|---|
| 2.93 | Mean overall SPF for GSHP - H2 system boundary |
| 3.03 | Mean space heating SPF for GSHP - H2 system boundary |
| 2.7 | Mean DHW SPF for GSHP - H2 system boundary |
| 2.77 | Mean overall SPF for GSHP - H4 system boundary |
| 2.81 | Mean space heating SPF for GSHP - H4 system boundary |
| 2.61 | Mean DHW SPF for GSHP - H4 system boundary |

**Source:** Final report on the analysis of heat pump data from the renewable heat premium payment (RHPP) scheme, UCL (2017)

| COP value | Conditions |
|---|---|
| 4.55 | 5 ° C at evaporator inlet and 30 °C at condenser |
| 4.1 | 5 ° C at evaporator inlet and 35 °C at condenser |
| 3.7 | 5 ° C at evaporator inlet and 40 °C at condenser |
| 3.4 | 5 ° C at evaporator inlet and 45 °C at condenser |
| 3.15 | 5 ° C at evaporator inlet and 50 °C at condenser |
| 5.3 | 10 ° C at evaporator inlet and 30 °C at condenser |
| 4.65 | 10 ° C at evaporator inlet and 35 °C at condenser |
| 4.15 | 10 ° C at evaporator inlet and 40 °C at condenser |
| 3.75 | 10 ° C at evaporator inlet and 45 °C at condenser |
| 3.45 | 10 ° C at evaporator inlet and 50 °C at condenser |

**Source:** General review of ground-source heat pump systems for heating and cooling of buildings, Sarbu & Sebarchievici (2014)

**Typical COP value**
2.85-3.85 depending on flow temperature

The interviews lasted approximately 40 minutes each and were conducted via telephone. Data captured during the interview was recorded in an interview topic guide. Alongside minutes from each call, the findings from the interviews were summarised in a separate document and can be found documented throughout this report in the discussion of findings.

# Appendix F: Application of HVAC system framework to literature review

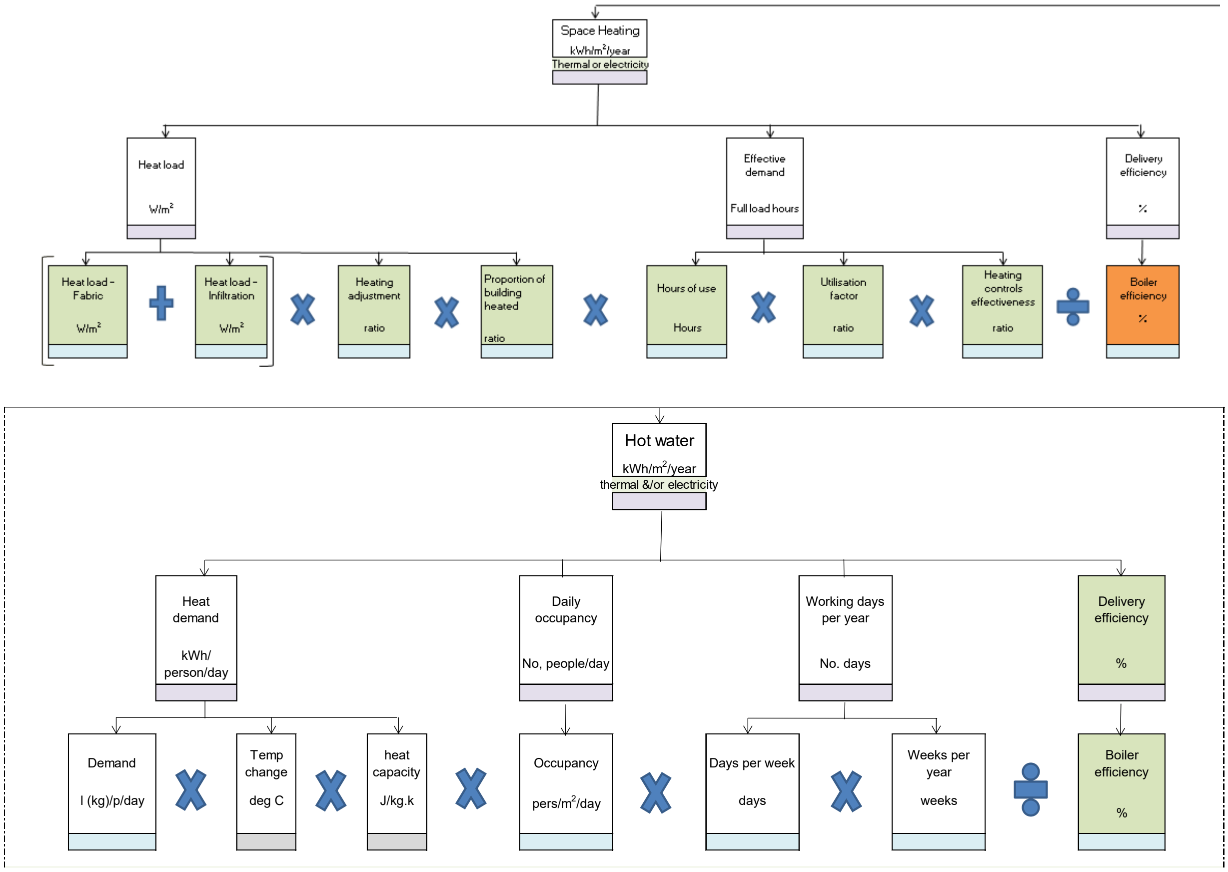
Figure 5 outlines the framework for describing the HVAC setup in each modelled building record. However, not all of the individual parameters in this table required the collection of associated cost and performance metrics. Some are descriptors of a system (for example the description of a building a requiring ‘heating only’ does not describe an associated element of HVAC plant). The study team therefore created a consolidated list of the key HVAC components for which cost and performance parameters were needed. These parameters are outlined in this appendix.

**Performance parameters**

During BEES, the calculation of energy intensities by building end use was conducted in a bottom-up approach using a child and grandchild variable methodology[36]. Two examples are provided for the ‘space heating’ and ‘hot water’ energy end uses in Figure 12. For space heating, the energy intensity was calculated using three child variables – heat load, effective demand, and system delivery efficiency. Each child variable was comprised of constituent grandchild variables – for example heat load was calculated using the sum of the heat load derived from the building’s fabric and infiltration rates, multiplied by the proportion of the building heated and any adjusted required to account for energy management practises.

[36] A child variable is a variable used to calculate the energy use intensity for a given energy end use. A grand-child variable is a sub-variable of a child variable.

**Figure 12: Examples of energy end use tree diagram used to construct the BEES Energy Use model**




## Cost parameters

The HVAC system components with a material cost were included in the literature review search and prioritised for recording in the Data Collection Sheet. For example, the key elements of a transition to an air source heat pump include a). the capital cost of the air source heat pump and b) the replacement of any emitters or distribution pipework, if using a low temperature distribution system. The table below shows examples of individual cost elements included in the modelling. These cover preparatory works, main installation and completion phases of a retrofit project.

**Table 13: Breakdown of cost parameters**

| Stage | Step |
|---|---|
| **Preparatory Works** | Strip out existing boiler and other redundant system items |
| | Strip out existing FCU and other redundant system items |
| | Builders work to create space/housing for new system |
| | Transformer uplift to provide additional capacity |
| **Installation** | ASHP installation |
| | Pumps, expansion vessel, pressurisation unit, pipework |
| | Power to ASHP |
| | Buffer tank |
| | Central BMS / Controls (Variable speed drive with multiple pressure sensors - BACS metering) |
| **Completion** | Service Pumps, expansion vessel, pressurisation unit, pipework |
| | Service drives on pumps (Variable speed drive with multiple pressure sensors - BACS metering) |
| | Service Floor/zone controls |
| | Flush out Distribution system; pipework |
| | Replace Heat emitters with larger LTHW heat emitters |

# Appendix G: Low carbon HVAC technologies modelled

Through evidence review and consultation with industry the study team developed a list of low carbon technologies that could be considered for non-domestic buildings as alternatives to the fossil fuel-driven technologies currently in place.

1. **Air-to-water heat pump:** Installation of an air source heat pumps or set of ASHPs capable of supplying all of the annual heating demand for the building. The heat pump(s) supply low temperature hot water for a central heating system. The modelling also includes a separate measure of a high-temperature air-to-water heat pump.

2. **Electric resistive heating:** installation of electrical convector or radiant panels capable of meeting all of the building's heating needs.

3. **Air-to-air heat pump:** Installation of an air source heat pumps or set of ASHPs capable of supplying all of the heating demand for the building. The heat pump(s) supply heating via an air-based Variable Air Volume system. Where cooling is required by the building as well as heating, it is assumed that this is a reversible heat pump.

4. **Air-to-water heat pump + natural gas boiler:** Installation of an air source heat pumps or set of ASHPs capable of supplying the majority of the annual heating demand for the building. The heat pump(s) supply low temperature hot water for a central heating system. The natural gas boiler already in place is retained and becomes the secondary heating plant, used during winter peaks as a backup in the case of faults with the ASHP. Where cooling is required by the building as well as heating, it is assumed that the heat pump is reversible. The hybrid heat pump option provides an advantage over a sole heat pump solution in terms of resilience. It also offers advantages at the national level, driving more efficient system outcomes.[37]

5. **Ground source heat pump:** Installation of a ground source heat pump capable of supplying all of the annual heating demand for the building. The heat pump(s) supply low temperature hot water for a central heating system. Where cooling is required by the building as well as heating, it is assumed that this is a reversible heat pump.

6. **Biomass boiler:** Installation of biomass boiler or set of boilers, or the modification of an existing natural gas-fired boiler system (where present) to be fired with biogas. It is assumed for the purposes of this study that biomass or biogas is delivered to site. The costs of on-site storage of biomass are not considered in the analysis for this study.

A series of further alternatives were considered and not taken forward for modelling:

1. **Hydrogen boiler:** Installation of hydrogen boiler or set of boilers, or the modification of an existing natural gas-fired boiler system (where present) to be fired with hydrogen. This alternative was not included within this study due to the highly nascent hydrogen market and the associated uncertainties with future prices and methods of production/distribution.

2. **Combined Heat and Power:** CHP involves the co-generation of heat and power from burning a fuel source such as natural gas or biomass. While uncommon in the overall non-domestic stock, CHP is considered applicable for buildings with high and constant heating and hot water demand such as hospitals, industrial buildings or leisure centres.

[37] https://www.ofgem.gov.uk/system/files/docs/2016/11/ofgem_future_insights_programme_-_the_decarbonisation_of_heat.pdf

Gas-driven CHP engines have in recent years been seen as economically advantageous driven by the price difference between the unit cost of electricity and natural gas, known as the 'spark spread'. Electricity is generated from a comparatively low-cost fuel, displacing the cost of purchasing electricity from the grid at a comparatively higher cost. CHP can also offer benefits in terms of resilience and providing CHP operators with access to markets for grid-balancing services which can offer a source of revenue.

The carbon benefit of using gas-driven CHP has diminished in recent years driven by the reduction in average grid carbon intensity of UK electricity. Given the long-term modelling horizons of this commission the study team did not deem CHP to be a 'low-carbon' HVAC alternative. While biomass-driven CHP can offer a low carbon alternative, it was not felt that this solution was sufficiently different to the 'biomass boiler' option in terms of carbon impacts. It was also anticipated that very few buildings would be suitable for this solution so was ruled out on 'de minimis' grounds.

3. **Heat pump/hydrogen hybrid:** An alternative to the 'Air-to-water heat pump + natural gas boiler' solution was considered in which the boiler element of the hybrid system was powered with hydrogen rather than natural gas. This was discounted from analysis following the industry engagement as participants reported that this solution was too technically complicated and currently unproven.

4. **District heating:** the viability of district heating as a source of heating and cooling is dependent on a number of local, context-specific factors. These include a large amount of space, proximity to an energy source and proximity to other buildings which may be connected to the same energy network. The information for each BEES building record did not allow for an accurate assessment of these factors

5. **District heating/air source heat pump hybrid:** for the reasons outlined in point (3).

6. **Water/Sewage source heat pumps:** Beyond the air source and ground source heat pumps, there are further sources of heat that can be accessed using heat pumps to supply building HVAC. Water-source and sewage-source heat pumps are further examples. These were not considered in this study because, like district heating, the viability of these technologies is dependant on highly context specific factors, principally the proximity of the building to a relevant heat source.

7. **Heat pump + underfloor heating:** it may lead to greater system efficiency to concurrently replace heating emitters with underfloor heating when applying a heat pump. The BEES survey did not include a question on underfloor heating for all sub-sectors.

# Appendix H: Archetype to HVAC solution screening

This appendix outlines a series of HVAC system transition scenarios that were excluded from the modelling. Figure 13 provides an illustration of the scenarios discounted at this stage. The numbers in this table correlate to the assumptions outlined below.

(1) Where a building has a centralised system for heating and/or cooling it is preferable to retain the current distribution system and medium (e.g. water, air, refrigerant) and replace the generation plant with a lower carbon alternative. This assumption was applied for several reasons. Firstly, the costs associated with the full-scale replacement of a heating distribution system – such as a system of pipework and radiators – was deemed to be excessively high to be justified for carbon reasons, especially where an appropriate low carbon heating alternative exists that allows the existing distribution system to be retained and repurposed. For example, for a building with direct gas radiant heating, it was deemed in appropriate to retrofit a wet distribution system of pipework and emitters at significant cost to enable an air to water heat pump, where an air to water heat pump could deliver equivalent carbon savings at much lower cost. In this example, the type of heating servicing offered by an air to air heat pump is also similar to that of the existing system, offering an additional benefit. In addition to the cost, the level of disruption and technical risk associated with the wholesale change of distribution systems was deemed to be too high, making it unlikely that this would be a favoured option by building operators and managers.

(2) Sites already using an air source heat pump, ground source heat pump, biomass boiler or have a connection to a district heating are already using one of the low carbon technologies considered by this study and should not be transitioned to a different system. For these buildings, only a BAU replacement was modelled.

(3) For buildings that use bulk fuels (such as oil or LPG) as a main heating fuel (and therefore are assumed to not be connected to the gas grid) which can be fitted with heat pumps, electric resistive heating or connection to district heating schemes.

(4) For buildings with localised heating solutions such as radiant gas heating, only similarly localised low carbon solutions were proposed.

(5) Transitions for which the existing and proposed replacement technology were not sufficiently different.

(6) Transitions for which the existing and proposed replacement technology did not represent a significant carbon saving.

(7) Buildings reported to have no heating system were not modelled for a heating system transition.

**Figure 13: HVAC transition scenarios selected for modelling**

| Archetype | % of stock by floor area | Description | BAU | LT A2W HP | Electrification | A2A HP | A2W HP/Gas Boiler Hybrid | GSHP | DH | Biomass boiler | HT A2W HP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | 8% | Gas radiant heating, variable cooling | | 1 | | 4 | 1 | 1 | 1 | 1 | 1 |
| 1 | 18% | Gas boiler, pipework, radiators or FCUs. No cooling | | | | 5 | | | | | |
| 3 | 12% | Gas boiler, pipework, radiators or FCUs. Local refrigerant cooling | | | | 1 | | | | | |
| 2 | 11% | Electric resistive heating, no cooling | | 1 | 5 | | 1 | 1 | 1 | 1 | 1 |
| 4 | 9% | Gas boiler, wet system, central | | | | 5 | | | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | chilled water cooling | | | | | | | | | |
| 5 | 8% | Gas boiler, wet system, central air cooling | | | | 5 | | | | | |
| 13 | 5% | Bulk fuels boiler | | | | 5 | 3 | | | | |
| 6 | 3% | Air-to-air heat pump, local refrigerant cooling | | 1 | 5 | 5 | 1 | | | | |
| 12 | 11% | Local gas warm air heating, variable cooling | | 1 | 6 | | 1 | | | | |
| 8 | 3% | Electric resistive heating, central air cooling | | 1 | 6 | | 1 | | | | |
| 28 | 2% | Air-to-air heat pump, central air cooling | | 1 | 5 | 5 | 1 | | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 3% | Electric resistive heating, central chilled water/refrigerant cooling | | 1 | 5 | | 1 | | | | |
| 27 | 1% | Air-to-air heat pump, central chilled water/refrigerant cooling | | 1 | 5 | 5 | 1 | | | | |
| 9 | 2% | No heating or cooling | 7 | | | | | | | | |
| 14 | 1% | Heat pump | | 2 | | | | | | | |
| 10 | 1% | No heating - just cooling | | 7 | | | | | | | |
| 16 | 1% | Gas boiler, wet system, cooling with VRV/VRF | | | 1 | | | | | | |
| 17 | 1% | District Heating | | 2 | | | | | | | |
| 18 | 0% | Biomass | | 2 | | | | | | | |

# Appendix I: External validation of project methodology

The study team sought external validation of the following project elements:

- the overall project approach to categorising buildings into archetypes based on HVAC characteristics;
- the cost and performance parameters to be used as the basis for quantifying the potential for low carbon HVAC systems
- the building and stock-level modelling outputs;
- the technical report.

Two external validation activities were undertaken:

- engaging a panel of experts via an independent trade body for a project approach review workshop;
- commissioning an industry expert for a detailed review of the modelling inputs and outputs.

The following section provides an account of these two validation exercises.

## Project approach workshop

The purpose of holding a project review workshop was to:

- invite scrutiny from sector experts on the project approach and methodology;
- seek validation of key performance and cost parameters gathered during the literature review;
- highlight and sense check known areas of weakness and steps taken to address them; and
- test the building archetype approach through a series of case studies in six key building sectors.

A workshop format was agreed by the study team to be the most effective method of validation as it allowed for open discussion among experts from different backgrounds and industries, and for focussed discussion of specific sectors and archetypes through a case study approach.

The workshop was organised in conjunction with the HVAC Systems Group of the Chartered Institution of Building Services Engineers. The attendees of the workshop included representatives from building performance & services engineering companies, industry & trade associations, design & engineering consultancies and energy & environmental management consultancies. The format and agenda were agreed with the BEIS team and comprised the following elements:

- Project aims and objectives. The overarching research questions were outlined.
- Project methodology discussion. The project methodology, assumptions, outcomes of industry engagement and outstanding decision points were outlined in detail to the panel and then opened up for discussion and scrutiny.
- Case study review. The group was separated into three cohorts. Each cohort were presented with the following relating to one of the six key building types for this study.
- The findings from the interview with the relevant sector expert (undertaken previously in the study). This consisted of comments on the viability of certain low carbon HVAC technologies in the given building type. The participants were asked to give their reflections.
- A description of the most common building HVAC setup found in the cohort for that building type. In some cases where the stock was heterogenous, two cases studies were presented. The participants were asked to consider and discuss the most appropriate options for low carbon HVAC retrofit. Each cohort looked at two different building types, meaning that all six were discussed.
- The main discussion points and findings of the workshop were summarised by the workshop host followed by final reflections from attendees.

The main discussion points were documented. Key reflections and findings can be found throughout this report.

**Model review**

The second element of the validation required an external expert to undertake a review of the modelling inputs and outputs. This consisted of reviewing the following:

- A table of performance parameters for key HVAC technologies, including lifetimes, coefficients of performance and efficiencies. This information had been gathered from the earlier extensive literature review and interviews with both supply chain experts and experts in specific building sectors;
- The cost breakdown for a series of notional HVAC transition scenarios;
- the cost and performance parameters to be used as the basis for quantifying the potential for low carbon HVAC systems;
- External review of building and stock-level modelling outputs;
- External review of the final technical report.

To conduct this review an individual with extensive experience of non-domestic building energy use and low carbon HVAC systems was engaged.

This publication is available from: www.gov.uk/government/publications/evidence-update-of-low-carbon-heating-and-cooling-in-non-domestic-buildings